Stainless and Carbon Steel Bolts Subjected to Tension and Shear Loading

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Dedication

For my beloved parents and my wife Hastia

“All life is problem solving.”
Karl Raimund Popper

Abstract

In steel structures, bolted connections made of austenitic and duplex stainless steel according to EN 1993-1-4 are predominantly designed and executed as non-preloaded category A (pure shear) bearing type connections, category D (pure) tension connections or as category A+D bolted connections subjected to combined tension and shear loading. The current European design rules were initially developed for carbon steel bolts and specified in EN 1993-1-8. However, the load bearing behaviour of austenitic and duplex stainless steel bolts is significantly affected by their specific material properties, such as nonlinearity, pronounced strain hardening and a transformation of austenitic to forming induced martensitic material in the tensile cross-section originating from the thread rolling process with a larger hardness and higher strength in the border of the cross-section of the threads. These specific material properties must already be considered in the design of these bolted connections. Therefore, it was crucial to address this normative gap through comprehensive investigations.

The load bearing behaviour of austenitic and duplex stainless steel bolts, as well as bolting assemblies, has been systematically examined through a combination of experimental and numerical investigations, complemented by reliability analyses. These comprehensive studies, conducted as part of the German IGF research project FOSTA P 1386/IGF-No. 20651 N, have been further extended through additional independent research at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen, Germany. The investigations comprised pure tension, single-shear and combined tension and shear loading scenarios. Finally, new and more economical "Ease of Use" design rules were proposed. These include an increase of the tension resistance $F_{t,Rd}$ of stainless steel bolts by $k_2 = 1.0$ (except countersunk bolts) harmonised with EN ISO 3506-1 regarding the minimum ultimate tensile load F_{mf}, new (higher) shear coefficients α for the shear resistance $F_{v,Rd}$ and new elliptical interaction equations for the unthreaded and threaded bolt part in the shear plane of stainless steel bolts. The proposed design rules were statistically verified in reliability analyses according to EN 1990, Annex D against $\gamma_{M2} = 1.25$ for connections, and implemented in the revision of EN 1993-1-4, FprEN 1993-1-4, and the renewed German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022.

In this thesis, the background of the new proposed design rules for stainless steel bolts was outlined, discussed in the context of different international design concepts, and extended by supplementary experimental and numerical investigations into the tension and single-/double-shear resistance of bolts and bolting assemblies. The correlation between tensile strength and shear strength was analysed in direct and indirect multi-step pathway analyses, and the steel grade and bolt property class were identified as key parameters.

Furthermore, extended statistical evaluations according to EN 1990, Annex D were performed and complemented by distribution analyses to prove the resulting partial safety factors γ_M* against the Eurocode safety requirements. Here, new assessment criteria were developed. Moreover, the conservative European design regulations of EN 1993-1-8 regarding the tension/shear carbon steel bolted connections were statistically re-evaluated since numerous recent experimental studies on carbon steel bolts have emerged but require further validation through statistical analysis. They were complemented by own experimental studies into the tension, single/double-shear and interaction resistances of carbon steel bolts. Combined with a thorough literature review, these findings were integrated into renewed reliability analyses to investigate the suitability of the existing design approaches. The culmination of the research efforts led finally to the proposal of new and more economical design rules for carbon steel bolts, which are harmonised with the proposed new design rules for austenitic and duplex

stainless steel bolts according to FprEN 1993-1-4 and in line with the normative requirements of EN ISO 898-1.

In conclusion, the newly proposed design rules for structural stainless and carbon steel bolts demonstrate their suitability in accurately describing the bolt tension, shear and interaction behaviour. These proposed rules offer engineers a coherent and “Ease of Use” design concept that fully aligns with the safety requirements of the Eurocode. Additionally, new annexes were proposed as amendments for future revisions of EN ISO 3506-1 and EN ISO 898-1, dealing with simplified test procedures for the shear and interaction resistance of stainless and carbon steel bolts.

Kurzfassung

In Stahlkonstruktionen werden Schraubenverbindungen aus nichtrostendem austenitischen und Duplexstählen nach EN 1993-1-4 überwiegend als nicht vorgespannte Scher/ Lochleibungsverbindungen der Kategorie A (reine Scherverbindungen), als (reine) Zugverbindungen der Kategorie D oder als Schraubenverbindungen der Kategorie A+D unter kombinierter Zug- und Abscherbeanspruchung bemessen und ausgeführt. Die aktuellen europäischen Bemessungsregeln hierzu wurden ursprünglich für Schrauben aus Kohlenstoffstahl entwickelt und in EN 1993-1-8 festgelegt. Jedoch wird das Tragverhalten von nichtrostenden austenitischen und Duplex-Schrauben durch ihre spezifischen Werkstoffeigenschaften, wie Nichtlinearität und ausgeprägte Kaltverfestigung, und eine durch das Gewindewalzen hervorgerufene Umwandlung von austenitischem in umformbedingtes martensitisches Material im Gewinde mit größerer Härte und Festigkeit im Randbereich des Gewindequerschnitts. Diese spezifischen Materialeigenschaften müssen bereits bei der Bemessung dieser Schraubverbindungen berücksichtigt werden. Daher war es wichtig, diese normative Lücke durch umfassende Untersuchungen zu schließen.

Daher wurde das Tragverhalten von Schrauben und Schraubengarnituren aus nichtrostendem austenitischen und Duplexstahl durch eine Kombination von experimentellen und numerischen Untersuchungen sowie statistischen Bewertungen systematisch untersucht. Diese umfangreichen Studien, die im Rahmen des deutschen IGF Forschungsvorhabens FOSTA P 1386/IGF-Nr. 20651 N durchgeführt wurden, sind durch zusätzliche unabhängige Forschungsarbeiten am Institut für Metall- und Leichtbau der Universität Duisburg-Essen, Deutschland, erweitert worden. Die Untersuchungen umfassten reine Zug-, Einzelabscher- und kombinierte Zug- und Abscherbelastungen. Schließlich wurden neue und wirtschaftlichere Bemessungsregeln vorgeschlagen, die eine einfache Anwendung ermöglichen. Diese beinhalten eine Erhöhung der Zugtragfähigkeit $F_{t,Rd}$ von Schrauben aus nichtrostendem Stahl um $k_2 = 1{,}0$ (mit Ausnahme von Senkkopfschrauben), harmonisiert mit EN ISO 3506-1 hinsichtlich der Mindestbruchkraft F_{mf}, neue (höhere) Scherfestigkeitskoeffizienten α für die Abschertragfähigkeit $F_{v,Rd}$ und neue elliptische Interaktionsgleichungen für Schraubenschaft bzw. Schraubengewinde in der Scherfuge für Schrauben aus nichtrostendem Stahl. Die vorgeschlagenen Bemessungsregeln wurden in Zuverlässigkeitsanalysen nach EN 1990, Anhang D gegen $\gamma_{M2} = 1{,}25$ für Verbindungen statistisch verifiziert und in der Überarbeitung von EN 1993-1-4, FprEN 1993-1-4, und der erneuerten allgemeinen bauaufsichtlichen Zulassung/Allgemeinen Bauartgenehmigung abZ/aBG Z-30.3-6:2022 umgesetzt.

In dieser Thesis wurden die Hintergründe der neu vorgeschlagenen Bemessungsregeln dargestellt, im Kontext verschiedener internationaler Bemessungskonzepte diskutiert und durch ergänzende experimentelle und numerische Untersuchungen zur Zug- und Einzel-/ Doppelscherfestigkeit von Schrauben und Schraubengarnituren erweitert. Die Korrelation zwischen Zug- und Scherfestigkeit wurde in direkten und indirekten mehrstufigen Pfadanalysen analysiert, und die Stahlsorte und die Schraubenfestigkeitsklasse wurden als Schlüsselparameter identifiziert.

Weiterhin wurden erweiterte statistische Auswertungen nach EN 1990, Anhang D durchgeführt und durch Verteilungsanalysen ergänzt, um die resultierenden Teilsicherheitsbeiwerte γ_M* gegenüber den Eurocode-Sicherheitsanforderungen nachzuweisen. Dabei wurden neue Bewertungskriterien entwickelt. Darüber hinaus wurden die konservativen europäischen Bemessungsregeln der EN 1993-1-8 für Schraubenverbindungen unter Zug und Abscheren aus Kohlenstoffstahl statistisch neu bewertet, da zahlreiche neuere experimentelle Studien zu Schrauben aus Kohlenstoffstahl vorliegen, die jedoch eine weitere

statistische Validierung erfordern. Sie wurden durch eigene experimentelle Untersuchungen über die Zug-, einschnittige/ zweischnittige Abscher- und Interaktionstragfähigkeit von Schrauben aus Kohlenstoffstahl ergänzt. In Verbindung mit einer umfangreichen Literaturrecherche wurden diese Erkenntnisse in erneute Zuverlässigkeitsanalysen integriert, um die Eignung der bestehenden Bemessungs-ansätze zu untersuchen. Die Kulmination der Forschungsbemühungen führte schließlich zum Vorschlag neuer und wirtschaftlicherer Bemessungsregeln für Schrauben aus Kohlenstoff-stahl, welche mit den vorgeschlagenen neuen Bemessungsregeln für Schrauben aus austenitischem und nichtrostendem Duplexstahl nach FprEN 1993-1-4 harmonisiert sind und den normativen Anforderungen der EN ISO 898-1 entsprechen.

Zusammenfassend lässt sich sagen, dass die neu vorgeschlagenen Bemessungsregeln für Schrauben aus nichtrostendem Stahl und Kohlenstoffstahl geeignet sind, dass Zug-, Scher- und Interaktionsverhalten von Schrauben genau zu beschreiben. Diese vorgeschlagenen Regeln bieten den Ingenieuren ein kohärentes und benutzerfreundliches Bemessungskonzept, das vollständig mit den Sicherheitsanforderungen des Eurocodes übereinstimmt. Darüber hinaus wurden neue Anhänge für künftige Überarbeitungen von EN ISO 3506-1 und EN ISO 898-1 vorgeschlagen, die sich mit vereinfachten Prüfverfahren für die Abscher- und Interaktionstragfähigkeit von Schrauben aus nichtrostendem Stahl und Kohlenstoffstahl befassen.

Preface and Acknowledgments

This thesis was written and finalised during my tenure as a laboratory engineer and deputy head of the Essen Laboratory for Steel Structures (ELSta) at the Institute for Metal and Lightweight Structures, University of Duisburg-Essen, Germany.

Without doubt, this remarkable journey would not have been possible without the support, guidance and encouragement of many individuals, to whom I extend my heartfelt gratitude.

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Hannover, January 2025 Christoph Abraham

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Appendix A: Detailed literature review on carbon and stainless steel bolts

Appendix B: Experimental programme and test matrixes

Appendix C: Summary of test results from the literature

Appendix D: Summary of tested stainless and carbon steel bolt series at UDE-IML

Appendix E: Determination of partial safety factors according to EN 1990, Annex D

Appendix F: Technical drawings of the test rigs

Appendix G: Derivations of the theoretical and nominal resistance functions for the reliability analyses

Abbreviations and Symbols

Abbreviations

aBG	Allgemeine Bauartgenehmigung (German for "General construction technique permit"); design and exectution specifications
abZ	Allgemeine bauaufsichtliche Zulassung (German for "National technical approval“); product specifications
AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
AS	Standards Australia Limited
ASCE	American Society of Civil Engineers
ASD	Allowable Stress Design
ASS	Austenitic stainless steel
ASSDA	Australian Stainless Steel Development Association
ASTM	American Society for Testing and Materials
BCC	Body-centred cubic crystal structure
BCT	Tetragonal body-centred cubic crystal structure
BS	British Standards Institution (BSI)
BTQP	Bolt Tightening Qqualification Procedure; developed at UDE-IML
CE	Conformité Européenne (French for "European conformity")
CECS	China Engineering Construction Standardization Association
CEN	European Committee for Standardization
COV	Coefficient of variation
CPR	Construction Products according to EU-Regulation No. 305/2011
CS	Carbon steel material
CSA	Canadian Standards Association
DFG	Deutsche Forschungsgemeinschaft e.V. (German for “German Research Foundation“)
DIN	Deutsches Institut für Normung e.V. (German organisation, known as the German Institute for Standardization)
DMSSS	Design manual for structural stainless steel
DSS	Duplex stainless steel
DTI	Direct tension indicators according to EN 14399-9
Duplex	Biphasic metallurgical microstructure in nearly equal or 40 / 60 % proportions of austenitic and ferritic
EC-3	EN 1993-1-4
ECSC	European Coal and Steel Community

EN	Euronorm (abbreviated EN, from the German name Europäische Norm, "European Norm")
EN ISO	ISO standards in Europe adopted by CEN
$F_{b,Rd}$	Design bearing resistance per bolt
FCC	Face-centred cubic crystal structure
FE	Finite Element
FEM	Finite Element Method
FORM	First order reliability method
FOSTA	Research Association for Steel Application; German non-profit and legally independent research association within the steel sector
GB	China national standards, calles as “Guobiao Standards”
HB	Brinell hardness
HR	High-strength structural bolting assemblies for preloading, System HR according to EN 14399-3
HRC	Rockwell hardness, scale C
HV	High-strength structural bolting assemblies for preloading, System HV according to EN 14399-4
HV 0.1	Vickers hardness with a test force of 0.9807 N
HV 0.5	Vickers hardness with a test force of 9.807 N
HV 10	Vickers hardness with a test force of 98.07 N
IGF	Industrial Collective Research
in.	Inch (1 in. ≈ 25.4 mm)
IS	Bureau of Indian Standards (BIS)
ISO	International Organisation for Standardization
JSCE	Japan Soeciety of Civil Engineers
JSSC	Japanese Society of Steel Construction
LRFD	Load and Resistance Factor Design
LVDT	Linear variable differential transducers
MIL-STD	United States Military Standard, Group: Defense Standard
Mt	Million metric tons
NA	National annex
NASM	National Aerospace Standard by the Aerospace Industries Association (AIA/NAS)
NZS	Standards New Zealand
PC	(Bolt) property class
PHSS	Precipitation hardening stainless steel
prEN	Draft European standard

RCSC	Research Council on Structural Connections
RFCS	Research Fund for Coal and Steel from the European Commission
SANS	South African National Standard
SB	Structural bolting marking
SCI	The Steel Construction Institute, Ascot, UK
SEI	Structural Engineering Institute
SG	Steel grade in the pathway analysis
SLS	Serviceability Limit State
SP	Russian Standards
SS	Stainless steel material
SSG	Bolt shear in the pathway analysis
TNO	Netherlands Organization for Applied Scientific Research TNO
TSG	Bolt tensile strength in the pathway analysis
UDE-IML	Institute for Metal and Lightweight Structures at the University of Duisburg-Essen, Germany
ULS	Ultimate Limit State
VDI	VDI – Verein Deutscher Ingenieure e.V. (German for ”VDI – The Association of German Engineers”)
WAAM	Wire arc additive manufacturing

Latin symbols

5H6G	Standard tolerance class of internal threads applied in the frame of this thesis
6g	Standard tolerance class of external threads applied in the frame of this thesis
A1 to A8	Austenitic stainless steel grades according to EN ISO 3506-1
A (%)	Bolt elongation after fracture
A (mm²)	Gross cross-sectional area of the unthreaded bolt part
A_b	Nominal unthreaded body area of a bolt or threaded part according to North American regulations
A_{core}	Area of the bolt core covered by B8×40 tensile coupon test specimens
A_{cs}	Either as the gross cross-sectional area A of the unthreaded portion or the tensile stress area A_s of the threaded portion of the bolt depending on the cross-section in the shear plane
A_{d2}	Pitch diameter of the threaded bolt part
A_{d3}	Core cross-sectional area of the threaded bolt part
$A_{ds,meas}$	Measured reduced shank diameter for the determination of the tensile strength of the unthreaded bolt part

A_{exp}	Measured bolt elongation at fracture
A_{it}	Measured cross-sectional area in the shear plane
A_{meas}	Measured gross cross-sectional area of the unthreaded bolt part
$A_{meas,i}$	Individual measured gross cross-sectional area of the unthreaded bolt part
A_{min}	Minimum gross cross-sectional area A under consideration of the bolt product class
A_{nom}	Nominal gross cross-sectional area of the unthreaded bolt part
A_s	Tensile stress area of the threaded bolt part
$A_{s,meas}$	Measured tensile stress area of the threaded bolt part
$A_{s,meas,i}$	Individual measured tensile stress area of the threaded bolt part
$A_{s,min}$	Minimum tensile stress area A_s under consideration of the tolerance class of the threaded part
$A_{s,nom}$	Nominal tensile stress area of the threaded bolt part
A_{st}	Measured cross-sectional area in the shear plane
b	Mean value correction factor according to EN 1990
$b(r_e/r_n)$	Mean correction value of the experimental and nominal values
$b(r_e/r_t)$	Mean correction value of the experimental and theoretical values
b_A	Mean value correction factor of nominal and measured geometrical dimension A
b_{As}	Mean value correction factor of nominal and measured geometrical dimension A_s
$B_{p,Rd}$	Design punching shear resistance of the bolt head and the nut
C	Characteristic resistance in SLS
C1 to C6	Annonymised bolt producers
CC 1 to CC 3	Consequence classes according to EN 1990
D2 to D8	Duplex stainless steel grades according to EN ISO 3506-1
d	Bolt diameter
D	Nut diameter
d_0	Diameter of cylindircal test specimens
$d_{2,meas}$	Measured basic pitch diameter of the external thread
$d_{2,min}$	Minimum basic pitch diameter of the external thread according to the tolerance class
$d_{3,meas}$	Measured minor diameter of the external thread
$d_{3,min}$	Minimum minor diameter of the external thread according to the tolerance class
d_h	Bolt hole diameter
d_{hst}	Hole diameter of the shear inserts for standard fasteners

d_{hstf}	Hole diameter of the shear inserts for fitting bolts
d_{meas}	Measured diameter of the unthreaded part of the fastener
d_s	Diameter of the unthreaded bolt part
E	Young's modulus
E_d	Design value for the effect of the actions
$\dot{e}_{Lc}$	Strain rate over the entire test length according to EN ISO 6892-1
$F_{exp,t}$	Experimental tension load component in an interaction test
$F_{exp,V}$	Experimental shear load component in an interaction test
F_{it}	Combined tension and shear load measured in the interaction test
$F_{it,max}$	Maximum load observed in the test defined as ultimate interaction load and further distinguished into $F_{it,max,axial}$ and $F_{it,max,shear}$
$F_{m,min}$	Minimum ultimate tensile load of a bolt according to EN ISO 898-1
F_{max}	Maximum load observed in the test
$F_{max,0}$	Maximum bolt force achieved in the tensile test
F_{mf}	Minimum ultimate tensile load of a bolt according to EN ISO 3506-1
$F_{mf,exp}$	Experimental ultimate tensile load of a bolt according to EN ISO 3506-1
F_{nt}	Nominal bolt tensile stress according to North American regulations
F_{nv}	Nominal bolt shear strength according to North American regulations
F_{pf}	Minimum load at 0.2 % non-proportional elongation according to EN ISO 3506-1
$F_{pf,exp}$	Experimental load at 0.2 % non-proportional elongation according to EN ISO 3506-1
f_{rv}	Required shear stress using LRFD or ASD load combinations according to ANSI/AISC 360-22
F_s	Shear load according to British Standard BS 5950-
$F_{s,Rd}$	Design slip resistance per bolt at the ultimate limit state
$F_{s,Rd,ser}$	Design slip resistance per bolt at the serviceability limit state
F_{st}	Shear load continuously measured in the single-shear test
$F_{st,max}$	Maximum load observed in the shear test defined as ultimate shear load
F_t	Tension load according to British Standard BS 5950-
$F_{t,Ed}$	Design tensile force per bolt for the ultimate limit state
$F_{t,Ek}$	Characteristic tensile force per bolt for the ultimate limit state
$F_{t,Rd}$	Design tension resistance per bolt
$F_{t,Rd}$	Characteristic tension resistance per bolt
$F_{t,Rd,A}$	Design tension resistance per bolt determined with the gross cross-sectional area A

$F_{t,Rd,As}$	Design tension resistance per bolt determined with the tensile stress area A_s
f_u	Tensile strength of a material
F_u	Specified bolt minimum tensile strength according to North American regulations
f_{ub}	Bolt tensile strength
$f_{ub,calc,As}$	Calculated tensile strength of the bolts from literature based on the nominal tensile stress area A_s
$f_{ub,calc,shank}$	Calculated tensile strength of the unthreaded bolt shank determined b1y machine tensile specimens
$f_{ub,calc,shank}$	Calculated tensile strength of the bolt shanks from literature based on the nominal gross cross-sectional area A
$f_{ub,exp}$	Experimental determined tensile strength of a bolt according to EN ISO 3506-1
$f_{ub,exp,6892-1}$	Tensile strength of a material determined in a tensile test according to EN ISO 6892-1 on machined tensile test coupon specimens
$f_{ub,exp,core}$	Experimental determined tensile strength of the bolt core
$f_{ub,exp,core}$	Tensile strength of the bolt core determined by B8×40 tensile coupon test specimens
$f_{ub,nom}$	Nominal tensile strength of a bolt
$f_{ub,shank}$	Tensile strength of the unthreaded portion of a bolt
$f_{ub,threads}$	Tensile strength of the threaded portion of a bolt
f_{uf}	Ultimate tensile strength of a bolt according to Australian and New Zealand Standards
$F_{v,Ed}$	Design shear force per bolt for the ultimate limit state
$F_{v,Ed,ser}$	Design shear force per bolt for the serviceability limit state
$F_{v,Ek}$	Characteristic shear force per bolt for the ultimate limit state
$F_{v,max}$	Maximum shear load
$F_{v,Rd}$	Design shear resistance per bolt
$F_{v,Rd,A}$	Design shear resistance per bolt determined with the gross cross-sectional area A
$F_{v,Rd,As}$	Design shear resistance per bolt determined with the tensile stress area A_s
$F_{v,Rk}$	Characteristic shear resistance per bolt and shear plane
$F_{v,y}$	Resulting shear load at the yield strength
f_y	Yield strength of a material
f_{yb}	Bolt yield strength
H8	ISO tolerance field H8 (+27 μm, -0 mm) according to EN ISO 286-1

I to IV	Failure mode definitions of carbon and stainless steel bolts subjected to pure tension loading
$k_{d,n}$	Fractile factors according to EN 1990 for the ULS design
$k_{d,\infty}$	Fractile factors according to EN 1990 for the ULS design with $n \rightarrow \infty$
k_r	Reduction of the shear resistance of a bolt in long joints as bolted lap connections according to Australian Standard AS 4100
l_{th}	Free threaded length for tensile tests according to EN ISO 3506-1
N	Bolt tension load
n	Number of tests
$N_{max,A}$	Bolt tension resistance based on the gross cross-sectional area A
$N_{max,As}$	Bolt tension resistance based on the tensile stress area A_s
$N_{net,Rd}$	Net area plastic resistance along the critical path
N_t	Tensile force in a bolt according to Chinese National Standard GB 50017
N_t^b	Design bolt tensile resistance according to Chinese National Standard GB 50017
N_{tf}	N_{tf} is the nominal tensile capacity of a bolt according to Australian and New Zealand Standards
N_{tf}	Nominal tensile capacity of a bolt according to AS 4100
N_v	Shear force in a bolt in the investigated shear plane according to Chinese National Standard GB 50017
N_v^b	Design bolt shear resistance according to Chinese National Standard GB 50017
P	Pitch of the threaded bolt part
P_f	Failure probability
P_{nom}	Tension resistance according to British Standard BS 5950-1
P_s	Shear resistance according to British Standard BS 5950-1
Q	Scattering parameter according to EN 1990
Q_x-Q_y	Normal probability plots on the x- and y-axis
r	Pearson’s correlation coefficient
R	Resistance conditions, e.g. $R_{threads}$ as the load bearing resistance of the free loaded bolt threads
$\dot{R}$	Stress rate for tensile tests according to EN ISO 6892-1
RC 1 to RC 3	Reliability classes according to EN 1990
R_d	Design value of the resistance in ULS
r_d	Design resistance function
r_{di}	Individual design resistance value
r_e	Experimental resistance function according to EN 1990
r_{ei}	Individual experimental resistance value according to EN 1990

R_{eL}	Lower yield strength
R_k	Effect of the characteristic action in ULS
R_m	Tensile strength of a material
R_{mf}	Minimum ultimate strength of a bolt according to EN ISO 3506-1
r_n	Nominal resistance function according to EN 1990
R_n/Ω	Allowable tensile strength per bolt (ASD)
r_{ni}	Individual nominal resistance value according to EN 1990
$R_{p,0.2}$	Definition of the elastic limit based on 0.2 % non-proportional plastic elongation
R_{pf}	Minimum yield strength of a bolt according to EN ISO 3506-1
r_t	Theoretical resistance function according to EN 1990
r_{ti}	Individual theoretical resistance value according to EN 1990
s_Δ^2	Standard deviation according to EN 1990
$S_{0,meas}$	Measured cross-sectional area of a tensile coupon test specimen
S_A	Safety factor S_A = 1.10 according to German VDI Guideline 2230 Part 1
S_p	Minimum proof stress of the nut
t_2	Plate thickness in the transition region between the gross cross-section A and the tensile stress area A_s of the bolt
T_f	Design shear force acting on the bolt according to CSA S16
T_r	Design tensile resistance per bolt according to CSA S16
T_r	Design tensile resistance of a bolt according to CSA S16
v_c	Displacement velocity according to EN ISO 6892-1
V_f	Design shear force acting on the bolt according to CSA S16
V_f	Nominal shear capacity of a bolt according to AS 4100
$V_{max,A}$	Bolt shear resistance based on the gross cross-sectional area A
$V_{max,As}$	Bolt shear resistance based on the tensile stress area A_s
V_r	Design shear resistance of a bolt according to CSA S16
V_r	Coefficient of variation according to EN 1990
V_{Xi}	Coefficients of variation of each basic variable according to EN 1990
V_δ	Coefficient of variation of errors according to EN 1990
$\underline{X}$	Independent basic variables according to EN 1990

Greek symbols

α	Shear coefficients according to EN 1993-1-4
α_E	Sensitivity factor for action effects according to EN 1990

$\alpha_{EC\text{-}3,exp}$	Experimental shear coefficient $\alpha_{EC\text{-}3,exp,i}$ as the ratio of the experimental bolt shear and tension resistance determined according to EN 1993-1-4
$\alpha_{EC\text{-}3,exp,i}$	Experimental individual shear coefficient $\alpha_{EC\text{-}3,exp,i}$ as the ratio of the experimental bolt shear and tension resistance determined according to EN 1993-1-4
α_{exp}	Experimental shear coefficients according to EN 1993-1-4
α_{fy}	Shear coeffiicient determined at the tensile and shear yield strength
α_{nom}	Nominal shear coefficients according to EN 1993-1-4
$\alpha_{phys,exp}$	Real physical ratio of the experimental bolt shear and tension resistance
$\alpha_{phys,exp,i}$	Real physical individual ratio of the experimental bolt shear and tension resistance
$\alpha_{proposed}$	Proposed shear coefficient for standardisation in the frame of this thesis
α_R	Sensitivity factor for resistances according to EN 1990
α_{rt}	Weighting factor for Q_{rt}
α_δ	Weighting factor for Q_δ
α_v	Shear coefficients according to EN 1993-1-8 for carbon steel bolts
β	Loading angle related to the longitudinal axis of the fastener
β	Loading angle
β	Reliability index according to EN 1990
δ_i	Error term according to EN 1990
δ_{it}	Combined displacement measured in the interaction test
$\delta_{it,axial}$	Calculated axial displacement measured in the interaction test
$\delta_{it,max}$	Resulting combined displacement at $F_{it,max}$,
$\delta_{it,transv}$	Calculated shear displacement measured in the interaction test
δ_{st}	Shear displacement measured in the single-shear test
$\delta_{st,max}$	Resulting shear displacement at $F_{st,max}$
γ_c	Safety factor γ_c = 1.0 for connections according to Russian Standards
γ_F	Partial safety factor for the effects of the actions (loading side)
γ_m	Partial safety factor γ_m considering material uncertainties according to EN 1990
γ_m	Safety factor of γ_m = 1.1 for bolted connections in crane construction according to EN 13001-3-1
γ_M	Partial safety factor based on experimental and theoretical values
γ_M*	Partial safety factor based on experimental and nominal values
γ_{M0}	Recommended partial safety factor γ_{M0} = 1.0 for cross-section design checks according to EN 1993-1-4

γ_{M1}	Recommended partial safety factor γ_{M1} = 1.1 for stability design checks according to EN 1993-1-4
γ_{M2}	Recommended partial safety factor γ_{M2} = 1.25 for bolted and welded connections according to EN 1993-1-4 and EN 1993-1-8
γ_{Rd}	Partial safety factor γ_{Rd} considering inaccuracies in the resistance function
γ_{sbs}	Additional safety factor for bolted connections in crane construction according to EN 13001-3-1
μ	Mean value of the normal distribution
σ	Stress tensor consisting of nine components σ_{ij}
σ	Standard deviation
σ_{ax}	Principial axial stress of a bolt subjected to tensile loading
σ_e	Equivalent stress
σ_E	Standard deviation of action effects according to EN 1990
$\sigma_{it,A}$	Resulting axial stress in the unthreaded part A of the fastener at $F_{it,max}$
$\sigma_{it,As}$	Resulting axial stress in the threaded part A_s of the fastener at $F_{it,max}$
σ_R	Standard deviation of resistances according to EN 1990
σ_{rad}	Radial stress component of a bolt subjected to tensile loading
σ_T	Cohension strength of material
σ_{tan}	Tangential stress component of a bolt subjected to tensile loading
σ_u	Ultimate stress of a material
σ_x, σ_y, σ_z	Principal normal stresses
σ_y	Yield stress of a material
$\tau_{b,max}$	Maximum shear stress in the bolt
$\tau_{b,y}$	Resulting shear stress at the yield strength in the bolt
τ_F	Shear yield strength according to the maximum shear stress theory by Tresca
$\tau_{it,A}$	Resulting shear stress in the unthreaded part A of the fastener at $F_{it,max}$
$\tau_{it,As}$	Resulting shear stress in the threaded part A_s of the fastener at $F_{it,max}$
τ_{max}	Maximum shear stress
τ_{mean}	Mean shear stress
$\tau_{st,A}$	Resulting shear stress in the unthreaded part A of the fastener at $F_{st,max}$
$\tau_{st,As}$	Resulting shear stress in the threaded part A_s of the fastener at $F_{st,max}$
τ_u	Ultimate shear stress of a material
$\tau_{ub,exp,i}$	Experimental individual ultimate shear stress
τ_{xy}	Shear stresses: τ_{xy}, τ_{xz}, τ_{yx}, τ_{yz}, τ_{zx}, τ_{zy}

τ_y	Yield shear stress of a material
φ	Definition of the loading angle in the interaction resistance functions
$\Phi \cdot R_n$	Design tensile strength per bolt according to North American regulations (LRFD)
$\Phi \cdot V_f$	Design shear capacity per bolt with $\Phi = 0.80$ (LRFD) according to Australian Standard AS 4100

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Table D.59: Specifications, geometrical parameters and tests results of EN ISO 4017 – C6 – M16×100 – 10.9 ..... D.59

Appendix E

Table E.1: Values for $k_{d,n}$ depending on the amount of test data n according to EN 1990, Annex D E.2

1 Introduction and problem definition

1.1 General

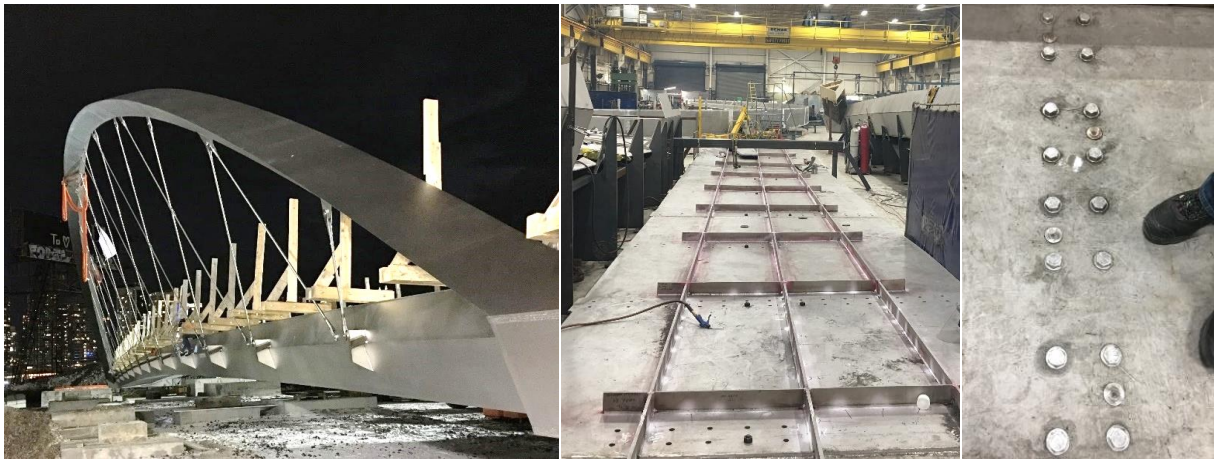
Stainless steel is the world's most crucial synthetic metal with production numbers of 55.3 million metric tonnes (Mt) in 2022, currently the fourth most demanded metal by delivered weight after carbon steel (1878.5 Mt), cast iron (112.7 Mt) and aluminium (63.2 Mt) [1–3]. *Stainless steel* is the generic term for a family of fully recyclable iron-based alloys that contain a minimum of 10.5 % chromium. In conjunction with low carbon content (from 0.03 % to greater than 1.00 %), chromium imparts supreme material properties like high strength, high ductility [4–6] and especially excellent corrosion resistance due to its transparent and closely adhering chromium oxide layer on the stainless steel surface, the so-called passive layer. In addition, other alloying elements can be added to resist even high-aggressive chemical environments and to realise other intended advantageous material properties. These include improved ductility, pronounced strain hardening, superior fatigue behaviour [7], heat resistance [8–11] and fire resistance [12–15], excellent impact toughness at low and high temperatures [16–18] as well as high fracture toughness even under seismic loading conditions [19, 20].

Stainless steel has already successfully and sustainably been used in a wide range of market segments, see Figure 1.1-1, like architecture, art and design, the oil and gas industry, chemical process industry, water treatment, energy, marine and defence, mechanical engineering, pharmaceutical tanks and food-grade, patio furniture, water tubing, cable trays, wires, surgical instruments and kitchen material [21–27]. Primarily, the construction industry benefits from stainless steel due to its high strength and ductility, attractive appearance and lower lifecycle costs compared to corrosion-prone carbon steel, enabling the creation of slender and elegant steel structures [28, 29]. Furthermore, stainless steel reinforcing bars can reduce the risk of structural damage caused by corrosion in roads, bridges, buildings and marine environments [30–38]. Entirely new possibilities for structural applications emerge in the field of additive manufacturing of stainless steels, like wire arc additive manufacturing (WAAM) [39–46].

Figure 1.1-1: Wide range of market segments and applications for stainless steel; © stock.adobe.com[1)]

[1)] Oil & Gas: © currahee shutter; Silo & Tank construction: © IuSh; Chemical process industry: © Ivan Traimak; Building & Construction: © Maksym Yemelyanov; Architecture: © Jürgen Fälchle; Art & Design: © Akaberka

However, stainless steel is significantly more expensive than carbon steel with a price ratio of four (or even six) to one [47], but the outstanding material properties of stainless steel and increased service life of more than 100 years combined with low maintenance requirements often compensate for the higher initial costs in the construction process. Thus, it can become a competitive and sustainable alternative to traditional carbon steel structures. Worldwide, architects and engineers already have been successfully designing and executing steel structures made of structural stainless steel components [48–53]. For example, the Garrison Crossing Pedestrian and Cycle Bridge in Toronto, Canada, was constructed by a stainless steel single arch rib of triangular shape and executed with slip-resistant bolted connections made of stainless steel, see Figure 1.1-2 (a). To take another example, the Helix Pedestrian Bridge in Singapore connects two delicate helix structures that act together as a tubular truss and are made of corrosion-resistant duplex stainless steel of grade 1.4462 to withstand tropical climate with heavy rainfall, see Figure 1.1-2 (b).



(a) Garrison Crossing Bridge in Toronto, Canada; © Sobrino, J.A., pedelta

(b) Helix Pedestrian Bridge in Singapore; © Manaois III, S. (left), Kung, B. (right)

Figure 1.1-2: Examples of bridges made of structural stainless steel

Connections play a pivotal role in these structures, underscoring the critical significance of understanding the structural behaviour of bolted connections made of stainless steel. This has been a focal point in previous and ongoing research endeavours, encompassing examining connections at the level of individual components and scrutinising the entire joint [54–62]. Consequently, the increased use of stainless steel in structural applications coincides with growing demand from the construction industry for bolted or welded connections. Thus, stainless steel bolts, nuts and washers are required whenever bolted connections are of critical importance in a structure and require special attention both in design and execution. Structural bolting assemblies made of stainless steel, consisting of bolts and nuts, and as far as needed washers, are the appropriate choice whenever difficult corrosive conditions exist, or regular

maintenance is not possible. Stainless steel bolting assemblies are generally characterised by high strength with good ductility, coping with extreme operating temperatures of between -269 °C and +800 °C, good fire resistance and enhanced fatigue strength, especially when the bolt threads are rolled [63].

Among various stainless steel bolts, austenitic stainless steel comprises approximately 70 % of the usage share in the construction industry [64]. Nevertheless, there has been a growing trend in the use of duplex stainless steel grades in recent years. Characterised by a biphasic metallurgical structure with approximately equal proportions of austenitic and ferritic components, duplex stainless steel is increasingly employed in structural applications. This choice is favoured when higher strengths, enhanced impact toughness and superior corrosion resistance are deemed advantageous [65]. Whenever austenitic or duplex stainless steel bolting assemblies are used in structural applications, they are predominantly used as non-preloaded bolted connections like tension connections, bearing type connections or bolted connections subjected to combined tension and shear. The load bearing characteristics of these non-preloaded bolted connections will be discussed in this thesis.

Preloading of austenitic and duplex stainless steel bolting assemblies is also highly demanded by the construction industry. Unfortunately, preloading of stainless steel bolts is currently not permitted in steel structures according to EN 1090-2 [66] and EN 1993-1-4 [67] unless all necessary tightening parameters for a secure preloading are clearly defined in a procedure test on a case-by-case basis. This restriction stems from the lack of knowledge about the reliability of these preloaded bolted connections. However, based on extensive research activities at the Institute for Metal and Lightweight Structures at the University of Duisburg-Essen (UDE-IML), it can be concluded that preloading of austenitic and duplex stainless steel bolting assemblies is in principle possible when an appropriate lubricant is applied, and that preload losses showed comparable results to those of carbon steel bolts. Hence, to provide guidance, a Bolt Tightening Qualification Procedure (BTQP) [68, 69] for stainless steel bolting assemblies was developed and already implemented in the recently drafted ISO 17607-6 [70]. Nevertheless, this thesis will not delve into the topics of preloading and the viscoplastic deformation behaviour of stainless steel bolting assemblies. Examples of preloaded and non-preloaded bolted connections are presented in Figure 1.1-3.

Figure 1.1-3: Examples of preloaded and non-preloaded bolted connections; © stock.adobe.com[1)]

[1)] Upper row: © Nordroden; © LightChaser; © Etajoe; Lower row: © Surkaman; © Dvoinik (middle, right)

1.2 Problem definition

In Europe, the design and execution of structures made of stainless steel must be carried out according to EN 1993-1-4 and EN 1090-2. If opening clauses exist, the design rules can be further specified at the national level; for example, in Germany, by DIN EN 1993-1-4/NA [71]. Furthermore, the current 4th Edition of the Design Manual for Structural Stainless Steel (DMSSS) [64] provides further guidance. The existing design rules for non-preloaded stainless steel bolted connections under pure shear and pure tension, specified as category A and category D connections according to EN 1993-1-8 [72], are essentially based on the regulations of bolted connections made of carbon steel. However, not only the unique and nonlinear mechanical behaviour of stainless steel, which differs from that of carbon steel, must be considered but also the design rules and their applicability must be checked and validated to fulfil the safety concept of the Eurocode. This verification is essential to meet the safety standards outlined in the Eurocode, which imposes rigorous criteria for ensuring a safe, reliable and sustainable structural application. An overview of non-preloaded bolted categories according to EN 1993-1-8 is presented in Figure 1.2-1.

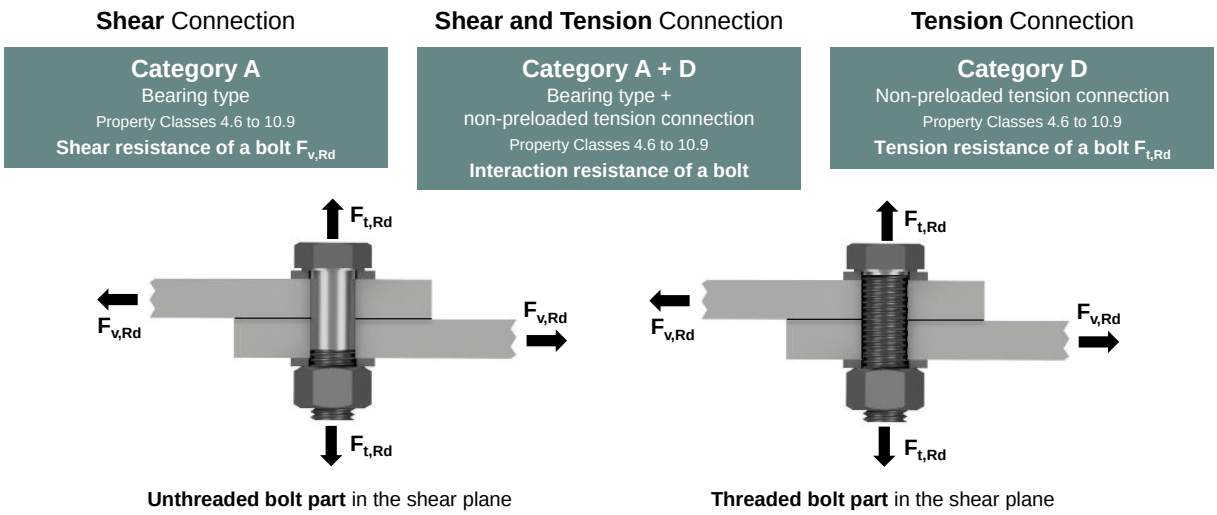


Figure 1.2-1: Overview of non-preloaded bolted categories according to EN 1993-1-8

With very few exceptions, no systematic studies were available in the past to cover the load bearing behaviour of austenitic and duplex non-preloaded bolted connections regarding the tension, shear and tension/shear interaction behaviour of stainless steel bolts. Mainly studies at ultimate and serviceability limit states about the bearing resistance $F_{b,Rd}$ of stainless steel bolted connections covering thin and thick plates can be found in current research and scientific exchange of specific subjects, such as fire resistance. Furthermore, EN 1993-1-4 is limited to austenitic and duplex stainless steel bolting assemblies of property classes (PC) 50, 70, and 80. Consequently, EN 1993-1-4 does not yet consider the new PC 100 of bolts, which is already included in the current EN ISO 3506-1 [73]. In addition, the current version of EN 15048-1 from 2007 [74] and the more recent but not yet introduced version from 2016 [75], do not include duplex stainless steel bolting assemblies and the new PC 100. Consequently, these bolting assemblies are currently unavailable with structural bolting (SB) marking and even without SB marking challenging to obtain on the European market since they have not yet been considered in the current design standards or recommendations. Nevertheless, high-strength austenitic and duplex stainless steel bolts comparable to the property classes defined for carbon steel bolts in PC 8.8, 10.9, 12.9 and even higher are available on the market and designated by the bolt manufacturer as “88”, “109”, “129” etc., see Figure 1.2-2. High-strength bolting assemblies in PC 8.8 and 10.9 are used increasingly in the construction industry due

to their comparatively higher yield strengths, analogous to those for carbon steel bolts defined in EN ISO 898-1 [76]. Despite not being incorporated into EN ISO 3506-1, these bolts meet the criteria outlined in EN 15048-1 [75]. In the frame of this thesis, for simplicity and in contrast to the current normative regulations, these bolts are also designated as PC 8.8, 10.9 and 12.9, whereby it is always clearly stated if the bolts are made of stainless steel or carbon steel.

Bolts fabricated from ferritic and martensitic stainless steel are addressed in EN ISO 3506-1 but EN 1993-1-4 does not incorporate them. Presently, these types of bolts have minimal significance in the European construction industry.

PC 8.8 with $R_{pf,min,8.8}$ = 640 N/mm² and $R_{mf,min,8.8}$ = 800 N/mm² Manufacturer's designation: “Bumax 88”	**PC 10.9** with $R_{pf,min,10.9}$ = 900 N/mm² and $R_{mf,min,10.9}$ = 1000 N/mm² Manufacturer's designation: “Bumax 109”	**PC 12.9** with $R_{pf,min,12.9}$ = 1080 N/mm² and $R_{mf,min,12.9}$ = 1200 N/mm² Manufacturer's designation: “Bumax 129”

Figure 1.2-2: Examples of stainless steel bolts in property class comparable to those for carbon steel bolts in PC 8.8, 10.9 and 12.9, which are not yet included in EN ISO 3506-1; © BUMAX AB, Sweden

In principle, bolts made of austenitic stainless steel have a different load bearing behaviour compared to bolts made of carbon steel, which is based, among other things, on the manufacturing process and the resulting locally different material properties in the threaded and unthreaded parts of bolts. On the contrary, duplex stainless steel bolts already exhibit a more homogeneous material behaviour (which still differs from that of carbon steel bolts), while bolts made of carbon steel have a largely homogeneous material and strength distribution over the unthreaded and threaded bolt parts. It is obvious that the different material properties and the different load bearing behaviour of stainless steel bolts should be considered in the design.

Therefore, in the previous German national regulations of abZ Z-30.3-6:2017 [77], which have been partly transferred to the German National Annex of EN 1993-1-4 in the meantime and are no longer part of abZ Z-30.3-6, the different load bearing behaviour was considered by calculating the shear resistance $F_{v,Rd}$ of austenitic stainless steel bolts always with the smaller tensile stress area A_s of the bolt but with increased shear coefficients α compared to EN 1993-1-4. However, this approach contrasts with EN 1993-1-4 and EN 1993-1-8, which differ in whether the bolt’s unthreaded (gross cross-sectional area, A) or threaded part (tensile stress area, A_s) is in the shear plane. The determination of the shear resistance $F_{v,Rd}$ according to EN 1993-1-4 of a bolt with threaded part in the shear plane yields to a lower shear resistance $F_{v,Rd}$ compared to the German regulation of DIN EN 1993-1-4/NA. For the unthreaded portion in the shear plane, EN 1993-1-4 results in higher shear resistance $F_{v,Rd}$ of a bolt ($A_s/A \approx 78$ %), corresponding to either under or over dimensioning. In the past, only conservative estimates could be made for the shear resistance of duplex stainless steel bolts, as no systematic studies were available. Furthermore, an international comparison of the design regulations reveals contradictory design concepts. In this way, there was an urgent need for large-scale systematic experimental investigations and a statistical assessment for the shear resistance $F_{v,Rd}$ of austenitic and duplex bolting assemblies to check the safety requirements of the Eurocode.

In addition, the design rules of EN 1993-1-4 regarding the tension resistance $F_{t,Rd}$ were only adopted from EN 1993-1-8 without any modifications for stainless steel bolting assemblies and without any consideration of the pronounced strain hardening, especially of austenitic bolts. In

an international comparison, different approaches allow a more economical design of the tension resistance of stainless steel bolts. The necessity of considering the specific material behaviour of stainless steel in the design rules can also be demonstrated by the fact that under pure tensile stress, austenitic bolts predominantly fail in the gross cross-section A of the bolt due to a transformation of austenitic to forming induced martensitic material in the tensile cross-section originating from the thread rolling process with a larger hardness and higher strength in the border of the cross-section of the threads (tensile stress area), which is not the case in the shank area.

For duplex bolts, analogous to carbon steel bolts, the intended bolt failure occurs in the freely loaded threaded part due to the smaller tensile stress area A_s of the bolt.

Additionally, the tension resistance of bolts $F_{t,Rd}$ according to EN 1993-1-4 is of major importance in bolted connections whenever stainless steel bolting assemblies are subjected to combined tension and shear loading as category A+D bolted connections. In this case, an additional interaction design check is required to prevent overstressing or failure of the bolt.

Investigations into the load bearing behaviour of stainless steel bolting assemblies under combined tension and shear loading are urgent for three reasons:

1. the shear coefficients α, which were based on only a few experimental investigations for austenitic bolts or only conservative estimates for duplex bolts, have a direct impact on the combined load bearing capacity,
2. the conservative bilinear interaction model of EN 1993-1-8, which was adopted for bolted connections of stainless steels without any further modification by EN 1993-1-4 and the German National Annex DIN EN 1993-1-4/NA, was discussed for bolted connections made of carbon steel within the scope of the revision of EN 1993-1-8, and
3. the tension/shear interaction concepts needed to be verified in systematic experimental investigations so that a reliable and “Ease of Use” design approach can be developed to ensure an economical and statistically reliable design.

The current bilinear design approach according to EN 1993-1-4 leads to a conservative design of the overall construction due to the lower shear resistance of the bolts made of stainless steel. This increases not only the material usage but also the construction process costs.

Finally, there is an urgent need for experimental clarification and statistical validation regarding the design of austenitic and duplex stainless steel bolting assemblies as non-preloaded bolted connections subjected to tension, shear and combined tension and shear loading. In order to close this gap, investigations have been carried out at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen, Germany (UDE-IML) within the German research project FOSTA P 1386 / IGF-No. 20651 N titled “Load bearing capacity of bolted connections loaded in shear and tension made of stainless steel M12 to M36” [78] and further studies. Here, for the first time, systematic experimental investigations were conducted into the load bearing behaviour of austenitic and duplex stainless steel bolts and bolting assemblies subjected to tension, single-shear and interaction loading. Finally, new and more economical design approaches were proposed and verified by statistical evaluations according to EN 1990, Annex D [79]. The proposed new design rules for the tension resistance $F_{t,Rd}$, shear resistance $F_{v,Rd}$ and interaction resistance of austenitic and duplex stainless steel bolts have already been implemented in FprEN 1993-1-4 [80] and the German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022 [81].

Additionally, it must be evaluated whether the design rules for carbon steel bolted connections according to EN 1993-1-8 and EN 1993-1-8:2024 [82] need a fundamental revision. Various

new experimental studies into carbon steel bolts under tension, shear, and interaction have become available but have not been implemented in a statistical re-evaluation in the past. Furthermore, new design rules developed for carbon steel bolts for EN 1993-1-8:2024 were not statistically verified according to EN 1990, Annex D. Therefore, a renewed review of the safety concept of the Eurocode for carbon steel bolting assemblies is indicated.

1.3 Objectives

As discussed before, an uncritical adoption of existing design concepts and standards for carbon steel to stainless steel bolted connections is not expedient. In the frame of this thesis, the background of the new proposed design for austenitic and duplex stainless steel bolts for FprEN 1993-1-4:2024 and the German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022 will be outlined comprehensively, critically discussed and complemented by detailed statistical evaluations as well as supplementary experimental and numerical investigations. In contrast to the prior conducted research activities, the main objective of this thesis is to provide a comprehensive and deeper insight into the proposed new design rules for stainless steel bolts and to verify these new design rules based on an extended database and further studies.

It has also been investigated whether more suitable and economical design rules for non-preloaded carbon steel bolts can be realised and harmonised with the design rules of stainless steel bolted connections (“Ease of Use”).

The main objectives of this PhD thesis are:

- to give a comprehensive overview about the current European normative situation of stainless steel bolts and bolting assemblies including an international comparison of the different existing design rules for non-preloaded bolted connections,
- to provide a comprehensive overview about the existing studies regarding the tension, shear and interaction behaviour of stainless and carbon steel bolts,
- to clarify the international specifications regarding shear and interaction testing of bolts and to prove the comparability between single-shear and double-shear testing,
- to verify the tension $F_{t,Rd}$, shear $F_{v,Rd}$ and interaction resistance of stainless and carbon steel bolts with an unthreaded or threaded part in the shear plane based on supplementary studies and statistical evaluations according to EN 1990, Annex D,
- to determine and analyse resulting partial safety factors γ_M* for the tension resistance $F_{t,Rd}$, shear resistance $F_{v,Rd}$ and interaction resistance of stainless and carbon steel bolts by conducting extended reliability analyses and to verify them against the partial safety factor for connections γ_{M2} = 1.25 according to EN 1993-1-4,
- to perform correlation analyses between the tensile and shear strength of stainless steel bolts in order to identify key parameters of the shear resistance,
- to provide normative amendments for a more economical, reliable and harmonised design of the tension resistance $F_{t,Rd}$, shear resistance $F_{v,Rd}$ and interaction resistance of stainless and carbon steel bolts and bolting assemblies for FprEN 1993-1-4 and EN 1993-1-8:2024 [82],
- to develop drafts for a single-shear test procedure and a universal test procedure (tension, shear and interaction) for fasteners for their implementation to EN ISO 898-1 and EN ISO 3506-1.

1.4 Methodical approach and outline

Comprehensive investigations are needed to close the gap of knowledge of the load bearing behaviour of non-preloaded austenitic and duplex stainless steel bolts and bolting assemblies regarding their tension resistance $F_{t,Rd}$, shear resistance $F_{v,Rd}$ and interaction resistance. New and more economical design rules, which are derived from the findings of this thesis, are already implemented in FprEN 1993-1-4:2024 and abZ/aBG Z-30.3-6:2022 and further verified by supplementary studies, in-depth statistical evaluations according to EN 1990, Annex D and safety assessments based on extended databases. Furthermore, it is aimed to improve the existing design rules for carbon steel bolts subjected to tension, shear and combined tension and shear loading.

This thesis is divided into nine chapters, which are depicted in Figure 1.4-1.

Figure 1.4-1: Chapter structure and distinct parts of this PhD thesis

The state of the art of structural stainless and carbon steel bolts subjected to tension and shear loading is presented in **Chapter 2**. Herein, an overview of the current normative situation of non-preloaded bolting assemblies according to EN 15048-1 and the normative regulations of stainless steel bolts, nuts and washers according to the EN ISO 3506 series are outlined. The different load bearing behaviour of stainless steel bolts compared to those of carbon steel bolts is introduced and accompanied by a brief overview of mechanical theories, explanations regarding the correlation between shear and tensile strength, and strength increasing effects of stainless steel bolts caused by the manufacturing process. Furthermore, a comprehensive overview of existing investigations into the load bearing behaviour of carbon and stainless steel bolts subjected to tension, shear and combined tension and shear loading is provided.

Chapter 3 shows a comparison of selected international design codes, standards and guidelines for the design of the tension, shear and combined tension and shear resistance of bolted connections made of carbon and stainless steel. Herein, the main design approaches and design concepts of these international standards regarding the tension, shear and interaction resistances are identified and compared with each other.

The tension resistance $F_{t,Rd}$ of stainless steel bolts is discussed in **Chapter 4**. Based on extended test data from literature and supplementary experimental studies in the frame of this thesis, a detailed reliability analysis according to EN 1990, Annex D is conducted to verify the resulting partial safety factors γ_M* for the tension resistance $F_{t,Rd}$ of stainless steel bolts and bolting assemblies against the partial safety factor of $\gamma_{M2} = 1.25$ for connections. These investigations are complemented by a safety assessment over all tested bolts.

The shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolts is discussed in **Chapter 5**. The available test data from literature and experimental investigations considering single-shear and supplementary double-shear tests are evaluated to propose new and more economic shear coefficients α for statistical evaluation according to EN 1990, Annex D. Furthermore, the differences between single and double-shear testing of bolts are investigated in experimental and numerical studies, and key parameters of the bolt shear resistance are identified and complemented by pathway and correlation analyses between the tensile and shear strength.

The interaction behaviour of stainless steel bolts is investigated in **Chapter 6**. The results from literature and interaction tests are discussed, compared with design concepts from current research discussions and standards/guidelines. Finally, new design concepts are proposed, statistically verified by a detailed reliability analysis and complemented by a safety assessment for a more economic design of bolted connections made of stainless steel.

Chapter 7 examines whether the design approaches developed for stainless steel bolts can also be applied to carbon steel bolts for harmonisation and “Ease of Use”. Therefore, tension, single-/double-shear and interaction tests on carbon steel bolts and bolting assemblies are conducted and complemented by an extensive literature review. Finally, detailed reliability analyses of the new harmonised design approaches for carbon steel bolts are conducted.

Amendments for standardisation for stainless and carbon steel bolting assemblies are provided in **Chapter 8** and focus on a harmonised more economical design of the tension resistance $F_{t,Rd}$, shear resistance $F_{v,Rd}$ and interaction resistance. Drafts for a single-shear and a universal test procedure (tension, single-shear and interaction) for fasteners are proposed as informative annexes to EN ISO 898-1 and EN ISO 3506-1.

Finally, **Chapter 9** provides an overall summary and conclusions based on all experimental, numerical and statistical investigations and studies on the safety assessment carried out in the frame of this thesis. Furthermore, an outlook on future investigations into stainless and carbon steel bolts subjected to combined tension and shear and further topics is given.

1.5 German research project FOSTA P 1386 / IGF-No. 20651 N and RFCS SIROCO

Major parts of this thesis are embedded in the completed German IGF research project FOSTA P 1386 / IGF-No. 20651 N “Load bearing capacity of bolted connections loaded in shear and tension made of stainless steel M12 to M36” [78], and further independent research activities conducted at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen (UDE-IML), Germany. The research project was funded by the German Federation of Industrial Research Associations (AiF) via the Research Association for Steel Application (FOSTA) from April 2019 until March 2021. In this thesis, it will always be stated which investigations were part of the IGF project and which go beyond that.

Prior to the German research project, the RCFS European research project “Execution and reliability of slip-resistant connections for steel structures using CS and SS” SIROCO (RFSR-CT-2014-00024) [61] was conducted at UDE-IML (project coordinator) and ten European partners from July 2014 until June 2017. The research project dealt with an improved test procedure for measuring the slip-factor, innovative preloading methods and coating systems for carbon and stainless steel surfaces to increase the surface roughness and development of design and execution rules for preloading of stainless steel bolts and slip-resistant connections made of stainless steel including proposed classifications for slip factors for common surface conditions and treatments, see [83–93]. Furthermore, the basic preloading and tightening

behaviour as well as the viscoplastic deformation behaviour of austenitic and stainless steel bolting assemblies were systematically investigated [68, 94–100].

The results of RFCS SIROCO were indirectly incorporated into the presented investigations as they already emphasised the urgent need for new design rules to consider the particularly nonlinear load bearing characteristics of bolts and bolting assemblies made of stainless steel for a more economic but safe and reliable design.

2 State of the art: Structural stainless and carbon steel bolts subjected to tension and shear loading

2.1 General

Chapter 2 introduces the state of the art of structural stainless and carbon steel bolts and bolted connections subjected to tension, shear and combined tension and shear loading. The European design standards EN 1993-1-8 [72] and EN 1993-1-8:2024 [82] classifies bolted connections into five categories, which are introduced in the following including the required design verifications structural engineers must carry out for bolted connections in steel structures with particular interest to non-preloaded category A (pure shear connection) and category D (pure tension connections). Since most of the design rules for austenitic and duplex stainless steel bolting assemblies have historically developed or been adopted from the normative regulations established for carbon steel bolting assemblies, further details about carbon steel bolts are also presented whenever required.

In order to give a general overview about the normative regulations and main characteristic of stainless steel, stainless steel bolts, nuts and washers according to the EN ISO 3506 standard series are outlined with particular interest to these bolting assemblies' mechanical properties in contrast to bolting assemblies made of carbon steel according to EN ISO 898-1/-2 [55, 61]. Additionally, different stainless steel grades are introduced and the mechanical behaviour of carbon and stainless steel is discussed. Furthermore, an overview of non-preloaded and preloaded structural bolting assemblies is provided based on the European harmonised standards EN 15048-1 [74, 75] and EN 14399-1 [101].

In structural applications, bolts and bolting assemblies are mainly loaded under pure shear or pure tension as category A or D bolted connections. However, also a combined tension and shear loading interaction can occur. Consequently, the superposition of tension and shear stresses in different proportions depending on the loading angle must be considered in the design in order to prevent overstressing and failure of the bolt. To provide a general overview, selected mechanical theories of *Rankine*, *Tresca* and *von Mises* to describe the interaction of tension and shear stresses of ductile metal materials are briefly summarised and the resulting uniaxial and multiaxial stress states of a bolt subjected to tension, shear and combined tension and shear loading are briefly introduced.

In particular, the correlations between yield strength and tensile strength as well as ultimate shear strength and tensile strength are discussed in the context of the presented mechanical theories and compared with experimental investigations from meta-studies in literature. Additionally, the construction principle, possible failure mechanism and failure types of bolts are presented as well as the impact of (cold) rolling versus cutting thread production types on the bolt's local strength distribution.

Furthermore, an overview of existing experimental and numerical investigations into the load bearing behaviour of carbon and stainless steel bolts subjected to tension, shear and combined tension and shear loading are presented. Conclusions from the literature review are drawn regarding the main findings of these bolted connections for further investigations in the frame of this thesis.

Finally, this chapter ends with a summary and conclusions.

2.2 Bolts and bolted connections in steel structures

2.2.1 General

Although riveted and welded connections were used for steel structures up until the 1950s, the bolted connection was known as a replacement solution. At this time, applications were comprised in cases where the installation conditions did not allow for settling rivets, the connection needed to be disassembled or larger tensile forces had to be transferred. Currently, bolted connections have largely replaced riveted connections for a variety of reasons, including ease of installation and primarily no need for special equipment [102], steady development of bolting technology (e.g. injection bolts, high-strength bolting assemblies for preloading made of carbon steel and stainless steel), better knowledge of the mechanical behaviour including substantial influences and disturbances, and finally high economic efficiency and productivity on construction sites and in factories. Consequently, without bolts and bolted connections, steel construction would not be conceivable as a form of industrialised building [103, 104]. For instance, in Germany, the application of high-strength structural bolting assemblies in bolted connections became more common in steel structures around the 1950s. For further information, see [105–116].

According to EN 1993-1-8, connections in steel structures are of major and critical importance and are usually made either with bolts, pins, rivets or welds, see Figure 2.2-1 as example. In the context of this thesis, the focus will be placed exclusively on bolts and bolted connections.

(a) Bolts (b) Pins (c) Rivets

Figure 2.2-1: Connections in steel structures according to EN 1993-1-8 made either of bolts (a), pins (b), rivets (c) or welds (a, b, c); © Abraham, Christoph

By definition, a bolt is a punctiform connecting element that allows connections between two or more parts of a solid compound. This solid compound is realised by paired threads between bolt and nut and the rotation of the nut or bolt head. While the mechanical behaviour of non-preloaded and preloaded bolting assemblies made of carbon steel is well known after decade-long experience in steel construction (but still requires urgent clarification, standardisation and research), the application of non-preloaded and preloaded bolting assemblies made of stainless steel offers a promising alternative for the construction industry. Especially when critical environments and aggressive corrosion conditions are present. Thus, it could be shown that preloading of bolts covered by EN ISO 3506-1 [73] is in principle possible and provides new opportunities to utilise potential of stainless steel.

Depending on the intended area of application (steel structures or mechanical engineering) and type of application (non-preloaded or preloaded bolted connection), a variety of bolt types have become established in standardisation and exist on the market, exemplarily presented in Figure 2.2-2. These type of bolts are available either in carbon steel exclusively (e.g. HR and HV high-strength structural bolting assemblies according to EN 14399-3 [117] and EN 14399-4 [118]) or both in carbon and stainless steel (e.g. EN ISO 4014 [119], EN ISO 4762 [120] and EN ISO 4017 [121] bolts). Further information is given in Chapter 2.2.3.

Figure 2.2-2: Large product range of bolting assemblies, for example System HV bolting assemblies (left: © Peiner Umformtechnik GmbH, Germany) and various stainless steel bolting assemblies (right; © BUMAX SE, Sweden)

2.2.2 Categories of bolted connections according to EN 1993-1-8

The primary distinction between bolted connections is between shear and tension connections, categorised based on the type of loading perpendicular (shear connection) or parallel (tension connection) to the bolt axis. Based on the primary distinction, EN 1993 1-8, Clause 3.4 and EN 1993-1-8:2024, Clause 5.4 [82], both classify bolted connections into five categories A to E, presented in Figure 2.2-3 and Table 2.2-2: categories A to C are bolted shear connections and categories D and E are bolted tension connections. While the bearing type connections according to category A, which are widely used in steel structures and assuming predominantly static actions without load reversal, and the tensile connections according to category D, are part of the non-preloaded bolted connections, the slip-resistant connections of categories B and C, as well as the tensile connections of category E, are always designed and executed as preloaded bolted connections.

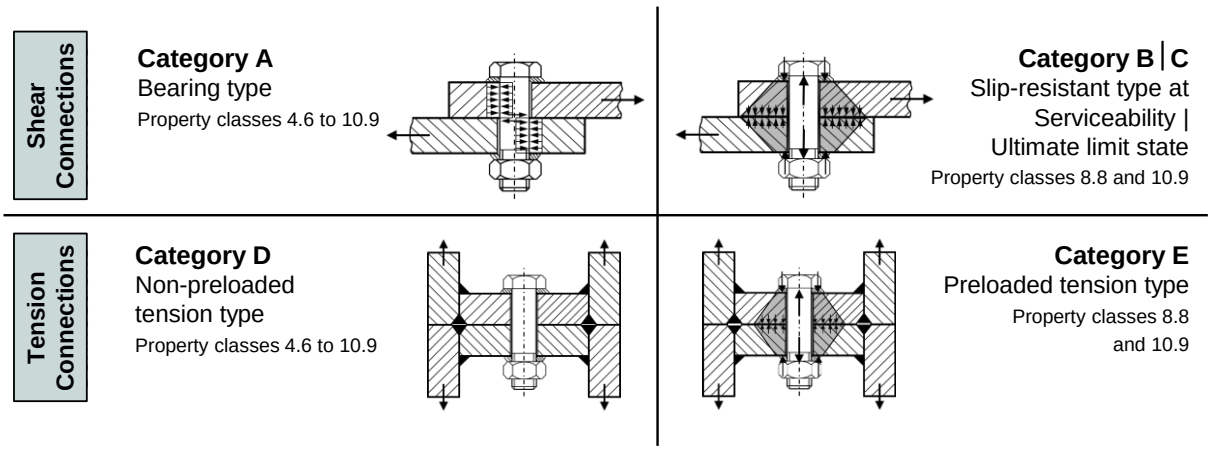
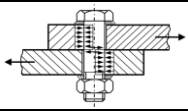
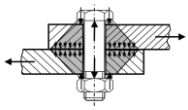
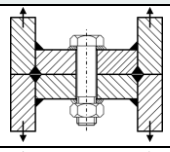
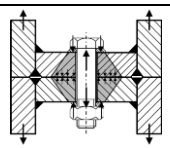


Figure 2.2-3: Overview about bolted categories according to EN 1993-1-8

Nevertheless, non-preloaded designed bolted connections of category A+D can also be executed as preloaded bolted connections in order to improve serviceability, e.g. increasing the stiffness of the connection and limiting deformation. Slip-resistant connections, which are typically used in lattice towers, bridges, radio masts and wind turbine towers, are required whenever the steel structure is subjected to heavy impact loads, alternate loading and/or fatigue. In particular, the slip must be prevented either at serviceability limit state (category B) or ultimate limit state (category C).

The design criteria for bolted connections to prove the structural safety of the steel structure and further specifications for each category are summarised in Table 2.2-1.

Table 2.2-1: Categories of bolted connections and design criteria according to EN 1993-1-8, Table 3.2

Bolted category		Design criteria	Specifications
Shear connections			
	**A** **Bearing type**	$\mathbf{F_{v,Ed} \leq F_{v,Rd}}$	No preloading required. Property classes from 4.6 to 10.9 may be used.
		$F_{v,Ed} \leq F_{b,Rd}$	
	**B** Slip-resistant at serviceability	$F_{v,Ed,ser} \leq F_{s,Rd,ser}$	Preloaded property classes 8.8 or 10.9 bolts should be used.
		$F_{v,Ed} \leq F_{v,Rd}$	
		$F_{v,Ed} \leq F_{b,Rd}$	
	C Slip-resistant at ultimate	$F_{v,Ed} \leq F_{s,Rd}$	Preloaded property classes 8.8 or 10.9 bolts should be used.
		$F_{v,Ed} \leq F_{b,Rd}$	
		$\Sigma F_{v,Ed} \leq N_{net,Rd}$	
Tension connections			
	**D** **Non-preloaded**	$\mathbf{F_{t,Ed} \leq F_{t,Rd}}$	No preloading required. Property classes from 4.6 to 10.9 may be used.
		$F_{t,Ed} \leq B_{p,Rd}$	
	**E** Preloaded	$F_{t,Ed} \leq F_{t,Rd}$	Preloaded property classes 8.8 or 10.9 bolts should be used.
		$F_{t,Ed} \leq B_{p,Rd}$	

With: $F_{v,Ed}$ is the design shear force per bolt for the ultimate limit state; $F_{v,Rd}$ is the design shear resistance per bolt; $F_{b,Rd}$ is the design bearing resistance per bolt; $F_{v,Ed,ser}$ is the design shear force per bolt for the serviceability limit state; $F_{s,Rd,ser}$ is the design slip resistance per bolt at the serviceability limit state; $F_{s,Rd}$ is the design slip resistance per bolt at the ultimate limit state; $N_{net,Rd}$ is the net area plastic resistance along the critical path; $F_{t,Ed}$ is the design tensile force per bolt for the ultimate limit state; $F_{t,Rd}$ is the design tension resistance per bolt; $B_{p,Rd}$ is the design punching shear resistance of the bolt head and the nut.

2.2.3 Normative situation: European harmonised standards of non-preloaded and preloaded structural bolting assemblies

Structural bolting assemblies in steel structures can generally be divided into two European harmonised standards according to EU-Regulation No. 305/2011 for Construction Products (CPR) [122] summarized below:

- **Non-preloaded structural bolting assemblies** (for bolted categories A, D) refer to the *European harmonized standard EN 15048-1* and can be divided into
  - *standard bolts for metal construction* (e.g. hexagon head bolts according to the standards EN ISO 4014 [119, 123], EN ISO 4016 [124, 125], EN ISO 4017 [121, 126] and EN ISO 4018 [127, 128] as well as hexagon socket head cap bolts according to EN ISO 4762 [120]), which are generally failing in the free loaded bolt threads of the threaded part based on the intended design principle of these bolts with $A_s < A$,
  - *German bolts for steel construction* (DIN 7990 [129] and DIN 7968 [130]).
- **Preloaded structural bolting assemblies** (for bolted categories B, C, E) refer to the *European harmonized standard EN 14399-1* [101] and distinguishes between two types of high-strength structural bolting assemblies for preloading with
  - *Type HR* (as System HR according to EN 14399-3 with or without direct tension indicators (DTI) in line with EN 14399-9 [131], if provided, and System HRC according

to EN 14399-10 [132]), which is designed in a way that the ductility is achieved predominantly by plastic elongation of the bolt (with a minimum height of the nut ≥ 0.9·D and thread length of the bolt according to EN ISO 888 [133]),

- *Type HV* (as System HV according to EN 14399-4 with or without direct tension indicators, if provided), which is designed in a way that the ductility is mainly achieved by plastic deformation of the paired bolt and nut threads (therefore with nut height ≈ 0.8·D and short thread length).

In the frame of this thesis, the focus is placed exclusively on non-preloaded tension, shear and combined tension and shear bolted connections.

2.2.4 Non-preloaded structural bolting assemblies according to EN 15048-1

The execution standard for steel structures EN 1090-2 [66] specifies all technical requirements of steel structures and refers explicitly in Clauses 5.6.3 and 5.6.6 to EN 15048-1 for “non-preloaded bolting assemblies” which are allowed to be used in steel structures. EN 15048-1, as a kind of umbrella standard, does not refer any specific product standards but defines all requirements regarding the performance of structural bolting assemblies made of carbon and austenitic stainless steel depending on the properties of their matched components. Compared with the building supervisory authority introduced EN 15048-1 from 2007 [74], the technical requirements of EN 15048 from 2016 [75] (not yet introduced by the supervisory authority) only refer to the product characteristics of the bolting assembly that are required for CE marking. Furthermore, EN 15048-1:2016-09 specifies that the term “bolting assembly” includes bolt and nut but not washer anymore.

All these requirements must be fulfilled by non-preloaded structural bolting assemblies if they want to be applied in steel structures in order to get the CE-marking and the SB-marking (SB as abbreviation for ”structural bolting”) both on the bolt head and on the nut. Consequently, SB-marked bolting assemblies are clearly identifiable. For example, bolting assemblies which fulfil the requirements of EN 15048-1 are those used in the presented investigations consisting of partially or fully threaded hexagon head bolts according to EN ISO 4014 and EN ISO 4017 or hexagon socket head cap bolts according to EN ISO 4762 in combination with normal-size hexagon nuts according to EN ISO 4032. Nevertheless, it must be emphasized that the version of EN 15048-1 from 2007 and the more recent version of EN 15048-1 from 2016 both do not include bolting assemblies made of duplex stainless steel and the new PC 100. Only austenitic stainless steel grades A2, A3, A4 and A5 in property classes PC 50, 70 and 80 are covered. Consequently, these bolting assemblies are currently not available with SB marking.

2.3 Stainless steel bolts and bolting assemblies according to EN ISO 3506

2.3.1 General

“Stainless steel” is the generic term of a family of fully recyclable iron-based alloys that contain a minimum of 10.5 % chromium. Combined with low carbon content from 0.03 % to greater than 1.00 %, chromium imparts supreme material properties like high strength, outstanding ductility [4, 5] and excellent corrosion resistance. In order to achieve the intended mechanical and physical material properties, other alloying elements like nickel, molybdenum, titanium, aluminium, sulphur, phosphorus, niobium, copper, nitrogen or selenium can be added to resist even difficult, high-aggressive chemical environments. Other intended material properties, achieved with substitutional or interstitial chemical elements influencing the microstructure in different ways, include improved ductility, pronounced strain hardening, superior fatigue

behaviour [6], heat resistance [8–11, 134], fire resistance [11–14], excellent impact toughness at low and high temperatures [15–17] and high fracture toughness even under seismic loading [18, 19].

When exposed to air or any other oxidizing environment, immediately a transparent and closely adhering chromium-rich oxide layer establishes on the stainless steel surface, the so-called passive layer with a thickness about 5×10^{-6} mm. If the surface is damaged by scratching or cutting, the passive layer reforms immediately in the presence of oxygen and will not react further with the atmosphere. It is worth mentioning that the stability of the thin passive layer depends mainly on the corrosiveness of its environment, the chemical composition of the stainless steel and the surface treatment.

2.3.2 Stainless steel grades

In principle, taking the three matrix phases (austenitic, ferritic, martensitic) that may coexist in the microstructure as crystal lattice, stainless steels can be distinguished into five categories: austenitic, ferritic, duplex, martensitic and precipitation hardening stainless steels. Each group has its own unique mechanical and physical material properties covering a wide range of corrosion resistances for a variety of applications.

In the following, the main mechanical and physical characteristics of austenitic and duplex stainless steel materials are briefly summarised under consideration of [64, 135–141]:

- *Austenitic stainless steel* with 17-18 % chromium content and 8-11 % nickel additions are the most widely used non-ferromagnetic stainless steels available on the market and predominantly used in the construction industry for structural applications. The face-centred cubic crystal structure (FCC) with austenitic γ-phase leads to high ductility, good cold formability and weldability as well as significantly better toughness in low and high temperatures (from -269 °C to +800 °C) compared to structural carbon steel. For this reason, austenitic stainless steels are also preferred in cryogenics. It is worth mentioning that austenitic stainless steel can be strengthened only by cold working but not by heat treatment, and their corrosion resistance can be further enhanced by chromium and other alloying elements like molybdenum and nitrogen.

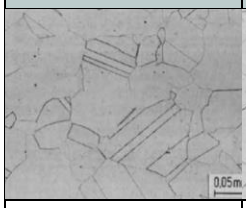
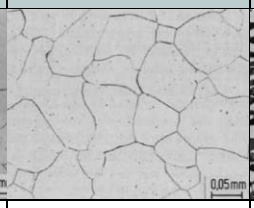
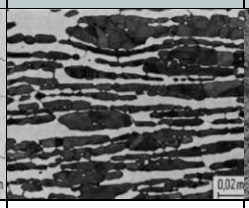
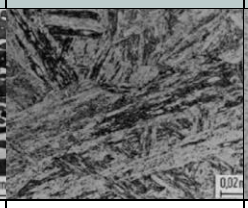
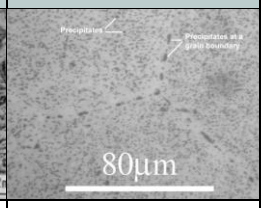
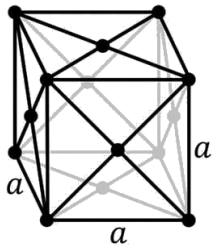
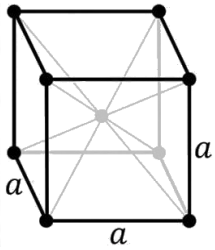
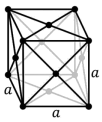
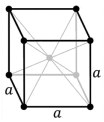
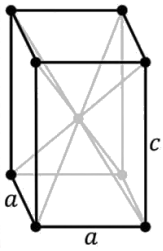
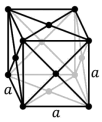
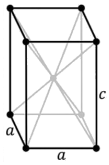
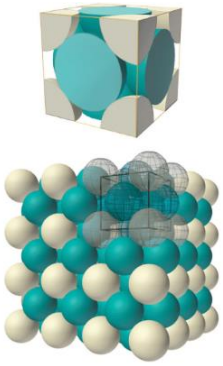
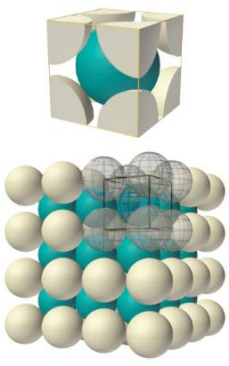
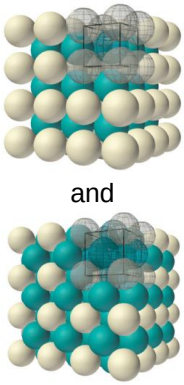
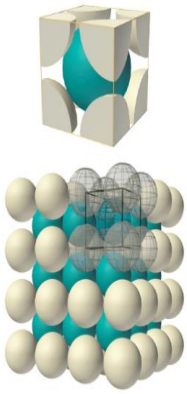
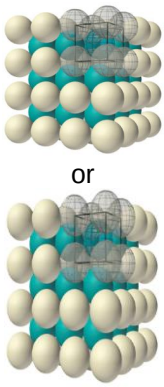
  Cold working of austenitic stainless steel can partially transform austenite to martensite. Consequently, as martensite is ferromagnetic, cold worked austenitic stainless steels can show a partially magnetic behaviour usually occurring at sharp corners, sheared edges or machined surfaces. The most used steel grades are 1.4301 and 1.4307 (widely known as AISI ”304” and “304L”; the “L” stands for low carbon). Improved corrosion resistance can be achieved by grades 1.4401 and 1.4404 (knows as AISI “316” and “316L” ; the “L” stands for low carbon), which are popular for fasteners, while steel grade 1.4571 should be specified for welded sections. Furthermore, austenitic stainless steels with high chromium content are available on the market and will be introduced in the revision of the EN 10088 standard series.

- *Duplex stainless steel* is defined as a biphasic metallurgical microstructure in nearly equal or 40 / 60 % proportions of austenitic and ferritic with high chromium content of 20 to 26 %, additionally 1 to 8 % nickel and low contents of molybdenum and nitrogen. In recent years, duplex stainless steels have been increasingly used in a variety of structural applications whenever high strengths complemented by high impact toughness and supreme corrosion resistance are required [38]. They are magnetic due to the ferritic α-phase and about twice as strong as austenitic stainless steels in the annealed condition, which allows for instance the use of slender sections in the structure to compensate for the high price.

Analogues to austenitic grades, duplex can be strengthened by cold working but not heat treatment. Duplex stainless steels show good weldability and resistance to stress corrosion cracking. Nevertheless, due to the significant higher strengths, the ductility and formability is reduced compared to austenitic stainless steels. The commonly used steel grade for standard duplex stainless steel is 1.4462, while 1.4162 or 1.4662 designated as “Lean Duplex” are a more cost-effective alloy with reduced contents of nickel and molybdenum. Furthermore, duplex steels are also available as “Super Duplex” or even “Hyper Duplex” on the market for highest corrosion resistances for critical environmental conditions.

In the construction industry, mainly austenitic and duplex stainless steel grades are used (as EN 1993-1-4 permits the application of austenitic, ferritic and duplex, while martensitic and precipitation hardening stainless steels are excluded for structural purposes). By the fact that the mechanical and physical properties of stainless steel are decisively defined by the metallurgical and specific crystal lattice structure, a comparative overview of the different steel groups is shown in Table 2.3-1. The metallurgical aspects and post-treatment processes are not further discussed but can be found in standards and literature, as they have major impact on the final material properties of stainless steels, see [65, 138, 139, 141].

Table 2.3-1: Crystal lattice of the metallurgical structure of the five stainless steel groups acc. to [64, 135–141]

Austenitic stainless steel	**Ferritic** stainless steel	**Duplex** stainless steel	**Martensitic** stainless steel	**Precipitation hardening** stainless steel
				
		 FCC and  BCC		 FCC or  BCT
Face-centred cubic crystal structure (FCC)	Body-centred cubic crystal structure (BCC)	Combination of FCC and BCC in nearly equal proportions	Body-centred tetragonal crystal structure (BCT)	Depending on the steel grade of the subgroup FCC or BCT
		 and		 or
Packing density 74.1 %	Packing density 68.0 %	Packing density ≈ 71.0 %	Packing density ≈ 71.0 %	Packing density 74.1 % or 71.1 %

2.3.3 Mechanical behaviour of stainless steels compared to carbon steel

The mechanical behaviour of stainless steel differs from that of carbon steel due to the different crystal lattice structures and metallurgical characteristics as well as post-treatment processes of stainless steel during the fabrication, which should be considered in the design process and reflected in the safety assessment of the Eurocode in order to allow a safe and reliable design of structures made of stainless steel.

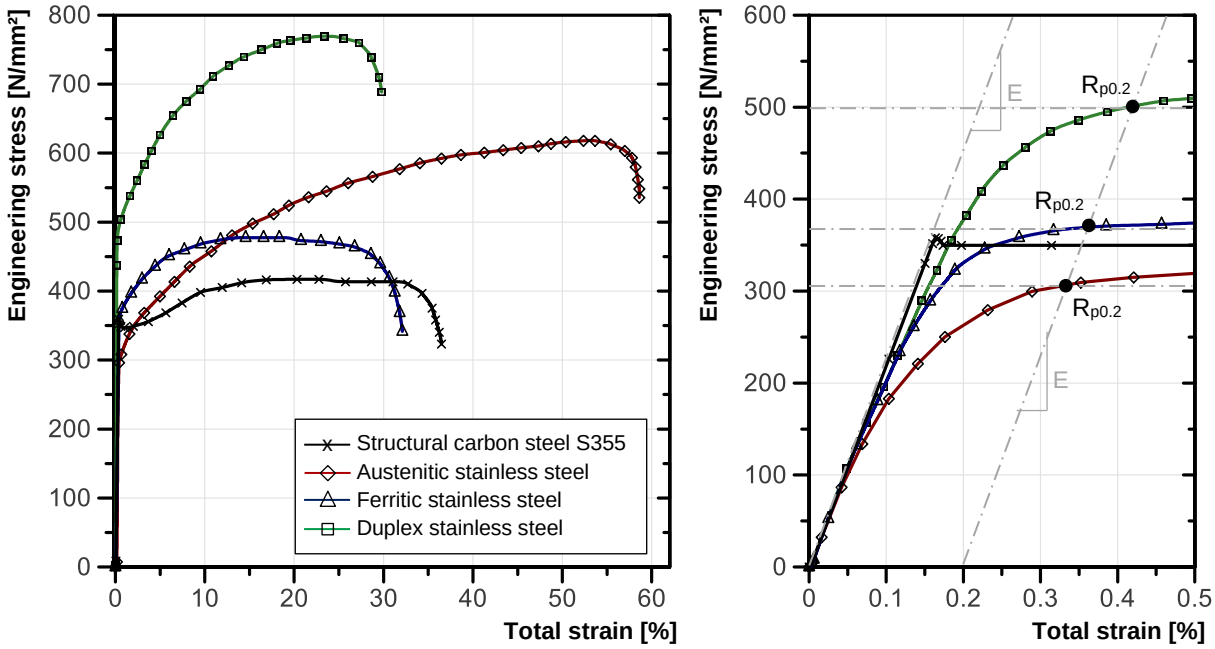
In order to address the different mechanical behaviour of austenitic and duplex stainless steel, the main characteristics regarding the load bearing behaviour of stainless steel in structural applications compared to structural carbon steel are briefly outlined in the following:

- Stainless steel shows a strain rate-dependent nonlinear stress-strain behaviour compared to carbon steel, including plastic deformation already below the yield strength,
- pronounced strain hardening and cold working of especially austenitic stainless steel but also duplex stainless steels complemented by outstanding high ductility even for cryogenic applications,
- time and temperature-dependent creep and stress relaxation already at room temperature as viscoplastic deformation behaviour,
- anisotropic mechanical response and asymmetry under compression and tension loading of stainless steel, and
- excellent impact toughness at low and high temperatures and high fracture toughness even under seismic loading.

The stress-strain behaviour of stainless steel differs fundamentally from that of structural steel, as exemplarily presented in Figure 2.3-1. Here, the full stress-strain curves until fracture are presented, while Figure 2.3-1 (b) focuses on the engineering strain between 0 and 0.5 % in order to show different definitions of the yield strength for carbon and stainless steel. While unalloyed structural carbon steels are characterised by a linear-elastic material behaviour with a clearly defined yield point (here as the lower yield strength R_{eL} for S355 structural carbon steel) and followed by a pronounced plastic plateau (as instable plastic flow of the material known as “Lüders bands” characterised by dynamic strain aging) before strain hardening of the material begins, stainless steels exhibit more round nonlinear engineering stress-strain curves without a clearly defined elastic-plastic limit. Consequently, the pronounced nonlinear behaviour of stainless steels becomes relevant already under low loading condition, as plastic deformations already occur at lower loads below the yield point which is not the case for carbon steels. Due to the lack of a sharply defined yield point, EN 1993-1-4 determines the elastic limit $R_{p,0.2}$ as the 0.2 % non-proportional plastic strain, see Figure 2.3-1 (b).

The nominal Young’s modulus (E) of austenitic and duplex stainless steel is slightly lower with 200.000 N/mm² instead of 210.000 N/mm² for structural carbon steel, while for ferritic stainless steel EN 1993-1-4 and EN 10088-1 specify a nominal Young’s modulus of 220.000 N/mm². However, the Design Manual or Structural Stainless Steels (4th Edition) recommend a value of 200.000 N/mm² for all stainless steel grades, which is already integrated in the current version of FprEN 1993-1-4 [80]. The austenitic and duplex stainless steel stress-strain curves can be characterised by pronounced strain hardening until the maximum stress (defined as tensile strength R_m) is achieved. Main factors affecting the stress-strain behaviour of stainless steels are cold working, asymmetry under tensile and compression load, anisotropy and the strain-rate sensitivity. The process of “cold working” is defined as plastic deformation of a metal at a temperature below its specific recrystallization temperature. Consequently, cold working is a powerful strengthening mechanism by virtue of strain hardening, but also useful for shaping

materials for structural applications. Examples of different strengthening mechanism for stainless steels are solid solution strengthening, dislocation strengthening, precipitation strengthening and strengthening due to grain size refinement. Further information can be found in [141].



(a) Full engineering stress-strain curves (b) Definition of the elastic limit $R_{p,0.2}$

Figure 2.3-1: Stress-strain-curves of stainless steels in comparison to S355 structural steel (a) and definition of the elastic limit $R_{p,0.2}$ based on 0.2 % of plastic strain (b) according to [64]

The strain hardening resulting from the cold working of stainless steels is particularly pronounced in austenitic microstructures, leading to significant increases in both the 0.2% plastic limit of elasticity ($R_{p,0.2}$) and the tensile strength R_m due to associated plastic deformation, for example during cold forming of sheet metal or during the cold rolling of bolt threads, which is further discussed in Chapter 2.4.8. Here, a transformation of austenitic to forming induced martensitic material occurs in the bolt's tensile cross-section originating from the thread rolling process with a larger hardness and higher strength in the border of the cross-section of the threads. Like structural carbon steel, also for stainless steels an increase in strengths is generally accompanied by decrease of ductility and toughness. Due to the relatively high basic ductility of austenitic and duplex stainless steels, the practical consequences for this are manageable in most cases [64, 135–137].

Furthermore, the influence of the deformation speed on the stress-strain behaviour is greater for stainless steels than for carbon steels. With increasing strain-rate, greater strengths can be achieved for stainless steel. For further general information regarding the stress-rate sensitivity of stainless steel, see [142–148]. Regarding the strain-rate sensitivity of bolted connections, for instance Fransplass et al. [149] investigated in 2011 the tensile behaviour of carbon steel M5 threaded rods in PC 4.6 at quasi-static and elevated rates of strain from 10^{-3} to 1.9×10^{3} mm/s. Researchers could demonstrate that 1. the strength of the threaded assembly increased with increase strain-rate and 2. the strain-rate had also an influence on the failure mode of the threaded assembly. Furthermore, in 2019, Cai and Young [150] conducted experimental investigations on 36 carbon and stainless steel bolted connections subjected to shear loading at different strain rates of 10 mm/min (≈ 16.7 mm/s) and 20 mm/min (≈ 33.3 mm/s). Cai and Young concluded that *"the higher strain rate on the bolted connection specimens, the higher ultimate load was obtained. The ultimate loads were averagely 2 % to*

6 % higher, while the corresponding elongations were averagely 8 % to 9% higher for the test results obtained from the strain rate of 20 mm/min compared with those obtained from the lower strain rates. […] It is shown that increasing the strain rate up to 20 mm/min generally has no effect on the bearing failure mode of the carbon steel and stainless steel bolted connections. The resulting strengths and failure modes were compared with the results predicted by the bolted connection design rules in international design."

Furthermore, stainless steel suffers from time-dependent inelastic deformation already observed at room temperature as viscoplastic deformation subdivided into creep and stress relaxation. The viscoplastic deformation behaviour led to major concerns in the past about the use of stainless steels in structural applications. In order to address this concern for bolted connections, a comprehensive investigation has been conducted in the European RFCS SIROCO project [83]. Thus, it can be concluded that a safe and reliable preloading of stainless steel bolting assemblies is in principle possible when an appropriate lubricant is applied and galling can avoided by using a proper lubricant, even for over-elastic tightening. Furthermore, studies into preload losses showed comparable results to those from carbon steel bolts.

However, deviating from the isotropic and symmetric mechanical behaviour of carbon steel, cold worked stainless steels tend to show asymmetric behaviour when subjected to tensile and compression. Additionally, anisotropic behaviour can be observed with increasing cold worked strength level, giving rise to different stress-strain characteristics depending on the rolling direction in particular of sheet material, see [136]. However, in the context of the design and execution of bolts made of austenitic or duplex stainless steel, the anisotropic behaviour is not explicitly considered in the standards. Here, it must only be assured that the bolts fulfil the mechanical and physical requirements specified in EN 15048-1 and EN ISO 3506-1.

2.3.4 Normative specifications of stainless steel bolts and nuts

The EN ISO 3506 standard series specifies the mechanical properties of corrosion-resistant stainless steel fasteners. The series is divided into the following six parts, of which Parts 1 and 2 are of particular interest:

- Part 1: Bolts, screws and studs with specified grades and property classes [73],
- Part 2: Nuts with specified grades and property classes [151],
- Part 3: Set screws and similar fasteners not under tensile stress [152],
- Part 4: Tapping screws [153],
- Part 5 (as Draft ISO/FDIS 3506-5:2021-09): Special fasteners also including fasteners from nickel alloys for high temperature applications [154], and
- Part 6 (as ISO 3506-6:2020-04): General rules for the selection of stainless steels and nickel alloys for fasteners [155].

EN ISO 3506-1 accentuates that the physical properties (in particular corrosion resistance) of stainless steel fasteners result from the chemical composition of the material, while the mechanical properties are depending on the manufacturing processes: Fasteners made of austenitic and duplex stainless steels are generally produced by cold forming and consequently, their local material properties are not as homogeneous compared to quenched and tempered fasteners. Both the mechanical properties and the chemical composition of bolts and nuts of stainless steel fasteners are covered in EN ISO 3506-1/ -2. In the last years, these standards were under revision and were republished in 2020 with a few significant changes

and further specifications, technically and editorially mainly following EN ISO 898-1 and -2 for carbon steel bolts. The following three aspects should be emphasised in particular:

(1) Bolting assemblies made of stainless steel are the appropriate choice whenever difficult environmental or chemical corrosive conditions exist, or regular maintenance is not possible. Nowadays, bolting assemblies made of austenitic stainless steel are widespread on the market and are used predominantly for almost all stainless steel bolted connections in the construction industry about 70 % [64, 136]. However, with the development of duplex stainless steel, duplex bolting assemblies become nowadays more demanded because of their outstanding corrosion resistance (in practical terms often distinguished by the pitting resistance equivalent number, usually abbreviated "PREN"). Herein, duplex is a comprising term for different types of austenitic-ferritic steel grades, such as lean duplex, duplex, super duplex, or even hyper duplex (not covered in EN ISO 3506-1 but available on the market).

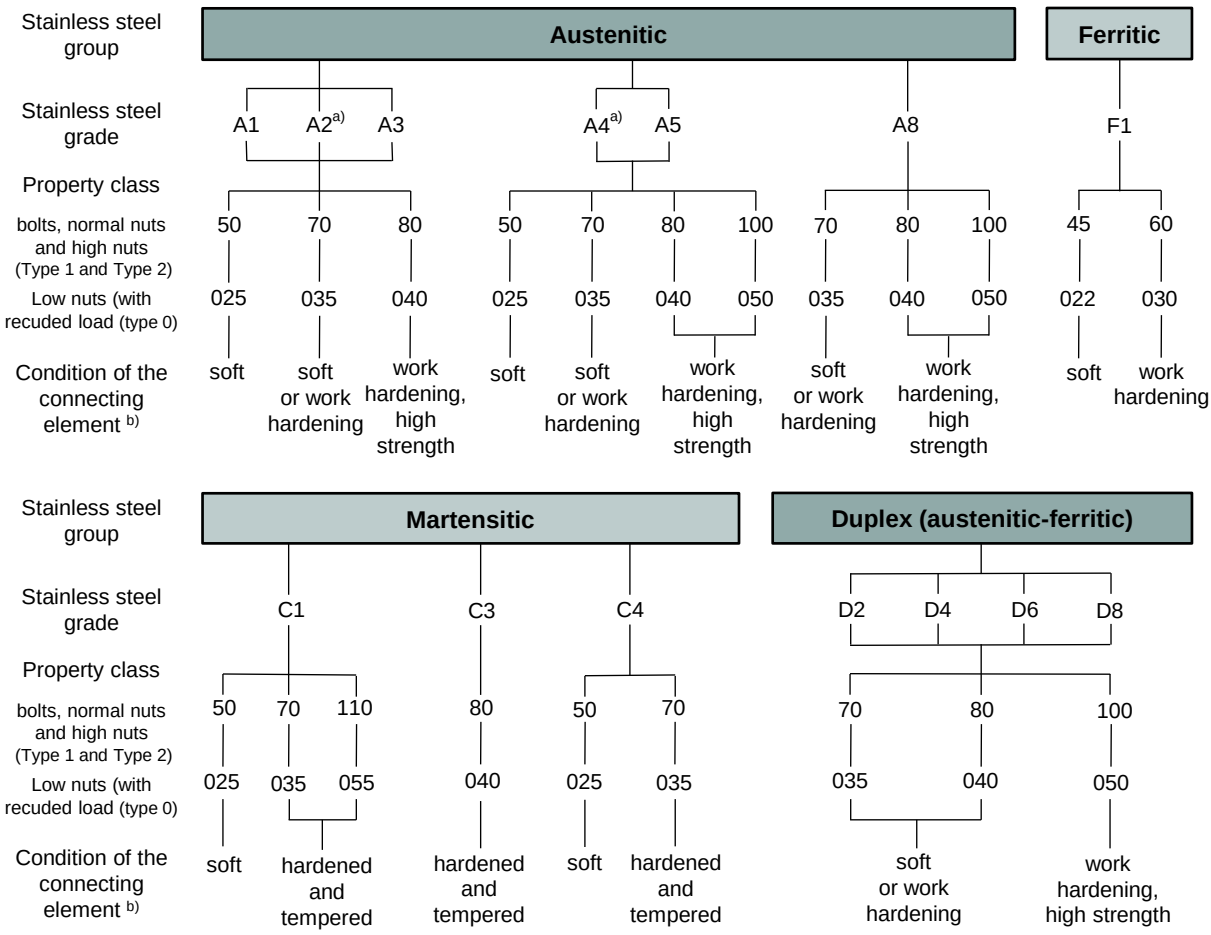
(2) The highest considered property class has been raised from PC 80 to PC 100 to meet the increasing demands of high-strength stainless steel bolts for the construction industry. The different mechanical properties are achieved by strain hardening depending on the rate of cold working. Ferritic and martensitic bolts are not covered in the scopes of EN 1993-1-4, FprEN 1993-1-4 and EN 15048-1 and have not been considered in this thesis.

(3) The designation system for stainless steel grades and property classes for fasteners (bolts and nuts) is presented in Figure 2.3-2 in order to clearly identify the stainless steel grade, property class and corrosion resistance. It classifies the stainless steel material by the letters "A" for austenitic, "F" for ferritic, "C" for martensitic and "D" for duplex. Additionally, the chemical composition and resulting corrosion resistance are given by a number (1, 2, 3 4, 5, 6 or 8 for austenitic and 2, 4, 6 or 8 for duplex); "1" representing the least and "8" the most durable corrosion resistance. The designation of the property class (second block) for stainless steel bolts according to EN ISO 3506-1 consists of a number representing 1/10 of the minimum tensile strength (in N/mm²) of the fastener, e.g. "A4-70" indicates molybdenum containing austenitic stainless steel with corrosion resistance "4" and PC 70, that means a minimum tensile strength R_{mf} of 700 N/mm² of the bolt. For stainless steel nuts, the property class as second block indicates the minimum proof stress S_p (in N/mm²) for normal and high nuts (Type 1 and 2), while for low nuts (Type 0) the property classes are presented in Figure 2.3-2. They can be easily identified by zero as the first digit followed by two digits representing 1/10 of the minimum proof stress (in N/mm²) of the nut, e.g. "050" is equal to S_p = 500 N/mm².

Finally, the mechanical properties for austenitic and duplex stainless steel bolts according to EN ISO 3506-1 are summarised in Table 2.3-2. Additionally, the common designations of stainless steels used for fasteners based on ISO 3506-6 are also included and connected with stainless steel grades and steel numbers according to EN 10088 standard series [156–163] as well as corrosion classes, see [64, 84, 155].

From a comparison of the mechanical properties between carbon and stainless steel bolts presented in Table 2.3-2, it becomes clear that the property classes of EN ISO 3506-1/-2 do not fully correspond to the property classes specified in EN ISO 898-1/2 of carbon steel bolts and nuts: The minimum stresses at 0.2 % non-proportional elongation (defined as the yield strength) of PC 80 and 100 bolts are lower compared to those of PC 8.8 and 10.9 with min. $R_{pf,80}$ = 600 N/mm² vs. min. $R_{p,0.2,8.8}$ = 660 N/mm² (for structural bolting d ≥ 12 mm) and min. $R_{pf,100}$ = 800 N/mm²vs. min. $R_{p,0.2,10.9}$ = 940 N/mm². However, the tensile strength, which is of major importance in the design of bolted tension and shear connections, is almost identical. For instance, the tensile strengths of PC 80 and 100 are nearly comparable to those

of PC 8.8 and 10.9 with min. $R_{mf,80}$ = 800 N/mm² vs. min. $R_{m,8.8}$ = 830 N/mm² (for d ≥ 12 mm) and min. $R_{mf,100}$ = 1000 N/mm² vs. min. $R_{m,10.9}$ = 1040 N/mm² (see [164]). Furthermore, the nominal strength values to be considered in the design of bolted connections with bolts of PC 8.8/10.9 vs. PC 80/100 shows that the nominal tensile strengths of carbon steel and austenitic / duplex bolts are identical with nom. $f_{ub,8.8/80}$ = 800 N/mm² and nom. $f_{ub,10.9/100}$ = 1000 N/mm². On the contrary, the nominal yield strengths are smaller for austenitic and duplex stainless steel bolts with nom. $f_{yb,80}$ = 600 N/mm² vs. nom. $f_{yb,8.8}$ = 640 N/mm² and even smaller for PC 100 with nom. $f_{yb,100}$ = 800 N/mm² vs. nom. $f_{yb,10.9}$ = 900 N/mm². Nevertheless, austenitic and duplex stainless steel bolting assemblies with mechanical properties comparable to PC 8.8, 10.9 and 12.9 (and even higher) for carbon steel bolts already exist on the market, although not covered by EN ISO 3506-1/-2 but fulfilling the requirements of EN 15048-1.



a) Low carbon austenitic stainless steels with carbon content not exceeding 0.030 % may additionally be marked with an "L" after the grade. Example: A4L-80.

b) For information only.

Figure 2.3-2: Designation system for stainless steel grades and property classes for bolts and nuts according to EN ISO 3506-1/ -2

Analogues to EN ISO 898-1/ -2 for carbon steel bolts, the mechanical properties of stainless steel bolts and nuts must be tested and reviewed for conformity. The applicability of the test methods for fasteners with full and reduced loadability are summarised in Clause 8 of EN ISO 3506-1. Furthermore, EN ISO 3506-1 specifies the minimum ultimate tensile loads $F_{m,min}$ defined as the product of the nominal tensile strength R_{mf} and the nominal tensile stress area $A_{s,nom}$ following the regulations of EN ISO 898-1 for carbon steel bolts.

Table 2.3-2: Mechanical properties for carbon steel bolts according to EN ISO 898-1 compared to austenitic and duplex stainless steel bolts according to EN ISO 3506-1 and EN ISO 3506-6

Steel group	Steel grade	Property class	Tensile strength R_{mf}	Yield strength[1)] R_{pf}	Elongation after fracture A
			Min. (N/mm²)	Min. (N/mm²)	Min. [mm]
Carbon steel	Not further distinguished	4.6	400	240	22 %
		5.6	500	300	20 %
		8.8	830 (d ≥ M12)	660 (d ≥ M12)	12 %
		10.9	1040	940	9 %
		12.9	1220	1100	8 %
Austenitic[2)] stainless steel	**A1, A2, A3, A5**	50	500	210	0.6d
		70	700	450	0.4d
		80	800	600	0.3d
	A4	50	500	210	0.6d
		70	700	450	0.4d
		80	800	600	0.3d
		100	1000	800	0.2d
	A8	70	700	450	0.4d
		80	800	600	0.3d
		100	1000	800	0.2d
Duplex[3)] stainless steel	**D2, D4, D6, D8**	70	700	450	0.4d
		80	800	600	0.3d
		100	1000	800	0.2d

[1)] Defined as resulting stress at 0.2 % non-proportional elongation in accordance with EN ISO 3506-1. | [2)] Common designations of stainless steels used for fasteners according to ISO 3506-6 [155]: **A1**: Designed for machining (1.4570, 1.4305) | **A2:** Basic austenitic (1.4301, 1.4307) | **A3:** Stabilised basic austenitic (1.4541, 1.4550) | **A4:** Molybdenum containing austenitic (1.4401, 1.4404, 1.4432, 1.4436 or 1.4435) | **A5:** Stabilised molybdenum austenitic (1.4571) | **A8:** Super austenitic (1.4529, 1.4547) | [3)] **D2:** Lean duplex (1.4482, 1.4362) | **D4:** Lean duplex (1.4162, 1.4062) | **D6:** Standard duplex (1.4462) | **D8:** Super duplex (1.4410, 1.4501, 1.4507)

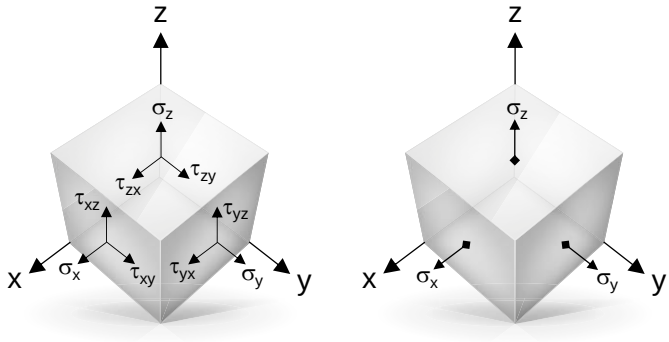
2.4 Mechanical principles of bolts subjected to tension, shear and interaction

2.4.1 General

On the loading side, the Cauchy stress tensor σ is a second order tensor and indicates the stress state at a given point inside an arbitrary material in the deformed state, placement or configuration. The stress tensor σ consists of nine components σ_{ij}, which are completely defining the stress state and include both the normal and shear stresses acting inside a material. The three principal (normal) stresses (σ_{11}, σ_{22}, σ_{33} or simplified to σ_x, σ_y, σ_z) act perpendicular to the sectional areas of an isolated stress cube. They are attributable to active tensile or compressive forces. In each case, the two shear forces of each sectional area lie in a plane and act perpendicular to the normal stress. There are a total of six different shear stresses: τ_{xy}, τ_{xz}, τ_{yx}, τ_{yz}, τ_{zx}, τ_{zy}. Shear stresses are generated, for example, through vertical loading, bending or torsion in a body. The first index position in the shear stress vector i (for example z in τ_{zy}) indicates to which stress normal the shear stress belongs (in this case the z-axis), while the second position j indicates the direction of the shear stress vector (in this case the y-axis), see Figure 2.4-1.

On the resistance side, in principle, all strength hypotheses assign a “virtual” uniaxial stress state as equivalent to the real multiaxial stress state based on a defined material-mechanical criterion. Its largest normal stress, the equivalent stress σ_v, can be compared with the yield

strength σ_y as beginning of plastic deformation for ductile materials like carbon and stainless steel or the ultimate strength σ_u for brittle materials if failure occurs at fracture as characteristic values of the material. Depending on the intended application and material, different strength and failure hypotheses exist like *Rankine*, *Coulomb-Mohr* or *Modified Mohr* for brittle materials and *Tresca*, *von Mises*, *Hill*, *Hosford* and *Gurson* for ductile materials. The leading concept is always to predict failure of a material by comparing the resulting stress state in the material with the material properties like tensile strength f_u for brittle materials or yield strength f_y for ductile materials [165]. Therefore, the three most popular strength hypotheses for practical calculations of Rankine, Tresca and von Mises are briefly presented in the following.



$$\sigma_{ij} \equiv \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix} \equiv \begin{pmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{pmatrix}$$

(a) Cartesian stress components (b) Principal stresses (c) Cauchy stress tensor

Figure 2.4-1: Definition of general cartesian stress components (a), principal stresses (b) and stress tensor (c) according to [165]

Furthermore, the correlations between yield/ultimate strength and shear strength as well as the resulting stress states of bolts subjected to tension and shear loading are discussed. The construction principle of bolts and the different failure types are presented and complemented by an overview of strength increasing effects of different thread production types on stainless steel bolts.

2.4.2 Maximum principal stress theory by Rankine

The maximum principal stress theory by William John Macquorn Rankine (Scottish engineer and physicist; born in 1820, died in 1872) is the oldest failure theory and requires a brittle material (e.g. cast iron) or brittle material behaviour (e.g. martensitic hardened steel) with limited deformation capacity. According to Rankine's theory, brittle or cleavage fracture occurs under static loading as soon as the maximum normal stress σ_x reaches the cohesion strength σ_T of the material, which is generally the tensile strength $\sigma_T = f_u$ of brittle materials. For the technically important case of 2D biaxial loading, the equivalent stress σ_e according to Rankine can also be formulated directly in the three load stresses σ_x, σ_y and τ_{xy}, see (Eq. 2.4-1).

$$\sigma_{e,MPS} = \sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x + \sigma_y}{2}\right)^2 + \tau_{xy}^2} \leq \sigma_T \quad \text{with } \sigma_1 > 0 \qquad \text{(Eq. 2.4-1)}$$

In the case of combined tensile and shear stresses, the equation can be further reformulated to (Eq. 2.4-2) with axial tensile stress σ_x, the condition of $\sigma_y = 0$ and shear stresses $\tau_{xy} = \tau_s$.

$$\sigma_{e,MPS} = \sigma_1 = \frac{\sigma_x}{2} + \sqrt{\left(\frac{\sigma_x}{2}\right)^2 + \tau_s^2} \leq \sigma_T \quad \text{with } \sigma_1 > 0 \qquad \text{(Eq. 2.4-2)}$$

However, the maximum principal stress theory by Rankine totally disregards the mutual effect of other principal stresses and shearing stresses on other planes in the material. If for example the material is loaded in pure shear with $\sigma_1 = |\sigma_3| = \tau_{max}$ and $\sigma_2 = 0$, then consequently failure

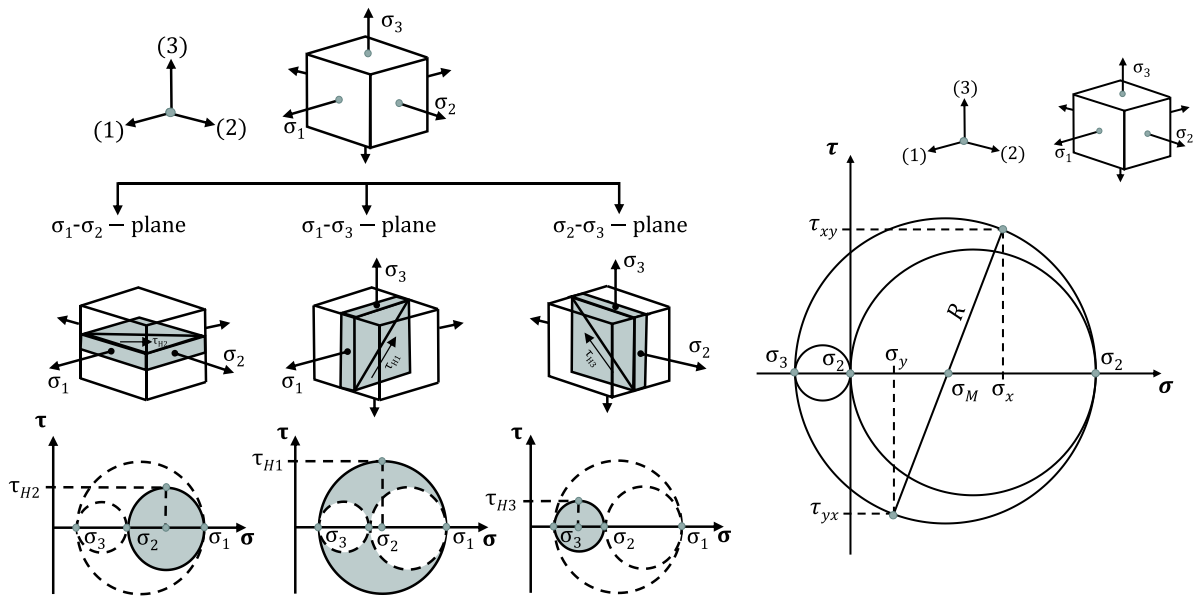
will occur when τ_{max} reaches the cohesion strength σ_T of the material as yield strength f_y or tensile strength f_u of the material. However, many experiments show that failure (here defined as beginning of plastic deformation) occurs much earlier when $|\tau_{max}|$ reaches about $0.6 \cdot f_y$ in ductile materials. Furthermore, some brittle materials such as cast iron with lamellar graphite show significantly higher stresses under compression compared to tension. The leading failure mechanism changes from cleavage failure to shear failure, which is not covered by Rankine's maximum principal stress theory.

2.4.3 Maximum shear stress theory by Tresca

The maximum shear stress theory was presented in 1864 by Henri Edouard Tresca (French engineer; born in 1814, died in 1885) and is based on the idea that plastic deformation occurs as sliding processes in the crystal lattice of the material triggered by shear stresses. The theory presupposes a ductile material or ductile material behaviour with failure by yielding defined as the beginning of plastic deformation. In contrast to Rankine, the maximum principal stress is not decisive for failure, but the maximum shear stress τ_{max} occurring in the material. The ductile material fails by yielding once the maximum shear stress τ_{max} exceeds the shear yield strength τ_F, see (Eq. 2.4-3).

$$\sigma_{e,MSS} = \underbrace{\frac{\sigma_1 - \sigma_3}{2}}_{\tau_{max}} \leq \underbrace{\frac{f_y}{2}}_{\tau_F} = \sigma_1 - \sigma_3 \leq f_y \quad \text{with } \tau_{max} = \frac{\sigma_{max} - \sigma_{min}}{2} = \frac{\sigma_1 - \sigma_3}{2} \wedge \tau_F = \frac{f_y}{2} \qquad \text{(Eq. 2.4-3)}$$

Depending on the magnitude of the principal normal stresses (σ_1, σ_2 and σ_3) acting on the material, the greatest shear stress can occur in different diagonal planes of the stress cube characterised by the principal normal stresses as σ_1- σ_2-plane, σ_1-σ_3-plane and σ_2-σ_3-plane. The maximum of the associated three main shear stresses (τ_1, τ_2, τ_3) defined as difference of principal stresses is always decisive for a failure, see Figure 2.4-2.



(a) Planes of maximum shear stresses in a stress cube

(b) Mohr's stress circle for 2D stress state

Figure 2.4-2: Planes of maximum shear stresses in a stress cube and Mohr's stress circle for 2D stress state according to [165]

In case of 2D biaxial loading, the equivalent stress σ_e according to Tresca can also be formulated directly in the load stresses, see (Eq. 2.4-4) and (Eq. 2.4-5).

$$\sigma_{e,MSS} = \sqrt{(\sigma_x - \sigma_y)^2 + 4 \cdot \tau_{xy}^2} \quad \text{if } \sigma_x \cdot \sigma_y \leq \tau_{xy}^2 \qquad \text{(Eq. 2.4-4)}$$

$$\sigma_{e,MSS} = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right) + \tau_{xy}^2} \quad \text{if } \sigma_x \cdot \sigma_y > \tau_{xy}^2 \qquad \text{(Eq. 2.4-5)}$$

In the case of combined tensile and shear stresses, the equation can be further simplified and reformulated to (Eq. 2.4-6) with axial tensile stress σ_x, $\sigma_y = 0$ and shear stresses $\tau_{xy} = \tau_s$.

$$\sigma_{e,MSS} = \sqrt{\sigma_x^{\ 2} + 4 \cdot \tau_s^2} \qquad \text{(Eq. 2.4-6)}$$

It follows that the theoretical ratio between shear and yield strength of the maximum shear stress theory by Tresca is about $f_y / 2 = 0.50$ with failure by yielding defined as the beginning of plastic deformation.

2.4.4 Shape modification hypothesis (or maximum distortion energy theory) by von Mises

According to the shape modification hypothesis (also known as maximum distortion energy theory) developed independently by James Clerk Maxwell, Maksymillian Tytus Huber, Heinrich Hencky and by Richard Edler von Mises (Austrian engineer; born in 1883, died in 1953), the shape modification energy stored in an elastically deformed volume element is decisive for the material stress. The shape modification energy is the energy required for changing the shape of a material in a defined spatial stress state. The equivalent stress is calculated in general form according to (Eq. 2.4-7) and principal normal stresses according to (Eq. 2.4-8).

According to the shape modification hypothesis, failure is defined analogous to the maximum shear stress theory by yielding as beginning of plastic deformations and therefore, the von Mises failure theory is preferred for ductile materials or ductile material behaviour. Thus, the von Mises equivalent stress σ_e is used to predict yielding of materials under complex loading from the results of simple uniaxial tensile tests. Prior to yielding, the material behaviour and response can be assumed to be linear-elastic, nonlinear-elastic or viscoelastic.

$$\sigma_{V,SMH} = \sqrt{\frac{1}{2} \cdot ((\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2) + 3 \cdot (\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2)} \leq f_y \qquad \text{(Eq. 2.4-7)}$$

$$\sigma_{V,SMH} = \sqrt{\frac{1}{2} \cdot ((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)} \leq f_y \qquad \text{(Eq. 2.4-8)}$$

The equation (Eq. 2.4-7) can be further simplified and reformulated to (Eq. 2.4-9) with axial tensile stress σ_x, $\sigma_y = 0$ and shear stresses $\tau_{xy} = \tau_s$ for the case of combined tensile and shear stresses.

$$\sigma_{e,SMH} = \sqrt{\sigma_x^{\ 2} + 3 \cdot \tau_s^2} \qquad \text{(Eq. 2.4-9)}$$

The theoretical ratio between shear and yield strength according to the shape modification hypothesis by von Mises is about $f_y / \sqrt{3} \approx 0.577$ and therefore higher than Tresca's approach. The shape modification hypothesis shows good agreement with experimental studies of ductile materials and allows a more economical design of structures, while the maximum shear stress theory by Tresca is more conservative. Figure 2.4-3 shows a graphical comparison between the limit curves according to von Mises and Tresca for the failure of ductile materials in 2D biaxial stress state.

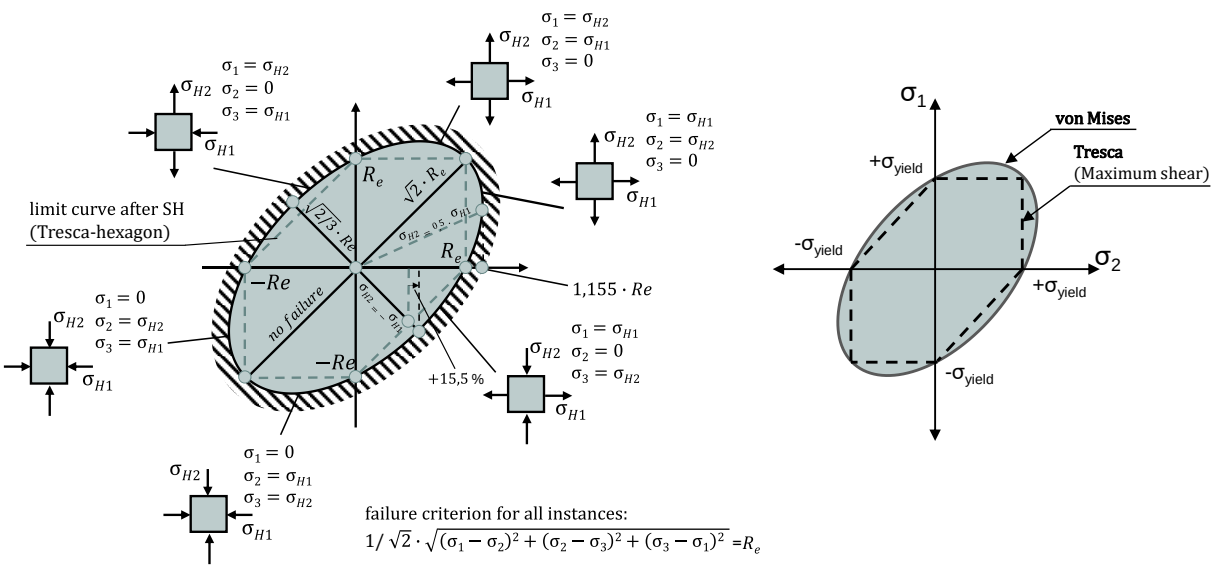


Figure 2.4-3: Comparison of the limit curves between the maximum shear stress theory by Tresca and the shape modification hypothesis by von Mises for the case of 2D biaxial stress state according to [165]

In the case of the maximum shear stress theory by Tresca, the limit curve is shaped like a so-called "Tresca hexagon". In contrast, the failure hypothesis of von Mises shows an elliptical limit curve partially exceeding the Tresca hexagon limit curve. Both limit curves intersect the coordinate axes at the yield strength ± f_y (assuming symmetric behaviour under compression and tension, which is not valid for stainless steels). No yielding and plastic deformation occurs if the stress state characterised by the two (non-zero) principal stresses is within the limit curve.

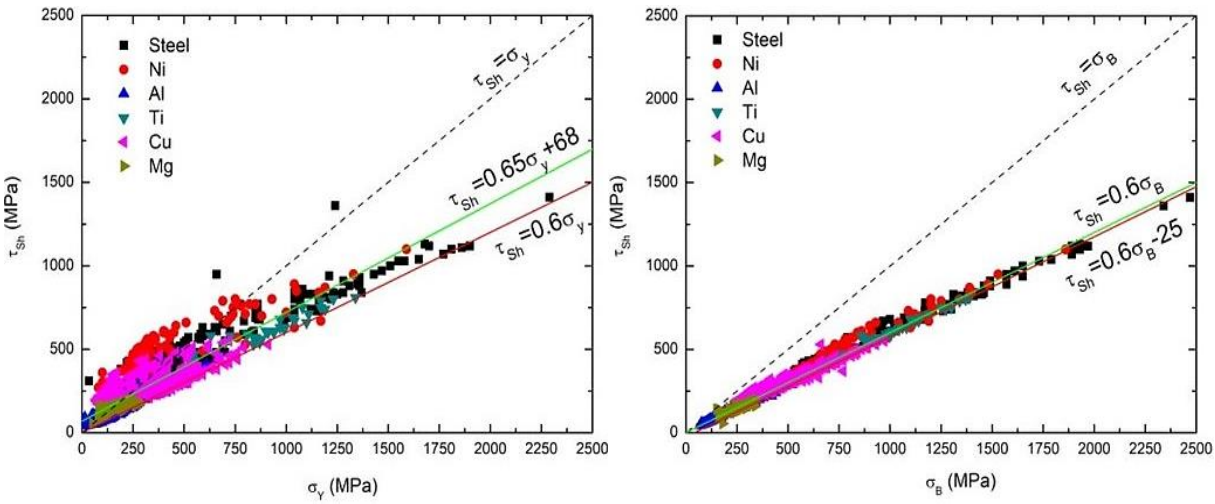
However, there is a crucial difference between the failure hypotheses of Tresca, von Mises and the experimental studies and design concepts: In pure shear and combined tension and shear tests on bolts, always the bolt tensile strength f_{ub} serves as the failure criterion and not the yield strength. Additionally, the ductility and plastic deformation capacity of a bolt as well as the pronounced strain hardening behaviour are not considered by the failure theories but become significant to accurately describe the load bearing behaviour of bolts subjected to tension, shear and interaction loading. Consequently, in the following the correlations between shear yield strength τ_y and yield strength f_y as well as between shear ultimate strength τ_u and tensile strength f_u based on experimental investigations are introduced and discussed.

2.4.5 Correlations between yield or ultimate strength and shear strength

In engineering practice, the designer frequently needs data on material's shear strength and therefore, the most popular rule of thumb has become established that the shear strength τ of a ductile material is about factor 0.6 of the yield strength σ_y, which is slightly higher than the theoretical shear strength of the von Mises failure hypothesis about $\tau_y = (1/\sqrt{3}) \cdot \sigma_y = 0.577 \cdot \sigma_y$. The shape modification hypothesis of von Mises is applied in EN 1993-1-1, Clause 6.2.5 [166] for the design of steel structures under vertical loading or shear. However, various studies regarding the shear strength of ductile materials and metals have observed distinctly higher ratios between shear strength and yield or tensile strength. Some of these higher shear/tensile strength ratios are already implemented into standards, recommendations and guidelines, e.g. the German VDI 2230-1 [167] guideline, which is known worldwide for designing and calculating preloaded bolted connections in mechanical engineering. Here, VDI 2230-1 defines the shear strength τ_B as shear ultimate strength τ_u and proposes reference values of shear strength ratios τ_B / R_m referring to the tensile strength clearly higher than 0.577, e.g. 0.80 to 0.85 for structural carbon steel, 0.65 to 0.85 for heat-treatable steel and 0.80 for solution-

annealed austenitic steel. A detailed comparison of selected international design rules regarding the shear resistance and resulting shear coefficients can be found in Chapter 3.4.3.

As part of a meta-study conducted by Genov [168], the dependencies of the shear strength and Brinell hardness on the yield and the ultimate strengths were investigated systematically by collecting data of 1996 materials into a database containing six classes of metal alloys: steel, nickel, aluminium, titanium, copper and magnesium alloys. As shown in Figure 2.4-4 (a), for 95 % of all materials the "rule of thumb" of $\tau_y = 0.6 \cdot f_y$ is fulfilled (although the scattering of data points is large until 750 N/mm²), showing a high level of conservatism in the results. The best fit line is given by $\tau_y = 0.65 \cdot f_y + 68$. On the contrary, a graphical comparison between the obtained shear strength τ and tensile strength $\sigma_b = \sigma_u$ shows a strikingly small scattering of data points, see Figure 2.4-4 (b). The rule of thumb $\tau_u = 0.6 \cdot f_u$ line divides the data: 51 % of the data points are above the line, while 49 % are below the line. The best fit line is calculated by Genov with $\tau_u = 0.60 \cdot f_u - 25$ and brings 93 % of the data points above the line.



(a) Plot of the experimentally obtained shear strength values τ_y vs. yield strength σ_y

(b) Plot of the experimentally obtained shear strength values τ_u vs. tensile strength σ_u

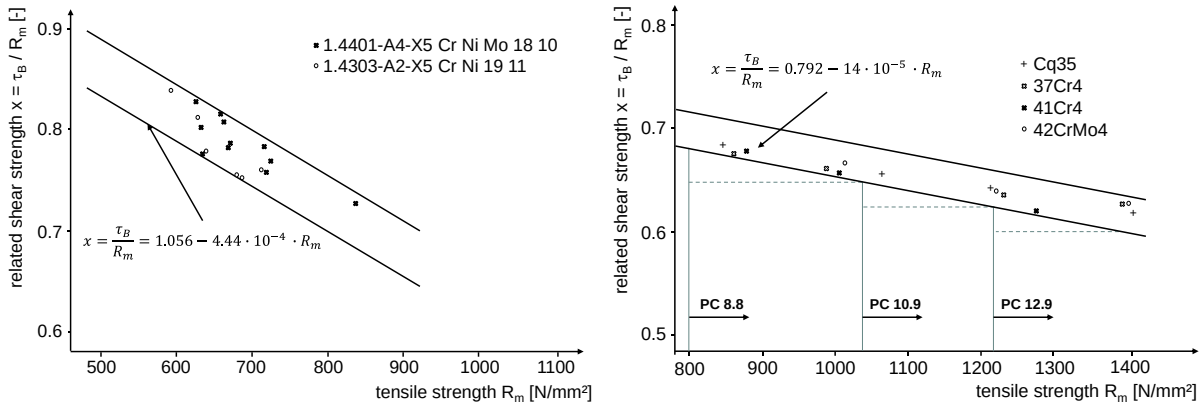
Figure 2.4-4: Plot of the experimental shear strength values τ_y vs. yield strength f_y (a) and plot of the experimentally obtained shear strength values τ_u vs. tensile strength f_u (b); © Georgi Genov [168]

As a conclusion, Genov proposes scaling with respect to the tensile strength f_u instead of the yield strength f_y by (Eq. 2.4-10) leading to a more economic approach by removing the systematic underestimation of the shear resistance of materials based on f_y, which is based on the failure theories of Tresca and von Mises.

$$\tau_u = 0.6 \cdot \sigma_u - 25 \qquad \text{(Eq. 2.4-10)}$$

Furthermore, upon closer examination of Figure 2.4-4, it becomes apparent that the ratios between the shear yield strength τ_y and yield strength f_y or the shear ultimate strength τ_u and tensile strength f_u consistently exhibit a gradual decrease for steel materials as tensile stresses increase. The correlation between the shear and tensile strength of quenched and tempered steels as well as austenitic stainless steels for high-strength bolts was already investigated by Thomala in [169]. The objective was to determine the required height of a bolt head for different steels in order to prevent shear failure of the bolt head. Therefore, a limited number of tensile and double-shear tests of unnotched bars were conducted and the ratio of the shear and tensile strength were determined. Based on the results, lower and upper limit lines were developed. The results are graphically summarised in Figure 2.4-5. Thomala concluded that for the quenched and tempered carbon steels usually used for high-strength bolts, the ratio of shear and tensile strength decreases approximately linearly from 0.70 to 0.60 in the range

from 800 N/mm² to 1400 N/mm², see Figure 2.4-5 (a). For austenitic stainless steels, which are characterised by pronounced strain hardening and high ductility, the decrease of shear and tensile strength also follows a linear relationship but the shear strengths of austenitic stainless steels are generally higher compared to the quenched and tempered steels, as presented in Figure 2.4-5 (b).



(a) Comparison of the tensile strength and shear/tensile strength ratio of quenched and tempered steels

(b) Comparison of the tensile strength and shear/tensile strength ratio of austenitic stainless steels

Figure 2.4-5: Comparison of the tensile strength and shear/tensile strength ratio of quenched and tempered steels as well as austenitic stainless steels for high-strength bolts according to [169]

As a basis for implementation in the revision of the (withdrawn) German design standard DIN 18800-1 [170] and the ongoing European development of Eurocode 3 for steel structures, numerous systematic experimental and statistical investigations were carried out into carbon steel bolts, threaded rods and unnotched studs by Knobloch and Schmidt [171–173] at the former Department of Steel Construction at the University of Essen, now the Institute for Metal and Lightweight Structures at the University of Duisburg-Essen (IML), Essen, Germany. Since in most standards the shear strength is already given as a function of the tensile strength and a close correlation of both material properties is assumed, the dependency between shear and tensile strength for bolts was investigated by Knobloch and Schmidt [171, 172]. Afterwards, Knobloch [173] extended the studies by analysing the correlations between shear, tensile/yield strength and elongation at fracture for bolts with stochastic methods. He concluded that:

- a “tight” positive linear relationship between shear strength and tensile strength of ductile metallic materials could be confirmed with a Pearson’s correlation coefficient [174] of $r > 0.95$. Therefore, it is reasonable to link the shear strength to the tensile strength in the form of a shear coefficient α in design standards,
- however, the variability of the shear coefficient with the property class, which has been proven in many experimental studies on bolts, is primarily not an expression of a correlation between shear and tensile strength but an expression of a dependence on the ductility and plastic deformation capacity of the bolt material (which explains the higher shear resistance of austenitic stainless steels observed by Thomala),
- nevertheless, if for “Ease of Use” the tensile strength is preferred as a reference for shear strength for bolts, it must be used as a synonym for ductility according to Knobloch [173]. This is permitted by the coupling of tensile strength and ductility for the property classes in EN ISO 898-1.

Dörre et al. [175] from Fraunhofer Institute for Large Structures in Production Engineering IGP in Rostock, Germany, were also aware of the correlation problem of the tensile and shear strength in a bolt. Therefore, they produced tensile and shear specimens from the same bolt.

Furthermore, they applied the Gaussian law of error propagation and second-order Taylor approximations to the statistical determination of quantiles. The following chapters consider their experimental investigations and results.

2.4.6 Stress states of bolts subjected to tension and shear loading

Subjecting a bolt in the longitudinal direction under pure tensile or in the transverse direction under shear loading results to different spatial stress states, which can be either uniaxial for the unthreaded part or multiaxial due to the notch effect of the threaded part of a bolt. The resulting stress states of a bolt subjected to different loading types are schematically presented in Figure 2.4-6 based on investigations of Kloos and Thomala [176, 177] and further studies.

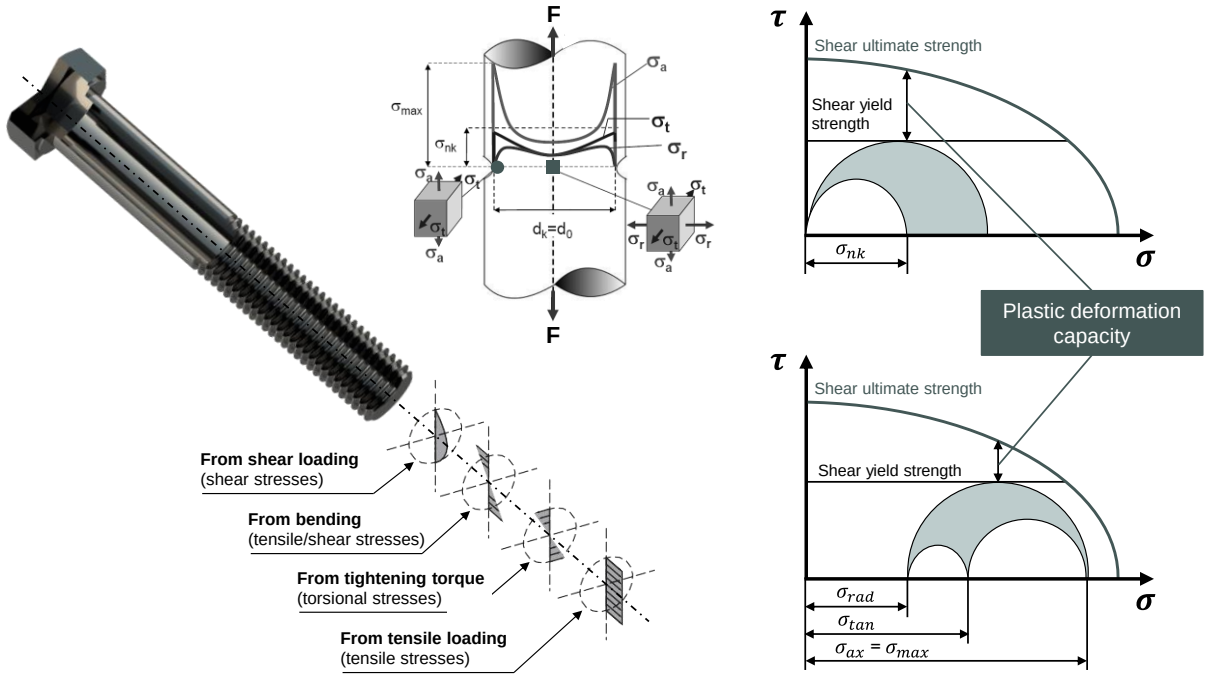


Figure 2.4-6: Resulting stress states of a bolt under different loadings according to [176, 177]

It can be shown that under pure tensile loading with a force F an infinitesimal element at any place of the unthreaded bolt shank is only affected by constant principal axial stresses $\sigma_{xx} = \sigma_{ax}$ running parallel to the longitudinal axis of a bolt. Since the highest shear stresses τ_{max} occur in the uniaxial stress state in a coordinate system, which is inclined by 45° to the main axis system, the unthreaded part of a bolt generally fails after necking with a fracture surface that is mostly inclined at 45° to the direction of tensile loading. If the bolt shank as an unnotched component is subjected only to principial axial stress σ_{ax}, no superposition of stresses must be considered and consequently, the plastic deformation capacity of the bolt shank is significantly increased compared to the threaded part. The constant axial nominal stress in the bolt shank can be calculated by (Eq. 2.4-11).

$$F = \sigma_{ax,nom} \cdot \frac{\pi \cdot d^2}{4} \Leftrightarrow \sigma_{ax,nom} = \frac{F}{\frac{\pi \cdot d^2}{4}} \qquad \text{(Eq. 2.4-11)}$$

In contrast, the threaded part of a bolt under pure tensile loading is affected by all principial stress components as a multiaxial stress state and can be further distinguished into the stress states of thread root and core of the threaded part. An infinitesimal element at the thread root is affected by the tensile stress component σ_{ax} parallel to the longitudinal axis as a maximum stress of a bolt clearly exceeding the nominal stress due to the notch effect, while the tangential stress component $\sigma_{yy} = \sigma_{tan}$ is following the helical thread structure as a compressive stress component. Additionally, the radial stress component $\sigma_{zz} = \sigma_{rad}$ perpendicular to the bolt surface is nearly zero. However, an infinitesimal element at the core of threaded part is characterised by a reduced principial axial stress σ_{ax} below the nominal stress and nearly equal tangential and radial stresses, which lead to a triaxial stress state and finally a ductile failure surface under 45° [176, 177]. Compared to the untreaded part, the plastic deformation capacity of the threaded bolt part is reduced due to the stress triaxiality.

Whenever a bolt is applied to shear loading, either the unthreaded or the threaded part of a bolt is positioned in each shear plane and the associated cross-sectional area must be considered in the design for the determination of the shear resistance of a bolt. As a result of a shear force F, the shear stress in the circular cross-section of the unthreaded bolt part shows a parabolic distribution on the gross cross-sectional area of the bolt shank A with maximum shear stress τ_{max} at the neutral axis and zero stresses at the ends of the shank diameter d, presented in Figure 2.4-6. The mean shear stress τ_{mean} and the maximum shear stress τ_{max} of the bolt shank can be calculated by (Eq. 2.4-12).

$$F = \tau_{mean} \cdot \frac{\pi \cdot d^2}{4} \Leftrightarrow \tau_{mean} = \frac{F}{\frac{\pi \cdot d^2}{4}} \wedge \tau_{max} = \frac{4}{3} \cdot \tau_{mean} \qquad \text{(Eq. 2.4-12)}$$

In the case of the threaded bolt part in the shear plane, the parabolic shear stress distribution is constituted perpendicular to the tensile stress area A_s with maximum shear stress τ_{max} at the neutral axis and zero stresses at the ends of the threads. Due to the smaller cross-section of the tensile stress area A_s compared to the gross cross-sectional area of the bolt shank with an average ratio of $A_s/A \approx 0.78$ for bolt dimensions M12 to M36, it becomes obvious that the resulting shear resistance of a bolt with threaded part in the shear plane is smaller in the amount of the ratio A_s/A compared to the pure shear resistance of the unthreaded bolt part.

However, Renner and Lange in [178–183] from the Institute for Steel Construction and Materials Mechanics of the Technical University of Darmstadt, Germany, conducted experimental and numerical investigations into the combined tension and shear behaviour of carbon steel bolts. In their numerical studies, Renner and Lange illustrate that when a bolt undergoes deformation in the longitudinal direction due to tensile loading, it results in the formation of compression rings within the bolt threads. This process induces restrained transverse contraction, as depicted in Figure 2.4-7. Importantly, this phenomenon ultimately contributes to the stabilisation of the threaded cross-section under shear loading, as documented in [178–183]. Furthermore, Song et al. [5] conducted experimental and numerical investigations into the combined tension and shear behaviour of austenitic stainless steel bolts. They performed numerical studies with a simplified unthreaded bolt shank just as a round bar with increased cross-section up to $0.82 \cdot A$ and predicted almost the same load bearing behaviour compared to a helical threaded numerical model (under the condition of same material properties). The required increase of the cross-sectional area according to [5] seems to confirm the stabilising influence of the bolt threads. Additionally, Knobloch questioned for the case “bolt threads in the shear plane” if the tensile stress area A_s is the correct cross-sectional area or whether the cross-section under shear loading would have to be corrected.

Knobloch compared shear resistances of the core cross-sectional area (A_{d3}), tensile stress area (A_s) and the effective cross-sectional area based on the pitch diameter (A_{d2}) with each other in order to examine which mechanical model is best suited to describe the shear failure of the threaded part of a bolt. The result of Knobloch show that the *"virtual shear stress cross-section"* should be the average of A_s and A_{d2}. However, for simplification, the conservative tensile stress area A_s was preferred for further investigations [173]. Nevertheless, it could be demonstrated that the helical threads converted to a simple round bar with increased cross-sectional area leads to comparable load bearing capacities, which contributes to the stabilisation of the helical threaded cross-section under shear loading. The mean value of the tensile stress area (≈ 0.78 · A) and the effective cross-sectional area (≈ 0.84 · A) corresponds almost to the cross-section value of 0.82 · A found iteratively by Song et al. [5] for their simplified numerical studies without helical threads.

Finally, whenever a bolt is subjected to combined tension and shear loading, all present tensile and shear stresses are superposed, and the bolt's resulting maximum load bearing capacity decreases accordingly. As per the mechanical principles and stress theories previously discussed, the resistance of a bolt attains its peak under pure tension loading and reaches its lowest point under pure shear. When subjected to combined tension and shear loading, the load bearing capacities fall somewhere between these extremes. From a practical point of view, however, experimental investigations carried out at the UDE-IML as part of this thesis and studies by Renner and Lange (carbon steel bolts) and Song et al. (carbon and stainless steel bolts) have already revealed higher maximum load bearing capacities of carbon and stainless steel bolts at loading angles of 15° to the longitudinal axis of the bolt in most cases.

In order to gain a deeper insight, the tension, shear and interaction behaviour of the unthreaded and threaded portion of a bolt will be discussed comprehensively in Chapters 4, 5, 6 and 7. Here, the conditions and main parameters that increase the load bearing capacity of bolts under shear and combined tension and shear will be examined and discussed.

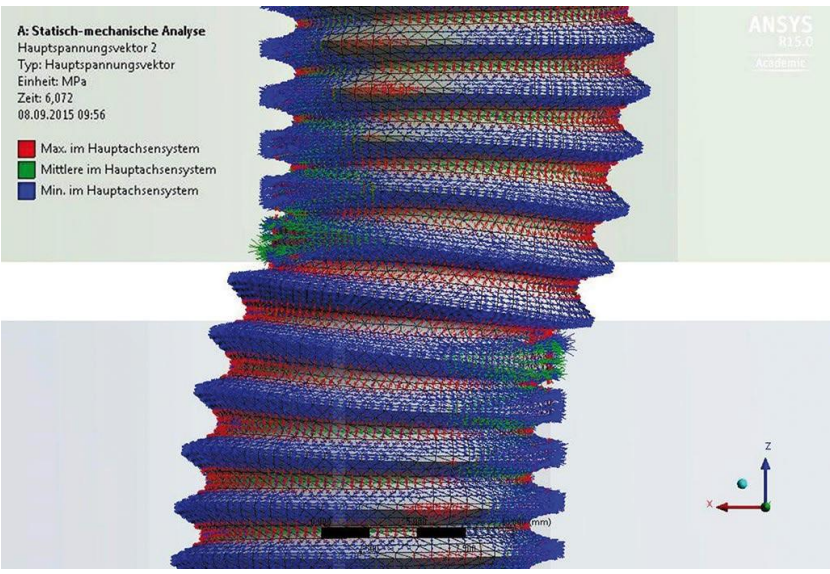


Figure 2.4-7: Primal vectors of the threads in the shear plane of PC 4.6 bolts under 45° according to [183]; © Renner and Lange, TU Darmstadt

2.4.7 Bolt construction principle and definition of bolt failure types under tension

In general, the construction principle of a bolted connection is determined by mechanical and design considerations in such a way that in the case of overstressing a bolt under tensile load,

failure occurs intentionally in the free loaded bolt threads to ensure that a significant plastic deformation of the bolt threads can be achieved. Furthermore, before bolt failure occurs, a critical connection can easier be identified and maintained, for example due to the leakage of bolted flange connections or noise development during dynamic loading. The fulfilment of this principle requires specific coordination of all load bearing capacities R_i of the individual parts of a bolt and nut that are susceptible to fracture in the case of overstressing as presented in Figure 2.4-8, while the clamped parts (e.g. plates and washers) are not considered here [176].

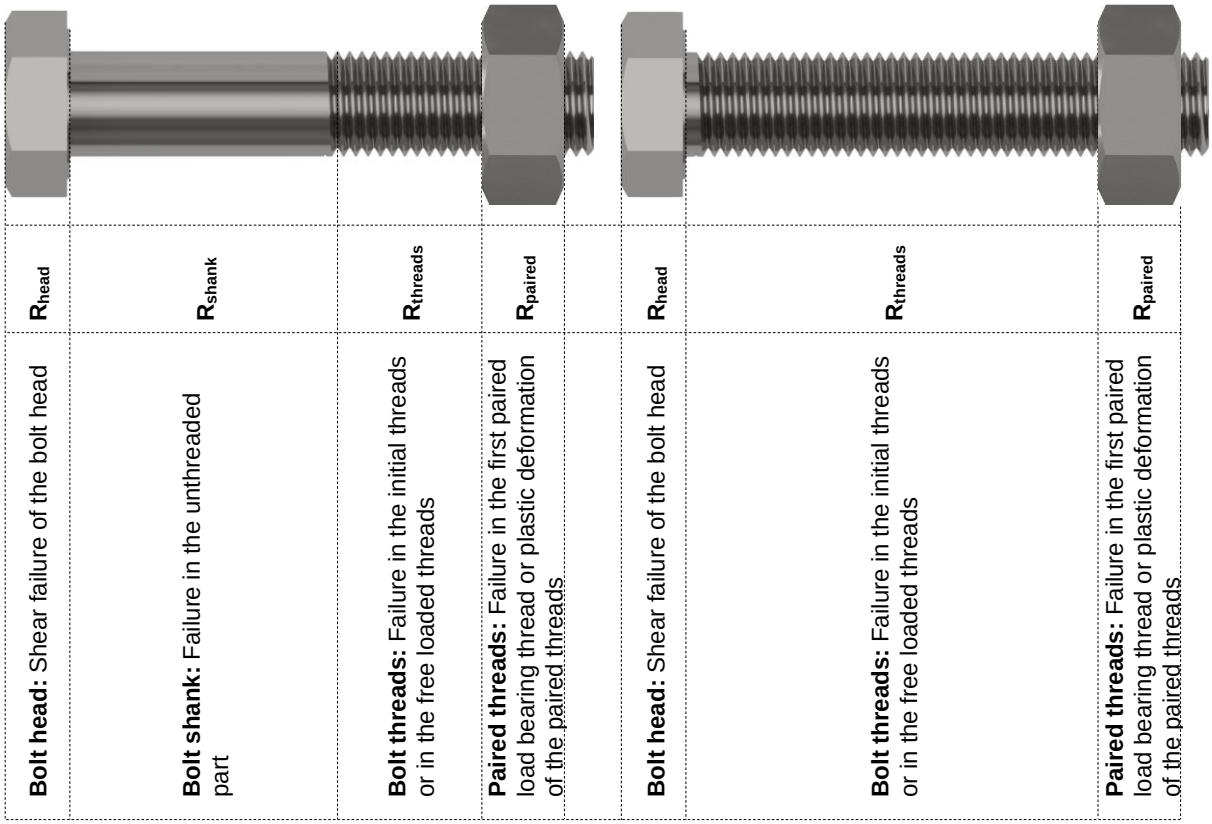


Figure 2.4-8: General construction principle of a bolt and nut of a partially threaded EN ISO 4014 bolt (left) and fully threaded EN ISO 4017 bolt (right)

The predominant failure mechanism of partially threaded carbon steel and duplex stainless steel bolts is positioned in the free threaded part of the bolt as multiaxial stress state failure, if sufficient deformation capacity of the threaded bolt part is provided. In order to achieve this intentional bolt failure in case of overstressing, the resistance conditions R of (Eq. 2.4-13) must be fulfilled.

$$R_{threads} < R_{head} \wedge R_{threads} = f_{ub,threads} \cdot A_s < R_{shank} = f_{ub,shank} \cdot A \wedge R_{threads} < R_{paired} \qquad \text{(Eq. 2.4-13)}$$

Only if the load bearing resistance of the free loaded bolt threads $R_{threads}$ is smaller compared to the bolt head R_{head}, the unthreaded bolt shank R_{shank} and the paired threads of bolt and nut R_{paires}, bolt failure occurs intentionally in the free loaded bolt threads, see Table 2.4-1 (defined as failure mode I). Subjected to (quasi-)static loading, the resulting multiaxiality stress state of a bolt caused by geometrical discontinuities and/or material inhomogeneities has a significant impact on the load bearing capacity: Suppose a bolt material is characterised by sufficient ductility. In that case, the stress concentrations in the thread roots even cause an increase in resistance (called “notch hardening effect”), while under dynamic loading, bolt failure occurs at the point of highest notch stresses generally in the first load bearing paired bolt and nut thread [176].

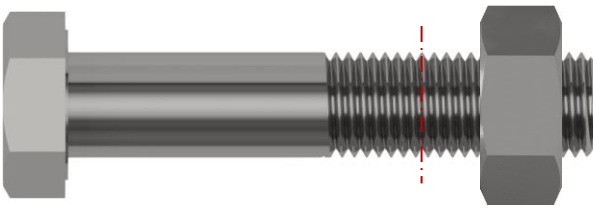
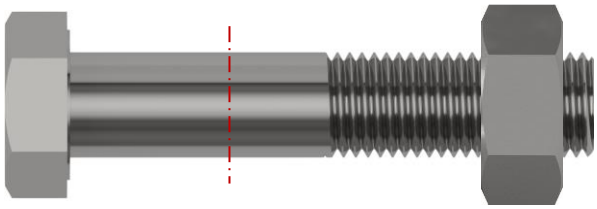
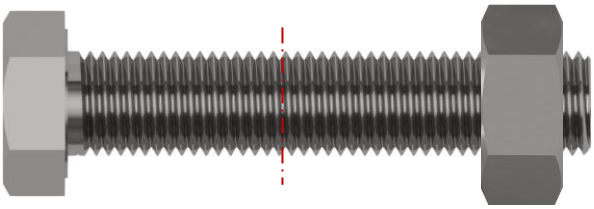
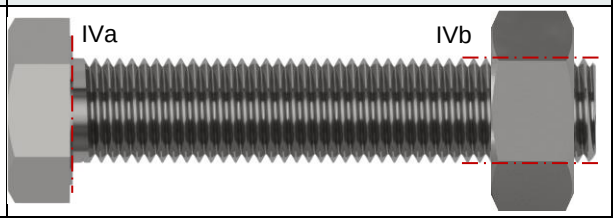
In contrast, the predominant failure mechanism of austenitic stainless steel bolts subjected to pure tension loading shifts to the unthreaded part (as uniaxial stress state failure), although the gross cross-sectional area A of the bolt is larger than the tensile stress area A_s, as presented in Table 2.4-1 (failure mode II). The shifting of the failure position is caused by the forming process of the bolt threads by rolling (see Chapter 2.4.8) which leads to an increased tensile strength by transformation of the face-centred (FCC) austenitic γ-phase to forming induced martensitic material in the threaded part. Due to the martensitic tetragonal body-centred cubic (BCT) ferromagnetic α'-phase and the high distorted crystal lattice, a larger hardness and higher strength at the edges of the cross-section of the threaded part (tensile stress area A_s) results which is not the case in the unthreaded part (gross cross-sectional area A) of the bolt. In the core material of the threaded bolt part only minor strength-increasing transformation takes place. Consequently, this leads to a higher tensile strength of the tensile stress area A_s compared to the gross cross-sectional area A for austenitic stainless steel bolts and tension failure occurs in the unthreaded part of the bolt. Thus, for austenitic stainless steel bolts with bolt failure in the unthreaded part, (Eq. 2.4-13) must be reformulated to (Eq. 2.4-14).

$$R_{threads} < R_{head} \wedge R_{threads} = f_{ub,threads} \cdot A_s > R_{shank} = f_{ub,shank} \cdot A \wedge R_{threads} < R_{paired} \qquad \text{(Eq. 2.4-14)}$$

As pointed out in Chapter 2.3.4, the mechanical properties of austenitic and duplex stainless steel bolts are determined in a tensile test on the whole bolt according to the specifications of EN ISO 3506-1, Clause 9.1. Consequently, only the tensile strength f_{ub} in the failing part of the bolt is known – either in the bolt shank ($f_{ub,shank}$) or in the free loaded bolt threads ($f_{ub,threads}$). In the case of partially threaded bolts, no precise statement can be made for the other, non-failed bolt part. Nevertheless, if the resistance of the austenitic threaded part $R_{threads}$ is greater than R_{shank} and notch hardening effects are neglected for simplification, then it can be concluded that the mean tensile strength $f_{ub,threads}$ over the whole cross-section of the bolt threads has to be at least about the ratio A/A_s higher than $f_{ub,shank}$ (with $A/A_s \approx 1.25$ as mean nominal ratio for bolt dimensions M12 to M36). Obviously, the calculation of the cross-sections should also include the specific product class of a bolt for the bolt shank diameter d and the tolerance class of the bolt threads for geometric parameters d_2 and d_3. On the contrary, bolting assemblies made of carbon steel or duplex stainless steel either have a largely uniform material structure with only minor differences due to the thread production process (carbon steel), or the different material structures are prevalent but cannot compensate the geometrical difference in cross-sections A and A_s (duplex stainless steel). Therefore, as a simplification for design rules, it can be assumed $f_{ub} = f_{ub,threads} \approx f_{ub,shank}$.

The different failure modes of carbon and stainless steel bolts subjected to pure tension loading are presented in Table 2.4-1. It distinguishes between failure mode I (tensile failure in the bolt threads of partially threaded bolts), failure mode II (tensile failure in the bolt shank of partially threaded bolts), failure mode III (tensile failure in the bolt threads of fully threaded bolts) and failure mode IV (shear failure of the bolt head (IVa) or failure by stripping of the paired threads between bolt and nut (IVb), cf. [176, 184]). The definitions of the failure modes and failure position are also applied in the ongoing investigations in the following chapters of this thesis.

Table 2.4-1: Failure mode definitions of carbon and stainless steel bolts subjected to pure tension loading

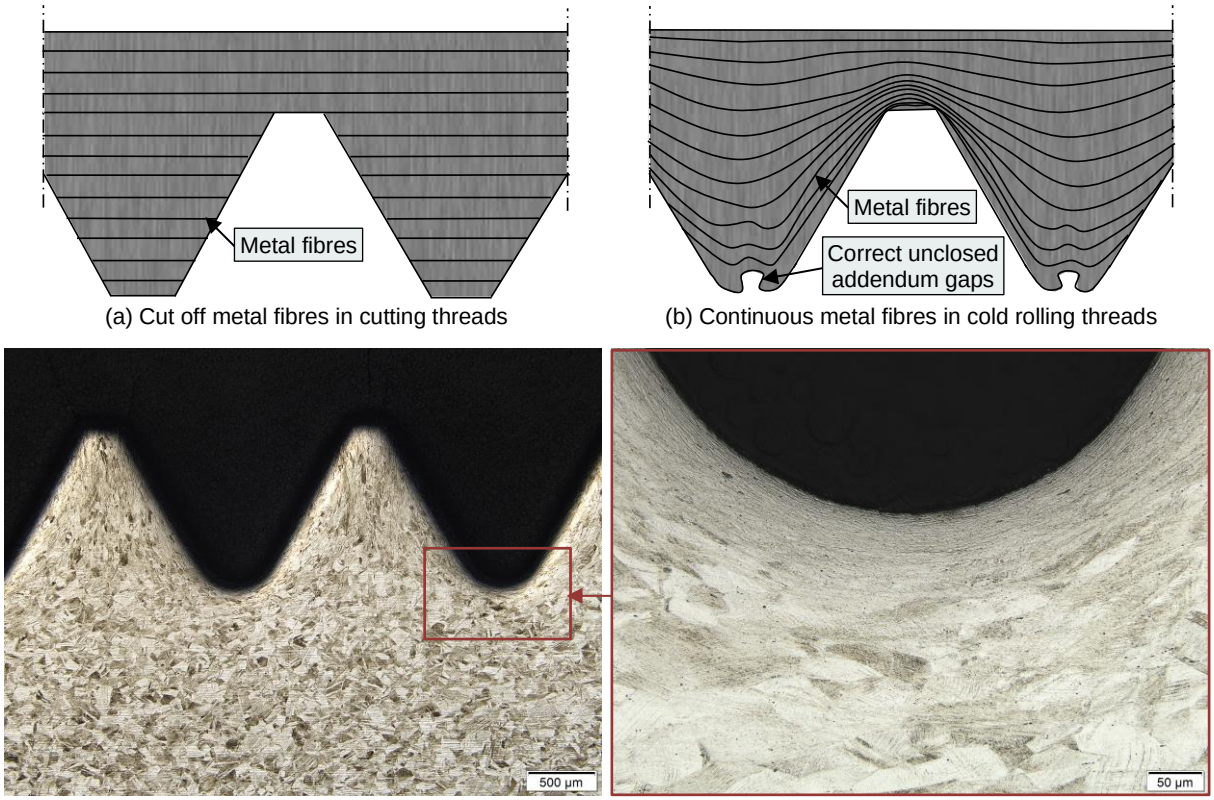
Failure mode I Failure in the threaded part as multiaxial shear failure under 45°	**Failure mode II** Failure in the unthreaded part as uniaxial tensile failure
Typical failure type of carbon steel and duplex stainless steel bolts in pure tension $f_{ub,threads} \cdot A_s < f_{ub,shank} \cdot A_{shank}$ $f_{ub,threads}$ is known, but $f_{ub,shank}$ is unknown	General failure type of an austenitic stainless steel bolt in pure tension $f_{ub,threads} \cdot A_s > f_{ub,shank} \cdot A_{shank}$ $f_{ub,shank}$ is known, but $f_{ub,threads}$ is unknown But: $f_{ub,threads} \cdot A_s > f_{ub,shank} \cdot A$
	
Failure mode III Failure in the threaded part as multiaxial shear failure under 45°	**Failure mode IV** Shear failure of the bolt head (IVa) or failure by stripping of the paired threads between bolt/nut (IVb)
Failure type of carbon steel and austenitic/duplex stainless steel bolts in pure tension $f_{ub,threads} \cdot A_s$, $f_{ub,threads}$ is known	Failure type of carbon steel and austenitic/duplex stainless steel bolts in pure tension
	

2.4.8 Strength increasing effects of different thread production types on stainless steel bolts

According to Song and Liu [185], the manufacturing processes and methods for threaded components can be classified into five types: cutting, forging, casting, powder metallurgy and electrodischarge machining. Here, the casting method (metal liquid are cast into pattern and threads can be obtained after cooling but generally low precision and extensive post-treatment is required), powder metallurgy sintering method and electrodischarge machining are not commonly used and not further discussed. The forging method can be characterised as a chipless processing method and includes rolling, extrusion (to extrude internal threads with drilling or specialised machines), punching (as warm or cold punching) and pressing. Nowadays, the most commonly used methods are cutting and cold rolling as they guarantee continuous machining and higher production rate [185–187]. Therefore, the cutting method and the cold rolling method are briefly presented and compared in the following with particular interest to stainless steel bolts.

Cutting manufacturing methods (like milling, planning, slotting and hobbing) are well-known and convenient to use. The threads are shaped by machining the material. The original metal fibre structure of the workpiece is not changed, but the metal fibres are due to machining cut off as presented in Figure 2.4-9 (a), which is important from mechanical point of view. On the contrary, cold rolling forming methods at room temperature as a type of chipless processing method uses intentionally the plasticity of the workpiece to form permanently corresponding threads under the plastic deformation applied by a roller. Based on the theory of metal plastic deformation, the metal fibres of the workpiece and microstructure are continuous, and the pronounced strain hardening by cold working or the transformation of austenitic to forming

induced martensitic material significantly improves the mechanical properties of the threads, see Figure 2.4-9 (b, d) and [104, 176, 185, 188].



(a) Cut off metal fibres in cutting threads

(b) Continuous metal fibres in cold rolling threads

(c) Microscopic view of the cold rolling threads of a M16 A4-70 stainless steel bolt (Zoom factor: 25×)

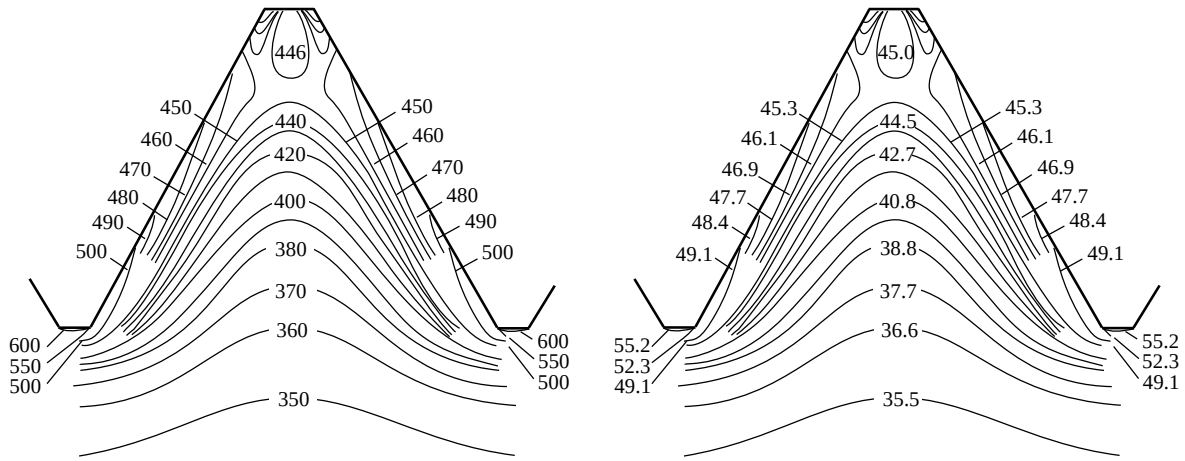
(d) Microscopic detail view of the cold rolling threads of a M16 A4-70 stainless steel bolt (Zoom factor: 200×)

Figure 2.4-9: Schematic representation of metal fibres in cutting threads (a), cold rolling threads (b) and example of microscopic views of cold rolling threads (c, d); © UDE-IML

During the cold rolling process and based on the principle of constant volume, the rolls displace the material from the thread core (defined as “dedendum”) and allow flow in the direction of the thread flanks to thread crest (“addendum”). Consequently, the microstructure is following the plastic forming flow and displaced but not interrupted, see Figure 2.4-9. Proper application and correct setting of the rolling parameters like rolling force, rolling speed, friction conditions, lubrication, feed rate and time of cold rolling leads to well-formed threads with high strength, excellent surface quality and high dimensional accuracy without over rolling [185, 189, 190]. Nowadays, various 2D and 3D numerical studies deal with forming and thread rolling methods in order to investigate systematically the influence and interaction of these rolling parameters on the finished thread; for further information see [191–205]. Furthermore, a major advantage of cold rolling threads is that during the plastic deformation imprinted compressive stresses remain in the threads as first-order residual stresses (which are nearly homogenous across several material grains) and enhance the fatigue strength. Therefore, cold rolled threads are superior to cut threads particularly for high-strength bolt property classes with elevated yield strengths. Further information regarding the fatigue behaviour of bolts can be found in [176, 206–208], while the fatigue behaviour of stainless steel bolts is discussed in [7].

In the context of stainless steel bolts, cold rolling of the threads are of special signficance as austenitic or duplex stainless steels cannot be post heat-treated and especially austenitic grades are characterised by very pronounced cold working and strain hardening. During the plastic deformation of the cold rolling process, with increasing deformation degree the metal grain becomes stretched, pressed and refines radially distributed along the thread surface with finest high-density grain at the dedendum, while the grains at the addendum are the coarsest.

The degree of grain density and therefore plasticised and strain hardened microstructure correlates with the hardness and strength of the thread material. The maximum hardness can be observed at the dedendum with stretched, high-density grain and thick hardening layer, which is progressively decreasing at the thread flanks, while the addendum of the threads is characterised by the lowest hardness and thinnest hardening layer due to medium-density grain and medium plastic deformation compared to the flanks and dedendum [185]. As an example, the different Vickers hardness [209] distribution of a M8 thread of tempered chrome vanadium steel [188] is presented in Figure 2.4-10 (a) and for comparison also converted to Rockwell Hardness HRC [210] in Figure 2.4-10 (b). The maximum hardness must also be considered in the cold rolling process by ensuring a sufficiently high hardness of the dies and rollers, especially for rolling austenitic bolts with high cold working capacity and hardness.



(a) Vickers hardness HV 0.1 (b) Converted to Rockwell hardness HRC

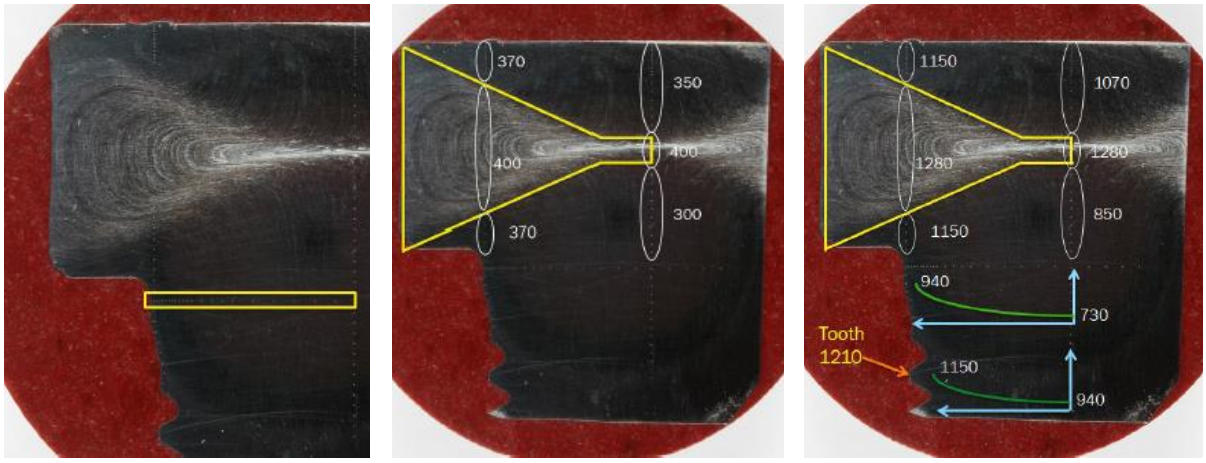
Figure 2.4-10: Hardness distribution of a M8 cold rolling thread made from tempered chrome vanadium steel with a core hardness of 340 HV 0.1 (≈ 34.4 HRC) according to [188]

Obviously, there is no hardening layer on the cutting thread and the microstructure in cutting threads is almost not influenced with equal-axial distributed grain and metal fibres over the threads. Consequently, almost the same hardness and material strength can be observed in the threads after the cutting process.

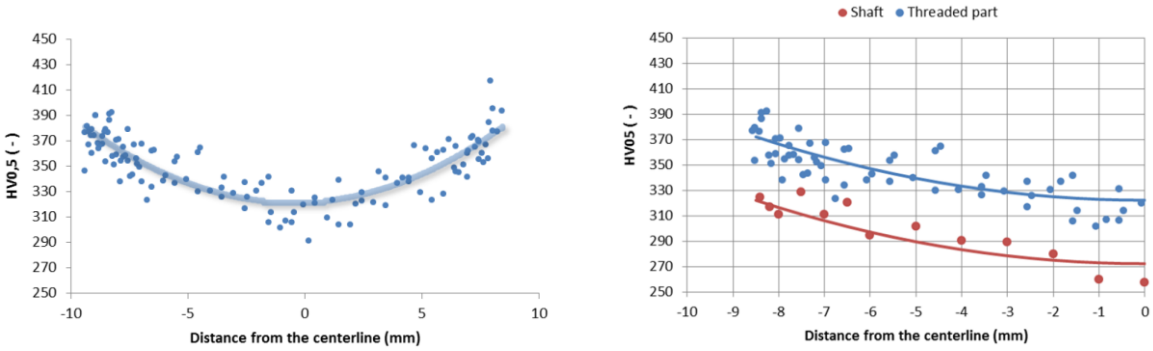
To investigate the resulting HV 0.5 hardness and yield strength distribution in 1.4404 austenitic stainless steel bolting assemblies, Timo Manninen from Outokumpu Tornio Research Centre, Finland, and Anders Söderman from bolt manufacturer BUMAX AB, Sweden, specialised on stainless steel sheet material and bolts respectively, conducted experimental studies on M20 A4 Bumax 88 bolts, nuts and washers [211]. They concluded a parabolic yield strength distribution in the unthreaded and threaded bolt part with maximum values at the shank edges and bolt thread tooths, see Figure 2.4-11 (c, d, e). Thus, the influence of the varying degrees of strain hardening and cold working below the recrystallisation temperature on the hardness and yield distribution is measurable between the core, bolt shank and threads and consistent with other studies from literature on carbon steel bolts but can now be explicitly correlated with the pronounced strain hardening of austenitic bolts.

The high hardness also has two practical consequences in construction: Firstly, when determining the shear resistance of the threaded bolt part, sufficiently high hardness of the shear adapters must be ensured, as otherwise, the pronounced hardening of the austenitic stainless steel bolt threads may lead to damage to the shear adapters, and erroneous shear resistances may occur. Secondly, it must be ensured in the execution that the calculated bearing resistance $F_{b,Rd}$ according to EN 1993-1-4 and FprEN 1993-1-4 can actually be

activated and that the bolt hole bearings are not damaged prematurely or even fail due to the high hardness of the threaded bolt part in the shear plane.



(a) Indentation marks in the shank (b) HV 0.5 hardness in the bolt head (c) Yield strength distribution



(d) Measured HV 0.5 hardness distribution in the threaded bolt part (e) Comparison of the measured hardness between the unthreaded and threaded bolt part

Figure 2.4-11: Distribution of hardness and yield strength in A4 M20 Bumax 88 bolt, nut and washer; © Outokumpu Tornio Research Centre, Finland, and BUMAX AB, Sweden [211]

2.5 Existing investigations into carbon and stainless steel bolts subjected to tension and shear

2.5.1 General

A variety of investigations and studies on non-preloaded bolted connections made of carbon and stainless steel are attracting intense research activities. However, the majority of these studies exclusively focus on the bearing and net section failure behaviour of carbon steel, as well as austenitic, ferritic, or duplex stainless steel plates. Herein, many experimental and numerical studies deal with about the bearing resistance $F_{b,Rd}$, and are complemented by discussions regarding the suitability of existing design concepts and the structural performance of these bolted connections under critical environmental conditions like fire [12–15, 212] and seismic loading [19, 20]. For completeness, selected studies focussing on the bearing and net section resistance of plates made of stainless steel of category A bearing type connections are briefly introduced in Chapter 2.5.2. Focussing on fasteners itself, comprehensive overviews about existing studies on the load bearing behaviour of carbon and stainless steel bolts and bolting assemblies subjected to shear, tension and combined tension and shear loading are provided based on a literature review. Here, the main conclusions of the relevant publications on carbon steel bolts and austenitic and duplex bolts regarding the resulting tension $F_{t,Rd}$, shear $F_{v,Rd}$ and interaction resistance are summarised in Chapter 2.5.3 (carbon steel bolts) and

Chapter 2.5.4 (stainless steel bolts). A literature review of each study on carbon and stainless steel bolts is presented in Appendix A.

Finally, for the purpose of a more in-depth investigation and to close gaps of knowledge, own experimental investigations on carbon steel bolts as well as austenitic and duplex stainless steel bolts are conducted in the frame of this thesis and presented in Chapters 4 to 6 regarding the bolt tension, shear and interaction resistance.

2.5.2 Literature review on the bearing and net section resistance of stainless steel plates

In order to give a brief overview, Bouchaïr and Baptista [213] investigated in 2002 the strength and deformation of stainless steel bolted cover-plate joints with reference to Eurocode 3.

They highlighted that, owing to the nonlinear stress behaviour, stainless steel demands careful consideration in design, as it may experience excessive joint deformations at the serviceability limit state. The experimental and analytic investigations showed that different ultimate state joint strengths are safely predicted, however, the net section and bearing resistances are underestimated. As a continuation of these findings, Bouchaïr, Averseng and Abidelah [214] concern in 2008 about cover plate connections and T-stubs, where the bolts are loaded in shear or in tension. The authors emphasize that in bearing, criteria on deformation limits have to be considered for cover plate connection, and in T-stubs, strain hardening of stainless steel exhibits a continuous increase of the applied load and can influence the failure mode.

In 2010, Salih et al. are continuing the research activities on the bearing failure [215] as well as numerical investigation of net section failure, see [216] and [217], in stainless steel bolted connections. The proposed bearing design equations distinguish between thin and thick plates as well as criteria (following Bouchaïr, Averseng and Abidelah [214]) if deformation under service loads is a design consideration (serviceability limit state) or is not a design consideration (ultimate limit state). The proposed equations were finally modified and verified on the basis of experimental data from the literature and implemented in the 4th Edition of the Design Manual for Structural Stainless Steel (DMSSS) [64, 136] as well as FprEN 1993-1-4 (and editorial aligned with EN 1993-1-8:2024). Furthermore, Cai and Young [56] analysed the structural behaviour of cold-formed stainless steel bolted connections with bearing and net section failure modes on austenitic stainless steel grades 1.4301 and 1.4571 and lean duplex stainless steel. They showed that the failure modes predicted by the European design codes are more accurate than the North American and Australian/New Zealand predictions. Further recent studies deal with the high temperature resistance [218] and fire resistance [212] of stainless steel bolts under bearing, the net section failure under tension loading [219] and experimental investigation of bolted connections at different strain rates [55].

2.5.3 Literature review on the tension, shear and combined tension and shear load bearing behaviour of carbon steel bolts

An overview of various existing experimental studies from literature carried out between 1964 and today into the load bearing behaviour of carbon steel bolted connections subjected to tension, shear and combined tension and shear loading are summarised in chronological order in Table 2.5-1. Furthermore, the main research specifications like bolt types, bolt diameter/ lengths and property classes are outlined, as well as the test programme regarding the conducted tension, shear and interaction tests.

As already mentioned, a chronological literature review is summarised in Appendix A.

Table 2.5-1: Overview of existing studies into the tension, shear and combined tension and shear load bearing behaviour of carbon steel (CS) bolts

Year of publication	Conducted by	Steel type	Bolt type	Bolt diameter and bolt length	Bolt property class	Tension tests[1)]	Single-shear tests[1)]	Double-shear tests[1)]	Interaction tests[1)]	Number of tests	Data suitable for the following studies?
1964	Wallart and Fischer [220]	CS	Partially threaded bolts: A354 BC, A354 BD, A440 and A325	7/8 in. (≈ M22) + 1 in. (≈ M24), bolt lengths of 5 ¼ in. to 9 ½ in.	A354 BC with f_{ub} = 776 N/mm² A354 Bd with f_{ub} = 1138 N/mm² A440 with f_{ub} = 1145 N/mm² A352 with f_{ub} = 793 N/mm²	-	-	S/T	-	219	No[2)]
1965	Chesson et al. [221]	CS	Partially threaded bolts: A325 low/high hardness + A354 BD	¾ in. (≈ M20), bolt lengths 3, 4 and 6 in. + 1 in. (≈ M24), bolt length of 3 in.	A352 with f_{yb} ≈ 569 N/mm² f_{ub} ≈ 776 N/mm² A354 BC with f_{yb} ≈ 718 N/mm² f_{ub} ≈ 828 N/mm²	X	S/T	-	S/T	115	No[2)]
1971	Bilderbeek [222]	CS	Partially and fully threaded	M12, M20	PC 4.6, 8.8, 10.9	X	S/T	-	S/T	175	Yes
1973	Hassler [223]	CS	Unthreaded rods	d = 24 mm	PC 4.6	X	-	S	S	25	Yes
1974	Rhodes and Harvey [224]	CS	Threaded	No information available	No information available	-		T	-	36	No
1979	Shakir-Khalil and Ho [225]	CS	Partially threaded bolts[3)]	M20×90, M20×100, M20×140	PC 4.6	X	S/T	-	S/T	51	Yes
1980	Scheer [226]	CS	Partially and fully threaded	M12, M20, M27	PC 4.6, 5.6, 10.9	X	S	-	-	231	Yes
1982	Godley and Needham [227]	CS	Partially threaded bolts and HFSG bolts	M16×80 M20×90, M24×100, M24×110	PC 8.8	X	-	S/T	-	194	No[4)]
1983	Scheer [228]	CS	Partially and fully threaded	M12, M20, M27	PC 4.6, 5.6, 10.9	X	S/T	-	-	95	Yes
1987	Knobloch/Schmidt [171], complemented in 1990 by Knobloch/Schmidt [172] and Knobloch [173] (PhD thesis)	CS	Unthreaded rods and threaded rods	Unthreaded rod with d = 24 mm, threaded rods as M16 and M24	Unthreaded rod as St 37-2 (≈ PC 4.6), St 52-3 (≈ PC 5.6), C45 (≈ PC 8.8) and 42CrMo4 (≈ PC 10.9); Threaded rods in PC 5.6 and 10.9[5)]	X	-	S/T	S/T	150	Yes
1989	Petersen [229]	CS	Partially threaded, HV bolts	M16	PC 10.9	X	-	S	-	19	No
1990	Valtinat and Dangelmaier [230]	CS	Fully threaded bolts acc. to DIN 933 [231]	M16×95 to 130 M20×100 to120, M24×100 to 140	PC 5.6, 10.9	X	-	T	-	151	Yes
1990	Knobloch/Schmidt [172]	See Knobloch/Schmidt [171] from 1987									
1990	Knobloch [173] (PhD thesis)										
1996	Steurer [232][6)]	CS	Partially/fully threaded bolts EN 14399-4, EN ISO 4014, EN ISO 4017, DIN 7990	M12×70, M16×80/100, M20×80/90/110/120/130/150/160, M24×100/140/160 Threaded rods	PC 8.8, 10.9	X	-	-	-	244	No[6)]
2010	Friede and Lange [233]	CS	Partially threaded bolts	M16	PC 10.9		S	-	-	13	Yes
2010	Friede et al. [234]	CS	Partially threaded HV bolts	M16×55, M20×70, M24×80, M30×90	PC 10.9	-	S/T	-	-	54	No[7)]

Table 2.5-1: Overview of existing studies of the tension, shear and combined tension and shear load bearing behaviour of carbon steel (CS) bolts (Cont.)

Year of publication	Conducted by	Steel type	Bolt type	Bolt diameter and bolt length	Bolt property class	Tension tests[1)]	Single-shear tests[1)]	Double-shear tests[1)]	Interaction tests[1)]	Number of tests	Data suitable for the following istudies?
2012	Renner and Lange [178]	CS	Partially/fully threaded bolts EN ISO 4014, DIN 7990, EN ISO 4017, EN ISO 4018, EN 14399-4, EN ISO 4019[8)]	M20×115, M20×120	PC 4.6, 8.8, 10.9, 12.9	X	S/T	S/T	S/T	158	Yes
2013	Renner and Lange [179]										
2014	Renner and Lange [180]										
2014	Renner and Lange [181]										
2015	Renner and Lange [235]										
2016	Renner [182] (PhD thesis)										
2019	Renner and Lange [183]										
2019	Dörre et al. [175]	CS	Partially/fully threaded bolts EN 14399-4, EN ISO 4014, EN ISO 4017, DIN 7990	(M8, M10), M12, M16, M20 in different lengths	PC 4.6, 5.6, 8.8., 10.9	X	S/T	S/T	-	240	Yes
2020	Li et al. [236, 237]	CS	Partially/fully threaded bolts + countersunk	M16, M20, M24	PC 10.9, 12.9	X	S/T	-	S/T	186	Yes
2020	Song et al. [5]	CS	Partially/fully threaded bolts EN ISO 4014 EN ISO 4017	M20	PC 8.8	X	S/T	-	S/T	28	Yes

[1)] X: Tension tests were conducted; -: No tests were conducted; S/T: Shear tests with unthreaded (S) and/or threaded (T) part of a bolt in the shear plane | [2)] Bolts and bolt material are based on North American standards and are not directly comparable to European or German bolts. Consequently, the test results are not considered in the following investigations. | [3)] For the case threaded part in the shear plane, the threads were cut after production manually which must be seen critical. | [4)] The studies of Godley and Needham mainly focus on HSFG bolts which are not part of the following studies. | [5)] The threaded rods in PC 5.6 and 10.9 are not fulfilling the normative requirements regarding the minimum tensile strength and elongation at fracture. Nevertheless, Knobloch/Schmidt used the threaded rods in their investigations and stated that they mechanical properties are “sufficient enough to simulate bolts in steel structures”. | [6)] Since Steurer deals with special testing conditions and different configurations, treatments and coatings of bolts and nuts subjected to pure tension loading, they will not be part of the following investigations.| [7)] Shear tests are dealing with special testing conditions in the transition between shank and threads. Thus, the test results are not considered in the following investigations. | [8)] EN ISO 4019 is not existing. Presumably, fully threaded EN ISO 4017 or EN ISO 4018 bolts were used.

It must be mentioned that the presented overview in Table 2.5-1 summarises the existing studies to be used in steel structures. It is worth noting that further studies addressing testing conditions such as fire exist, which have not been incorporated into this thesis. Recent studies on the load bearing behaviour of carbon steel bolts during and/or after fire can be found by Lange and González (2012, only tensile tests) [238], Ketabdari et al. (2019, only tensile tests) [239], Kawohl and Lange (2016, tensile, shear and interaction tests) [240] and Daryan and Ketabdari (2019, only tensile tests) [241]. Further studies dealing with the tension and shear resistance of carbon steel bolts or fasteners in composite structures can be found by El-Lobody and Lam (2002, only shear tests) [242], Hou et al. (2012, only shear tests) [243], Ding et al. (2017, only shear tests) [244], Qi et al. (2017, only shear tests) [245] and Yan et al. (2018, tensile and shear tests) [246]. Various numerical investigations complement all these experimental studies in recent years to assist the understanding of the load bearing behaviour of bolts subjected to tension and shear loading. Herein, Pavlović et al. (2013) [247], Grimsmo et al. (2016) [248], Francavilla et al. (2016) [249], Long et al. (2016) [250], Hu et al. (2016) [251], Hedayat et al. (2017) [252] and D'Aniello et al. (2017) [253] developed numerical FE models to simulate the load bearing behaviour of structural bolts under pure tension and pure shear loading. In order to simulate the failure mechanism of these bolts as accurately as

possible, Vasdravellis et al. (2014) [254], Rehman et al. (2016) [255] and Yang et al. (2017) [256] pointed out the necessity of calibrating fracture models for structural bolts on the example of composite structures and the importance of stress triaxiality in FE simulations, which will not be discussed in further detail here.

The main conclusions of the above presented studies regarding tension, shear and interaction resistance of carbon steel bolts can be summarised to the following aspects:

- **Effect of initial bolt preload on the shear strength:** *No or minor, negligible effect.*
  Wallart and Fischer [220] (1964) showed that there is no consistent variation of ultimate shear strength with initial bolt preload. In their experimental investigations, *"the variation in mean shear strengths for the different magnitudes of preload was almost the same as the variation in the individual bolt shear strengths for a given preload"*. Wallart and Fischer conclude that at ultimate load only a small amount of initial preload is remaining in a bolt, which consequently does not affect the shear strength of the bolt. Herein, they refer to the findings from Chesson et al. [221] that bolts subjected to shear and tension up to 20 to 30 % of the tensile strength do not greatly influence the shear strength. The negligible effect of initial preload was also confirmed by Bilderbeek [222] (1971). Friede and Lange [233] (2010) explained the minor effect of preloading on the shear resistance in the ultimate limit state by the fact that the bolt plasticises in the failure state, which already results in a reduction of the bolt preload.

- **Effect of the material of the shear block/adapters:** *No effect on the shear strength.*
  Experimental investigations from Wallart and Fischer [220] (1964) proved that the variation in ultimate shear strength due to different materials of the shear adapters (ASTM A440 carbon steel [257] versus quenched and tempered steel condition with high hardness) is not greater than the difference in ultimate shear strengths of bolts tested from the same lot. However, the resulting shear deformation can differ significantly caused by elastic and plastic bearing deformation depending on the test rig. Chesson et al. [221] (1965) and Bilderbeek [222] (1971) came to the same result in their studies. Furthermore, Renner and Lange [178–180, 183, 181, 182, 235] used a test rig made of S355 structural steel and do not report any damage to the hole bearing or other adverse effects on the load bearing capacity of carbon steel bolts. This is remarkable due to the low hardness of the S355 structural steel of 150 HB to 190 HB as Brinell hardness according to EN ISO 6506-1 [258] and ASTM E10 [259], even far below the beginning of the HRC Rockwell hardness scale according to EN ISO 6508-1 [210] and ASTM E18 [260].

- **Effect of the shear plane location:** *Shear resistance of bolts is highly affected by the related shear area in the unthreaded and/or threaded part of a bolt.*
  Wallart and Fischer [220] (1964) showed that the shear resistance of high-strength bolts made of carbon steel is directly affected by the related shear area. The resulting shear load-deformation curves for different failure planes in the unthreaded and/or threaded part of a carbon steel bolt according to Wallart and Fischer are presented in Figure 2.5-1 (a). They demonstrated that the highest average shear strength and deformation capacity were obtained when both shear planes are in the unthreaded bolt part (about ≈ 70 % of the tensile strengths, Lot T). On the contrary, both shear planes in the threaded bolt part result to the lowest shear strength (about ≈ 60 % of the tensile strengths, Lot S). As presented in Figure 2.5-1 (a), a combination of the unthreaded and threaded part in the shear plane (Lot R) was about ≈ 63.5 % of the tensile strength and is below the arithmetical average of Lot T and Lot S. According to Friede et al. [234] (2010) *"the full shear resistance is not yet achieved when the shear plane coincides with the end of the unthreaded cross-section.*

Only when the unthreaded bolt part projects beyond the shear plane by approximately 0.1·d the full shear resistance of the unthreaded part section can be assumed".

- **Effect of lubrication and condition of the faying surfaces:** *Minor influence.*
  The effect of lubrication and condition of the faying surfaces was also investigated by Wallart and Fischer [220] (1964). As presented in Figure 2.5-1 (b), bolts tested in lubricated test rigs had 2 to 5 % lower shear strengths compared to tests conducted in clean mill scale faying surfaces. Herein, the authors assumed load transfer through friction.

- **Effects of the grip lengths and clamping length:** *No or minor, negligible effect.*
  No significant differences in the achieved shear resistances of bolts with different clamping lengths were found by Wallart and Fischer [220] (1964). A positive influence of longer grip lengths on the bolt shear resistance as well as a negative impact on the shear resistance caused by bending of bolts with greater lengths were assumed but could not be confirmed by testing for both cases. Chesson et al. [221] (1965) could only observe a slight increase of the load bearing capacity of the bolts subjected to combined tension and shear. The effect of the clamping length on the shear and interaction resistance of carbon steel bolts was investigated in numerical FEM studies by Renner and Lange [178–183, 235] but no significant impact was found.

- **Effect of the bolt diameter:** *No or minor, negligible effect.*
  The effect of the bolt diameter on the ultimate shear strength was investigated by Wallart and Fischer [220] (1964). No significant differences in the achieved shear resistances of different bolt diameter were found. Chesson et al. [221] and Renner and Lange [178–183, 235] confirm this in their studies and conclude that the effect of bolt diameter on the relative bolt strengths is negligible for the bolt diameter applied in structural applications. However, it is worth mentioning that it is difficult to compare different bolt diameters and lengths due to varying mechanical properties by the bolt material and forming and rolling process.

- **Effect of the bolt hole diameter:** *No or minor, negligible effect.*
  The effect of the bolt hole diameter was investigated in numerical FEM studies by Renner and Lange [178–183, 235] (for carbon steel bolts) and in the frame of the German research project FOSTA P 1386 / IGF-No. 20651 N [78] (but exclusively for stainless steel bolts). It was found in both numerical studies that a variation of the bolt hole diameter and the hole tolerance has no impact on the ultimate shear strength of bolts and that only the shear displacement is increasing with larger bolt hole diameter. However, the numerical FEM model of both studies is strongly simplified and movement and skewing of the bolt in the bolt hole depending on the hole clearance cannot be modelled realistically. This needs to be examined by experimental and enhanced numerical investigations. Furthermore, experimental validation on the shear and interaction resistance of bolts in slotted and oversize holes is still missing. In the North American region, e.g. Allan [261] (1967) was focusing on oversized and slotted holes on the behaviour of bolted connections.

- **Effect of the bolt property class:** *Higher bolt property classes lead to reduced shear deformation and shear-tensile strength ratio due to reduced plastic deformation capacity.*
  Already in the early studies of Chesson et al. [221] (1965) it was shown that higher property classes of carbon steel bolts lead to reduced shear deformation and to a lower shear-tensile/strength ratio, see Chapter 2.4.5. Thomala [169] and Wiegand et al. [176] confirmed an approximately linear relationship between the shear coefficient α and the tensile strength for carbon steel bolts, almost independently of the chemical composition of the bolt material itself. Furthermore, Knobloch [173] (1990) stated that the variability of the shear coefficient with the bolt property class is primarily not an expression of a correlation

between shear and tensile strength. Instead, it reflects a dependence on the ductility and plastic deformation capacity of the bolt material. Generally, higher bolt property classes are directly correlated to reduced ductility and plastic deformation capacity.

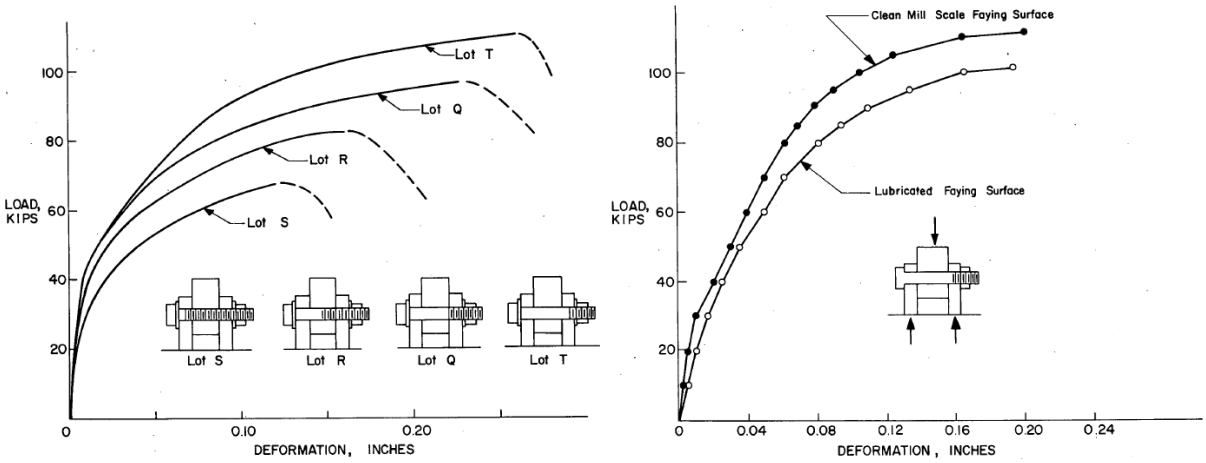
- **Effect of the gap:** *Increasing shear resistance of bolts may occur by accumulation of bolt material in the gap between the shear planes.*
  Dörre et al. [175] (2019) emphasize the importance of the shear plane itself: even a minor gap between the shear plates during testing might accumulate bolt material in the shear plane which can lead to erroneously higher shear resistance of bolts.

- **Effect of the testing procedure:** *Shear testing under tension results to lower shear strengths compared to compression testing and is on the safe side.*
  Wallart and Fischer [220] (1964) investigated the resulting shear resistances for bolts tested in tension and compression test rigs to evaluate the effect of the testing procedure itself. They found that the resulting shear strengths under tension was 6 to 13 % lower compared to shear tests under compression, see Figure 2.5-2. Consequently, shear testing in tension test rigs is more conservative and on the safe side. Wallart and Fischer concluded that the reduced shear strength of a carbon steel bolt in a test rig under tension is based on the “lap plate prying mechanism”. Due to the uneven bearing deformations of the tested bolt, the machine load does not act at the centreline of the test rig anymore and the outer plates or components of the test rig are subjected to bending outward by an additional prying moment. This out-of-plane deformation can also be observed by shear connections made of thin carbon or stainless steel plates/sheets under tensile loading.

- **Effect of the testing procedure as single-shear versus double-shear testing:** *Double-shear testing recommended but contradictory data about the shear resistances of bolts.*
  Renner and Lange [178–183] emphasize the importance of double-shear tests in order to determine the pure shear resistance of bolts as there is no pure shearing in single-shear tests due to the axial twisting of the bolts and higher failure loads are achieved in single-shear tests. This could be confirmed in their experimental studies as the single-shear tests are always achieving higher shear resistances (between 5 to 13 %; cf. [182]). Also the German VDI Guideline 2230 Part 1, Clause 5.5.6.1 recommends the determination of the shear resistance of bolts in a double-shear test rig according to the withdrawn and not replaced German testing standard DIN 50141 [262] and the still current German aviation standard LN 65150 [263] from 1977. However, the double-shear test rig of Renner and Lange is not following the technical specifications given in both testing standards regarding the geometrical specifications/tolerances as well as the hardness of the shear block. The shear block of Renner and Lange was made of comparatively “soft” S355 structural steel (which should not have any impact on the ultimate shear strength of the bolts, as presented above). On the contrary, Dörre et al. [175] (2019) achieved in their investigations under following mainly the specifications of DIN 50141 higher shear resistances in a double-shear test rig. Therefore, based on Dörre et al. [175], the single-shear test rig was identified in their studies as the more critical case. However, it is worth mentioning that deviating from DIN 50141, the double- shear tests were carried out with two bolts with one shear plane instead of one bolt subjected to two shear planes. Nevertheless, the higher bolt shear resistance in double-shear test rigs was also confirmed by preliminary tests in FOSTA P 1386 / IGF-No. 20651 N [78]. Finally, there is a need for clarification of the single- or double-shear testing procedure here, see Chapter 5.

- **Description of the interaction behaviour of carbon steel bolts:** *Quadratic interaction is assumed, which is mainly influenced by the related bolt cross-section in the shear plane.*

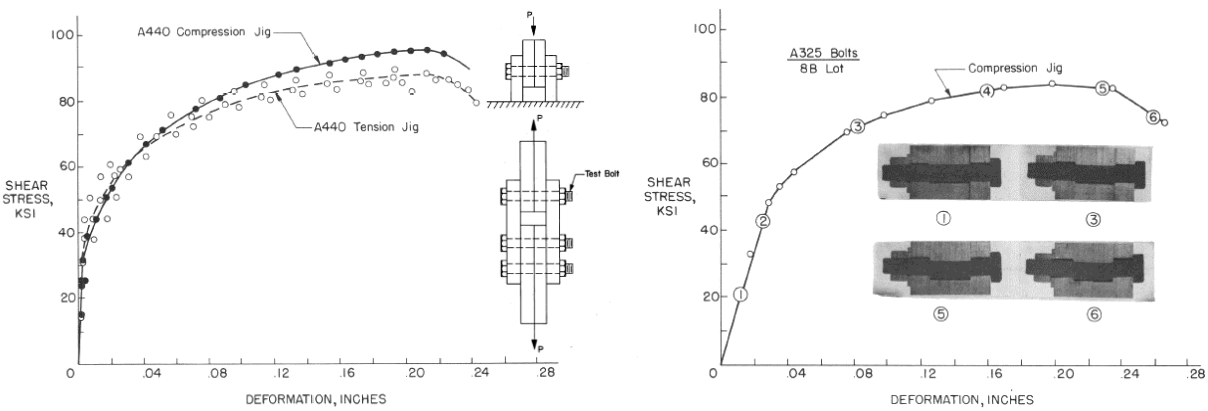
Chesson, Faustino and Munse [221, 264] (1964) as well as Bilderbeek [222] (1971) were assuming a quadratic interaction relationship between the tension and shear components in carbon steel bolts, which is following the shape modification hypothesis by von Mises. The quadratic bolt interaction approach was finally confirmed and proposed by Knobloch and Schmidt [171] (1987) for the revised German design standard DIN 18800-1 and the preparations for EN 1993-1-1. Further approaches to describe the interaction resistance of bolted connections from selected international standards and literature are discussed in detail in Chapter 3.5. At this stage, it can be concluded that the interaction behaviour of carbon steel bolts is mainly influenced by the related bolt cross-section in the shear plane and the bolt property class as the ratio of shear strength to tensile strength is reduced with increasing property class. Furthermore, Renner and Lange observed that carbon steel bolts under 15° loading with unthreaded part in the shear plane generally fail as tensile failure in the threaded bolt part. With increasing loading angle and higher shear loading ratio, finally the failure mechanism shifts to the unthreaded bolt part. Additionally, Renner and Lange experienced that higher load bearing capacities compared to the pure tension resistance of about ≈ 5 to 9 % were achieved under a 15° combined loading angle for all tested carbon steel bolts with an unthreaded part in the shear plane.



(a) Shear load-deformation curves for different failure planes in the unthreaded and/or threaded part of a carbon steel bolt

(b) Effect of lubrication on the faying surfaces on the shear-deformation relationship

Figure 2.5-1: Effects of the shear plane location and lubrication according to Wallart and Fischer [220]



(a) Typical shear stress-deformation curves for A354 BC bolts tested in compression and tension

(b) Deformation of A325 bolts at various stages of loading by saw-sections

Figure 2.5-2: Typical shear stress-deformation curves for A354 BC bolts tested in compression and tension and deformation of A325 bolts at various stages of loading according to Wallart and Fischer according to [220]

2.5.4 Literature review on the tension, shear and combined tension and shear load bearing behaviour of stainless steel bolts

As already mentioned, compared to the bearing and net section resistance of stainless steel plates, the available data of experimental and numerical studies about the load bearing behaviour of stainless steel bolts or bolting assemblies under tension, shear and combined tension and shear loading are limited. The normative regulations were mainly adopted by the design rules developed for carbon steel bolts and only checked by a few experimental studies, which are summarised in chronological order in Table 2.5-2. Again, the main research specifications like bolt types, bolt diameter/lengths and property classes including performed tension, shear and interaction tests are outlined. Analogues to carbon steel bolts, a chronological literature review of each study is summarised in Appendix A.

Table 2.5-2: Overview of existing studies into the tension, shear and combined tension and shear load bearing behaviour of austenitic (ASS), duplex (DSS) and precipitation hardening (PHSS) stainless steel bolts

Year of publication	Conducted by	Steel type	Bolt type	Bolt diameter and bolt length	Bolt corrosion and property class	Tension tests[1)]	Single-shear tests[1)]	Double-shear tests[1)]	Interaction tests[1)]	Number of tests	Data suitable for the following studies?
1974	Errera et al. [265]	CS	Partially threaded bolts	¼ inch, 3/8 inch, ½ inch, ¾ inch	≈ PC 8.8 (CS)	-	S	S	-	25	No[2)]
1984	Thomala [169]	ASS	Unnotched bars A2 (1.4303), A4 (1.4401)	d = 4 mm, d = 8 mm; d = 12 mm	Comparable to PC 50, 70 and 80	X	-	S	-	57	No
1990	The Steel Construction Institute, Technical report 21 [266] for the 1st Edition of DMSSS [267]	ASS	Fully threaded bolts	M16 and M20 from three different suppliers	A4-70, A4-80	X	-	T	T	87	Yes
1999	Bouchair and Muzeau [268]	ASS	Partially threaded bolts	M12×40, M16×50, M20×50	A4-80	X	-	S/T	-	35	Yes
2000	The Steel Construction Institute [269], ECSC report										
2000	Ryan [270]										
2001	Bouchaïr et al. [271]										
2007	The Steel Construction Institute, Stainless Steel in Fire (SSIF) [272]	ASS	Partially threaded bolts acc. to DIN 931 with rolled threads	M12×50	A2-70, A4-80	X	-	S	-	5[3)]	Yes
2012	Steeve and Wingate [273]	PHSS	Partially threaded bolts	7/8-inch bolts (≈ M10)	NAS1956C14, Alloy 660 with $f_{yb,min}$ = 724 N/mm² and $f_{ub,min}$ = 1241 N/mm²	X	S/T	-	S/T	46[4)]	No
2014	Cai and Young [274]	ASS	Fully threaded bolts	M6, M8, M10, M12	A4-80	-	T	T	-	-[5)]	No[5)]
2020	Song et al. [5, 6]	ASS DSS	Partially/fully threaded bolts EN ISO 4014, EN ISO 4017	M16×100, M20×100/140, M24×100,	A4-70, A4-80, A4-8.8, A4-10.9, D6-10.9, D6-12.9	X	S/T	S/T	S/T	207	Yes
2022	Zhao et al. [275]	ASS	Fully threaded bolts	M8	A2-70	-	-	T	-	-[6)]	No[6)]

[1)] X: Tension tests were conducted; -: No tests were conducted; S/T: Shear tests with unthreaded (S) and/or threaded (T) part of a bolt in the shear plane | [2)] Quenched and tempered medium carbon steel bolts were used. Consequently, the test results are not considered in the following investigations. | [3)] Only bolting assemblies made of stainless steel tested at room temperature are considered. | [4)] Precipitation hardening stainless steel bolts are not covered in the frame of the thesis. Therefore, the test results are not considered in the following investigations. | [5)] Only bolts M6, M8, M10 and M12 were used in the bearing tests. However, the tensile strength was not measured. Therefore, the test results are not considered in the following investigations. | [6)] Only groups of M8 bolts were used in the shear tests with different connection lengths, which are excluded in steel construction.

Embedded in [78] and further studies, extensive systematic experimental investigations into the load bearing behaviour of austenitic and duplex stainless steel bolts were carried out. The

main results of the tension, shear and interaction resistance of these stainless steel bolts are presented in Chapters 4, 5 and 6. The main findings of the above presented studies regarding the tension, shear and interaction resistance of stainless steel bolting assemblies can be summarised to the following additional aspects:

- **Tension resistance of stainless steel bolts:** *Bolt material with clear overstrength and different failure types compared to carbon steel bolts.*
  Ryan [270] (2000) states that the tension resistance of tested austenitic stainless steel bolts (A4-80) due to overstrength are significantly above the normative requirements which are considering the reduction factor of $k_2 = 0.9$.

- **Shear resistance of stainless steel bolts:** *Stronger correlation between shear and tensile strength with higher shear coefficients compared to carbon steel bolts.*
  Thomala [169] (1984) and Wiegand et al. [176] (2007) confirmed an approximately linear relationship between the shear coefficient α and the tensile strength for unnotched A2 and A4 austenitic stainless steel bolt material, independently of the chemical composition of the bolt material itself. They concluded that the shear strength and thus the shear coefficient α decrease with increasing tensile strength analogues to carbon steel bolts. Thomala emphasize the importance of the plastic deformation capacity regarding the ultimate shear and tensile strength. According to Thomala [169], austenitic stainless steel shows higher shear coefficients τ_m / R_m and a stronger correlation between the ultimate shear and tensile strength compared to carbon steel bolt material clearly above $1 / \sqrt{3} \approx 0.577$. Furthermore, Ryan [270] confirmed that the ultimate shear strengths of austenitic bolts tested in tension test rigs are about ≈ 5 % lower than those tested in compression. Consequently, also for stainless steel bolts, shear testing in tension test rigs was identified as the critical case.

  According to Dünkel [184, 276], for austenitic bolts always the smaller tensile stress area A_s should be used for the determination of the shear resistance, since austenitic stainless steel bolts fail after exceeding the minimum ultimate tensile load in the weakest area, which can be either in the unthreaded or threaded part of the bolt due to the locally different transformation of austenitic to forming induced martensitic material. This was finally adopted in the German national annex DIN EN 1993-1-4/NA deviating from the European design rules of EN 1993-1-4 and EN 1993-1-8.

  Steeve and Wingate [273] confirmed in their experimental investigations for precipitation hardening austenitic stainless steel bolts that an initial preload does not affect the ultimate tension, shear and interaction resistance. Furthermore, Song et al. [5, 6] concluded from single-shear and double-shear tests very similar load-deformation behaviour. The resulting shear resistance per shear plane in double-shear test rigs was slightly (1 to 4 %) lower than in single-shear test rigs.

- **Interaction resistance of stainless steel bolts:** *The bilinear interaction design rule of EN 1993-1-4 is significantly on the safe side for austenitic and duplex stainless steel bolts with unthreaded and threaded part in the shear plane.*
  The conservatism of the bilinear interaction approach according to EN 1993-1-4 was already shown by the Steel Construction Institute (SCI), UK in 1990 [266]. The conservative approach of EN 1993-1-4 for the unthreaded and threaded part of a bolt in the shear plane could also be confirmed by more recent studies by Song et al. [5, 6] in 2020. Their proposed design rules are strongly related to Australian Standard AS 4100 with slightly modified shear coefficients and retaining a quadratic interaction approach. Like for carbon steel

bolts, the effects of grip length and exposed threaded length have no significant impact on the interaction resistance of austenitic and duplex stainless steel bolts [5, 6].

Analogues to carbon steel bolts, also the interaction behaviour of austenitic and duplex bolts is mainly influenced by the related bolt cross-section in the shear plane and the bolt property class as the tension/shear ratio decreases with increasing PC. Furthermore, from the data of Song et al. [5, 6], the observation of Renner and Lange [178–183] can be confirmed that in at least one carbon steel bolt series in PC 8.8 as well as one austenitic A4-10.9 tested series higher maximum loads compared to the pure tension resistance under 15° combined loading with unthreaded part in the shear plane were achieved.

Nearly all studies emphasize the outstanding high bolt elongation and ductility of particularly austenitic stainless steel bolts compared to carbon steel bolts especially in the case of uniaxial tensile failure in the unthreaded part of a bolt. For structural applications, the outstanding high ductility of stainless steel bolts can be utilised for instance in steel beam-to-column connections, see [277], even under impact loading [4]. In addition, Song et al. [6] (2020) point out that significant bending deformation, which could be observed in tests, leads to a complex failure mechanism combining tension, shear and bending stresses.

2.6 Summary and conclusions

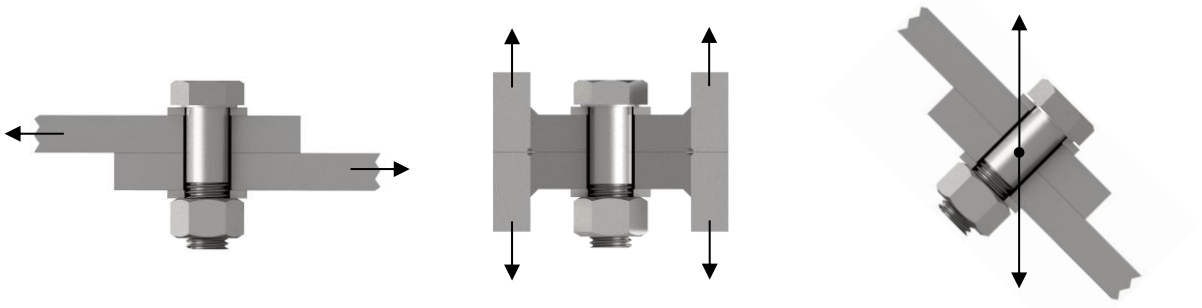
The state of the art of structural bolts and bolted connections made of carbon and stainless steel was introduced. The primary distinction of bolted connections according to EN 1993-1-8 is made between shear and tension connections based on the type of loading perpendicular (as a pure category A shear connection) or running parallel (as a pure category D tension connection) to the bolt axis. EN 1993-1-8 classifies bolted connections into five categories. These categories have been discussed in terms of the design verifications that structural engineers must conduct to ensure the safety and reliability of bolted connections in steel structures. Furthermore, a brief overview of non-preloaded and preloaded structural bolting assemblies was provided based on the European harmonised standards EN 15048-1 and EN 14399-1. According to the EN ISO 3506 standard series, stainless steel bolts, nuts and washers were outlined with particular interest to the stainless steel grades, the bolting assemblies' mechanical properties in contrast to carbon steel bolts including normative specifications. To gain a general overview, selected mechanical theories of Rankine, Tresca and von Mises to describe the interaction of tension and shear stresses of ductile metal materials were briefly summarised. Consequently, also the resulting stress states of a bolt subjected to tension and shear loading were introduced and the correlations between shear and yield/tensile strength were discussed and compared with meta-studies from literature.

Finally, anoverview of existing experimental and numerical investigations into the load bearing behaviour of carbon and stainless steel bolts subjected to tension, shear and combined tension and shear loading were presented. The main conclusions of these studies were presented for carbon and stainless steel bolts in order to identify the key parameter to describe accurately the resistances of carbon and stainless steel bolts under tension, shear and combined tension and shear.

3 Comparison of selected international design rules for bolted connections made of carbon and stainless steel

3.1 General

In Chapter 3, selected international design rules for non-preloaded bolted connections made of carbon and stainless steel will be introduced. Thus, selected international design codes, standards and guidelines regarding the tension, shear and combined tension and shear resistance of bolted connections made of carbon and stainless steel (mainly as slightly modified design approaches from carbon steel) from Europe, Germany, the UK, USA, Canada, Australia, New Zealand, Japan, South Africa, India, China and Russia are presented in order to give a comprehensive overview. The different approaches are compared and discussed with regard to the mechanical concepts and resulting load bearing capacities of the bolt shear, tension and interaction resistances presented in Figure 3.1-1 and compared with the design rules and resulting resistances from the Eurocode.



(a) Category A
Bearing type connection
⇒ *Shear resistance $F_{v,Rd}$ of a bolt*

(b) Category D
Non-preloaded tension connection
⇒ *Tension resistance $F_{t,Rd}$ of a bolt*

(c) Category A+D
Combined shear and tension
⇒ *Interaction resistance ($F_{v,Rd}$; $F_{t,Rd}$) of a bolt*

Figure 3.1-1: Shear, tension and interaction resistance of stainless or carbon steel bolts

3.2 Overview of selected international design rules for bolted connections

The design regulations of stainless steel, in particular bolted connections made of stainless steel, are essentially based on the regulations of bolted connections made of carbon steel: The basic design concept is intentionally maintained in most cases and only slightly modified to provide the structural engineer with an already well-known and “Ease of Use” design concept. Ultimately, this approach contributes to the promotion of stainless steel within the construction industry.

However, the unique nonlinear mechanical behaviour of stainless steel differs from that of carbon steel and should already be considered in the design process. Additionally, the design rules and their suitability must be statistically verified to fulfil the safety requirements of the Eurocode or other design codes for safe, reliable and sustainable applications. Finally, the increasing demand for structural stainless steel and bolted connections made of stainless steel in the construction industry is accompanied by the need for more economical design standards for stainless steel.

In order to provide a comprehensive overview, selected international design standards, codes and guidelines regarding the tension, shear and interaction resistance of carbon and stainless steel bolted connections are summarised in Figure 3.2-1 and Table 3.2-1 to Table 3.2-6. The design rules from Europe, in particular, the UK (Table 3.2-1) and Germany (Table 3.2-2), the

USA and Canada (Table 3.2-3), Australia and New Zealand (Table 3.2-4), India, South Africa, Japan, China and Russia (Table 3.2-5) as well as international (ISO) design rules (Table 3.2-6) were considered including the publication date and status (standard/guideline, active/withdrawn).

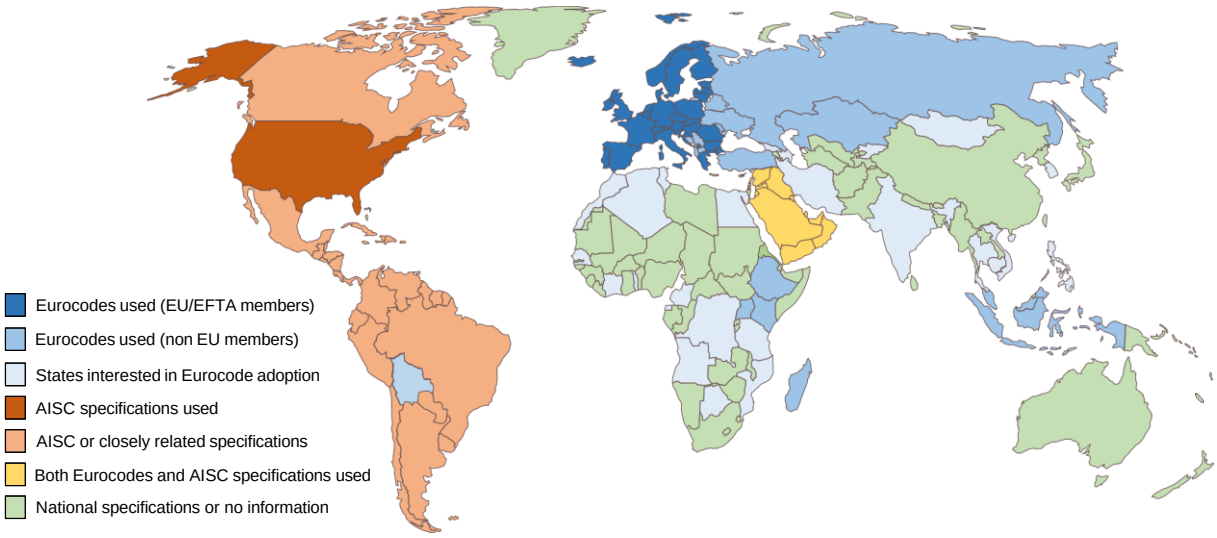


Figure 3.2-1: Global overview about the design standards used according to [278]; © Baddoo, N., SCI – The Steel Construction Institute, Ascot, UK

In Europe, the design and execution of bolted connections made of carbon steel can be carried out according to Eurocode 3 with EN 1993-1-8 [72] and EN 1090-2 [66]. The European design standard EN 1993-1-8 has been revised so that the revised standard EN 1993-1-8:2024 [82] is already available. However, the design rules for carbon steel bolted connections regarding the tension, shear and combined tension and shear resistance have finally not been changed in the revision process but only clarified at two points:

- The bilinear equation for combined tension and shear was specified by the additional requirement of $F_{t,Ed}/F_{t,Rd} \leq 1$ to contribute to pure tension failure, and
- The shear resistance may be based on the gross cross-section A of the bolt if the shaft of the bolt extends past the shear plane by at least $x = \max(0.1 \cdot d;\ 0.5 \cdot t_2)$, where x is the distance of the shear plane to the beginning of the transition region between the gross cross-section A and the tensile stress area A_s of the bolt, d is the bolt diameter, and t_2 is the plate thickness. For a detailed explanation, see Chapter 3.4.

Additionally, within the Eurocode 3 family, bolted connections made of carbon steel for structural cold-formed steel members and sheeting (metal lightweight structures) can be designed according to EN 1993-1-3 from 2010 [279]. The revision of this standard includes, among other things, minor modifications regarding the design resistances of bolts. This only focuses on the net-section resistance. Finally, the (unpublished) draft version EN 1993-1-3:2024 [280] has been prepared.

Bolted connections in crane constructions are regulated in EN 13001-3-1 [281] to prove the relevant limit states and to prove structural integrity of the steel structure. The current version was published in March 2019 and shows some differences compared to the Eurocode 3 design rules: 1. All bolted connections must be snug tightened to avoid slippage of the connection. 2. The unthreaded bolt part must always be positioned in the shear plane (which means that the threaded part in the shear plane is not permitted according to EN 13001-3-1). 3. The shear-tensile strength ratio of a bolt is defined as a constant value of $1/\sqrt{3} \approx 0.577$ for all property classes (PC 4.6, 5.6, 8.8, 10.9, 12.9) based on the von Mises shape modification hypothesis

(see Chapter 2.4.4). In contrast to the Eurocode 3 standards, the design check is carried out with the yield strength f_{yb} instead of the tensile strength f_{ub} and a partial safety factor of $\gamma_m = 1.1$ based on yielding as failure criterion instead of $\gamma_{M2} = 1.25$, which consequently leads to significantly lower and therefore more conservative shear resistances of a bolt per shear plane. Furthermore, the bolt design shear resistance in crane construction is directly linked to the number of shear planes by an additional safety factor γ_{sbs}. The shear resistance of single-shear connections is reduced by $\gamma_{sbs} = 1.3$ compared to double-/multi-shear connections with $\gamma_{sbs} = 1.0$. It's worth noting that this distinction is not explicitly accounted in the Eurocode or other standards.

In Europe, the design and execution of structures made of stainless steel can be carried out according to Eurocode 3 with EN 1993-1-4 [67] and the execution standard for steel structures EN 1090-2. The current 4th Edition of the Design Manual for Structural Stainless Steel (DMSSS) [64] provides further guidance. The current European design rules for non-preloaded stainless steel bolted connections under tension, shear and combined tension and shear loading, specified as category A, category D and category A+D connections according to EN 1993-1-8, are essentially based on the regulations of bolted connections made of carbon steel. The latest draft version of the revision of EN 1993-1-4, FprEN 1993-1-4 [80], has finally been extended to austenitic and duplex bolting assemblies of PC 100. New and more economical and statistically verified design rules were proposed by Stranghöner/Abraham for non-preloaded bolted connections made of stainless steel. The proposed design rules are based on systematic experimental and statistical investigations embedded in the German research project FOSTA P 1386 / IGF-No. 20651 N and further studies conducted at UDE-IML, see [78], [164, 282, 283]. The design rules can be further specified at the national level, e.g. the German National Annex according to DIN EN 1993-1-8/NA [284] or E DIN EN 1993-1-8/NA [285] (structural carbon steel bolts in steel structures), DIN EN 1993-1-3/NA [286] and E DIN EN 1993-1-3/NA [287] (carbon steel bolts in metal lightweight structures) or DIN EN 1993-1-4/NA [71] (stainless steel bolts). The German general building approval abZ Z-30.3-6 “Products, components and fasteners made of stainless steels” [288] from 2014 gave further normative specifications of the design of non-preloaded bolted connections, which were transferred to DIN EN 1993-1-4/NA and are not part of the abZ Z-30.3-6:2017-05 [77] anymore. The different material properties and load bearing behaviour of stainless steel bolts were taken into account by calculating the shear resistance $F_{v,Rd}$ of austenitic stainless steel bolts always with the smaller tensile stress area A_s of the bolt but with increased shear coefficients α compared to EN 1993-1-4. This approach is based on [184, 276, 289, 290] and contrasts with EN 1993-1-4 as well as EN 1993-1-8, which differ between the unthreaded (gross cross-sectional area A) or threaded bolt part (tensile stress area A_s) in the shear plane. Finally, the proposed and statistically verified design rules for FprEN 1993-1-4 by Stranghöner/Abraham for the tension $F_{t,Rd}$, shear $F_{v,Rd}$ and interaction resistance of stainless steel bolts were already implemented in abZ/aBG Z-30.3-6:2022 [81].

The German standard DIN 18800-1 [170] and the British standard BS 5950-1 [291] also dealt with the design of steel structures and carbon steel bolted connections. Both standards were withdrawn nationally due to the introduction of the Eurocodes and replaced by the Eurocode 3-family. However, they were influential in developing harmonised European design rules regarding the interaction load bearing behaviour, which will be discussed later.

Table 3.2-1: Summary of the design rules for non-preloaded bolted connections in the European Union (EU) and the UK

Region	Design of non-preloaded carbon steel bolted connections	Design of non-preloaded stainless steel bolted connections
European Union	**Steel structures:** ***EN 1993-1-8:2010-12*** *[72]* Title: Eurocode 3: Design of steel structures - Part 1-8: Design of joints; German version EN 1993-1-8:2005 + AC:2009 Published: December 2010 Status: Standard/Active ***EN 1993-1-8:2024 (draft)*** *[82]* Title: Eurocode 3 - Design of steel structures - Part 1-8: Joints Unpublished draft from September 2024 Status: Standard/Unpublished draft ***EN 1993-1-3:2010-12*** *[279]* Title: Eurocode 3: Design of steel structures - Part 1-3: General rules - Supplementary rules for cold-formed members and sheeting; German version EN 1993-1-3:2006 + AC:2009 Published: December 2010 Status: Standard/Active ***EN 1993-1-3:2024 (draft)*** *[280]* Title: Eurocode 3 - Design of steel structures - Part 1-3: Cold formed members and sheeting Unpublished draft from March 2024 Status: Standard/Unpublished draft **Steel structures in cranes:** ***EN 13001-3-1:2019-03*** *[281]* Title: Cranes - General Design - Part 3-1: Limit States and proof competence of steel structure; German version EN 13001-3-1:2012+A2:2018 Published: March 2019 Status: Standard/Active	**Steel structures:** ***EN 1993-1-4:2015-10*** *[67]* Title: Eurocode 3: Design of steel structures - Part 1-4: General rules - Supplementary rules for stainless steels; German version EN 1993-1-4:2006 + A1:2015 Published: October 2015 Status: Standard/Active ***FprEN 1993-1-4:2024 (E)*** *[80]* Title: Eurocode 3: Design of steel structures – Part 1-4: General rules – Stainless steel structures; Date: 2024-10 Published: - Status: Standard/Final Draft ***Design Manual for Structural Stainless Steel, 4th Edition (DMSSS)*** *[64], [135]* The Steel Construction Institute/SCI, Part I & II: Recommendations & worked examples; Part III: Commentary; Design Manual from the RFCS research project "Promotion of new Eurocode rules for structural stainless steels" (PUREST; contract 709600; Final report [292]) Published: February 2018 Status: Guideline/Active
United Kingdom (UK)	**Steel structures:** ***BS 5950-1:2000*** *[291]* Title: Structural use of steelwork in building - Part 1: Code of practice for design - Rolled and welded sections Published: May 2001 Status: Standard/Withdrawn Comment: Withdrawn on 30 March 2010 due to the introduction of the Eurocodes and therefore replaced by EN 1993-1-8.	

In the North American region, various design standards and guidelines are available for bolted connections made of carbon steel and stainless steel. In the United States of America (USA), the design of non-preloaded bolted connections made of carbon steel is regulated by ANSI/AISC 360-22 [293] as "Specification for structural steel buildings" of the American National Standards Institute (ANSI) and American Institute of Steel Construction (AISC). Further guidance on carbon steel high-strength bolts is given by the "Specification for structural joints using high-strength bolts" of the Research Council on Structural Connections (RCSC, 2020) [294]. In Canada, the Canadian Standards Association defines the design of steel structures in CSA S16 [295] from 2019 in its current 9th Edition.

Table 3.2-2: Summary of the design rules for non-preloaded bolted connections in Germany

Region	Design of non-preloaded carbon steel bolted connections	Design of non-preloaded stainless steel bolted connections
Germany	**Steel structures:** ***E DIN EN 1993-1-8/NA:2024-10*** *[285]* Title: National Annex - Nationally determined parameters - Eurocode 3 – Part 1-8: Joints Published: Oktober 2024 Status: Standard/Draft ***DIN EN 1993-1-8/NA:2020-11*** *[284]* Title: National Annex - Nationally determined parameters - Eurocode 3: Design of steel structures - Part 1-8: Design of joints Published: November 2020 Status: Standard/Active ***E DIN EN 1993-1-3/NA:2025-04*** *[287]* Title: National Annex to DIN EN 1993-1-3:2024, Eurocode 3 - Design of steel structures - Part 1-3: Cold-formed members and sheeting Status: Standard/Draft ***DIN EN 1993-1-3/NA:2017-05*** *[286]* Title: National Annex - Nationally determined parameters - Eurocode 3: Design of steel structures - Part 1-3: General rules - Supplementary rules for cold-formed members and sheeting Status: Standard/Active ***DIN 18800-1:2008-11*** *[170]* Title: Steel structures - Part 1: Design and construction Published: November 2008 Status: Standard/Withdrawn Comment: Replaced by EN 1993-1-8. **Mechanical engineering:** ***VDI 2230 Part 1*** *[167]* Title: Systematic calculation of highly stressed bolted joints - Joints with one cylindrical bolt Published: November 2015 Status: Guideline/Active	**Steel structures:** ***DIN EN 1993-1-4/NA:2020-11*** *[71]* Title: National Annex - Nationally determined parameters - Eurocode 3: Design of steel structures - Part 1-4: General rules - Supplementary rules for stainless steels Published: November 2020 Status: Standard/Active ***abZ/aBG Z-30.3-6, 20.04.2022*** *[81]* Title: Z-30.3-6, Products, components and fasteners made of stainless steels Period of validity: 01 May 2022 to 01 May 2027 Status: German national technical approval/ General construction technique permit; Active Comment: Proposed design rules of FprEN 1993-1-4 regarding the tension, shear and interaction resistance were transferred. ***abZ Z-30.3-6, 12.05.2017*** *[77]* Title: Z-30.3-6, Products, components and fasteners made of stainless steels Period of validity: 01 May 2017 to 01 May 2022 Status: General building approval/Withdrawn ***abZ Z-30.3-6, 22.04.2014*** *[288]* Title: Z-30.3-6, Products, components and fasteners made of stainless steels Period of validity: 01 May 2014 to 01 May 2017 Status: General building approval/Withdrawn Comment: Normative specifications regarding the design of non-preloaded stainless steel bolts were implemented in DIN EN 1993-1-4/NA and are consequently not part of the revised General building approval abZ Z-30.3-6:2017-05.

This standard summarises rules and requirements for the design, fabrication and erection of steel structures based on the limit states design approach. Generally, structural bolts and bolting assemblies in CSA S16 are referred to ASTM standards (American Society for Testing and Materials), e.g. ASTM F3125/F3125M-21 [296] specification for high-strength bolts (replacing the widely used ASTM standards A325, A325M, A490, A490M, F1852 and F2280 in North American steel structures).

On the contrary, the design of non-preloaded stainless steel bolted connections was regulated in the past by SEI/ASCE 8-02 [297] published by the Structural Engineering Institute (SEI) and the American Society of Civil Engineers (ASCE). Since 2022, the revised SEI/ASCE 8-22 [298] has been published, whereby the design rules for bolts remain apart from editorial and formal changes, see [299]. Further design regulations and assistance are provided in the design standard ANSI/AISC 370-21 [300], accompanied by the new AISC 313-21 [301] code of practice for structural stainless steel buildings, which is given here for completeness. Additional

design rules and specifications can be found in the 2nd Edition of the Design Guide 27 [302], intended to be a companion to both standards ANSI/AISC 370-21 and AISC 313-21. Thus, the 1st Edition of the AISC Design Guide 27 [303] from 2013 is replaced.

Table 3.2-3: Summary of the design rules for non-preloaded bolted connections in the USA and Canada

Region	Design of non-preloaded carbon steel bolted connections	Design of non-preloaded stainless steel bolted connections
 United States of America (USA)	**Steel structures:** ***ANSI/AISC 360-22*** *[293]* Title: Specification for structural steel buildings Published: 1 August 2022 Status: Standard/Active ***RCSC:2020-06, RCSC – Research Council on Structural Connections*** *[294]* Title: Specification for structural joints using high-strength bolts Published: June 2020 Status: Standard/Active	**Steel structures:** ***SEI/ASCE 8-22 [298]*** Title: Specification for the design of cold-formed stainless steel structural members Published: January 2022 Status: Standard/Active Comment: ASCE 8-22 [298] is superseding the previous ASCE 8-02 [297]; see also [299]. ***ANSI/AISC 370-21*** *[300]* Title: Specification for structural stainless steel buildings Published: June 2021 (First Edition) Status: Standard/Active ***AISC 313-21*** *[301]; (here only informative)* Title: Code of standard practice for structural stainless steel buildings Published: June 2021 (First Edition) Status: Standard/Active Comment: Refers to design rules of AISC 370. ***AISC Design Guide 27, 1st Edition*** *[303]* Title: Design Guide 27, Structural stainless steel Published: January 2013, Revised March 2015 Status: Guideline/Withdrawn ***AISC Design Guide 27, 2nd Edition*** *[302]* Title: Design Guide 27, Structural stainless steel Published: April 2022 Status: Guideline/Active Comment: BTQP integrated in the annex. In general, the 2nd Edition serves as a companion to ANSI/AISC 370-21 and AISC 313-21.
 Canada	**Steel structures:** ***CSA S16:19*** *[295]* Title: Design of steel structures Published: September 2019 as 9th Edition and revised in December 2019 Status: Standard/Active	

In Australia, the Australian Standard AS 4100 [304], prepared by the Standards Australia Committee BD-001, specifies minimum requirements for the design and the engineering aspects of fabrication, erection and modification of steelwork in carbon steel structures. The design rules are developed in accordance with the limit states design method. In the context of bolted connections, design rules regarding the tension, shear and interaction resistance of carbon steel bolts can be found in Chapter 9 of AS 4100. The New Zealand Steel Structures Standard NZS 3404 Part 1 and Part 2 [305] from 1997 largely follows the Australian Standard AS 4100. Structural engineers apply the NZS 3404 Part 1 standard to design steel structures and analogues to AS 4100 to set out minimum requirements for the design, fabrication, erection and modification of steelwork in structures by the limit state design method or the

alternative design method. Additionally, NZS 3404 Part 2 is a commentary which provides background to the content of Part 1. NZS 3404 Part 1 contains many cross-references to the specifications of various Australian standards, e.g. AS 1275 [306] for the tensile stress area A_s of a bolt. The following chapters will compare the tension, shear and interaction resistance of bolts between the Australian and New Zealand standards. Furthermore, the linkage between Australia and New Zealand leads to common standards, e.g. for bolts AS/NZS 1111 [307] and AS/NZS 1252 [308].

The design of stainless steel structures could be done for Australia and New Zealand by AS/NZS 4673 [309] titled "Cold-formed stainless steel structures", published in November 2001 but withdrawn by Australian Standards in February 2021. The framework of the AS/NZS 4673 standard was parallel with the already presented SEI/ASCE 8-02 standard from the USA, which is expected to replace the specifications from Australia and New Zealand. In the AS/NZS 4673 standard, the design rules (as tension, shear and interaction resistance) for bolts made of stainless steel complying both with ASTM standards (Clause 5.3.7 "Stainless steel bolts to ASTM standards") or EN ISO 3506-1 standards (Clause 5.3.8 "Stainless steel bolts to ISO 3506"). Further guidance is also given by the ASSDA Australian Stainless Reference Manual from 2020 (8th Edition) [310].

Table 3.2-4: Summary of the design rules for non-preloaded bolted connections in Australia and New Zealand

Region	Design of non-preloaded carbon steel bolted connections	Design of non-preloaded stainless steel bolted connections
 Australia	**Steel structures:** ***AS 4100:2020*** *[304]* Title: Steel structures Published: August 2020, Amendment 1:2021 was published in September 2021 Status: Standard/Active	**Steel structures:** ***AS/NZS 4673:2001*** *[309]* Title: Cold-formed stainless steel structures Published: November 2001 Status: Standard/Withdrawn February 2021 Comment: Design rules for bolts made of stainless steel complying with ASTM or EN ISO 3506-1 standards; embedded in the framework of SEI/ASCE 8-02. ***ASSDA 2020*** *[310]* Title: Australian Stainless Reference Manual Published: 2020 (8th Edition) Status: Guideline/Active
 New Zealand	**Steel structures:** ***NZS 3404 Parts 1 and 2:1997*** *[305]* Title: Steel structures standard Published: June 1997 Status: Standard/Active	**Steel structures:** ***AS/NZS 4673:2001*** *[309]* Title: Cold-formed stainless steel structures Published: November 2001 Status: Standard/Withdrawn February 2021 Comment: Design rules for bolts made of stainless steel complying with both ASTM and EN ISO 3506-1 standards; embedded in the framework of SEI/ASCE 8-02.

Additionally, the design standards, codes and guidelines of carbon and stainless steel bolted connections from India, South Africa, Japan, China and Russia are summarised in Table 3.2-5.

Table 3.2-5: Summary of the design rules for non-preloaded bolted connections in India, South Africa, Japan, China, Russia and from the International Organization for Standardization

Region	Design of carbon steel bolted connections	Design of stainless steel bolted connections
India	**Steel structures:** ***IS 800:2007*** *[311]* Title: General construction in steel – Code of practice (3rd revision) Published: February 2008 Status: Standard/Active ***IS 4000:1992(R2017)*** *[312]* Title: Code of practice for high strength bolts in steel structures Published: 1992, Reaffirmed in January 2017 Status: Standard/Active Comment: Rules shall be conforming to IS 800.	
South Africa	**Steel structures:** ***SANS 10162-1:2011*** *[313]* Title: The structural use of steel Part 1: Limit-states design of hot-rolled steelwork Published: May 2011 (2nd Edition) Status: Standard/Active ***SANS 10162-2:2011*** *[314]* Title: The structural use of steel Part 2: Limit-states design of cold-formed steelwork Published: 2011 (2nd Edition) Status: Standard/Active	**Steel structures:** ***SANS 10162-4:1997 (SABS 0162-4)*** *[315]* Title: The structural use of steel Part 4: The design of cold-formed stainless steel structural members Published: July 2017, Approved January 1998, Stage date September 2017 Status: Standard/Active
Japan	**Steel structures:** ***JSCE:2007 (1st Edition)*** *[316]* Title: Standard specifications for steel and composite structures, I General provisions, II Structural planning, III Design Published: December 2009 Status: Standard/Active	**Steel structures:** ***JSSC:2007 – Stainless steel constr.*** *[317]* Title: The design and construction specifications for stainless steel structures Published: November 2007, 3rd Edition (only available in Japanese) Status: Standard/Active
China	**Steel structures:** ***GB 50017-2017*** *[318]* Title: Code for design of steel structures Published: December 2017, implemented in July 2018 Status: Standard/Active	**Steel structures:** ***CECS 410-2015*** *[319]* Title: Technical specification for stainless steel structures Published: July 2015, implemented in December 2015 Status: Standard/Active
Russia	**Steel structures:** ***SP 16.13330.2017*** *[320]* Title: Steel structures Published: August 2017 Status: Standard/Active	**Steel structures:** ***SP 198.1325800.2014*** *[321]* Title: EN 1993-1-4:2006, Eurocode 3: Design of steel structures - Part 1-4: General rules - Supplementary rules for stainless steels Published: October 2015 Status: Standard/Active Comment: Russian standard refers to Eurocode EN 1993-1-4 from 2006.

Furthermore, the international standard ISO 10721-1 “Steel structures - Part 1: Materials and design” from the International Organization for Standardization is introduced, see Table 3.2-6. For the sake of completeness, it must be noted that a working draft of ISO 17607-6 titled “Steel structures – Execution of structural steelwork – Part 6: Bolting” is currently being processed

and deals with the execution of structural bolts made of carbon steel and stainless steel. The draft standard provides normative references to bolting products made of stainless steel like EN ISO 3506-1/-2, ASTM A193/A193M, ASTM A320/ A320M, ASTM F593 and ASTM A1082/ A1082M standards. In addition, methods are given to avoid galling and seizure of stainless steel structural bolts.

Table 3.2-6: Summary of the design rules for non-preloaded bolted connections from the ISO – International Organization for Standardization

Region	Design of carbon steel bolted connections	Design of stainless steel bolted connections
International	**Steel structures:** ***ISO 10721-1:1997-02*** *[322]* Title: Steel structures - Part 1: Materials and design Published: February 1997 Status: Standard/Active	
	Steel structures: ***ISO 17607-6:2023-12*** *[70]* Title: Steel structures – Execution of structural steelwork – Part 6: Bolting Published: - Status: Standard	

3.3 Tension resistance of carbon and stainless steel bolts

3.3.1 General

The tension resistance of carbon and stainless steel bolts is mainly described as the product of the tensile strength f_{ub} and the tensile stress area A_s or the gross cross-sectional area A (partially or in total) of a bolt, depending on which design code, standard or guideline is used. The tension resistance is also of primary importance for two other structural design aspects:

- Firstly, the tensile load bearing capacity of a bolt is essential in the context of determining the shear coefficient α defined as the ratio between the pure shear resistance and the pure tensile resistance of a bolt, and
- secondly, the tension resistance is important in the context of the load bearing behaviour under combined tension and shear loading as interaction resistance of carbon and stainless steel bolts.

3.3.2 Selected international design rules of the tension resistance of bolts

The following selected international design rules regarding the tension resistance of carbon and stainless steel bolts are summarised in Table 3.3-1 and Table 3.3-2.

The presented selected design rules are to be understood as examples and do not claim to be completed. The focus is on obtaining a comprehensive overview of the existing design standards, codes, and guidelines for carbon and stainless steel bolts in steel construction.

Table 3.3-1: Summary of selected active international design rules for the determination of the tension resistance of an individual bolt made of carbon (CS) and stainless steel (SS) with reduction factor k_2

Standard, Code or Guideline	Steel type	Tension resistance design concept	
EN 1993-1-8:2010-12 *[72]* *Table 3.4*	CS	$F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$ $F_{t,Rd}$ is the design tension resistance per bolt; k_2 is the reduction factor with $k_2 = 0.63$ for countersunk bolts, otherwise $\mathbf{k_2 = 0.9}$; f_{ub} is the nominal tensile strength of a bolt; A_s is the tensile stress area of a bolt; γ_{M2} is the partially safety factor for connections according to EN 1993-1-1, $\gamma_{M2} = 1.25$. In Indian Standard IS 800, $T_{db} = F_{t,Rd}$, $A_n = A_s$ and the partial safety factor γ_{M2} is replaced by $\gamma_{mb} = 1.25$, see Clause 5.4.1. Furthermore: $0.90 \cdot f_{ub} \cdot A_s < f_{yb} \cdot A \cdot (\gamma_{mb}/\gamma_{m0})$ with $\gamma_{mb} = 1.25$ and $\gamma_{m0} = 1.10$.	(Eq. 3.3-1)
EN 1993-1-8:2024 (draft) *[82]*[1)] *Table 5.7*	CS		
E DIN EN 1993-1-8/NA:2024-10 *[285]* ***DIN EN 1993-1-8/NA:2020-****[284]* *NDP to 3.1.1(3)*	CS		
EN 1993-1-3:2010-12 *[279]* *Table 8.4*	CS		
EN 1993-1-3:2024 (draft) *[280]* *Table 10.5*	CS		
E DIN EN 1993-1-3/NA:2024-05 *[287]*	CS		
DIN EN 1993-1-3/NA:2017-05 *[286]* *NDP to Table 8.4*	CS		
Design Manual for Structural Stainless Steel, 4th Edition *[64], [135]* *Clause 7.2.4*	SS		
EN 1993-1-4:2015-10 *[67]* *Clause 6.1*	SS		
SP 198.1325800.2014 *[321]* *Clause 14.2.9*	SS		
IS 800:2007 *[311]* *Clause 10.3.5*	CS		
FprEN 1993-1-4:2024 *[80]* *Clause 10.2(4)*	SS	$F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$ $F_{t,Rd}$ is the design tension resistance per bolt; k_2 is the reduction factor with $k_2 = 0.63$ for countersunk bolts, otherwise $\mathbf{k_2 = 1.0}$; f_{ub} is the nominal tensile strength of a bolt; A_s is the tensile stress area of a bolt; γ_{M2} is the partially safety factor for connections according to EN 1993-1-1, $\gamma_{M2} = 1.25$. According to ISO 10721-1, the variables are changing to $F_t = F_{t,Rd}$. $f_d = f_{ub}/\gamma_{rc}$ and $A_{sp} = A_s$. The partial safety factor γ_{rc} is not further specified.	(Eq. 3.3-2)
abZ/aBG Z-30.3-6:2022-05 *[81]* *Clause 3.3.2*	SS		
AS/NZS 4673:2001 *[309]* *Clause 5.3.8.2 (Stainless steel bolts complying with ISO 3506)*	SS		
ISO 10721-1:1997-02 *[322]* *Clause A.8.8.3.1*	CS		

[1)] According to EN 1993-1-8:2024 (draft), the reduction of the tension resistance $F_{t,Rd}$ is just given by 0.9 (and has to be multiplied with 0.7 for countersunk bolts) without the symbol k_2. Nevertheless, the design approach is still equal to the EN 1993-1-8:2010 approach.

Table 3.3-2: Summary of selected active international design rules for the determination of the tension resistance of an individual bolt made of carbon (CS) and stainless steel (SS) without reduction factor k_2

Standard, Code or Guideline	Steel type	Tension resistance design concept	
ANSI/AISC 360-22 *[293]* *Clause J3-1*	CS	$\text{LRFD}: \phi \cdot R_n = F_{nt} \cdot A_b = \underbrace{0.75 \cdot F_u}_{F_{nt}} \cdot A_b$ $\text{ASD}: \frac{R_n}{\Omega} = F_{nt} \cdot A_b = \underbrace{0.75 \cdot F_u}_{F_{nt}} \cdot A_b$ $\Phi \cdot R_n$ is the design tensile strength per bolt with $\Phi = 0.75$ (LRFD); R_n/Ω is the allowable tensile strength per bolt with $\Omega = 2.00$ (ASD); F_{nt} is the nominal tensile stress with $0.75 \cdot F_u$ e.g. from Table J3.2 of AISC 360 or Table 1 of RCSC; F_u is the specified minimum tensile strength; A_b is the nominal unthreaded body area of a bolt or threaded part (equal to the gross cross-sectional area of a bolt). The SEI/ASCE 8-22 specification is based on the LRFD method, while the ASD concept is described in Appendix D of the specification with $\Omega = 3.00$ (ASD). R_n is replaced by P_n. The AS/NZS 4673 standard is complying with ASTM bolt standards ASTM A 193/A, ASTM A 276 and uses different variables: $N_{ft} = R_n$, $A_f = A_b$ and $f_{nt} = F_{nt}$.	(Eq. 3.3-3)
RCSC:2020-06, Research Council on Structural Connections *[294]* *Clause 5.1*	CS		
ANSI/AISC 370-21 *[300]* *Clause J3-1*	SS		
AISC 313-21 *[301]* *Clause 1.5*	SS		
AISC Design Guide 27, 2nd Edition *[302], Clause Table 10-4*	SS		
SEI/ASCE 8-02 (withdrawn) *[297]* *Clause 5.3.4-1*	SS		
SEI/ASCE 8-22 *[298]* *Chapter 10*	SS		
AS/NZS 4673:2001 *[309]* *Clause 5.3.7.3 (Stainless steel bolts complying with ASTM standards)*	SS		
CSA S16:19 *[295]* *Clause 13.12.1*	CS	$T_r = 0.75 \cdot \phi_b \cdot A_b \cdot F_u$ T_r is the design tensile resistance per bolt with $\Phi_b = 0.8$ as resistance factor for bolts; A_b is the cross-sectional area of a bolt based on its nominal diameter; F_u is the specified minimum tensile strength. In SANS 10162-1, the specified minimum tensile strength F_u is replaced by variable f_u.	(Eq. 3.3-4)
SANS 10162-1:2011 *[313]* *Clause 13.12.1.3*	CS		
AS 4100:2020 *[304]* *Clause 9.2.2.1*	CS	$\phi \cdot N_{tf} = \phi \cdot \underbrace{A_s \cdot f_{uf}}_{N_{tf}}$ N_{tf} is the nominal tensile capacity of a bolt with $\Phi = 0.8$ as capacity factor for bolts; A_s is the tensile stress area of a bolt specified in AS 1275; f_{uf} is the ultimate tensile strength of a bolt. The AS/NZS 4673 standard modifies the capacity factor for bolts to $\Phi = 0.67$ complying with ISO 3506 bolt standards and uses different variables: $N_{ft} = N_{tf}$, $A_{bs} = A_s$ and $f_{nt} = f_{uf}$.	(Eq. 3.3-5)
NZS 3404 Parts 1 and 2:1997 *[305]* *Clause 9.3.2.2 and Table 3.3*	CS		
AS/NZS 4673:2001 *[309]* *Clause 5.3.8.3 (Stainless steel bolts complying with ISO 3506 standards)*	SS		

A deeper analysis of the different international design concepts and approaches regarding the bolt tension resistance reveals that, apart from the different safety concepts and factors, the main difference can be found in the presence (Table 3.3-1) or absence (Table 3.3-2) of a reduction factor of the tension resistance: The European design approaches of EN 1993-1-8 carbon steel and EN 1993-1-4 for stainless steel bolts both include a reduction factor generally abbreviated as k_2 (except for the EN 1993-1-8:2024 draft) and defined as $k_2 = 0.9$ (except for countersunk bolts with $k_2 = 0.63$), which reduces the characteristic tension resistance down to

90 %. In an international comparison, reducing the bolt tension resistance with k_2 = 0.9 is only followed by Indian Standard IS 800, Russian Standard SP 198.1325800 and the Design Manuals of Structural Stainless Steel (DMSSS), which are all related or based on the Eurocode standards.

Within the framework of the introduction of the Eurocodes, the reduction factor k_2 = 0.9 was established and served to compensate for uncertainties and inaccuracies in the design concept of the tension resistance for carbon steel bolts. Further information regarding the statistical evaluation and the European normative revision process of EN 1993-1-8 are discussed comprehensively in Chapter 7.4.2. However, the reduction of the tension resistance down to 90 % of a bolt made of carbon or stainless steel cannot be found in the North American (USA, Canada), Australian and New Zealand as well as South African design concepts. Besides the different safety concepts, the tension resistance is defined either as the product of the nominal tensile strength and 75 % of the nominal unthreaded body area of a bolt as nominal gross cross-sectional area A (North American and South African approach) or as the product of the nominal tensile strength and the nominal tensile stress area A_s of a bolt (Australian and New Zealand approach), see Table 3.3-1. As already mentioned, the average ratio between the nominal tensile stress area A_s and the nominal gross cross-sectional area A is according to EN ISO 898-1 and EN ISO 3506-1 about $A_s/A \approx 0.78$ for bolt dimensions M12 to M36, as presented in Table 3.3-3. Consequently, the North American and South African approaches to the bolt tension resistance are related to the tensile stress area A_s by considering only 75 % of the nominal unthreaded body area of a bolt A and, therefore, slightly on the safe side (with the exception of bolt diameter M12, see Table 3.3-3).

Table 3.3-3: Comparison of the nominal cross-sectional areas $A_{s,nom}$ and A_{nom} for bolt dimensions M12 to M36

Bolt dimension	M12	M16	M20	M24	M30	M36
Nominal tensile stress area $A_{s,nom}$ of a bolt[1)] [mm²]	84.3	157	245	353	561	817
Nominal gross cross-sectional area A_{nom} of a bolt [mm²]	113	201	314	452	707	1018
Ratio $A_{s,nom}/A_{nom}$ [-]	0.75	0.78	0.78	0.78	0.79	0.80
Mean ratio $A_{s,nom}/A_{nom}$ [-]	0.78					
[1)] According to EN ISO 898-1 and EN ISO 3506-1.						

Finally, the different selected design equations regarding the tension resistance of carbon and stainless steel bolts presented in Table 3.3-1 and Table 3.3-2 can be further distinguished by the mechanical principle and the related safety concept: In total, three main design approaches for the bolt tension resistance as characteristic values without safety factors are identified. Furthermore, six design approaches for the tension resistance as design value considering the various safety concepts and safety factors are provided. The terminology of Eurocode 3 is used as far as possible to enable direct comparability. The main design concepts for the tension resistance of carbon and stainless steel bolts in normal round holes are described in the following, while countersunk bolts are excluded in all cases:

- **Approach 1:** Tension resistance of an individual bolt defined as the product of a reduction factor k_2 = 0.9, nominal tensile strength $f_{ub,nom}$ and nominal tensile stress area $A_{s,nom}$ acc. to standards EN 1993-1-8, EN 1993-1-8:2024, DIN EN 1993-1-8/NA or E DIN EN 1993-1-8/NA, EN 1993-1-3, EN 1993-1-3:2024, DIN EN 1993-1-3/NA and E DIN EN 1993-1-3/NA, the Design Manual for Structural Stainless Steel, 4th Edition, EN 1993-1-4, DIN EN 1993-1-4/NA, SP 198.1325800 and IS 800, see (Eq. 3.3-6).

$$F_{t,Rd} = \frac{k_2 \cdot f_{ub,nom} \cdot A_{s,nom}}{\gamma_{M2}} \quad \text{with } \gamma_{M2} = 1.25 \qquad \text{(Eq. 3.3-6)}$$

- **Approach 2:** Tension resistance of an individual bolt defined as the product of the nominal tensile strength $f_{ub,nom}$ and the nominal tensile stress area $A_{s,nom}$ in accordance with standards FprEN 1993-1-4, abZ/aBG Z-30.3-6, ISO 10721-1, AS 4100, NZS 3404 Parts 1 and 2 (Approach 2a) or AS/NZS 4673 for ISO bolts (Approach 2b), see (Eq. 3.3-7).

$$F_{t,Rd} = \frac{f_{ub,nom} \cdot A_{s,nom}}{\gamma_{M2}}$$ with γ_{M2} = 1.25 (Approach 2a), with γ_{M2} = 1.49 for ISO bolts (Approach 2b). (Eq. 3.3-7)

- **Approach 3:** Tension resistance of an individual bolt defined as the product of a factor 0.75 (nearly equal to the ratio of $A_s/A \approx 0.78$), the nominal tensile strength $f_{ub,nom}$ (= F_u) and nominal gross cross-sectional area A_b according to ANSI/AISC 360, US-RCSC, ANSI/AISC 370, AISC 313, AISC Design Guide 27, 2nd Edition, AS/NZS 4673 for ASTM bolts (Approach 3a and 3b), SEI/ASCE 8 (Approach 3c), CSA S16 and SANS 10162-1 (Approach 3d), see (Eq. 3.3-8).

$$\text{LRFD}: \phi \cdot R_n = F_{nt} \cdot A_b = \underbrace{0.75 \cdot F_u}_{F_{nt}} \cdot A_b$$

$$\text{ASD}: \frac{R_n}{\Omega} = F_{nt} \cdot A_b = \underbrace{0.75 \cdot F_u}_{F_{nt}} \cdot A_b$$

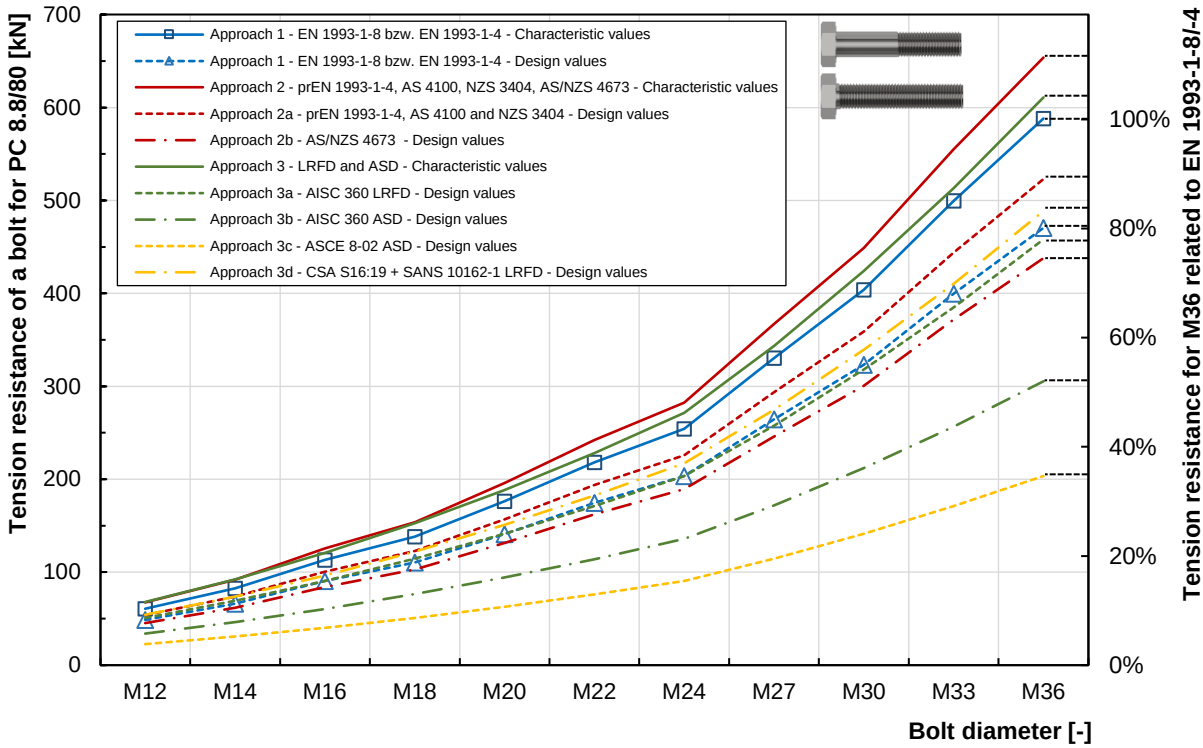
with Φ = 0.75 (LRFD; Approach 3a), with Ω = 2.00 (ASD; Approach 3b), with Ω = 3.00 (ASD; Approach 3c), with Φ = 0.80 (LRFD; Approach 3d). (Eq. 3.3-8)

3.3.3 Comparison of the resulting tension resistances for carbon and stainless steel bolts based on the main design approaches

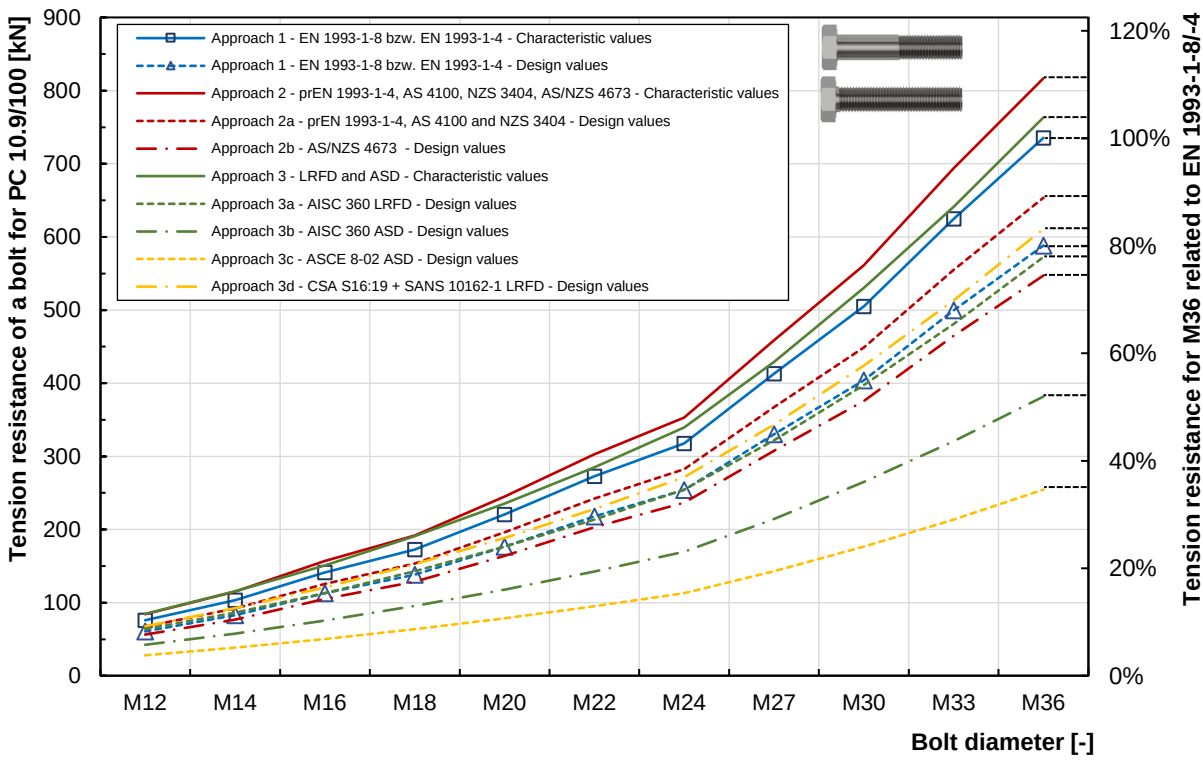
A graphical comparison of the different resulting tension resistances of a carbon or stainless steel bolt (as characteristic value and design value) across the bolt diameter M12 to M36 for PC 8.8/80 and PC 10.9/100 is presented in Figure 3.3-1. To allow a direct comparison of the different design concepts, all resulting tension resistances were calculated under the sole consideration of European EN ISO 898-1 carbon steel and EN ISO 3506-1 stainless steel bolts. Consequently, ASTM bolts made of carbon and stainless steel were not considered to determine the tension resistances for comparability. In order to visualise the differences of the resulting tension resistance of the above-identified main design concepts and approaches, the second y-axes of Figure 3.3-1 for PC 8.8/80 (a) and PC 10.9/100 (b) are normalised to the current design rule of EN 1993-1-8/-4 as 100 %.

It can be shown that for PC 8.8/80 and PC 10.9/100 across bolt diameters M12 to M36, the highest characteristic tension resistance is always achieved by Approach 2 ($f_{ub} \cdot A_s$) according to FprEN 1993-1-4, AS 4100, NZS 3404 and AS/NZS 4673 resulting to 111.1 % of the tension resistance referred to EN 1993-1-8/-4. Consequently, the second highest tension resistance is achieved by the North American and South African Approach 3 ($0.75 \cdot f_{ub} \cdot A$), resulting in 103.8 % and finally followed by Approach 1 according to the current EN 1993-1-8 and EN 1993-1-4 ($0.9 \cdot f_{ub} \cdot A_s$). If the safety factor is considered, the highest design tension resistance of a bolt can be observed by Approach 2a ($f_{ub} \cdot A_s / \gamma_{M2}$ with γ_{M2} = 1.25) according to FprEN 1993-1-4, AS 4100, NZS 3404 and AS/NZS 4673 resulting to 88.9 % of the reference tension resistance of EN 1993-1-4/ -8. In descending order, the design tension resistances result to 83.1 % for Approach 3d (SANS 10162-1 LRFD), 80 % for Approach 1 (as EN 1993-1-8 and EN 1993-1-4 with $0.9 \cdot f_{ub} \cdot A_s / \gamma_{M2}$ with γ_{M2} = 1.25), 77.9 % by Approach 3a (AISC 360 LRFD) and 74.4 % by Approach 2b (AS/NZS 4673 for ISO bolts). The lowest design tension resistances are achieved by Approach 3b (AISC 360 ASD, 1/Ω with Ω = 2.00) and particularly Approach 3c (SEI/ASCE 8-22 ASD, 1/Ω with Ω = 3.00), which is the most conservative approach due to the striking high safety factor of Ω = 3.00.

Approach 1: Tension resistance of an individual bolt defined as the product of a reduction factor $\mathbf{k_2 = 0.9}$, nominal tensile strength $\mathbf{f_{ub,nom}}$ and nominal tensile stress area $\mathbf{A_{s,nom}}$.	(Eq. 3.3-9)
Approach 2: Tension resistance of an individual bolt defined as the product of a reduction factor $\mathbf{k_2 = 1.0}$, nominal tensile strength $\mathbf{f_{ub,nom}}$ and nominal tensile stress area $\mathbf{A_{s,nom}}$.	(Eq. 3.3-10)
Approach 3: Tension resistance of an individual bolt defined as the product of a factor 0.75 (nearly equal to the ratio of $A_s/A \approx 0.78$), the nominal tensile strength $f_{ub,nom}$ (= F_u) and nominal gross cross-sectional area A_{nom} (= A_b).	(Eq. 3.3-11)



(a) Comparison of the tension resistances for a carbon or stainless steel bolt for PC 8.8/80



(b) Comparison of the tension resistances for a carbon or stainless steel bolt for PC 10.9/100

Figure 3.3-1: Graphical comparisons of the different design approaches for the tension resistances of a carbon or stainless steel bolt for bolt dimensions M12 to M36 for PC 8.8/80 (a) and PC 10.9/100 (b)

3.3.4 Requirement of the minimum ultimate tensile loads according to EN ISO 898-1 and EN ISO 3506-1

In addition to the design rules for carbon and stainless steel bolted connections in structural applications, the normative mechanical requirements of carbon and stainless steel bolts must be considered. The bolt specifications must guarantee the tension resistance of bolts specified in the design codes, standards and guidelines, also considering sufficient reserves due to adverse effects such as prying and bending as well as imperfections or improper handling on the construction site.

In Europe, EN ISO 898-1 (for carbon steel bolts) and EN ISO 3506-1 (for stainless steel bolts) already specify the requirement of a minimum ultimate tensile load in a slightly different way: For carbon steel bolts according to EN ISO 898-1, the minimum ultimate tensile load $F_{m,min}$ is defined as the product of the minimum tensile strength $R_{m,min}$ and the nominal tensile stress area $A_{s,nom}$. For stainless steel bolts, the minimum ultimate tensile load F_{mf} is defined as the product of the minimum tensile strength $R_{mf,min}$ and the nominal tensile stress area $A_{s,nom}$. According to EN ISO 898-1 and EN ISO 3506-1 and to achieve conformity, all fasteners with coarse thread and fine pitch thread must fulfil the criterion of the minimum ultimate tensile load $F_{m,min}$ or F_{mf} without any reduction factor k_2 as known from the European design standards EN 1993-1-8 (for carbon steel bolts) or EN 1993-1-4 (for stainless steel bolts).

Consequently, only those carbon and stainless steel bolts that comply with the minimum ultimate tensile load $F_{m,min}$ or F_{mf} (in addition to the other fulfilled requirements according to EN 15048-1) receive a CE-marking.

3.4 Shear resistance of carbon and stainless steel bolts

3.4.1 General

In steel structures, the shear resistance of a bolt made of carbon or stainless steel is generally defined as ultimate resistance as the product of the shear coefficient α, the tensile strength R_m (= f_{ub}) of the bolt and the cross-section of the bolt, which is in the shear plane: either the unthreaded or threaded portion of the bolt for single-shear bolted connections, or either the unthreaded or threaded portion of the bolt or a combination of both for double/multi-shear bolted connections, see Figure 3.4-1. As an additive principle, the shear resistance of a carbon or stainless steel bolt is the sum of the shear resistances of all shear planes of the bolt, which are subjected to shear loading in the unthreaded or threaded part of a bolt.

In general terms, the shear coefficient α is defined as the ratio between the shear stress τ_b at the yield strength (as shear yield strength $\tau_{b,y}$) or tensile strength (as shear ultimate strength $\tau_{b,u} = \tau_{b,max}$) and the yield strength $R_{p0,2}$ (= f_{yb}) or tensile strength R_m (= f_{ub}) of a bolt according to (Eq. 3.4-1):

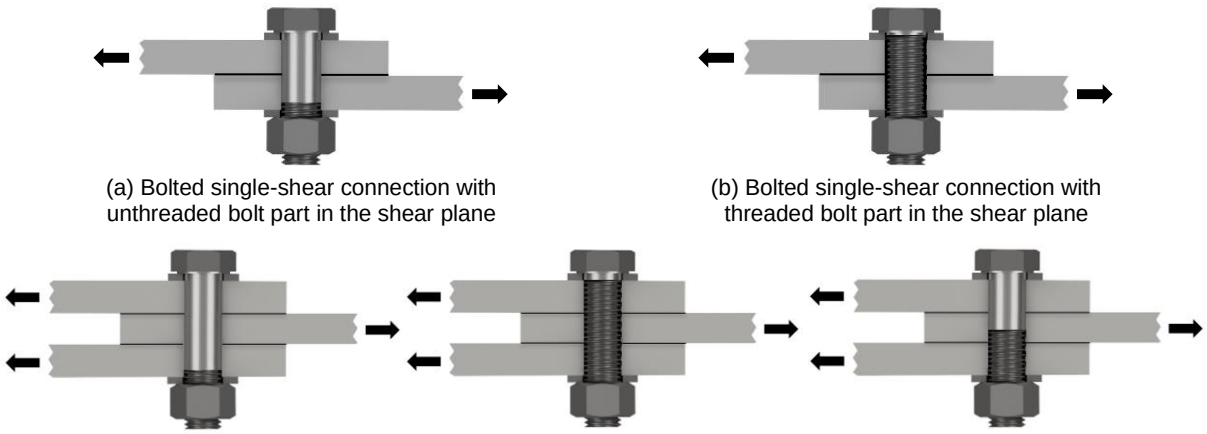
$$\alpha_y = \frac{\tau_{b,y}}{R_{p0,2}} \quad \text{or} \quad \alpha_u = \frac{\tau_{b,max}}{R_m} \qquad \text{(Eq. 3.4-1)}$$

with $\tau_{b,y}$ as the resulting shear stress at the yield strength or $\tau_{b,max}$ as maximum shear stress in the bolt depending on the cross-section in the shear plane, see (Eq. 3.4-2),

$$\tau_{b,y} = \frac{F_{v,y}}{A_{cs}} \quad \text{or} \quad \tau_{b,max} = \frac{F_{v,max}}{A_{cs}} \qquad \text{(Eq. 3.4-2)}$$

with $F_{v,y}$ as the resulting shear load at the yield strength or $F_{v,max}$ as the maximum shear load and A_{cs} either as the gross cross-sectional area A of the unthreaded portion or the tensile stress area A_s of the threaded portion of the bolt depending on the cross-section in the shear plane, and with $R_{p,0.2}$ as the yield strength or R_m as the tensile strength of the bolt according to EN ISO 898-1 for carbon steel bolts and EN ISO 3506-1 for stainless steel bolts. Additionally, the determination of the tensile strength is always based on the nominal tensile stress area A_s of the bolt, even if bolt failure occurs in the unthreaded part of a bolt, which is the predominant failure mode for austenitic stainless steel bolts.

The definition of the shear coefficient α is generally based on the ultimate resistances (α_u) as the ratio of the maximum shear stress $\tau_{b,max}$ and the tensile strength R_m (= f_{ub}) of the bolt. Usually, the shear coefficient α must be determined by testing. Therefore, an overview of the various international test procedures for determining the shear resistance is presented in Chapter 5.4 and supplemented by systematic experimental investigations on bolts made of stainless (Chapter 5) and carbon steel (Chapter 7). Nevertheless, it must be distinguished between the shear coefficients α determined by testing and those adjusted and statistically verified in a first-order reliability analysis to fit into the design concept yielding to an economical but safe and reliable design equation fulfilling the safety requirements of the design standards.



(a) Bolted single-shear connection with unthreaded bolt part in the shear plane

(b) Bolted single-shear connection with threaded bolt part in the shear plane

(c) Bolted double-shear connection with unthreaded <u>or</u> threaded bolt part in the shear planes

(d) Bolted double-shear connection with unthreaded <u>and</u> threaded bolt part in the shear planes

Figure 3.4-1: Different positions of the unthreaded and threaded part of a bolt in the shear plane(s)

3.4.2 Selected international design rules for the shear resistance of bolts

In Table 3.4-1 to Table 3.4-4, selected international design rules of the shear resistance of carbon and stainless steel bolts are summarised. The overviews of the different design rules are based on the already in Chapter 3.2 presented list of selected international design rules of bolted connections made of carbon and stainless steel. Again, the intention is to summarise the main design principles and to compare the different international design rules regarding the determination of the shear resistance per shear plane of individual partially threaded and fully threaded carbon and stainless steel bolts.

The different presented selected design rules regarding the shear resistance of carbon and stainless steel bolts can be summarised by the mechanical principle and the related cross-section to be applied to four main design rules depending on the related cross-sectional area:

- Shear resistance of an individual bolt per shear plane is based on either the gross cross-sectional area of the unthreaded part A or the tensile stress area A_s, see Table 3.4-1,

- Shear resistance of an individual bolt per shear plane is always based on the tensile stress area A_s, see Table 3.4-2,
- Shear resistance of an individual bolt per shear plane is always based on the gross cross-sectional area of the unthreaded part A, see Table 3.4-3,
- Shear resistance of an individual bolt per shear plane based on either the gross cross - sectional area of the unthreaded part A or the minor diameter A_{d3}, see Table 3.4-4.

Table 3.4-1: Summary of selected international design rules for the determination of the shear resistance of an individual bolt per shear plane of carbon (CS) and stainless steel (SS) bolted connections based on A or A_s

Standard, Code or Guideline	Steel type	Shear resistance design concept	
EN 1993-1-8:2010-12 *[72]* *Table 3.4*	CS	$F_{v,Rd} = \frac{\overbrace{\alpha \cdot f_{ub} \cdot A}^{\text{Bolt shank in the shear plane}}}{\gamma_{M2}}$ or $F_{v,Rd} = \frac{\overbrace{\alpha \cdot f_{ub} \cdot A_s}^{\text{Bolt threads in the shear plane}}}{\gamma_{M2}}$ $F_{v,Rd}$ is the design shear resistance per bolt; f_{ub} is the nominal tensile strength of a bolt; if the unthreaded part of the bolt is in the shear plane (A is the gross cross-sectional area of the bolt): α_v = 0.6; if the threaded part of the bolt is in the shear plane (A_s is the tensile stress area of the bolt): α_v = 0.6 for PC 4.6, 5.6 and 8.8; α_v = 0.5 for PC 4.8, 5.8, 6.8 and 10.9; γ_{M2} is the partially safety factor for connections according to EN 1993-1-1, γ_{M2} = 1.25. According to the DMSSS, 4th Edition, the recommended value of α (replaces α_v) for stainless steel bolts is 0.6 if the shear plane passes through the unthreaded or threaded portion of the bolt. According to EN 1993-1-4 for the shear resistance per shear plane of stainless steel bolts, the recommended values of α (replacing α_v) is 0.6 if the shear plane passes through the unthreaded portion and α = 0.5 if the shear plane passes through the threaded portion of the bolt. The DMSSS, 4th Edition states that the recommended value of α = 0.5 is "an error". Reference is given to the National Annex of EN 1993-1-4, DIN EN 1993-1-4/NA. According to VDI 2230 Part 1, the determination of the shear resistance $F_{v,Rd}$ of carbon steel bolts follows EN 1993-1-8. However, the determination of the shear resistance $F_{v,Rd}$ of stainless steel bolts is always based on the smaller tensile stress area A_s (cf. DIN EN 1993-1-4/NA). According to the VDI Guideline, S_A is the safety factor against shear failure of 1.1.	(Eq. 3.4-3)
EN 1993-1-8:2024 (draft) *[82]* *Table 5.7*	CS		
E DIN EN 1993-1-8/NA:2024-10 *[285]* ***DIN EN 1993-1-8/NA:2020-11*** *[284]* *NDP to 3.1.1(3)*	CS		
DIN 18800-1:2008-11 *[170]* *Clause 8.2.1.2 (withdrawn)*	CS		
VDI 2230-1:2015-11 *[167]* *Table 7*	CS		
DMSSS Design Manual for Structural Stainless Steel, 4th Edition *[64], [135]* *Clause 7.2.4*	SS		
EN 1993-1-4:2015-10 *[67]* *Clause 6.2*	SS		
FprEN 1993-1-4:2024 *[80]* *Clause 10.2(3) and Table 10.3*	SS		
abZ/aBG Z-30.3-6:2022-05 *[81]* *Clause 3.3.2 and Table 2*	SS		
SP 198.1325800.2014 *[321]* *Refers to EN 1993-1-4:2006-10 [323]*	SS		
AS/NZS 4673:2001 *[309]* *Clause 5.3.8.2 (Stainless steel bolts complying with ISO 3506)*	SS		
ISO 10721-1:1997-02 *[322]* *Clause A.8.8.3.2*	CS		

Table 3.4-2: Summary of selected international design rules for the determination of the shear resistance of an individual bolt per shear plane of carbon (CS) and stainless steel (SS) bolted connections always based on A_s

Standard, Code or Guideline	Steel type	Shear resistance design concept	
EN 1993-1-3:2010-12 *[279]* *Table 8.4*	CS	$F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$ $F_{v,Rd}$ is the design shear resistance per bolt; f_{ub} is the nominal tensile strength of a bolt; A_s is the tensile stress area of the bolt; α = 0.6 for PC 4.6, 5.6 and 8.8; α = 0.5 for PC 4.8, 5.8, 6.8 and 10.9 γ_{M2} is the partially safety factor for connections acc. to EN 1993-1-1, γ_{M2} = 1.25. According to DIN EN 1993-1-4/NA, the determination of the shear resistance $F_{v,Rd}$ is always based on the smaller tensile stress area A_s and with higher shear coefficients α compared to EN 1993-1-4 independent from the position of the shear planes in the unthreaded or threaded part: α = 0.75 for Austenitic PC 50; α = 0.68 for Austenitic PC 70 and 80; α = 0.50 for Duplex PC 50, 70 and 80. According to VDI 2230 Part 1, the determination of the shear resistance $F_{v,Rd}$ of stainless steel bolts is always based on the smaller tensile stress area A_s (cf. DIN EN 1993-1-4/NA). S_A is the safety factor against shear failure of 1.1.	(Eq. 3.4-4)
EN 1993-1-3:2024 (draft) *[280]* *Table 10.5*	CS		
E DIN EN 1993-1-3/NA:2024-05 *[287]* ***DIN EN 1993-1-3/NA:2017-05*** *[286]* *NDP to 8.3(13), Table 8.4*	CS		
DIN EN 1993-1-4/NA:2020-11 *[71]* *NDP to 6.2(3)*	SS		
abZ Z-30.3-6:2014-04 *[288]* *Clause 3.3.5.6*	SS		
VDI 2230-1:2015-11 *[167]* *Clause 5.5.6.3 and Table 7*	CS SS		

Table 3.4-3: Summary of selected international design rules for the determination of the shear resistance of an individual bolt per shear plane of carbon (CS) and stainless steel (SS) bolted connections always based on A

Standard, Code or Guideline	Steel type	Shear resistance design concept	
EN 13001-3-1:2019-03 *[281]* *Clause 5.2.3.1.2*	CS	$F_{v,Rd} = \frac{f_{yb} \cdot A}{\gamma_{Rb} \cdot \sqrt{3}} = \frac{f_{yb} \cdot A}{\gamma_m \cdot \gamma_{sbs} \cdot \sqrt{3}}$ $F_{v,Rd}$ is the design shear resistance per bolt; f_{yb} is the nominal yield strength of a bolt; A is the nominal gross cross-sectional area A of a bolt; γ_{sbs} is the specific resistance factor for bolted connections with γ_{sbs} = 1.0 for double or multi-shear connections and γ_{sbs} = 1.3 for single-shear connections.	(Eq. 3.4-5)
ANSI/AISC 360-22 *[293]* *Clause J3-1*	CS	Bolt threads are excluded from the shear planes $\text{LRFD}: \phi \cdot R_n = F_{nv} \cdot A_b = \underbrace{0.563 \cdot F_u}_{F_{nv}} \cdot A_b$ $\text{ASD}: \frac{R_n}{\Omega} = F_{nv} \cdot A_b = \underbrace{0.563 \cdot F_u}_{F_{nv}} \cdot A_b$ Bolt threads are not excluded from the shear planes $\text{LRFD}: \phi \cdot R_n = F_{nv} \cdot A_b = \underbrace{0.450 \cdot F_u}_{F_{nv}} \cdot A_b$ $\text{ASD}: \frac{R_n}{\Omega} = F_{nv} \cdot A_b = \underbrace{0.450 \cdot F_u}_{F_{nv}} \cdot A_b$ $\Phi \cdot R_n$ is the design tensile strength per bolt with Φ = 0.75 (LRFD); R_n / Ω is the allowable tensile strength per bolt with Ω = 2.00 (ASD);	(Eq. 3.4-6)
ANSI/AISC 370-21 *[300]* *Clause J3-1*	SS		
RCSC:2020-06, Research Council on Structural Connections *[294]* *Clause 5.1*	CS		
AISC 313-21 *[301]* *Clause 1.5*	SS		
AISC Design Guide 27, 2nd Edition "Structural Stainless Steel" *[302]* *Clause 10.3*	SS		

Table 3.4-3: Summary of selected international design rules for the determination of the shear resistance of an individual bolt per shear plane of carbon (CS) and stainless steel (SS) bolted connections always based on A (Cont.)

Standard, Code or Guideline		Steel type	Shear resistance design concept	
			F_{nv} is the nominal shear strength with $0.563 \cdot F_u$ (if bolt threads are excluded from the shear planes) or $0.450 \cdot F_u$ (if bolt threads are not excluded from the shear planes), from Table J3.2 of AISC 360 or from Table 1 of RCSC; F_u is the specified minimum tensile strength; A_b is the nominal unthreaded body area of a bolt or threaded part (equal to the gross cross-sectional area of a bolt). The RCSC specification modifies acc. to Table 5.1 the nominal shear strength F_{nv} to higher values of F_{nv} with $0.75 \cdot F_u$ (if bolt threads are excluded from the shear planes) or $0.60 \cdot F_u$ (if bolt threads are not excluded from the shear planes) for high-strength bolts of group 120, 144 and 150 (refers to ASTM F3125 [296] or ASTM F3148 [324] bolts with minimum ultimate tensile strengths of 120, 144 or 150 ksi). According to ANSI/AISC 370-21, stainless steel bolts and nuts shall be in accordance with one of the ASTM standards listened in Clause A3.3: ASTM A193/A193M [325] for high-temperature service, ASTM A320/A320M [326] for low-temperature service, ASTM A453/A453M [327], ASTM A1082/A1082M [328] (for austenitic, ferritic, martensitic and duplex bolts), ASTM F593 [329] (here as main standard of stainless steel bolts, hex cap screws and stainless steel studs). The dimension of bolting assembly shall be in accordance with ASME B18.2.1 (bolts) [330], ASME B18.2.2 (nuts) [331] and ASME B18.21.1 (washers) [332]. The AISC Design Guide 27 refers to AISC 370 for stainless steel bolts, but specifies the bolt types as ASTM F593 [333], ASTM A320 [326] and ASTM A193 [325] for austenitic stainless steel bolts, and ASTM A1082 [334] for duplex and precipitation hardening stainless steel bolts. Additionally, the shear resistances are tabulated in Table 10-3 depending on the manufacturing condition (e.g. machined or headed and rolled). The double-shear resistance of a bolt is defined as twice of the single-shear resistance.	

Table 3.4-3: Summary of selected international design rules for the determination of the shear resistance of an individual bolt per shear plane of carbon (CS) and stainless steel (SS) bolted connections always based on A (Cont.)

Standard, Code or Guideline	Steel type	Shear resistance design concept	
SEI/ASCE 8-02 *[297] (withdrawn)* *Clause 5.3.4-1*	SS	$\overbrace{\text{LRFD}: \phi \cdot R_n = F_{nv} \cdot A_b = \underbrace{0.60 \cdot F_u}_{F_{nv}} \cdot A_b}^{\text{Bolt threads are excluded from the shear planes}}$ $\overbrace{\text{LRFD}: \phi \cdot R_n = F_{nv} \cdot A_b = \underbrace{0.45 \cdot F_u}_{F_{nv}} \cdot A_b}^{\text{Bolt threads are not excluded from the shear planes}}$ The SEI/ASCE 8-22 specification modifies acc. to Table 6 the LRFD nominal shear strength F_{nv} to values of F_{nv} with $0.60 \cdot F_u$ (if bolt threads are excluded from the shear planes) or $0.45 \cdot F_u$ (if bolt threads are not excluded from the shear planes), but with $\Phi = 0.65$ as resistance factor leading to very conservative resistances; R_n is replaced by P_n. According to AS/NZS 4673, Clause 5.3.7.2 and Table 5.3.7, LRFD nominal shear strength F_{nv} is modified to values of F_{nv} with $0.80 \cdot F_u$ (if bolt threads are excluded from the shear planes) or $0.60 \cdot F_u$ (if bolt threads are not excluded from the shear planes), but with $\Phi = 0.65$ as resistance factor; R_n is replaced by V_{fv}. CSA S16:19 and SANS 10162-1:2011 state that $F_{nv} = 0.60 \cdot F_u$ (if bolt threads are excluded from the shear planes) or $0.70 \cdot 0.60 \cdot F_u$ (if bolt threads are not excluded from the shear planes), but with $\Phi = 0.80$ as resistance factor; the shear resistance is abbreviated as "factored shear resistance" V_r. For SANS 10162, the specified minimum tensile strength for bolts is given in the SANS 1700 series corresponding to EN ISO 898-1, in particular SANS 1700-1-1 [335] (Part 1: terminology/nomenclature) and SANS 1700-5-1 [336] (Part 5 is dealing with the mechanical properties). According to SP 16.13330.2017, F_{nv} is replaced by $\gamma_c \cdot \gamma_b \cdot R_{bs} = \alpha \cdot f_{ub}$ and includes different (design) shear coefficients α depending on the PC of the carbon steel bolt defined in Table 5 of SP 16.13330.2017 as $\alpha = 0.42$ for $f_{yb} \leq 300$ N/mm², $\alpha = 0.41$ for $300 < f_{yb} \leq 400$ N/mm², $\alpha = 0.40$ for $400 < f_{yb} \leq 936$ N/mm², $\alpha = 0.35$ for $f_{yb} > 936$ N/mm². γ_b is a service factor of the bolt joint and 1.0 for single bolting (with accuracy class A) and 0.9 for multibolting (and accuracy class B) and high strength bolts with nominal tensile strength $f_{ub} \geq 800$ N/mm². The safety factor γ_c is defined in Table 1 of SP 16.13330.2017 as $\gamma_c = 1.0$ for connections.	(Eq. 3.4-7)
SEI/ASCE 8-22 *[298]* *Clause 10*	SS		
AS/NZS 4673:2001 *[309]* *Clause 5.3.7.2 (Stainless steel bolts complying with ASTM standards)*	SS		
CSA S16:19 *[295]* *Clause 13.12.1.2*	CS		
SANS 10162-1:2011 *[313]* *Clause 13.12.1.2*	CS		
SP 16.13330.2017 *[320]* *Clause 14.2.9*	CS		

Table 3.4-4: Summary of selected international design rules for the determination of the shear resistance of an individual bolt per shear plane of carbon (CS) and stainless steel (SS) bolted connections based on A or A_{d3}

Standard, Code or Guideline		Steel type	Shear resistance design concept	
	AS 4100:2020 *[304]* *Clause 9.2.2.1*	CS	$\text{LRFD}: \phi \cdot V_f = 0.62 \cdot f_{uf} \cdot k_{rd} \cdot k_r \cdot (n_n \cdot A_c + n_x \cdot A_o)$ $\Phi \cdot V_f$ is the design shear capacity per bolt with $\Phi = 0.80$ (LRFD); f_{uf} is the minimum tensile strength of the bolt; k_{rd} is the reduction factor to account the reduced ductility of PC 10.9 bolts of $k_{rd} = 0.83$ when subjected to shear with bolt threads in the shear plane, otherwise $k_{rd} = 1.0$; k_r is the reduction factor to account for the length of a bolted lap connection; otherwise $k_r = 1.0$; n_n is the number of shear planes with threads intercepting the shear plane; A_c is the minor diameter area of the bolt (equal to A_{d3}) defined in AS 1275; n_x is the number of shear planes without threads intercepting the shear plane; A_o is the nominal plain shank area of the bolt (equal to A).	(Eq. 3.4-8)
	IS 800:2007 *[311]* *Clause 10.3.3*		IS 800:2007 defines the shear coefficient by $1/\sqrt{3}$ as a constant value for all bolt property classes defined in IS 1367-3 [337] (corresponding to SO 898-1) for high-strength bolt property classes. IS 3757 [338] covers the requirements for high-strength structural bolts in PC 8.8/10.9 for the use in bearing-type structural steel joints and excludes PC 12.9. In the design, A_c is replaced by A_{nb}, while A_o is replaced by A_{sb}. Furthermore, the reduction factor for lapped joints is defined by b_{lj} and slightly different from the approach of AS 4100.	

The main four design concepts for the shear resistance for individual carbon or stainless steel bolts per shear plane in normal round holes acc. to EN 1090-2 are described in the following:

- **Approach 1:** Then shear resistance of an individual bolt per shear plane is defined as the product of a shear coefficient α, nominal tensile strength $f_{ub,nom}$ and either the nominal gross cross-sectional area of the unthreaded part A_{nom}, see (Eq. 3.4-9) or the nominal tensile stress area $A_{s,nom}$ of a bolt, see (Eq. 3.4-10) depending on the position of the shear plane in the unthreaded or threaded part of a bolt according to EN 1993-1-8, EN 1993-1-8:2024, DIN EN 1993-1-8/NA, E DIN EN 1993-1-8/NA, the withdrawn German DIN 18800-1 (Approach 1a), the Design Manual for Structural Stainless Steel (4th Ed), EN 1993-1-4, FprEN 1993-1-4, ISO 10721-1 and the German VDI Guideline 2230 Part 1 (for carbon steel bolts; Approach 1b with safety factor S_A). The different shear resistances of the unthreaded and threaded part of a bolt are adjusted by various shear coefficients α,

$$F_{v,Rd} = \frac{\alpha \cdot f_{ub,nom} \cdot A_{nom}}{\gamma_{M2}}$$

with $\gamma_{M2} = 1.25$ per shear plane (Approach 1a),

with $\gamma_{M2} = S_A = 1.10$ per shear plane (Approach 1b), (Eq. 3.4-9)

$$F_{v,Rd} = \frac{\alpha \cdot f_{ub,nom} \cdot A_{s,nom}}{\gamma_{M2}}$$

with $\gamma_{M2} = 1.25$ per shear plane (Approach 1a),

with $\gamma_{M2} = S_A = 1.10$ per shear plane (Approach 1b). (Eq. 3.4-10)

- **Approach 2:** Shear resistance of an individual bolt per shear plane defined as the product of a shear coefficient α, nominal tensile strength $f_{ub,nom}$ and always the nominal tensile stress area $A_{s,nom}$ independent from the position of the shear plane in the unthreaded or threaded part of a bolt, see (Eq. 3.4-11) according to EN 1993-1-3, EN 1993-1-3:2024, DIN EN 1993-1-3/NA and E DIN EN 1993-1-3/NA, DIN EN 1993-1-4/NA (Approach 2a) and the German VDI Guideline 2230 Part 1 (for stainless steel bolts; Approach 2b),

$$F_{v,Rd} = \frac{\alpha \cdot f_{ub,nom} \cdot A_{s,nom}}{\gamma_{M2}} \quad \begin{array}{l} \text{with } \gamma_{M2} = 1.25 \text{ per shear plane (Approach 2a),} \\ \text{with } \gamma_{M2} = S_A = 1.10 \text{ per shear plane (Approach 2b).} \end{array} \qquad \text{(Eq. 3.4-11)}$$

- **Approach 3:** Shear resistance of an individual bolt per shear plane defined as the product of a shear coefficient α, nominal tensile strength $f_{ub,nom}$ (= F_u) and always the nominal gross cross-sectional area of the unthreaded part A_{nom} (= A_b) independent from the position of the shear plane in the unthreaded or threaded part of a bolt, see (Eq. 3.4-12), according to ANSI/AISC 360, ANSI/AISC 370, RCSC, AISC 313, the AISC Design Guide 27, 2nd Edition (LRFD Approach 3a / ASD 3b), SEI/ASCE 8, AS/NZS 4673 (Approach 3c), CSA S16 and SANS 10162-1 (Approach 3d). As a speciality, the Russian Standard SP 16.13330 has included the safety factor directly in the provided shear coefficients. However, a reconstruction is not possible and therefore, the Russian approach is not considered in the following. The different shear resistances of the unthreaded and threaded part of a bolt are again adjusted by different shear coefficients α,

$$\begin{array}{ll} \text{LRFD}: \phi \cdot R_n = F_{nv} \cdot A_b = \underset{F_{nv}}{\alpha \cdot F_u} \cdot A_b & \text{with } \Phi = 0.75 \text{ (LRFD; Approach 3a),} \\ & \text{with } \Omega = 2.00 \text{ (ASD; Approach 3b),} \\ \text{ASD}: \dfrac{R_n}{\Omega} = F_{nv} \cdot A_b = \underset{F_{nv}}{\alpha \cdot F_u} \cdot A_b & \text{with } \Phi = 0.65 \text{ (LRFD; Approach 3c),} \\ & \text{with } \Phi = 0.80 \text{ (LRFD; Approach 3d)} \end{array} \qquad \text{(Eq. 3.4-12)}$$

- **Approach 4:** Shear resistance of an individual bolt including all shear planes subjected to shear loading defined as the product of a constant shear coefficient α for both the unthreaded and threaded part of a bolt, nominal tensile strength $f_{ub,nom}$ (= f_{uf}) and a "virtual bolt cross-sectional area" considering the number of shear planes with threaded part in the shear plane multiplied by the minor diameter area $A_{c,nom}$ of the bolt (equal to $A_{d3,nom}$) defined in AS 1275 ($n_n \cdot A_c$) as well as the number of shear planes without threads intercepting the shear plane multiplied by the nominal plain shank area ($n_x \cdot A_o$) of the bolt according to AS 4100:2020. The Indian Standard IS 800:2007 follows this design approach with minor modifications. In contrast to Approach 1 and 3, the different shear resistances of the unthreaded and threaded part of a bolt are realised by a constant shear coefficient α but considering different cross-sectional areas, see (Eq. 3.4-13),

$$\text{LRFD}: \phi \cdot V_f = \alpha \cdot f_{uf} \cdot k_{rd} \cdot k_r \cdot (n_n \cdot A_c + n_x \cdot A_o) \quad \text{with } \Phi = 0.80 \text{ (LRFD).} \qquad \text{(Eq. 3.4-13)}$$

It must be mentioned that the above-presented design rules and summarised main approaches are only valid for individual bolts in normal round holes and joints with homogenous load distribution.

For further specification of the design of bolted shear connections, there are new regulations in EN 1993-1-8:2024, Clause 5.9.1(8), for carbon steel bolts concerning the cross-section to be applied in the transition region of the bolt as the region between the unthreaded gross cross-section A and the tensile stress area of the bolt (A_s). These new regulations for the European design of structural carbon steel bolts' shear resistance are based on various studies from Friede, Lange and Lange et al. [233, 234]. Corresponding references to the transition

area also exist in the North American standardisation, e.g. in ANSI/AISC 360, RCSC and further literature [261, 339].

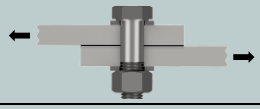
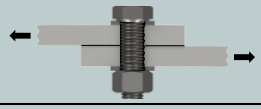
Furthermore, in order to consider inhomogeneous load distribution, additional specifications exist for long joints as bolted lap connections, for example, in EN 1993-1-8, Clause 3.8 for carbon steel bolts. The reduction of the shear resistance of a bolt is also considered in other standards, e.g. in the Australian Standard AS 4100 by the reduction factor k_r. Nevertheless, long joints such as bolted lap connections made of carbon or stainless steel are not considered in the following investigations.

3.4.3 Comparison of the shear coefficients α in standardisation and those obtained from the literature

In addition to the different design rules for determining the shear resistance of carbon steel and stainless steel bolts, different, inconsistent shear coefficients α exist in international standardisation. Therefore, a comprehensive overview of the shear coefficients from different international standards, codes and guidelines for carbon steel bolts is presented in Table 3.4-5. To ensure a direct comparison of the shear coefficients α from standardisation, additionally, if required, all provided shear coefficients are converted to Approach 1 of EN 1993-1-8 and EN 1993-1-4, which distinguishes between the unthreaded (based on A_{nom}) or threaded part (based on $A_{s,nom}$) of the bolt in the shear plane. It is evident that the German VDI Guideline 2230 Part 1 (following Approach 1), which has its origin in mechanical engineering and is well-known worldwide for the design of bolted connections in various applications, shows the highest shear coefficients for PC 4.6, 5.6, 8.8, 10.9 and 12.9. However, the application of PC 12.9 is generally not permitted in the construction industry in Germany due to the reduced ductility and risk of sudden failure as well as bolts in PC 4.8, 5.8 and 6.8 according to the current German National Annex of EN 1993-1-8, DIN EN 1993-1-8/NA. The provided shear coefficients (as τ_B/R_m ratio) of VDI Guideline 2230 Part 1 are equal for the unthreaded (based on A_{nom}) or threaded part (based on $A_{s,nom}$) of the bolt in the shear plane. This fact is remarkable because, in international standardisation, the reduced shear resistance of the threaded part is typically expressed in a reduced shear coefficient α, see Table 3.4-5.

In all international design regulations presented in Table 3.4-5, the shear coefficients α do not distinguish between single-shear and double/multi-shear carbon steel bolted connections, except from EN 13001-3-1, which deals with the general design of cranes and their limit states and structural integrity in steel structure. According to EN 13001-3-1, always the unthreaded part of a bolt must be positioned in the shear plane; the threaded part in the shear plane is not permitted. Furthermore, the yield strength f_{yb} is considered in the design instead of the ultimate (tensile) strength f_{ub} of a bolt. For the European design of cranes, it can be concluded that a single-shear bolted connection is defined by a lower shear coefficient $\alpha = 0.444$ compared to a double-/multi-shear bolted connection with a shear coefficient of $\alpha = 0.577$ (which is based on the shape modification hypothesis by von Mises of $\alpha_{fy} = 1/\sqrt{3}$). Finally, this means that normatively single-shear bolted connections are identified in EN 13001-3-1 as more critical connections for the design of crane structures with a reduced resulting shear resistance of these bolts.

Table 3.4-5: Overview of the converted shear coefficients α from different international standards, codes and guidelines for carbon steel bolts

Standard, Code or Guideline	Approaches and the related cross-sectional area	Shear plane in the unthreaded part of a bolt							Shear plane in the threaded part of a bolt						
															
		Property class							Property class						
		4.6	4.8	5.6	5.8	8.8	10.9	12.9	4.6	4.8	5.6	5.8	8.8	10.9	12.9
EN 1993-1-8:2010-12 *[72]* *Table 3.4*	Approach 1 (A_{nom} or $A_{s,nom}$)	0.60	0.60	0.60	0.60	0.60	0.60	-	0.60	0.50	0.60	0.50	0.60	0.50	-
EN 1993-1-8:2024 (draft) *[82]* *Table 5.9*	Approach 1 (A_{nom} or $A_{s,nom}$)	0.60	0.60	0.60	0.60	0.60	0.60	-	0.60	0.50	0.60	0.50	0.60	0.50	-
E DIN EN 1993-1-8/NA:2024 *[285]* ***DIN EN 1993-1-8/NA:2020-11*** *[284]*	Approach 1 (A_{nom} or $A_{s,nom}$)	0.60	-[1]	0.60	-[1]	0.60	0.60	-	0.60	-[1]	0.60	-[1]	0.60	0.50	-
DIN 18800-1:2008-11 *[170]* *Clause 8.2.1.2 (withdrawn)*	Approach 1 (A_{nom} or $A_{s,nom}$)	0.60	-	0.60	-	0.60	0.55	-	0.60	-	0.60	-	0.60	0.44	-
VDI 2230-1:2015-11 *[167]* *Clause 5.5.6.3 and Table 7*	Approach 1 (A_{nom} or $A_{s,nom}$)	0.70	-	0.70	-	0.65	0.62	0.60	0.70	-	0.70	-	0.65	0.62	0.60
ISO 10721-1:1997-02 *[322]* *Clause A.8.8.3.2*	Approach 1 (A_{nom} or $A_{s,nom}$)	-	-	-	-	0.60	0.60	-	-	-	-	-	0.50	0.50	-
EN 1993-1-3:2010-12 *[279]* *Clause 8.3 and Table 8.4*	Approach 2 (always $A_{s,nom}$)	0.47[2]	0.39[2]	0.47[2]	0.39[2]	0.47[2]	0.39[2]	-	0.60	0.50	0.60	0.50	0.60	0.50	-
EN 1993-1-3:2024 (draft) *[280]* *Table 10.5*	Approach 2 (always $A_{s,nom}$)	0.47[2]	0.39[2]	0.47[2]	0.39[2]	0.47[2]	0.39[2]	-	0.60	0.50	0.60	0.50	0.60	0.50	-
E DIN EN 1993-1-3/NA:2024 *[287]* ***DIN EN 1993-1-3/NA:2017-05*** *[286]* *NDP to 8.3(13), Table 8.4*	Approach 2 (always $A_{s,nom}$)	0.47[2]	0.39[2]	0.47[2]	0.39[2]	0.47[2]	0.39[2]	-	0.60	0.50	0.60	0.50	0.60	0.50	-
EN 13001-3-1:2019-03 *[281]* *Clause 5.2.3.1.2*	Approach 3 (always A_{nom})	1/√3/1.3 ≈ 0.444 (single-shear connection) 1/√3 ≈ 0.577 (double/multi-shear connection)							Threads in the shear plane are not permitted						
ANSI/AISC 360-16 *[293]* *Clause J3-1*	Approach 3 (always A_{nom})	0.563[3)4)]							0.577[3)4)5)]						
RCSC:2020-06 *[294]* *Clause 5.1*	Approach 3 (always A_{nom})	0.563[3)5)6)]						-	0.577[3)5)6)]						-
CSA S16:19 *[295]* *Clause 13.12.1.2*	Approach 3 (always A_{nom})	0.60[7)]						-	0.538[7)8)]						-
SANS 10162-1:2011 *[313]* *Clause 13.12.1.2*	Approach 3 (always A_{nom})	0.60						-	0.538[8)]						-
SP 16.13330.2017 *[320]* *Clause 14.2.9*	Approach 3 (always A_{nom})	0.42[8)]	0.41[8)]			0.40[8)]		0.35[8)]	0.42[8)]	0.41[8)]			0.40[8)]		0.35[8)]
AS 4100:2020 *[304]* *Clause 9.2.2.1*	A4 (A_{nom} or A_{d3})[9)]	0.62	-	-	-	0.62		-	0.57[9)]	-	-	-	0.57[9)]	0.47[9)]	-
IS 800:2007 *[311]* *Clause 10.3.3*	A4 (A_{nom} or A_{d3})[9)]	1/√3 ≈ 0.577						-	1/√3 ≈ 0.577						-
Minimum shear coefficient		0.42	0.39	0.41	0.39	0.40	0.39	0.35	0.42	0.41			0.40		0.35
Maximum shear coefficient		0.70	0.60	0.70	0.60	0.65	0.62	0.60	0.70	0.58	0.70	0.58	0.65	0.62	0.60

[1)] According to E DIN EN 1993-1-8/NA:2024-10, bolts in PC 4.8, 5.8 and 6.8 are not permitted in steel construction. | [2)] The shear coefficients were converted by $\alpha_{comp,EC3-1-8} = \alpha_{EC3-1-3} \cdot A_{s,nom}/A_{nom}$. | [3)] For Approach 3, the shear resistance of a bolt is always based on the gross cross-sectional area A_{nom} even when threads and transition area are not excluded from the shear plane. | [4)] Shear coefficient valid for bolts and threaded parts as A307 bolts, Group A (e.g. A325) bolts, Group B (e.g. A490) bolts [340] and Group C (e.g. F3043) bolts [341], which are deviating from the defined property classes in EN ISO 898-1. ANSI/AISC 360 states that only Group A and B bolts are allowed in snug-tightened connections. According to the Commentary of J3 in ANSI/AISC 360, Group C fastener assemblies have been added in this specification, as they were used in building structures in Japan [293]. The design rules of the tension and shear resistance are also valid for these high-strength bolts comparable to PC 14.9. | [5)] For direct comparability to EN 1993-1-8, the shear coefficients are converted by $\alpha_{comp,EC3-1-8} = \alpha_{AISC} / (A_{s,nom}/A_{nom})$. | [6)] Shear coefficients valid for bolts and threaded parts as Group 120 (ASTM F3125, A325) and Group 150 (ASTM F3125, A490) bolts. Group 150 is nearly comparable with PC 10.9 (Group 150: minimum tensile strength of 150 ksi ≈ 1034 N/mm²), therefore PC 12.9 is excluded in the design of the shear resistance of a bolt. | [7)] Bolts and bolt assemblies shall meet the requirements of ASTM A307 [342], ASTM A325/A325M, ASTM A490/A490M, ASTM F1852 or F2280 (replaced by ASTM F3125). | [8)] The shear coefficients are converted by $\alpha_{comp,EC3-1-8} = \alpha_{CSA} / (A_{s,nom}/A_{nom})$. | [8)] According to SP 16.13330.2017, no difference is made in design between unthreaded or threaded bolt part in the shear plane. For multibolting, accurance class B and high-strength bolts with $f_{ub} \geq 800$ N/mm² acc. to SP 16, the shear resistance is multiplied with a reduction factor of 0.9. | [9)] The shear coefficients for threaded part in the shear plane are converted by $\alpha_{comp,EC3-1-8} = \alpha_{AS4100} \cdot (A_{d3}/A_{s,nom})$.

As already stated, the determination of the shear resistance of a bolt per shear plane according to ANSI/AISC 360 and RCSC are always based on the nominal gross cross-sectional area A

of a bolt. According to both standards, the shear coefficient of an individual bolt per shear plane is taken as 0.625 times the nominal tensile strength, which is based on experimental studies from Kulak et al. [343], Fischer et al. [344, 345], Tide [346], Swanson et al. [347–349] and Frank [350]. In order to account for an increase in the shear load due to minor secondary effects which are resulting from simplification (e.g. equal load distributions in all bolts of a shear connection or imperfections), a reduction factor of 0.90 is applied for bolted connections up to 38 in. (≈ 950 mm) in length. For larger lapped joints > 38 in., the reduction faction is modified to 0.75 to consider non-uniform load distribution and secondary effects. Therefore, for bolted connections up to 38 in. in length, the shear coefficient for the unthreaded part in the shear plane according to ANSI/AISC 360 and RCSC is provided in (Eq. 3.4-14), while (Eq. 3.4-15) shows the shear coefficient for the threaded part in the shear plane including the reduction factor of 0.8, which is nearly the ratio of $A_{s,nom}/A_{nom} \approx 0.78$ known from the European regulations.

$$\alpha = 0.625 \cdot 0.9 = 0.563 \text{ for the unthreaded part in the shear plane,} \quad \text{(Eq. 3.4-14)}$$

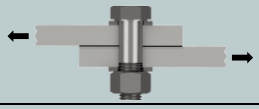
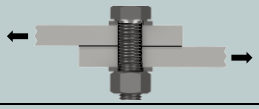
$$\alpha = 0.625 \cdot 0.9 \cdot 0.8 = 0.450 \text{ for the threaded part in the shear plane.} \quad \text{(Eq. 3.4-15)}$$

In addition, an overview of the shear coefficients α for austenitic and duplex stainless steel bolts is provided in Table 3.4-6. Martensitic, ferritic and precipitation hardening alloy stainless steel bolts are excluded from this overview. Herein, to enable a comparison of the shear coefficients α from different standards, all provided shear coefficients are again converted to Approach 1 of EN 1993-1-8 and EN 1993-1-4, which distinguishes between the unthreaded or threaded bolt part of the bolt in the shear plane.

It can be shown in Table 3.4-6 that the majority of the listed and converted shear coefficients are in the range of $0.50 \leq \alpha \leq 0.60$. The highest shear coefficients α up to $\alpha = 0.80$ for austenitic bolts in PC 50 and duplex bolts in PC 70 are provided by FprEN 1993-1-4, and the German national technical approval/General construction technique permit abZ/aBG Z-30.3-6 regulation from 2022. Both are based on systematic experimental investigations and reliability analyses in the framework of [78]. Analogues to carbon steel bolts, the VDI 2230 Part 1 Guideline provides high shear coefficients but is limited to the threaded bolt part in the shear plane due to the Approach 2, which is always based on the tensile stress area A_s and leading to smaller (converted) shear coefficients α for the unthreaded part of a bolt.

Generally, in the European and German design standards and design recommendations, the shear coefficients α for determining the shear resistance of a bolt per shear plane are provided for each bolt property class defined in EN ISO 3506-1. On the contrary, in North American standardisation, shear coefficients for the unthreaded or threaded part of a bolt in the shear plane are given in the design standards (e.g. ANSI/AISC 370) without a clear assignment to the bolt property classes. Instead, reference is made to ASTM bolt standards for stainless steel bolts, e.g. ASTM F593 “Standard Specification for Stainless Steel Bolts, Hex Cap Screws, and Studs”. Within these standards, different bolt property classes or groups, as well as steel grades (austenitic, ferritic, martensitic and precipitation hardening) and further specifications can be found depending on the standard and the intended structural application of these bolts (e.g. low or high-temperature applications according to ASTM A320 or ASTM A193).

Table 3.4-6: Overview of the converted shear coefficients α from different international standards, codes and guidelines for stainless steel bolts

Standard, Code or Guideline Approaches and the related cross-sectional area		Shear plane in the unthreaded part of a bolt 					Shear plane in the threaded part of a bolt 				
		Property class for austenitic (A) and duplex (D) bolts					Property class for austenitic (A) and duplex (D) bolts				
		50	70	80	100	120[1]	50	70	80	100	120[1]
EN 1993-1-4:2015-10 *[67]* *Clause 6.2*	Approach 1 (A_{nom} or $A_{s,nom}$)	A 0.60 D 0.60	A 0.60 D 0.60	A 0.60 D 0.60	-	-	A 0.50 D 0.50	A 0.50 D 0.50	A 0.50 D 0.50	-	-
FprEN 1993-1-4:2024 *[80]* *Clause 10.2(3) and Table 10.3*	Approach 1 (A_{nom} or $A_{s,nom}$)	A 0.80 D -[2]	A 0.70 D 0.80	A 0.70 D 0.70	A 0.60 D 0.60	-	A 0.80 D -[2]	A 0.70 D 0.80	A 0.70 D 0.70	A 0.60 D 0.60	-
abZ/aBG Z-30.3-6:2022-05 *[81]* *Clause 3.3.2 and Table 2*	Approach 1 (A_{nom} or $A_{s,nom}$)	A 0.8 D -[2]	A 0.70 D 0.80	A 0.70 D 0.70	A 0.60 D 0.60	-	A 0.80 D -[2]	A 0.70 D 0.80	A 0.70 D 0.70	A 0.60 D 0.60	-
Design Manual for Structural Stainless Steel, 4th Edition *[64]* *Clause 7.2.4*	Approach 1 (A_{nom} or $A_{s,nom}$)	A 0.60 D 0.60	A 0.60 D 0.60	A 0.60 D 0.60	-	-	A 0.60 D 0.60	A 0.60 D 0.60	A 0.60 D 0.60	-	-
SP 198.1325800.2014 *[321, 323]* *Refers to EN 1993-1-4:2006-10 [323]*	Approach 1 (A_{nom} or $A_{s,nom}$)	A 0.60 D 0.60	A 0.60 D 0.60	A 0.60 D 0.60	-	-	A 0.50 D 0.50	A 0.50 D 0.50	A 0.50 D 0.50	-	-
DIN EN 1993-1-4/NA:2020-11 *[71]* *NDP to 6.2(3)*	Approach 2[3] (always $A_{s,nom}$)	A 0.59 D 0.39	A 0.53 D 0.39	A 0.53 D 0.39	-	-	A 0.75 D 0.50	A 0.68 D 0.50	A 0.68 D 0.50	-	-
VDI 2230-1:2015-11 *[167]* *Table 7*	Approach 2[3] (always $A_{s,nom}$)	A 0.62 D 0.62	A 0.56 D 0.56	A 0.53 D 0.53	-	-	A 0.80 D 0.80	A 0.72 D 0.72	A 0.68 D 0.68	-	-
ANSI/AISC 370-21 *[300]* *Clause J3-1*	Approach 3[4] (always A_{nom})	A 0.55[5) 6)] D 0.55[5) 6)]			-	-	A 0.58[4)6)] D 0.58[4)6)]			-	-
AISC 313-21 *[301]* *Clause 1.5 refers to ANSI/AISC 370, Clause J3-1*	Approach 3[4] (always A_{nom})										
AISC Design Guide 27 *[302], 2nd Edition, Clause 10.3*	Approach 3[4] (always A_{nom})										
SEI/ASCE 8-02 *[297]* *Clause 5.3.4-1*	Approach 3[4] (always A_{nom})	A 0.60			-	-	A 0.58[8)]			-	-
prSEI/ASCE 8-22 *(draft) [298]* *Chapter 10*	Approach 3[4] (always A_{nom})	A 0.60 D 0.60[7)]			-	-	A 0.58[8)] D 0.58[7)8)]				
AS/NZS 4673:2001 *[309]* *Clause 5.3.7.2 (Stainless steel bolts complying with ASTM standards)*	Approach 3[4] (always A_{nom})	A 0.60			-	-	A 0.58[9)]			-	-
Minimum shear coefficient		A 0.55 D 0.39	A 0.53 D 0.39	A 0.53 D 0.39	A 0.60 D 0.60	-	A 0.50 D 0.50	A 0.50 D 0.50	A 0.50 D 0.50	A 0.60 D 0.60	-
Maximum shear coefficient		A 0.80 D 0.62	A 0.70 D 0.80	A 0.70 D 0.70	A 0.60 D 0.60	-	A 0.80 D 0.80	A 0.70 D 0.80	A 0.70 D 0.70	A 0.60 D 0.60	-

[1] PC 120 is not covered by EN ISO 3506-1/2. Nevertheless, stainless steel bolting assemblies in PC 120 and even PC 140 (comparable to PC 12.9 and PC 14.9 for carbon steel bolts) are already available on the market. | [2] Remark: According to EN ISO 3506-1, duplex stainless steel bolts in PC 50 does not exist. | [3] For comparability, the shear coefficients are converted by $\alpha_{comp,EC3\text{-}1\text{-}8} = \alpha_{NA/VDI} \cdot (A_{s,nom}/A_{nom})$. | [4] The shear coefficients for threaded part of a bolt in the shear plane are again converted by $\alpha_{comp,EC3\text{-}1\text{-}8} = \alpha_{AISC} / (A_{s,nom}/A_{nom})$. | [5] Stainless steel bolts and nuts shall be in accordance with ASTM A193/A193M, A320/A320M, A453/A453M, A1082/1082M or F593 according to AISC 370-21, Clause A3.3. The highest tensile strength is given by 160 ksi (≈ 1103 N/mm²) and the highest yield strength is provided by 95 ksi (≈ 695 N/mm²), therefore no shear coefficients of PC 100 and PC 120 are given. | [6] According to AISC Design Guide 17, 2nd Edition, Table 10.2, austenitic bolts covered for the design of the shear resistance are ASTM F593 (Group 1-3), ASTM A320 and A193 (Class 1/1A and Class 2) and duplex bolts covered by ASTM A1082 (alloy 2205). The maximum nominal tensile strength of these bolts is 125 ksi (≈ 1103 N/mm²) and maximum yield strength of 100 ksi (≈ 689 N/mm²), therefore limited shear coefficients to PC 8.8. | [7] According to SEI/ASCE 8-02, only austenitic and ferritic steel grades are given. Based on [299], it is expected that in the revision of SEI/ASCE 8 [298] also covers duplex stainless steel bolts. | [8] The shear coefficients are converted by $\alpha_{comp,EC3\text{-}1\text{-}8} = \alpha_{ASCE8} / (A_{s,nom}/A_{nom})$. | According to AS/NZS 4637:2001 (withdrawn), duplex stainless steel bolts are not covered. The shear coefficient for the threaded part of a bolt in the shear plane is converted by $\alpha_{comp,EC3\text{-}1\text{-}8} = \alpha_{AS/NZS} / (A_{s,nom}/A_{nom})$.

In the past, the shear coefficients α for stainless steel bolts according to EN 1993-1-4 were transferred from EN 1993-1-8 for carbon steel bolts and only checked with a few tests on austenitic stainless steel bolts, see [136, 137, 184, 270, 271, 276, 289]. At this stage, the specific material behaviour of austenitic stainless steel bolts, like nonlinearity and pronounced

failure in the unthreaded bolt part, was not considered in the design process at all. To close this normative gap, the current regulations of the German National Annex of EN 1993-1-4, DIN EN 1993-1-4/NA, were transferred from the former German technical approval abZ Z-30.3-6 from 2014 [288]. However, these national regulations are only based on a limited number of tests on cold-formed bolts made of austenitic stainless steels, see [289]. As investigations into shear coefficients for duplex bolts were not available at this time, they were conservatively estimated for abZ Z-30.3-6:2014 and EN 1993-1-4.

In contrast to EN 1993-1-4, FprEN 1993-1-4 and the new abZ/aBG Z-30.3-6 regulation from 2022 (Approach 1), the different material and load bearing behaviour of stainless steel bolts were considered in the design by determining the shear resistance of austenitic stainless steel bolts always with the smaller tensile stress area A_s ($A_{s,nom}/A_{nom} \approx 0.78$) regardless of whether the unthreaded or threaded portion of the bolt is in the shear plane (Approach 2). However, higher shear coefficients are applied to compensate the resulting reduction of shear resistance. These regulations are based on studies from Dünkel into the load bearing behaviour of bolted connections under pure shear loading [276, 184]. Dünkel points out that the strength of austenitic stainless steel bolts is adjusted in such a way that they fail after exceeding the minimum ultimate tensile load in the weakest bolt part, which can be either in the unthreaded or threaded part due to the locally different and pronounced transformation of austenitic to forming induced martensitic material with a larger hardness and higher strength in the border of the cross-section of the threads.

Since the tensile and yield strength of stainless steel bolts are determined according to EN ISO 3605-1 in a tensile test on the whole bolt, only the strengths in the failing part of the bolt are known – either in the unthreaded ($f_{ub,shank}$) or in the threaded ($f_{ub,threads}$) part of the bolt. No statement can be made for the other non-failed bolt part resulting in $f_{yb,threads} \neq f_{yb,shank}$ and $f_{ub,threads} \neq f_{ub,shank}$. For this reason, an unified design for the unthreaded and threaded part of a bolt is not possible according to Dünkel [184], and always the smaller tensile stress area A_s should be used for the determination of the shear resistance $F_{v,Rd}$ of stainless steel bolts on the safe side. The bolt shear resistances are presented in Chapter 3.4.4 in a comparative overview. However, although the normative background of DIN EN 1993-1-4/NA regarding the non-homogeneous strength distribution of austenitic bolts is correct, the following aspects have to be considered (see also [164]):

- The design equations for the shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolts according to EN 1993-1-4 and DIN EN 1993-1-4/NA rely on the nominal tensile strength $f_{ub,nom}$ according to EN ISO 3506-1, which is based on the nominal tensile stress area $A_{s,nom}$. Herewith, for austenitic stainless steel bolts and in case the unthreaded part is in the shear plane, considering the cross-section area A instead of the tensile stress area A_s for the shear resistance according to (Eq. 3.4-9) implicitly yield to a higher bolt tension resistance than achieved in testing ($f_{ub,nom} \cdot A_{nom} \neq f_{ub,nom} \cdot A_{s,nom}$). In this case, the resulting overestimation of the shear resistance must be compensated by the shear coefficient α to be used for design purposes.
- Alternatively, the European design format can be kept identical to that for carbon steel bolts, and the shear coefficients α have to be adjusted and validated by shear testing. Nevertheless, it can be concluded that the shear coefficient α must be validated by testing anyway. In this case, it can be assumed that the design concept must consider α-values for austenitic and duplex bolts separately, which cover the existing different material properties in the unthreaded and threaded part of a bolt and fulfil the safety requirements according to EN 1990, Annex D.

It is worth mentioning that the European intention of a simple and unified design approach ("Ease of Use") for carbon and stainless steel bolted connections is counteracted by the regulation of DIN EN 1993-1-4/NA. Furthermore, it must be noted that the reference of the shear coefficient to the smaller tensile stress area A_s has significant effects on the combined tension and shear load bearing behaviour (interaction resistance), see Chapter 6. Herein, the conservatism of the design rule according to DIN EN 1993-1-4/NA becomes evident, especially in the case of the unthreaded bolt part in the shear plane. Therefore, the design of carbon and stainless steel bolts' tensile, shear and interaction strength must always be considered holistically.

There is no difference between the design of austenitic and duplex stainless steel bolts, while the DIN EN 1993-1-4/NA regulation is conservative with a shear coefficient of only α = 0.50 for duplex bolts in PC 50, 70 and 80 as they were only conservatively estimated. Herewith, the α-values do not only indicate the shear/tensile strength ratio from a mechanical point of view but are an integral part of the design concept and consider the steel grade, property class and unthreaded or threaded portion of the bolt in the shear plane. Herewith, they are an essential part of the design verification for which the design equation has to be checked by a reliability analysis according to EN 1990, Annex D.

Finally, it can be shown in Table 3.4-6 that no shear coefficients for the design of austenitic and duplex stainless steel bolts in PC 100 (equivalent or comparable) of EN ISO 3506-1 from 2020 were given in the international standardisation. The current version of EN 1993-1-4 from 2015 considers only the design of austenitic and duplex bolts of PC 50, 70 and 80. Therefore, in the framework of [78] and further research activities conducted at UDE-IML, for the first time, statistically verified and more economic shear coefficients α for PC 100 of austenitic and duplex bolts could be provided for FprEN 1993-1-4 and also implemented in the updated German abZ/aBG Z-30.3-6 from 2022.

3.4.4 Comparison of the resulting shear resistances of carbon and stainless steel bolts based on the main design approaches

A graphical comparison of the different resulting shear resistances of a carbon or stainless steel bolt across the bolt diameter M12 to M36 are presented in Figure 3.4-2, Figure 3.4-3 and Figure 3.4-4. Here, the resulting shear resistances for carbon steel bolts according to EN ISO 898-1 with unthreaded part (a) and threaded part (b) in the shear plane for PC 8.8 are visualised in Figure 3.4-2, while Figure 3.4-3 and Figure 3.4-4 summarise the resulting shear resistances of austenitic and duplex stainless steel bolts according to EN ISO 3506-1 with unthreaded part (a) and threaded part (b) in the shear plane exemplarily for PC 80. In order to visualise the differences of the resulting shear resistance of the identified main shear design concepts, the second y-axes of the diagrams are normalised to the current design rules of EN 1993-1-8 (carbon steel bolts) and EN 1993-1-4 (austenitic and duplex bolts) as 100 %.

For carbon steel bolts in PC 8.8, it can be shown that due to the high shear coefficients α, the highest characteristic shear resistances with shear plane in the unthreaded and threaded part are provided by Approach 1b according to the German VDI Guideline 2230 Part 1 resulting to 108.3 % of the shear resistance referred to EN 1993-1-8, see Figure 3.4-2. Consequently, due to the low safety factor of 1.1, the German VDI Guideline 2230 Part 1 also provides the highest design shear resistance with 98.5 %, nearly equal to the reference resistance of EN 1993-1-8. Furthermore, the lowest characteristic shear resistances are achieved by Approach 2 according to EN 1993-1-3 with 80.3 % for the unthreaded part and by Approach 3d according to CSA S16 and SANS 10162-1 (LRFD) with 87.2 % of the reference shear resistance for the threaded part in the shear plane. The lowest design shear resistances for carbon steel bolts

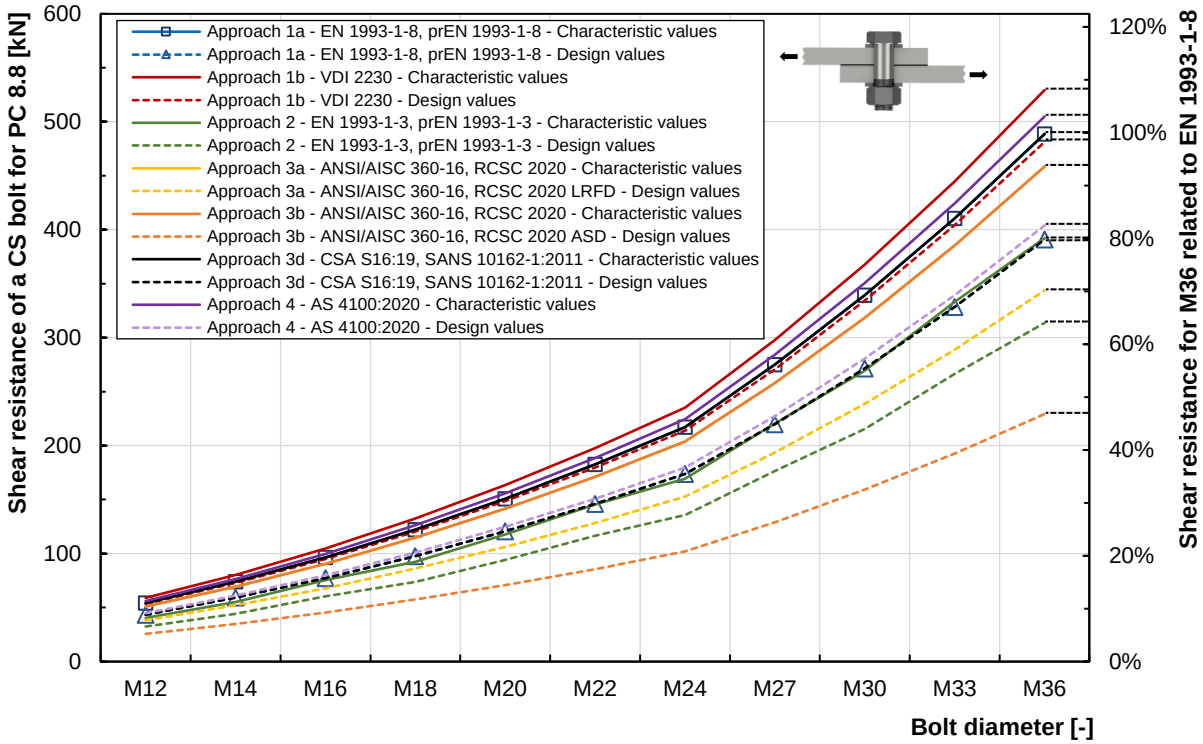
are achieved by Approach 3b according to ANSI/AISC 360 and RCSC by the Allowable Strength Design (ASD) concept with $\Omega = 2.00$ resulting in 46.9 % for the unthreaded and 46.7 % for the threaded bolt part in the shear plane.

For austenitic stainless steel bolts in PC 80, the highest characteristic bolt shear resistance is provided by Approach 1b according to FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022-05 with 116.7 % for the unthreaded and 140.0 % for the threaded part of a bolt in the shear plane. Furthermore, Approach 1b leads to design shear resistances of 93.3 % for the unthreaded and 112.0 % for the threaded part of the reference shear resistance, see Figure 3.4-3. On the contrary, the lowest characteristic shear resistances for the unthreaded part are given by Approach 3a/b (91.7 %), Approach 2a of DIN EN 1993-1-4/NA and Approach 2b by the German VDI Guideline 2230 Part 1 (both 91.0 %). For the threaded part of an austenitic bolt in the shear plane, Approach 1a according to EN 1993-1-4 leads to the lowest characteristic shear resistance of austenitic bolts. The lowest design shear resistances for the unthreaded and threaded part of austenitic bolts are based on Approach 3b according to North American ANSI/AISC 370, AISC 313 and AISC Design Guide 27 by the Allowable Strength Design (ASD) concept with $\Omega = 2.00$ resulting to 47.9 % for the unthreaded and 56.1 % for the threaded part of an austenitic bolt.

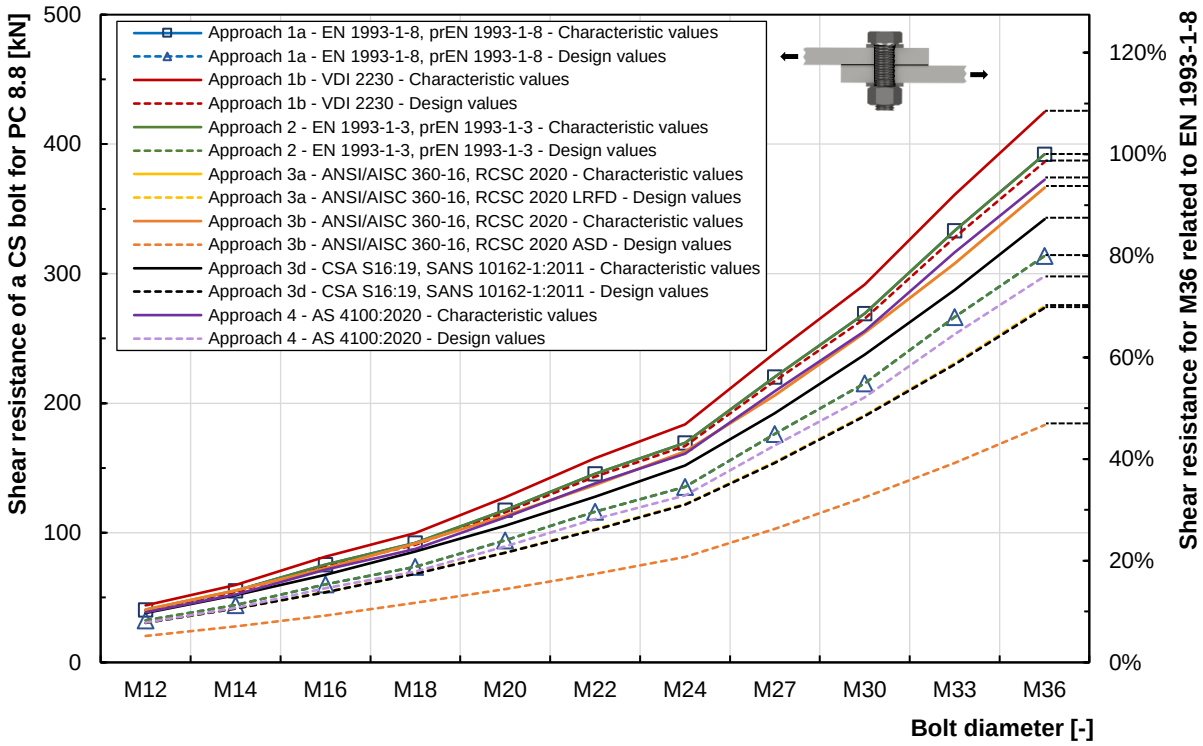
For duplex stainless steel bolts in PC 80, the highest characteristic shear resistance is again provided by Approach 1b according to FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022-05 with 116.7 % for the unthreaded part and 140.0 % for the threaded part of a bolt in the shear plane, see Figure 3.4-4. On the contrary, the lowest characteristic shear resistance for the unthreaded and threaded part of a bolt in the shear plane is provided by Approach 2a (always based on the nominal tensile stress area $A_{s,nom}$) according to DIN EN 1993-1-4/NA. As already pointed out, the German DIN EN 1993-1-4/NA regulation is very conservative with α of only $\alpha = 0.50$ for duplex bolts in PC 50, 70 and 80. Due to the same α-values for duplex bolts in PC 50, 70 and 80, the characteristic bolt shear resistances of DIN EN 1993-1-4/NA and EN 1993-1-4 (Approach 1a, here as reference resistance) are equal. The lowest design shear resistances for the unthreaded and threaded part of duplex bolts are provided by Approach 3b according to ANSI/AISC 370, AISC 313 and AISC Design Guide 27 by the Allowable Strength Design (ASD) concept with $\Omega = 2.00$ resulting to 47.9 % for the unthreaded and 56.1 % for the threaded part of a duplex stainless steel bolt.

Finally, it can be concluded that the calculation of the shear resistance $F_{v,Rd}$ of an austenitic and duplex stainless steel bolt for the threaded part in the shear plane according to the current EN 1993-1-4 yields to considerably lower shear resistance than the German regulation of DIN EN 1993-1-4/NA. For the unthreaded part in the shear plane, EN 1993-1-4 results in considerably higher shear resistance $F_{v,Rd}$ of a bolt, which corresponds to either a clear under or over dimensioning. Therefore, it was urgent to clarify the load bearing behaviour of bolting assemblies made of austenitic or duplex stainless steel in the context of the revision of EN 1993-1-4 in order to allow an economical but safe and reliable design of austenitic and duplex stainless steel bolting assemblies.

Approach 1: Shear resistance of an individual bolt based either the nominal gross cross-sectional area of the unthreaded part $\mathbf{A_{nom}}$ or the nominal tensile stress area $\mathbf{A_{s,nom}}$.	(Eq. 3.4-16; A) (Eq. 3.4-17; A_s)
Approach 2: Shear resistance of an individual bolt always based on the nominal tensile stress area $\mathbf{A_{s,nom}}$.	(Eq. 3.4-18)
Approach 3: Shear resistance of an individual bolt always based on the nominal gross cross-sectional area of the unthreaded part $\mathbf{A_{nom}}$.	(Eq. 3.4-19)
Approach 4: Shear resistance of an individual bolt based on either on the nominal gross cross-sectional area of the unthreaded part $\mathbf{A_{nom}}$ and/or the nominal minor diameter $\mathbf{A_{d3,nom}}$.	(Eq. 3.4-20)



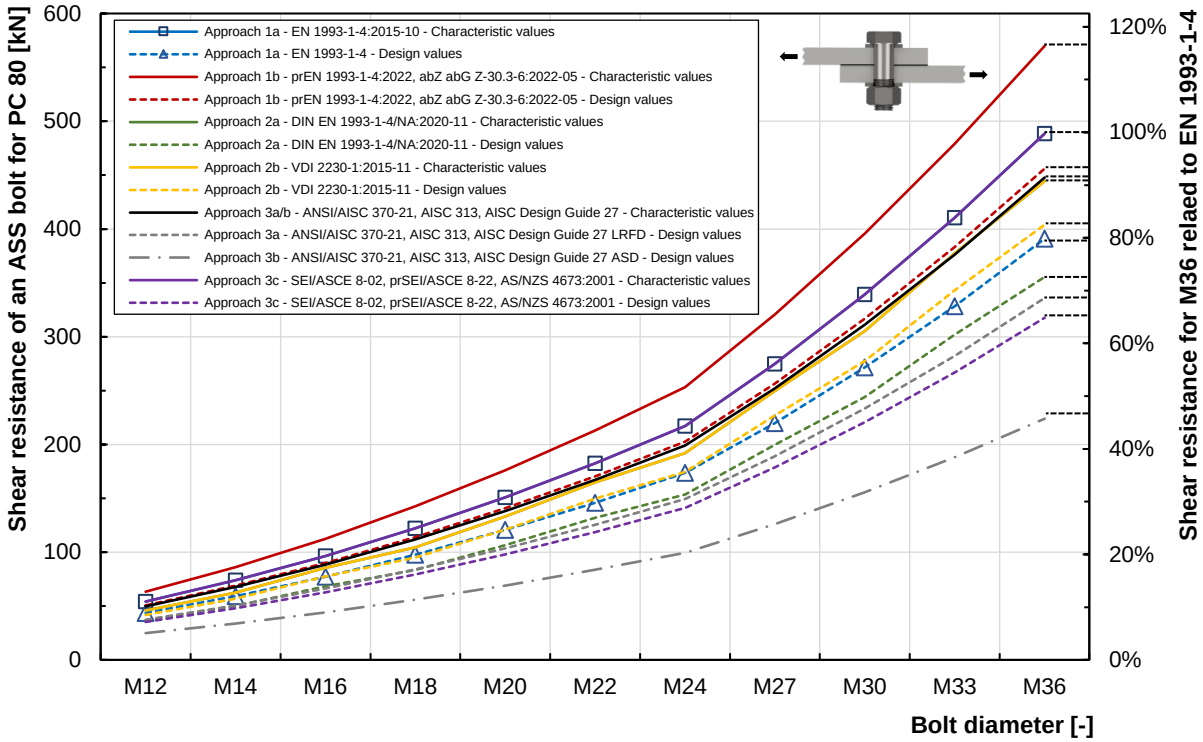
(a) Comparison for a carbon steel bolt with unthreaded part in the shear plane for PC 8.8



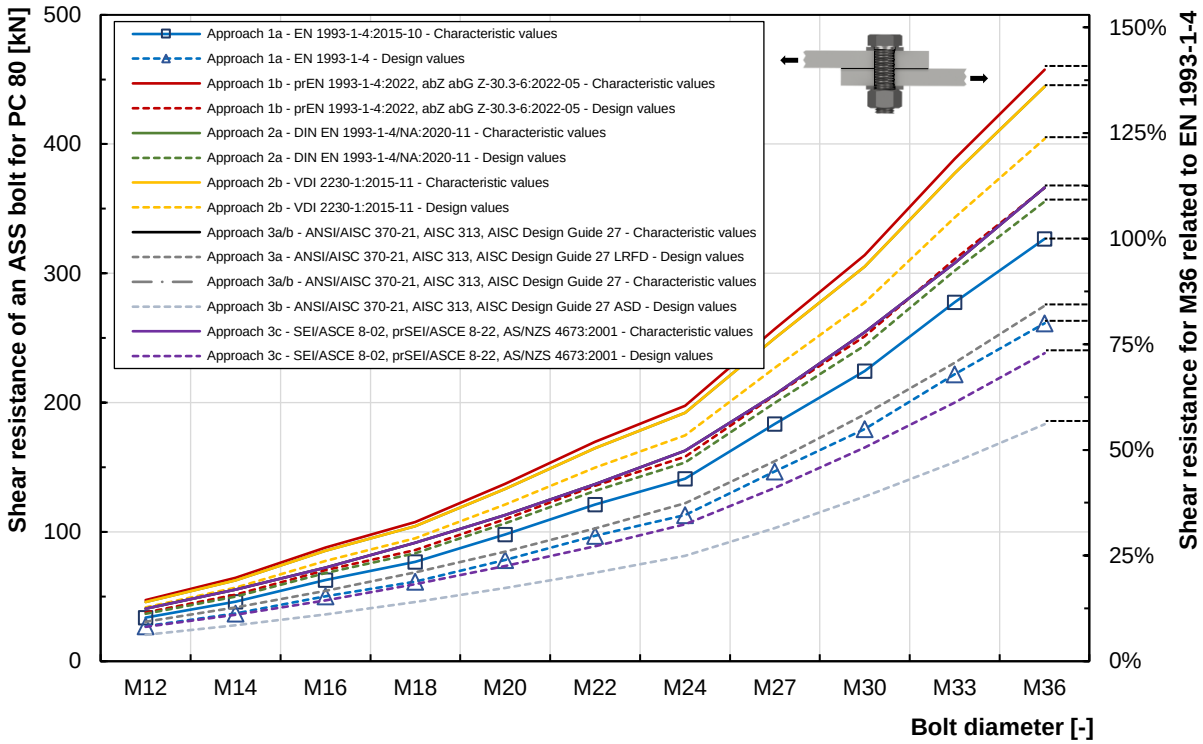
(b) Comparison for a carbon steel bolt with threaded part in the shear plane for PC 8.8

Figure 3.4-2: Graphical comparisons of the different design approaches for the shear resistances per shear plane of a carbon steel bolt with unthreaded (a) and threaded (b) part in the shear plane for PC 8.8

Approach 1: Shear resistance of an individual bolt based either the nominal gross cross-sectional area of the unthreaded part $\mathbf{A_{nom}}$ or the nominal tensile stress area $\mathbf{A_{s,nom}}$.	(Eq. 3.4-21; A) (Eq. 3.4-22, A_s)
Approach 2: Shear resistance of an individual bolt always based on the nominal tensile stress area $\mathbf{A_{s,nom}}$.	(Eq. 3.4-23)
Approach 3: Shear resistance of an individual bolt always based on the nominal gross cross-sectional area of the unthreaded part $\mathbf{A_{nom}}$.	(Eq. 3.4-24)
Approach 4: Shear resistance of an individual bolt based on either on the nominal gross cross-sectional area of the unthreaded part $\mathbf{A_{nom}}$ and/or the nominal minor diameter $\mathbf{A_{d3,nom}}$.	(Eq. 3.4-25)



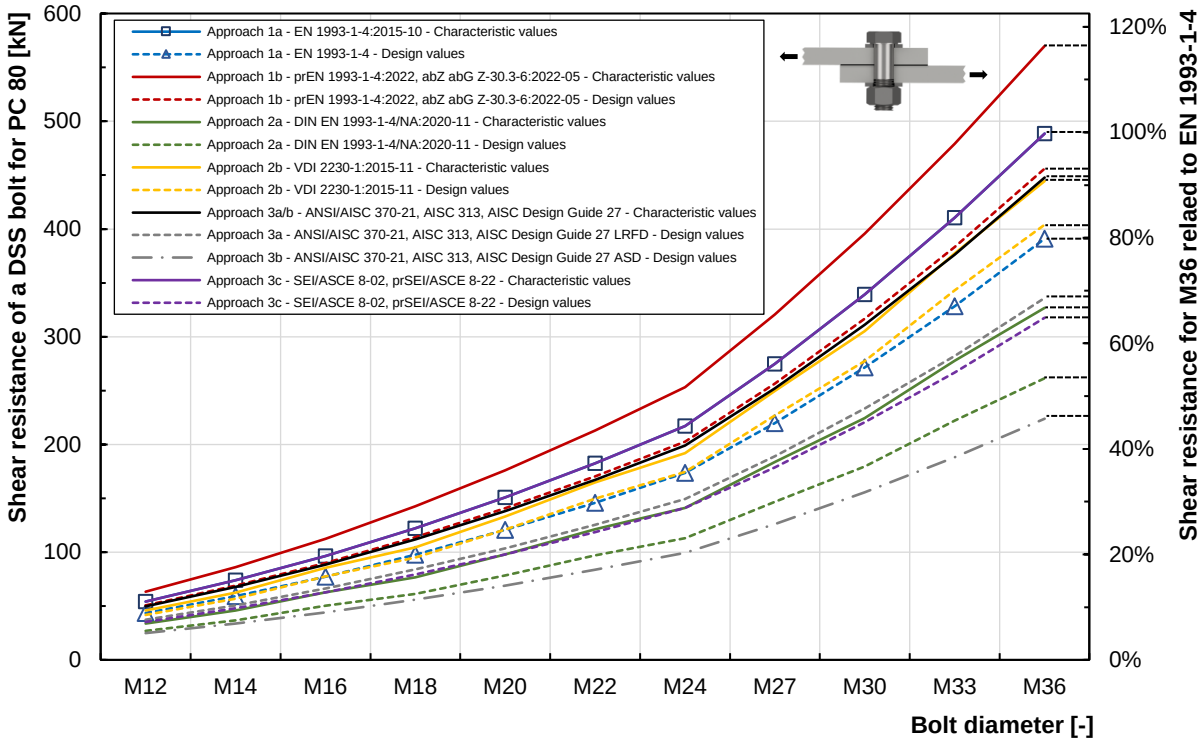
(a) Comparison of an austenitic stainless steel bolt with unthreaded part in the shear plane for PC 80



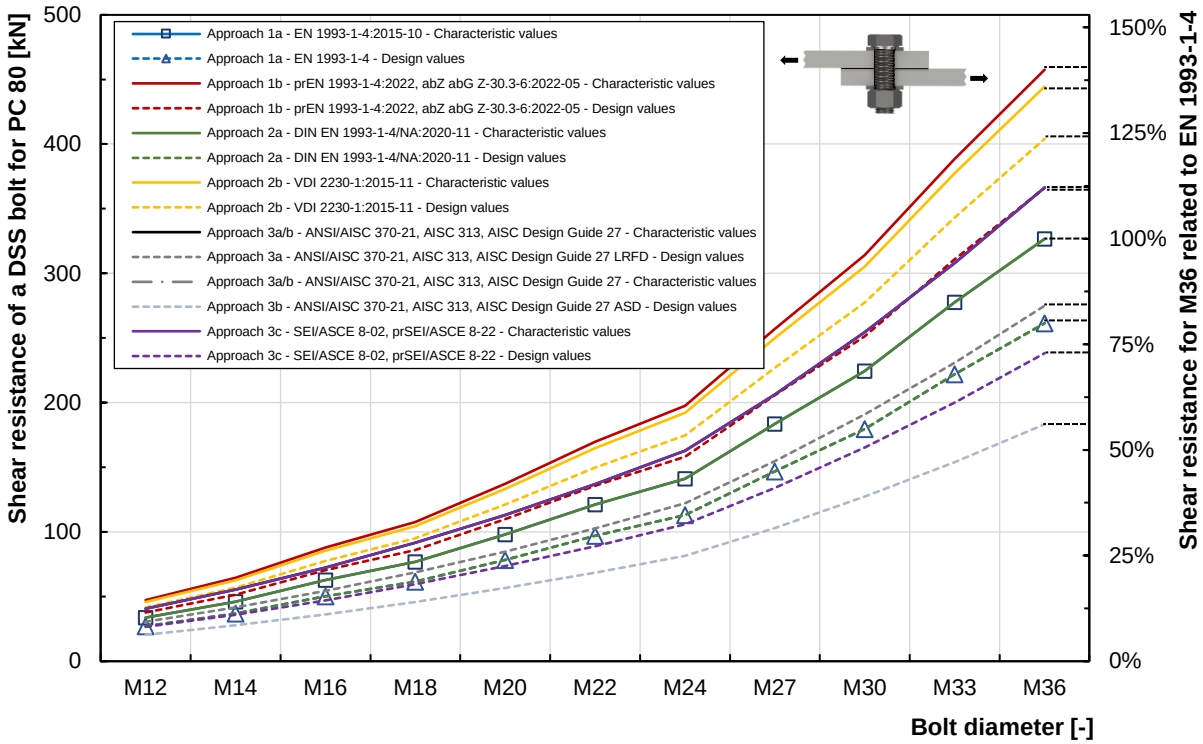
(b) Comparison of an austenitic stainless steel bolt with threaded part in the shear plane for PC 80

Figure 3.4-3: Graphical comparisons of the different design approaches for the shear resistances per shear plane of an austenitic stainless steel bolt with unthreaded (a) and threaded (b) part in the shear plane for PC 80

Approach 1: Shear resistance of an individual bolt based either the nominal gross cross-sectional area of the unthreaded part $\mathbf{A_{nom}}$ or the nominal tensile stress area $\mathbf{A_{s,nom}}$.	(Eq. 3.4-26, A) (Eq. 3.4-27, A_s)
Approach 2: Shear resistance of an individual bolt always based on the nominal tensile stress area $\mathbf{A_{s,nom}}$.	(Eq. 3.4-28)
Approach 3: Shear resistance of an individual bolt always based on the nominal gross cross-sectional area of the unthreaded part $\mathbf{A_{nom}}$.	(Eq. 3.4-29)
Approach 4: Shear resistance of an individual bolt based on either on the nominal gross cross-sectional area of the unthreaded part $\mathbf{A_{nom}}$ and/or the nominal minor diameter $\mathbf{A_{d3,nom}}$.	(Eq. 3.4-30)



(a) Comparison of a duplex stainless steel bolt with unthreaded part in the shear plane for PC 80



(b) Comparison of a duplex stainless steel bolt with threaded part in the shear plane for PC 80

Figure 3.4-4: Graphical comparisons of the different design approaches for the shear resistances per shear plane of a duplex stainless steel bolt with unthreaded (a) and threaded (b) part in the shear plane for PC 80

3.5 Interaction resistance of carbon and stainless steel bolts

3.5.1 General

In principle, and irrespective of the material, whenever bolting assemblies are subjected to a combination of tension and shear loading, it is crucial to ensure during the design process that bolt overstressing and potential failure, resulting from the superposition of tension and shear stresses, can be safely excluded. In order to describe the interaction resistance of bolts as accurately as possible, in the past, various interaction approaches were first developed for carbon steel bolts and implemented in the standardisation. Subsequently, these rules were conservatively adopted for bolts made of stainless steel based on only a few tests, mainly without sufficient statistical verification. Furthermore, in these former investigations [269–271], the design rules do not consider the unique and nonlinear mechanical properties of stainless steel bolts, like the pronounced strain hardening and outstanding ductility.

Following the von Mises equivalent stress σ_e of the shape modification hypothesis with axial tensile stress σ_x, $\sigma_y = 0$ and shear stresses $\tau_{xy} = \tau_s$, generally, a quadratic relationship can be assumed for carbon and stainless steel bolts subjected to combined tensile and shear stress, see Chapter 2.4.4 and (Eq. 2.4-7). As already stated in Chapter 2.5, the first tension, single-shear and interaction tests on carbon steel A325 and A354 bolting assemblies were conducted by Chesson, Faustino and Munse [221, 264] in 1964 and 1965. Based on their experimental investigations, they proposed different elliptical/quadratic interaction expressions for A325 and A354 BD bolts with the shear plane through the unthreaded or threaded bolt part including *"minimum factors of safety against ultimate of approximately 2, in tension, to 3.7, in single-shear through the shank"* [221]. In the following, Kulak et al. [343] simplified the different interaction expressions from Chesson, Faustino and Munse [221, 264]. Finally, they proposed an elliptical interaction equation for high-strength bolts under combined tension and shear, see (Eq. 3.5-1).

$$\frac{x^2}{(0.62)^2} + y^2 = 1.0 \qquad \text{(Eq. 3.5-1)}$$

Where x is the ratio of the shear stress on the shear plane to the tensile strength, and y is the ratio of the tensile stress to the tensile strength, which are independent of the bolt grade or the location of the shear plane.

In the further course, the elliptical/quadratic approach of Kulak et al. [343] was slightly modified by the American Institute for Steel Construction (AISC) and implemented in the Specification for Structural Steel Buildings ANSI/AISC 360. Herein, the LRFD and ASD designs of carbon steel bolts under combined tension/shear loading distinguish between the elliptical/quadratic design expression (which is since the revision of ANSI/AISC 360 from 2010 moved to the Commentary (J.3) section) and a simplified trilinear design rule (which is since 2010 given as the standard design approach based on the studies from Carter et al. [351]). Furthermore, the ANSI/AISC 370 Specifications for Structural Stainless Steel Buildings as well as the revised AISC Design Guide 27 (2nd Edition), both refer to the simplified trilinear approach for the design of bearing type connections subjected to combined tension and shear loading. The newly revised SEI/ASCE 8-22 "Specification for the Design of Cold-Formed Stainless Steel Structural Members" [298] provides a trilinear approach (presented in Table 3.5-4) for the design of stainless steel bolts under combined tension and shear loading. On the contrary, the RCSC High-Strength Bolts Specification [294] states that the elliptical interaction expression from Chesson et al. [264, 221] *"provides the best estimate of strength of bolts subject to combined tension and shear and is thus used in this Specification"*. A simplified trilinear bolt interaction

approach proposed by Carter et al. [351] in 1997 was given in earlier editions of the RCSC Specification but is now replaced by the more accurate elliptical/quadratic approach.

In Europe, the design of bolted connections subjected to combined tension and shear loading was also covered by a trilinear design expression in the United Kingdom according to the British Standard BS 5950-1 [291], which was introduced in 1975 (cf. Morris [352]). On the contrary, in Germany, the design and construction standard DIN 18800-1 for steel structures from 1981 [353] did not contain any bolt interaction equation. It was stated that in the case of combined loading of carbon steel bolts in tension and shear, all individual design verifications must be carried out independently, whereby the tension and shear resistances of the carbon steel bolts may be fully utilised without any verification of the resulting equivalent stress. Since the permissible stresses σ_z to be applied for the tension resistance were only about 50 % of the yield strength for carbon steel bolts in PC 4.6, 5.6 and 10.9, it was assumed that sufficient load bearing bolt resistances existed even for combined loading. As already stated in Chapter 2.5, Knobloch/Schmidt from the former Department of Steel Construction at the University of Essen, now the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen (UDE-IML), carried out various experimental investigations regarding the pure shear and combined tension and shear behaviour of carbon steel bolts in steel construction. They proposed a quadratic interaction for structural carbon steel bolts, which was implemented in the 1990 revision of DIN 18800-1 (Clause 8.2.1.4 (810)) and a basis for discussion in the ongoing normative process for Eurocode 3 for steel construction in 1988 in order to harmonise design procedures as common unified rules in a limit state design (LRFD) format. Interestingly, Knobloch/Schmidt [171] also proposed an interaction equation with an exponent of 1.7 for carbon steel bolts, which is proposed by Stranghöner/Abraham in a slightly modified form for FprEN 1993-1-4 and the German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022 [81] and discussed in great detail in Chapter 6. However, at that time, the bolt interaction equations with an exponent of 1.7 instead of 2 were rejected by Knobloch/Schmidt as being too conservative for the design of carbon steel bolts under combined tension and shear loading. Nevertheless, Knobloch [173] specifies that more experimental data and further statistical evaluations were required for a conclusive statement regarding the interaction behaviour of carbon steel bolts.

During the further course of the European normative process and based on the comments of the United Kingdom outlined in Report EUR 8849 DE [354] to the European Commission, the quadratic bolt interaction by Knobloch/Schmidt for DIN 18800-1:1990 was transformed into a trilinear design equation following the British Standard BS 5950-1 for easier handling ("Ease of Use") to be able to disregard small tensile components or small shear components in the design. However, it is outlined in the background documentation/TNO-report of the Eurocode 3 revision from 1988 that from a statistical point of view, the quality of the quadratic bolt interaction and simplified trilinear design equation *"is about equal"* [355]. However, further modifications were required to fulfil the safety requirements of the Eurocode against the partial safety factor γ_{M2} = 1.25 and to unify the tension resistance of carbon steel bolts on the tensile stress area A_s instead of the gross cross-sectional area A. As a result, primarily two interaction equations were developed for Eurocode 3 as presented in (Eq. 3.5-2) for the unthreaded bolt part in the shear plane and (Eq. 3.5-3) for the threaded bolt part in the shear plane (reformulated according to the current Eurocode terminology):

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.8 \cdot F_{t,Rd}} \leq 1.0 \quad \text{with} \quad \frac{F_{t,Ed}}{F_{t,Rd}} \leq 1.0 \qquad \text{(Eq. 3.5-2)}$$

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.4 \cdot F_{t,Rd}} \leq 1.0 \quad \text{with} \quad \frac{F_{t,Ed}}{F_{t,Rd}} \leq 1.0 \qquad \text{(Eq. 3.5-3)}$$

For simplification, only (Eq. 3.5-3) was finally proposed for the interaction resistance of carbon steel bolts for the unthreaded and threaded bolt part in the shear plane. However, the authors of the EC-3 Background Documentation from 1988 were aware of the conservatism for the loading case “unthreaded bolt part in the shear plane”. The result of these investigations is the bilinear interaction equation of EN 1993-1-8 (for carbon steel bolts) and EN 1993-1-4 (adopted for stainless steel bolts), which significantly reduces the combined load bearing capacity under high shear loading, in particular for the unthreaded bolt part.

3.5.2 Selected international design rules for the interaction resistance of bolts

As a continuation of the presented design rules for the tension and shear resistance, the following selected international design rules regarding the interaction resistance of carbon (CS) and stainless steel (SS) bolts are summarised briefly. The different design rules and approaches are based on Chapter 3.2 and present a comprehensive overview of international design rules for bolted connections made of carbon and stainless steel.

The different presented selected design rules regarding the interaction resistance of carbon and stainless steel bolts subjected to tension and shear loading can be further distinguished into four main design concepts:

- **Approach 1:** Bolt interaction resistance as square root design expressions, exemplarily presented in Table 3.5-1 for Chinese and Russian standards, which is beside the formal style equal to Approach 2 as quadratic design expression,
- **Approach 2:** Bolt interaction resistance as elliptical or quadratic design expressions as presented in Table 3.5-2 for selected international design rules,
- **Approach 3:** Bolt interaction resistance as bilinear design expressions, exemplarily presented in Table 3.5-3,
- **Approach 4:** Bolt interaction resistance as trilinear design expressions, exemplarily presented in Table 3.5-4.

Table 3.5-1: Summary of selected square root international design rules for the determination of the interaction resistance of an individual bolt of carbon steel (CS) bolted connections

Standard, Code or Guideline		Steel type	Interaction resistance design concept	
	GB 50017-2017 *[318]* *Clause 11.4.1.3* ***Square root expression***	CS	$\sqrt{\left(\frac{N_v}{N_v^b}\right)^2 + \left(\frac{N_t}{N_t^b}\right)^2} \leq 1.0$ According to GB 50017, N_v is the shear force in a bolt in the investigated shear plane, N_t is the tensile force in a bolt, N_v^b is the design bolt shear resistance and N_t^b is the design bolt tensile resistance. The Russian Standard SP 16 applies the same bolt interaction equation.	(Eq. 3.5-4)
	SP 16.13330.2017 *[320]* *Clause 14.2.13* ***Square root expression***	CS		

Table 3.5-2: Summary of selected elliptical/quadratic international design rules for the determination of the interaction resistance of an individual bolt of carbon (CS) and stainless steel (SS) bolted connections

Standard, Code or Guideline	Steel type	Interaction resistance design concept	
FprEN 1993-1-4:2024 *[80]* *Clause 10.2(5)* ***Elliptical by Stranghöner/Abraham***	SS	Unthreaded bolt part in the shear plane $\left(\frac{F_{v,Ed}}{F_{v,Rd,A}}\right)^{1.7}+\left(\frac{F_{t,Ed}}{1.25\cdot F_{t,Rd,As}}\right)^{1.7}\leq 1.0$ with $\frac{F_{t,Ed}}{F_{t,Rd,As}}\leq 1.0$ Threaded bolt part in the shear plane $\left(\frac{F_{v,Ed}}{F_{v,Rd,As}}\right)^{1.7}+\left(\frac{F_{t,Ed}}{F_{t,Rd,As}}\right)^{1.7}\leq 1.0$ with $\frac{F_{t,Ed}}{F_{t,Rd,As}}\leq 1.0$ Proposed by Stranghöner/Abraham for the revision of EN 1993-1-4, FprEN 1993-1-4, and abZ/aBG Z-30.*3-6:2022*; presented in detail in Chapter 6.	(Eq. 3.5-5)
abZ/aBG Z-30.3-6:2022-05 *[81]* *Clause 3.3.2* ***Elliptical by Stranghöner/Abraham***	SS		
DIN 18800-1:2008-11 *[170]* *Clause 8.2.1.4 (withdrawn)* ***Quadratic***	CS	Unthreaded bolt part in the shear plane $\left(\frac{V}{V_{max,A}}\right)^{2}+\left(\frac{N}{N_{max,A}}\right)^{2}\leq 1.0$ with $\frac{N}{N_{max,A_s}}\leq 1.0$ Threaded bolt part in the shear plane $\left(\frac{V}{V_{max,A_s}}\right)^{2}+\left(\frac{N}{N_{max,A_s}}\right)^{2}\leq 1.0$ No interaction has to be considered if: $\frac{V}{V_{max}}\leq 0.25$ or if $\frac{N}{N_{max}}\leq 0.25$ Following the interaction approach of the withdrawn DIN 18800-1, N is the bolt tension load; $N_{max,A}$ is the bolt tension resistance based on A; $N_{max,As}$ is the tension resistance based on A_s; V is the bolt shear load; $V_{max,A}$ is the bolt shear resistance based on A; $V_{max,As}$ is the bolt shear resistance based on A_s. The interaction equation of VDI 2230 Part 1 is based on the withdrawn DIN 18800-1:2008-11 and valid for carbon steel and stainless steel bolts with higher shear coefficients compared to EN 1993-1-8 or EN 1993-1-4. Analogues to DIN 18800-1, a bolt interaction check is not required if the shear or tension ratio is < 0.25. However, the determination of the shear resistance $F_{v,Rd}$ of stainless steel bolts is always based on the smaller tensile stress area A_s (cf. DIN EN 1993-1-4/NA). The safety factor is in the amount of 1.1 less than $\gamma_{M2} = 1.25$ in EN 1993-1-8. According to EN 13001-3-1, the general design of steel cranes include a quadratic interaction equation for bolts in support structures and is always based on the yield strength f_{yb} instead of f_{ub} and further reduced by safety factors for both the shear $F_{v,Rd}$ and tension resistance $F_{t,Rd}$.	(Eq. 3.5-6)
VDI 2230-1:2015-11 *[167]* *Clause 5.5.6.3, Table 7 and Eq. (221)* ***Quadratic***	CS SS		
EN 13001-3-1:2019-03 *[281]* *Clause 5.2.3.4* ***Quadratic***	CS		

Table 3.5-2: Summary of selected elliptical/quadratic international design rules for the determination of the interaction resistance of an individual bolt of carbon (CS) and stainless steel (SS) bolted connections (Cont.)

Standard, Code or Guideline	Steel type	Interaction resistance design concept	
ANSI/AISC 360-22 *[293]* *Clause Commentary J3* ***Quadratic***	CS	$\left(\frac{f_v}{\phi \cdot F_{nv}}\right)^2 + \left(\frac{f_t}{\phi \cdot F_{nt}}\right)^2 \leq 1.0$ (LRFD) $\left(\frac{\Omega \cdot f_v}{F_{nv}}\right)^2 + \left(\frac{\Omega \cdot f_t}{F_{nt}}\right)^2 \leq 1.0$ (ASD) According to ANSI/AISC 360-22, the nominal tensile stress F_{nt}, the nominal shear stress F_{nv}, the required tensile stress f_t and the required shear stress f_v as well as the safety factors $\Phi = 0.75$ (LRFD) or $\Omega = 2.00$ (ASD) have to be considered for the bolt interaction design. ANSI/AISC 370-21 refers to AISC 360 and only modifies the safety factors to $\Phi = 0.67$ (LRFD) or $\Omega = 2.25$ (ASD) for precipitation hardening stainless steel bolts. The RCSC "Specifications for Structural Joints Using High-Strength Bolts" contains the same LRFD and ASD interaction design rules for high-strength carbon steel bolts only slightly editorial adapted.	(Eq. 3.5-7)
ANSI/AISC 370-21 *[300]* *Clause Commentary J3* ***Quadratic***	SS		
RCSC:2020-06, Research Council on Structural Connections *[294]* *Clause 5.2* ***Quadratic***	CS		
AISC Design Guide 27, 2nd Edition *[302], Clause 10.3* ***Quadratic***	SS		
CSA S16:19 *[295]* *Clause 13.12.1* ***Quadratic***	CS	$\left(\frac{V_f}{V_r}\right)^2 + \left(\frac{T_f}{T_r}\right)^2 \leq 1.0$ According to the Canadian Standard CSA S16, V_f and T_f are design shear force and tensile force acting on the bolt, and V_r and T_r are design shear resistance and tensile resistance of the bolt. The safety concept of $\Phi_b = 0.80$ as resistance factor is comparable to $\gamma_{M2} = 1.25$ for connections of the Eurocode. The quadratic bolt interaction of Indian Standard IS 800 follows the Canadian CSA approach with only different symbols.	(Eq. 3.5-8)
IS 800:2007 *[311]* *Clause 10.3.6* ***Quadratic***	CS		
AS 4100:2020 *[304]* *Clause 9.2.2.3* ***Quadratic***	CS	$\left(\frac{V_f^*}{\phi \cdot V_f}\right)^2 + \left(\frac{N_{tf}^*}{\phi \cdot N_{tf}}\right)^2 \leq 1.0$ The Australian Standard AS 4100 specifies that a bolt required to resist both design shear and design tensile forces at the same time. Herein, V_f is the nominal shear capacity and N_{tf} is the nominal tensile capacity of a carbon steel bolt with $\Phi = 0.8$ as capacity factor for bolts.	(Eq. 3.5-9)
NZS 3404 Parts 1 and 2:1997 *[305]* *Clause 9.3.2.3* ***Quadratic***	CS		

The square root bolt interaction expression is rarely applied in standardisation like the Chinese Standard GB 50017:2017 and Russian Standard SP 16.13320.2017, both exclusively for carbon steel bolts. On the contrary, a large number of international standards are following the studies from Chesson, Faustino and Munse [221, 264] as well as Kulak et al. [343] who provide a quadratic bolt interaction design rule for carbon or stainless steel bolts subjected to combined tension and shear.

Interestingly, the bolt interaction approach of the German Guideline for VDI 2230 Part 1, which is often used in mechanical engineering, is still based on the withdrawn German design and

construction standard DIN 18800-1 from 1990. Herein, the proposed interaction approach based on the studies on Knobloch/Schmidt should also be applied to austenitic and duplex stainless steel bolts even under consideration of a reduced safety factor of $S_A = 1.1$ in comparison to the partial safety factor of $\gamma_{M2} = 1.25$ for connections according to the Eurocode. In contrast to other standards and in combination with high shear coefficients α, the carbon steel bolts' resulting design interaction resistances are the highest. However, the interaction resistance of stainless steel bolts is reduced according to VDI 2230 Part 1 since the shear resistance is always based on the threaded bolt part independent of the position of the shear plane. As already stated, the bi-/trilinear interaction approaches must be understood as simplified interaction equations, presented in Table 3.5-3 (bilinear) and Table 3.5-4 (trilinear). A detailed graphical comparison of the different load bearing behaviour of selected interaction equations is presented in Chapter 3.5.4.

Table 3.5-3: Summary of selected bilinear international design rules for the determination of the interaction resistance of an individual bolt of carbon (CS) and stainless steel (SS) bolted connections

Standard, Code or Guideline	Steel type	Interaction resistance design concept	
EN 1993-1-8:2010-12 *[72]* *Table 3.4* ***Bilinear***	CS	$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.4 \cdot F_{t,Rd}} \leq 1.0$ $F_{v,Rd}$ is the design shear resistance based on A or A_s depending on the position of the shear plane in the unthreaded or threaded bolt part, while $F_{t,Rd}$ is the design tension resistance per bolt always based on the tensile stress area A_s. According to the German DIN EN 1993-1-4/NA, the determination of the shear resistance $F_{v,Rd}$ is always based on the smaller tensile stress area A_s and with higher shear coefficients α compared to EN 1993-1-4 independent from the position of the shear planes in the unthreaded or threaded part: $\alpha = 0.75$ for Austenitic PC 50; $\alpha = 0.68$ for Austenitic PC 70 and 80; $\alpha = 0.50$ for Duplex PC 50, 70 and 80. Consequently, this also affects the interaction resistance of austenitic and duplex stainless steel bolts.	(Eq. 3.5-10)
E DIN EN 1993-1-8/NA:2024-10 *[285]* ***DIN EN 1993-1-8/NA:2020-11*** *[284]* ***Bilinear***	CS		
EN 1993-1-4:2015-10 *[67]* *Clause 6.1 refers to EN 1993-1-8* ***Bilinear***	SS		
DIN EN 1993-1-4/NA:2020-11 *[71]* *NDP to 6.2(3)* ***Bilinear***	SS		
DMSSS Design Manual for Structural Stainless Steel, 4th Edition *[64], [135]* *Clause 7.2.4* ***Bilinear***	SS		
SP 198.1325800.2014 *[321]* *Refers to EN 1993-1-4:2006-10 [323]*	SS		
EN 1993-1-8:2024 (draft) *[82]* *Table 5.9* ***Bilinear***	CS	$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right) + \left(\frac{F_{t,Ed}}{1.4 \cdot F_{t,Rd}}\right) \leq 1.0$ with $\frac{F_{t,Ed}}{F_{t,Rd,As}} \leq 1.0$ Compared to EN 1993-1-8:2010, the format of the interaction equation is slightly changed and defined more precisely regarding the maximum bolt tension component $F_{t,Rd}$, which was already stated in the Background Documentation of the Eurocode 3 revision from 1988. $F_{v,Rd}$ is the design shear resistance based on A or A_s depending on the position of the shear plane in the unthreaded or threaded bolt part, while $F_{t,Rd}$ is the design tension resistance per bolt always based on the tensile stress area A_s.	(Eq. 3.5-11)

Table 3.5-4: Summary of selected trilinear international design rules for the determination of the interaction resistance of an individual bolt of carbon (CS) and stainless steel (SS) bolted connections

Standard, Code or Guideline	Steel type	Interaction resistance design concept	
ANSI/AISC 360-22 *[293]* *Clauses J3-2, J3-3a and J3-3b* ***Trilinear***	CS	$R_n = F'_{nt} \cdot A_b$ $\text{with}: F'_{nt} = 1.3 \cdot F_{nt} - \frac{F_{nt}}{\phi \cdot F_{nv}} \cdot f_{rv} \leq F_{nt}$ (LRFD) $\text{with}: F'_{nt} = 1.3 \cdot F_{nt} - \frac{\Omega \cdot F_{nt}}{F_{nv}} \cdot f_{rv} \leq F_{nt}$ (ASD) According to ANSI/AISC 360-22, the available tensile strength of a bolt subjected to combined tension/shear shall be determined according to the limit states of tension and shear rupture with Φ = 0.75 (LRFD) or Ω = 2.00 (ASD). F_{nt} is the nominal tensile stress and F_{nv} is the nominal shear stress from Table J3.2 of ANSI/AISC 360-22. F'_{nt} is the nominal tensile stress which has to be modified to include the effects of shear stress. f_{rv} is defined as the required shear stress using LRFD or ASD load combinations. The available shear stress of the fastener shall equal or exceed the required shear stress, f_{rv}. However, if the required stress in either shear or tension is less than or equal to 30 % of the corresponding available stress, the effects of combined shear/tensile stress need not be investigated. The trilinear bolt interaction expressions of ANSI/AISC 360 based on Carter et al. [351] can also be reformulated to: $\left(\frac{f_v}{\phi \cdot F_{nv}}\right) + \left(\frac{f_t}{\phi \cdot F_{nt}}\right) \leq 1.3$ (LRFD) $\left(\frac{\Omega \cdot f_v}{F_{nv}}\right) + \left(\frac{\Omega \cdot f_t}{F_{nt}}\right) \leq 1.3$ (ASD) According to ANSI/AISC 370-22, for austenitic and duplex stainless steel bolts the safety factors Φ = 0.75 (LRFD) or Ω = 2.00 (ASD) are given. For precipitation hardening stainless steel bolts, the safety factors are modified to Φ = 0.67 (LRFD) or Ω = 2.25 (ASD).	(Eq. 3.5-12) (Eq. 3.5-13)
ANSI/AISC 370-21 *[300]* *Clauses J3-2, J3-3a and J3-3b* ***Trilinear***	SS		
AISC Design Guide 27, 2nd Edition "Structural Stainless Steel" *[302]* *Clause 10.3* ***Trilinear***	SS		
SEI/ASCE 8-22 *[298]* *Clause 10* ***Trilinear***	SS	$\phi \cdot P_n = \phi \cdot F'_{nt} \cdot A_b$ (LRFD) Unthreaded bolt part in the shear plane $\text{with}: F'_{nt} = 1.25 \cdot F_{nt} - 1.9 \cdot f_{rv} \leq F_{nt}$ Threaded bolt part in the shear plane $\text{with}: F'_{nt} = 1.25 \cdot F_{nt} - 2.4 \cdot f_{rv} \leq F_{nt}$ The SEI/ASCE 8-22 specification is based on the LRFD method with the resistance factor of Φ = 0.75. F_{nt} is the nominal tensile stress, f_v is the shear stress produced by the same factored loads. AS/NZS 4673:2001 follows the same trilinear interaction design approach as SEI/ASCE 8-2.2	(Eq. 3.5-14)
AS/NZS 4673:2001 *[309]* *Clause 5.3.7.4 (Stainless steel bolts complying with ASTM standards)* ***Trilinear***	SS		

Table 3.5-4: Summary of selected trilinear international design rules for the determination of the interaction resistance of an individual bolt of carbon (CS) and stainless steel (SS) bolted connections (Cont.)

Standard, Code or Guideline		Steel type	Interaction resistance design concept	
	BS 5950-1:2000 *[291] (withdrawn)* *Clause 6.3.4.4* ***Trilinear***	CS	$\frac{F_s}{P_s} + \frac{F_t}{P_{nom}} \leq 1.4$ The "simple method" interaction equation acc. to BS 5950-1 consists of the shear load F_s and the bolt shear resistance P_s as well as the tension load F_t and the tension resistance P_{nom}. In the simple method the prying forces need not to be calculated. The bolt interaction approach of SANS 10162-1 is in principle based on the withdrawn BS 5950-1 "simple method". However, the tension and shear resistance are always based on the gross cross-sectional area A and reduced to 75 %.	(Eq. 3.5-15)
	SANS 10162-1:2011 *[313]* *Clause 13.12.1.4* ***Trilinear***	CS		
	AS/NZS 4673:2001 *[309]* *Clause 5.3.8.4 (Stainless steel bolts complying with ISO 3506)* ***Trilinear***	SS	$\frac{V_{fv}^*}{0.44 \cdot V_{fv}} + \frac{N_{tf}^*}{0.94 \cdot N_{tf}} \leq 1.0$ The AS/NZS 4673 standard modifies the capacity factor for bolts to $\Phi = 0.67$ complying with EN ISO 3506 bolt standards	(Eq. 3.5-16)

3.5.3 Proposed interaction approaches and comments for the revision of EN 1993-1-8

In the normative process of EN 1993-1-8, for the 2nd Eurocode generation, a fundamental discussion regarding the suitability of the current bilinear bolt interaction design rule for structural carbon steel bolts was initiated.

As already discussed in Chapter 2.5.3, further experimental investigations into the interaction resistance of structural carbon steel bolts were carried out by Renner and Lange [178–183, 235] from the Technical University of Darmstadt, Germany. Their experimental programme and literature review confirmed that for the case "unthreaded bolt part in the shear plane", the former quadratic interaction equation by Knobloch/Schmidt for DIN 18800-1 overestimates the load bearing capacity for combined tension and shear loading but the bilinear interaction according to EN 1993-1-8 significantly underestimates it. As already outlined, the Background Documentation for the EC-3 revision from 1988 [355] was aware of the conservatism for the loading case "unthreaded bolt part in the shear plane". Furthermore, according to the results from Renner and Lange [178–183, 235], in the case that the threaded bolt part lies in the shear plane, the quadratic interaction describes the load bearing behaviour quite appropriately. In contrast, the bilinear interaction clearly underestimates the interaction resistance for carbon steel bolts. Therefore, finally, Renner/Lange modify the quadratic interaction by using an exponent of 1.5 instead of 2 and by considering the gross cross-sectional area A in the case "unthreaded bolt part in the shear plane" or the tensile stress area A_s in the case of "threaded bolt part in the shear plane", see (Eq. 3.5-17) and (Eq. 3.5-18) in Table 3.5-5. However, the studies of Renner/Lange included 158 tension, single-/double-shear and interaction tests. They were complemented by numerical FEM analyses but lacked entirely a thorough statistical evaluation according to EN 1990, Annex D of the proposed interaction approach. Therefore, a statement regarding the suitability of this approach for the design of carbon steel bolted connections subjected to combined tension and shear loading could not be made at all. Nevertheless, the European Project Team CEN/TC 250/SC3.T2 discussed transferring the Renner/Lange approach in the revision of EN 1993-1-8, and the amendment proposal AM-1-

8-2017-01 [356] was prepared. It was stated that the *"current regulation is partly unsafe and partly uneconomic"* as the reason for an amendment, see [356]. Due to the lack of statistical evaluation according to EN 1990, Annex D, Može [357] from CEN/TC 250/SC3.T2 conducted an extrapolation of the test results in Background documentation to EC-3 to the interaction design proposal by Renner/Lange. Herein, a new interaction strength model that is slightly modified to those in AM-1-8-2017-01 was developed by Može [357], compare (Eq. 3.5-21) and (Eq. 3.5-22), for which also a reliability analysis according to EN 1990, Annex D was missing. Može concluded that *"the statistical analysis would most likely lead to partial factor lower than 1.25"* [357]. Finally, it was decided in the normative process to keep the bilinear approach for the revision of EN 1993-1-8 on the uneconomic but safe side. Thus, also the German comment to the final draft of prEN 1993-1-8 [358], which follows the Renner/Lange approach in a slightly modified form by adding the A_s/A ratio to consider the unthreaded bolt part as presented in (Eq. 3.5-19) and (Eq. 3.5-20), was finally rejected. Consistently, Stranghöner emphasised in the Project Team Meeting on 19th June 2018 in London, UK, that *"the question which design equation fits best cannot be answered before the question of the safety factor is answered. And this can only be done by performing a reliability analysis (…) in which the model uncertainty and the safety aspect are considered"* [359].

Table 3.5-5: Summary of the proposed approaches and comments for prEN 1993-1-8 for the determination of the interaction resistance of an individual bolt of carbon steel (CS) bolted connection

Approaches for prEN 1993-1-8	Steel type	Interaction resistance design concepts	
Approach of Renner/Lange *[178–183, 235]* ***Elliptical***	CS	Unthreaded bolt part in the shear plane $\left(\frac{F_{v,Ed}}{F_{v,Rd,A}}\right)^{1.5}+\left(\frac{F_{t,Ed}}{F_{t,Rd,A}}\right)^{1.5}\leq 1.0 \quad \text{with} \quad \frac{F_{t,Ed}}{F_{t,Rd,As}}\leq 1.0$	(Eq. 3.5-17)
		Threaded bolt part in the shear plane $\left(\frac{F_{v,Ed}}{F_{v,Rd,As}}\right)^{1.5}+\left(\frac{F_{t,Ed}}{F_{t,Rd,As}}\right)^{1.5}\leq 1.0$	(Eq. 3.5-18)
German Comment to the Final Draft of prEN 1993-1-8 *[358]* *as slightly modified approach of Renner/Lange* ***Elliptical***	CS	Unthreaded bolt part in the shear plane $\left(\frac{F_{v,Ed}}{F_{v,Rd,A}}\right)^{1.5}+\left(\frac{F_{t,Ed}}{F_{t,Rd,As}}\cdot\frac{A_s}{A}\right)^{1.5}\leq 1.0 \quad \text{with} \quad \frac{F_{t,Ed}}{F_{t,Rd,As}}\leq 1.0$ No interaction has to be considered if: $\frac{F_{v,Ed}}{F_{v,Rd,A}}\leq 0.15 \quad \text{or if} \quad \frac{F_{t,Ed}}{F_{t,Rd,As}}\leq 0.15$	(Eq. 3.5-19)
		Threaded bolt part in the shear plane $\left(\frac{F_{v,Ed}}{F_{v,Rd,A}}\right)^{1.5}+\left(\frac{F_{t,Ed}}{F_{t,Rd,As}}\right)^{1.5}\leq 1.0$ No interaction has to be considered if: $\frac{F_{v,Ed}}{F_{v,Rd,As}}\leq 0.15 \quad \text{or if} \quad \frac{F_{t,Ed}}{F_{t,Rd,As}}\leq 0.15$	(Eq. 3.5-20)
Approach of Može *[357]* *Clause 3.2.1, Eq. 10* ***Elliptical***	CS	Unthreaded bolt part in the shear plane $\left(\frac{F_{v,Ed}}{F_{v,Rd,A}}\right)^{1.5}+\left(0.9\cdot\frac{F_{t,Ed}}{F_{t,Rd,As}}\right)^{1.5}\leq 1.0 \quad \text{with} \quad \frac{F_{t,Ed}}{F_{t,Rd,As}}\leq 1.0$	(Eq. 3.5-21)
		Threaded bolt part in the shear plane $\left(\frac{F_{v,Ed}}{F_{v,Rd,As}}\right)^{1.5}+\left(0.9\cdot\frac{F_{t,Ed}}{F_{t,Rd,As}}\right)^{1.5}\leq 1.0 \quad \text{with} \quad \frac{F_{t,Ed}}{F_{t,Rd,As}}\leq 1.0$	(Eq. 3.5-22)

At this point, it shall be emphasised that the proposed bolt interaction design equations by Renner/Lange, the German Comment and Može for prEN 1993-1-8 deal exclusively with structural carbon steel bolts and do not consider at all the load bearing behaviour of stainless steel bolts.

3.5.4 Comparison of the resulting interaction resistances of carbon and stainless steel bolts

For a direct comparison of the different interaction equations and their underlying load bearing behaviour of carbon or stainless steel bolts and bolting assemblies per shear plane, graphical comparisons are presented in Figure 3.5-1 for the unthreaded bolt part in the shear plane and Figure 3.5-2 for the threaded bolt part in the shear plane. Here and in the further course of this thesis, a representation of the shear ratio $F_{v,Ek}/F_{v,Rk}$ on the x-axis and tension ratio $F_{t,Ek}/F_{t,Rk}$ on the y-axis was preferred. The advantage is that this representation compares the interaction equations across all bolt diameters and bolt property classes, independent of the tension/shear load capacities (in kN) of the bolts and bolting assemblies and the different shear coefficients α depending on the steel grade and property class. It is important to note that all the interaction design concepts presented were derived from bolted connections made of carbon steel and are therefore not easily transferable to bolted connections made of stainless steel (except for the approach of Stranghöner/Abraham for FprEN 1993-1-4).

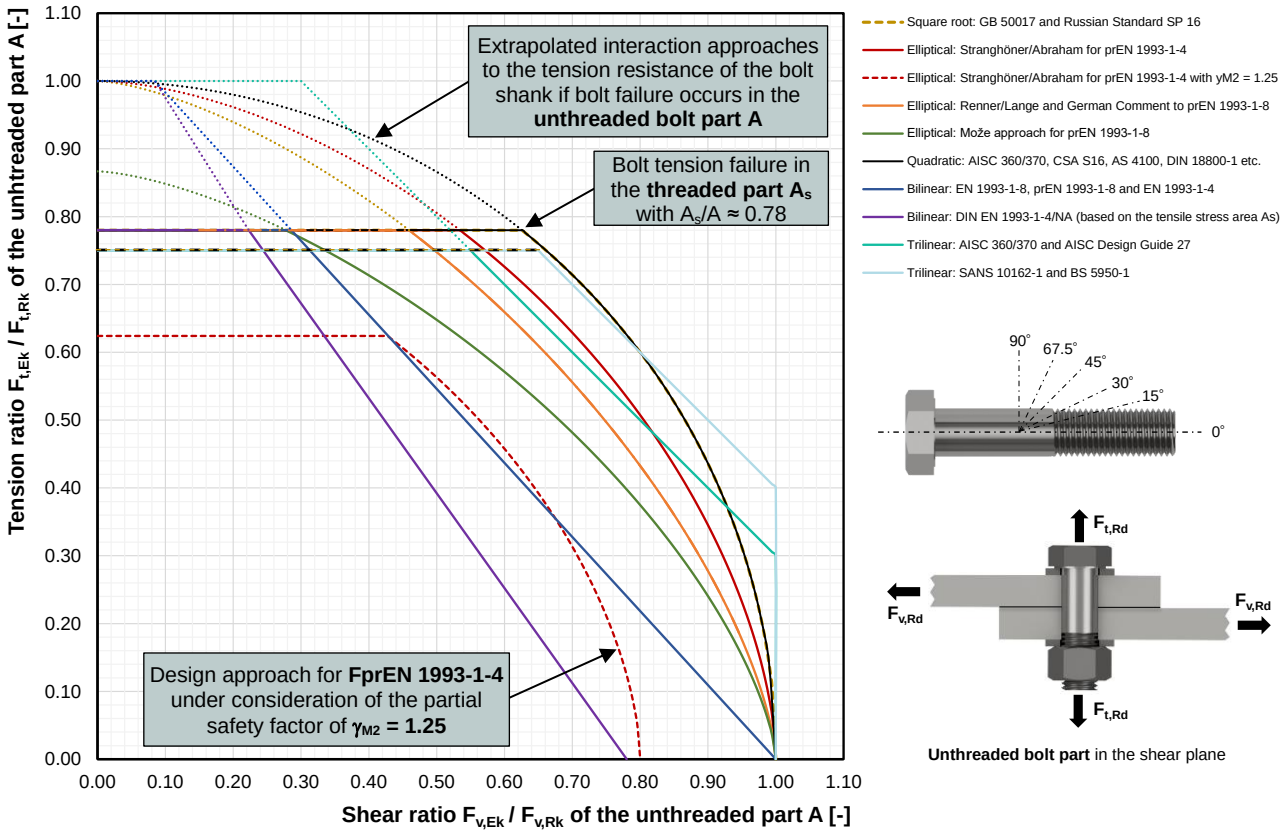


Figure 3.5-1: Graphical comparison of the different design approaches for the interaction resistance per shear plane of carbon or stainless steel bolting assemblies with unthreaded bolt part in the shear plane

It can be seen in Figure 3.5-1 for the unthreaded bolt part in the shear plane that the bilinear interaction equations of EN 1993-1-8, EN 1993-1-8:2024 (carbon steel) and EN 1993-1-4 (stainless steel), and in particular, DIN EN 1993-1-4/NA, leading to the smallest load bearing capacities. On the contrary, the quadratic bolt interaction equation (which is implemented in a variety of standards and codes, see Table 3.5-2), as well as the trilinear interaction equation of SANS 10162-1 and (withdrawn) BS 5950-1, represent the most economical approaches.

Other bolt interaction approaches are distributed between these two extremes. Since carbon steel bolts and duplex stainless steel bolts fail intentionally in the threaded bolt part (as the tensile stress area A_s), the interaction curves are cut at $A_s/A \approx 0.78$ and define an upper tension ratio plateau. However, the design of the tension resistance of bolts from the North American region does not refer to the tensile stress area A_s directly but to 75 % of the gross cross-sectional area A, leading to different horizontal plateaus of the bolt tension resistance, see Figure 3.5-1. In the case of austenitic bolts, tensile failure generally occurs in the unthreaded bolt part, which means that the tension resistance of the bolt shank A can also be utilised. However, the interaction equations do not consider this speciality of austenitic bolts since they were exclusively developed for carbon steel bolts and bolting assemblies (except for the approach of Stranghöner/Abraham for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022, which allows full utilisation of the unthreaded part A of austenitic bolts). Nevertheless, the interaction equations were extrapolated to the tension resistance of the unthreaded bolt part A (dotted line) to allow a direct comparison of the different approaches.

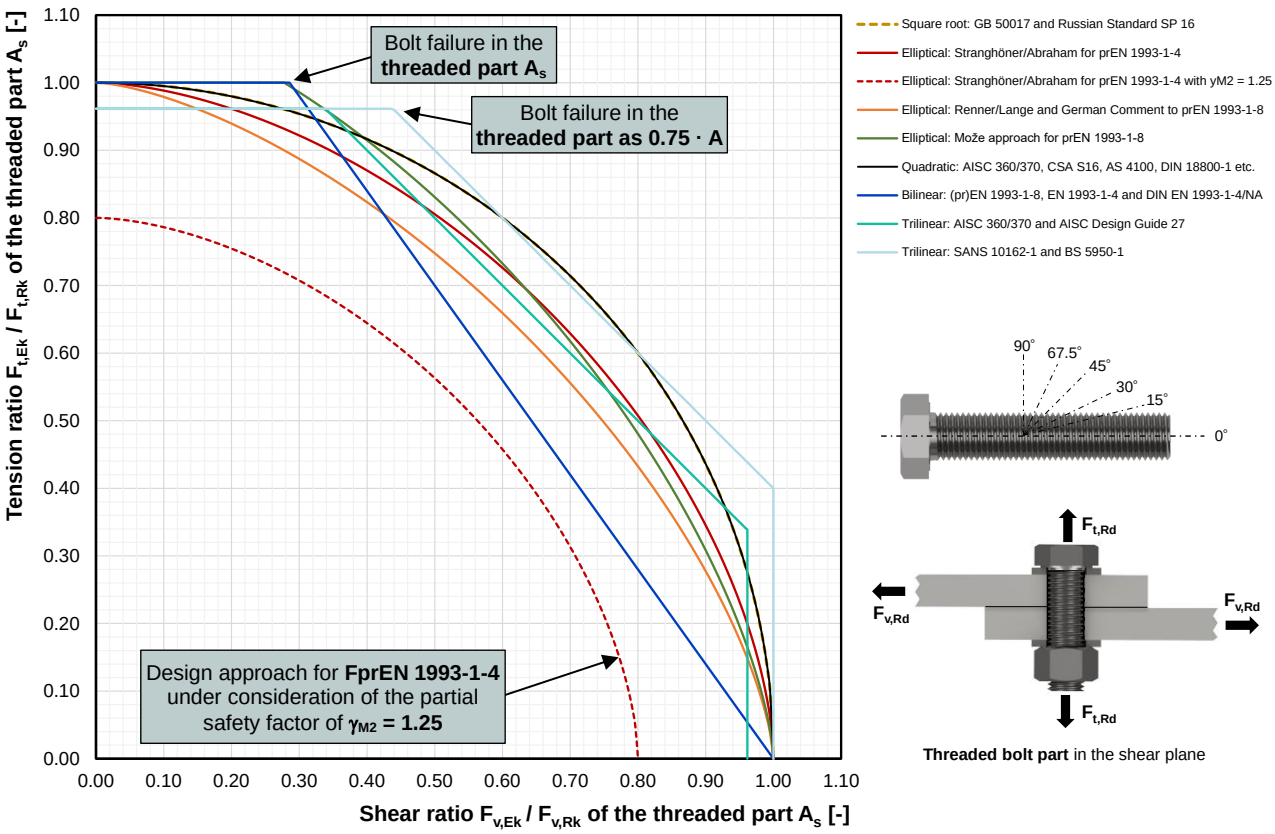


Figure 3.5-2: Graphical comparison of the different design approaches for the interaction resistance per shear plane of carbon or stainless steel bolting assemblies with threaded bolt part in the shear plane

The different interaction equations and approaches for the threaded bolt part in the shear plane are graphically presented in Figure 3.5-2. In contrast to the unthreaded bolt part in the shear plane, the interaction curves are generally closer together, whereby the bilinear approach of EN 1993-1-8 and EN 1993-1-8:2024 (for carbon steel bolts) as well as EN 1993-1-4 and DIN EN 1993-1-4/NA (for stainless steel bolts) are still leading to the smallest load bearing capacities. However, for shear ratios $F_{v,Ek}/F_{v,Rk}$ below ≈ 0.42, the elliptical interaction approach of Renner/Lange and German Comment to EN 1993-1-8:2024 draft even undercuts the bilinear equation. Furthermore, the quadratic interaction and the trilinear interaction equations of SANS 10162-1 and BS 5950-1 represent the highest load bearing capacities. Herein, the trilinear interaction equations of SANS 10162-1 and BS 5950-1 allow a high usage of the tension ratio $F_{t,Ek}/F_{t,Rk}$ about ≈ 0.4 with simultaneous full utilisation of the bolt shear resistance.

Again, the design of the tension resistance of bolts from the North American region is related to 75 % of the gross cross-sectional area A, leading to slightly different horizontal plateaus of the tension ratio $F_{t,Ek}/F_{t,Rk}$.

The extent to which the interaction approaches for the unthreaded and threaded bolt part in the shear plane presented here can adequately describe the interaction load bearing behaviour of bolted connections made of carbon and stainless steel is comprehensively discussed in Chapter 6 (stainless steel bolting assemblies) and Chapter 7 (carbon steel bolting assemblies) based on literature reviews and own experimental investigations.

3.6 Summary and conclusions

Selected international design rules for non-preloaded bolted connections made of carbon and stainless steel were introduced and compared regarding the resulting bolt tension, shear and interaction resistance and summarised to main design approaches. The design rules of stainless steel, in particular bolted connections made of stainless steel, are essentially based on the regulations of bolted connections made of carbon steel: The fundamental design concept is intentionally retained in most cases, with only minor modifications typically leaning towards the conservative side. It was shown that there are considerable differences in the tension, shear and interaction resistance of carbon and stainless steel bolts.

Especially, the following three aspects must be highlighted:

Firstly, in EN 1993-1-8 and EN 1993-1-4, the tension resistance $F_{t,Rd}$ of carbon or stainless steel bolts is reduced to 90 % compared to other international standards, justified by the fact that prying effects must be implicitly taken into account in the design. At the time of the introduction of the Eurocode, a reduction in the bolt tension design concept was necessary to fulfil the safety requirements of the Eurocode. However, high partial safety factors exceeding γ_{M2} = 1.25 for connections are mainly based on nominal tensile strengths implemented in the reliability analyses, as the experimental tensile strengths of the bolts were mainly unknown.

Secondly, the widely differing shear coefficients α in an international comparison for the design of the shear resistance $F_{v,Rd}$ of carbon and stainless steel bolts are striking. In particular, the German guideline VDI 2230 Part 1 contains relatively high shear coefficients, and thus high bolt shear resistances result as characteristic $F_{v,Rk}$ and design values $F_{v,Rd}$.

Thirdly, the pronounced conservative approach of the bilinear interaction equation according to Eurocode 3, especially for the case of "unthreaded bolt part in the shear plane", is striking compared to other international interaction equations. The quadratic bolt interaction or trilinear bolt approach as a simplified expression can be found in many design standards worldwide, allowing a higher utilisation of the interaction resistance compared to the EN 1993-1-8.

The extent to which the different tension, shear and interaction design rules and approaches for the unthreaded and threaded bolt part in the shear plane can adequately describe the load bearing behaviour of bolted connections made of carbon and stainless steel will be discussed in the following chapters.

4 Tension resistance of stainless steel bolts and bolting assemblies

4.1 General

In Chapter 4, an overview of the experimental investigations at UDE-IML complemented by an extended literature review, the proposed design approach and statistical evaluations according to EN 1990, Annex D [79] for the tension resistance $F_{t,Rd}$ of austenitic and duplex bolts and bolting assemblies is provided. Since the testing programmes, test procedures, main results and the statistical evaluations of the German IGF research project FOSTA P 1386 / IGF-No. 20651 N [78] and further investigations have already been published by Stranghöner/ Abraham in [100, 164, 282, 283, 360–364], the experimental investigations and statistical evaluations are only briefly outlined.

Within the framework of the thesis, the main priority are new, supplementary experimental investigations carried out beyond the scope of the German research project in order to extend the database for a more detailed statistical evaluation compared to [282] and to get further knowledge about the differences between:

a) the tension resistance and tensile strength $f_{ub,exp,3506\text{-}1}$ of austenitic and duplex stainless steel bolts determined in a tensile tests on the whole bolt according to EN ISO 3506-1, Clause 9.1 [73] (based on [78]),

b) the tension resistance and tensile strength $f_{ub,exp,15048\text{-}2}$ determined on bolting assemblies (consisting of bolt and nut excluding washers) according to EN 15048-2, Clause 6 [365] (supplementary experimental investigations),

c) the tensile strength $f_{ub,exp,shank}$ of the bolt shank determined by special machined bolts of the unthreaded part of a bolt if failure is occurring in the threaded part and therefore the tensile strength of the unthreaded part is unknown (based on [78]),

d) the tensile strength $f_{ub,exp,threads}$ of the bolt threads determined by tensile tests exclusively on the threaded bolt part, which is separated from the stainless steel bolts (supplementary experimental investigations), and

e) the tensile strength $f_{ub,exp,6892\text{-}1}$ determined by machined tensile test coupon specimens from partially and fully threaded austenitic and duplex bolts according to EN ISO 6892-1 [366] (supplementary experimental investigations).

Furthermore, a characterisation of the type of thread production (rolled or cut threads) and the relevant geometric parameters of the bolts regarding the gross cross-sectional area A and tensile stress area A_s are carried out and complemented by an extended statistical evaluation of the geometrical data.

Finally, within [78], a new and more economical design rule for the tension resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolts was developed and accompanied by reliability analyses according to EN 1990, Annex D to validate the proposed approach against the partial safety factor of $\gamma_{M2} = 1.25$ defined in EN 1993-1-1 [166] and prEN 1993-1-1:2020-08 [367]. However, as a supplement to [282], the conducted reliability analysis in this thesis is now based on an extended literature review (considering 90 instead of 51 tensile test results) and an extended database by 114 additional tensile tests on stainless steel bolting assemblies according to the testing specifications of EN 15048-2 [365]. The extended statistical evaluation is complemented by analyses of the distribution of the resulting partial safety factors γ_M* in order to improve the reliability of the proposed design approach for the tension resistance $F_{t,Rd}$

of austenitic and duplex stainless steel bolts. In total, the statistical evaluations are based on 300 tensile tests on bolts according to EN ISO 3506-1 including literature data. If the tensile tests according to EN 15048-2 on stainless steel bolting assemblies are integrated in the statistical evaluation, in total 414 tensile tests become available to prove the reliability of the proposed design approach.

Finally, Chapter 4 is summarised and conclusions of the experimental investigations and reliability of the new design approach regarding the tension resistance $F_{t,Rd}$ of stainless steel bolts and bolting assemblies are drawn. The proposed new design rules for the tension resistance $F_{t,Rd}$ of stainless steel bolts were already implemented in FprEN 1993-1-4 [80] and the German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022 [81].

4.2 Existing studies into the tension resistance of stainless steel bolts

A literature review regarding studies into the load bearing behaviour of stainless steel bolts under tension, shear and combined tension and shear has already be presented in Chapter 2.5.2 and an overview is given in Table 2.5-2. In the following, only those test data from publications are considered, which give a direct contribution to the tension resistance of stainless steel bolts, and where a clear description of the test procedure, the mechanical properties of the bolts and a classification to European bolt property classes is given. Existing studies into the tension resistance of stainless steel bolts are briefly introduced.

A limited test programme was conducted by the Steel Construction Institute (SCI) in 1990 covering tensile tests on fully threaded austenitic A4-70 (M16) and A4-80 (M16, M20) stainless steel bolting assemblies. In total, 42 tensile tests were conducted and evaluated against the European design rules from EN 1993-1-8 for carbon steel bolts. However, M20 A4-80 series from bolt supplier C does not fulfil the normative required minimum ultimate tensile load F_{mf} significantly with undercutting of ≈ -19 %. Therefore, the eight tensile tests of the M20 A4-80 series from bolt supplier “C” are not considered in the following. On the contrary, the remaining 32 test results clearly exceed the minimum ultimate tensile load F_{mf} of austenitic stainless steel bolts (with exception of one M16 A4-70 series again from bolt supplier “C” with resulting tension resistances slightly lower of ≈ -1.8 % compared to the F_{mf} according to EN ISO 3506-1).

In the framework of the ECSC project 7210-SA/327, experimental investigations into bolted connections made of stainless steel were carried out by Bouchair and Muzeau [268] (1999), The Steel Construction Institute [269] (2000), Ryan [270] (2000) and Bouchaïr et al. [271] (2001). Herein, Ryan [270] conducted in total four tensile tests on partially threaded austenitic stainless steel bolting assemblies (bolts and nuts) A4-80 for each M12×40, M16×50 and M20×50 samples and concluded that the tests are showing a good agreement with the predicted tension resistance taken as $f_{ub,exp} \cdot A_{s,nom}$ *“well above the design requirements of* $0.9 \cdot f_{ub,nom} \cdot A_{s,nom}$*”*. Consequently, the results are considered in the following investigations and in the reliability analysis of the bolt tension resistance $F_{t,Rd}$.

In 2007, the Steel Construction Institute [272] also conducted tensile tests within the frame of the European “Stainless steel in fire (SSIF)” research project. Herein, tensile tests on partially threaded M12×50 A2-70 and A4-80 austenitic stainless steel bolting assemblies at room temperature (as reference) and at various elevated temperatures were carried out in order to simulate fire condition. The tensile test data of the austenitic stainless steel bolts tested at room temperature is considered in the following investigations.

Furthermore, recently Song et al. [5, 6] carried out various experimental and numerical investigations regarding the load bearing behaviour of stainless steel bolted connections under

tension, single-/double-shear and combined tension and shear for austenitic stainless steel bolting assemblies (1.4401, A4-70, A4-80 and 1.4432, PC 8.8 and 10.9) and duplex stainless steel bolting assemblies (1.4462, PC 10.9 and 12.9) in 2020. Herein, Song et al. tested partially threaded (M20, EN ISO 4014) and fully threaded (M16/M20/M24, EN ISO 4017) stainless steel bolting assemblies under loading angles of 0°, 15°, 30°, 45°, 67.5° and 90°. The investigations focused on the failure mode, strength and ductility of the stainless steel bolts under different combinations of tension and shear. The tests were conducted with a test setup comparable to Chesson [221], Bilderbeek [222] and Shakir-Khalil and Ho [225]. However, the investigated duplex bolting assemblies of PC 12.9 did not achieve the normative requirements of the minimum tensile strength min. $R_{mf,12.9}$ in the tensile tests of min. $R_{mf,12.9}$ = 1200 N/mm² according to the product specification of the bolt manufacturer.

The test results from the studies found in the literature review are summarised in Table 4.2-1 including all relevant testing information and a statistical evaluation of the resulting coefficient of variation of each tested series. In case where the tension resistance of the unthreaded (shanked) part of a bolt could not be derived from the literature data directly due to failure of the bolt in the threaded part (cf. Chapter 2.4.7), the results from machined tensile specimens of the stainless steel bolts from the reference were used to calculate the tensile strength of the unthreaded bolt shank $f_{ub,calc,shank}$. Additionally, a graphical representation of the overstrength ratios defined as the mean maximum bolt force $F_{max,0°}$ achieved in the tensile tests compared to the minimum ultimate tensile load F_{mf} according EN ISO 3506-1 is presented in Figure 4.2-1.

Considering this figure, it can be concluded that:

- for austenitic stainless steel bolts, the resulting mean overstrength ratios $F_{max,0°}$ / F_{mf} from literature of the tension resistance are between 0.984 and remarkable high of 1.322. The lowest ratio is based on M16 A4-70 bolting assemblies slightly undercutting the requirement of the minimum ultimate tensile load F_{mf}, while the highest overstrength ratio can be found in M20 partially threaded A4-8.8 bolting assemblies,
- for duplex stainless steel bolts, the resulting mean overstrength ratios $F_{max,0°}$ / F_{mf} from literature of the tension resistance are between 0.949 (fully threaded M20×140 D6-12.9 bolting assemblies) and 1.040 (partially threaded M20×140 D6-12.9 bolting assemblies) and therefore significantly lower compared to the bolts made of austenitic stainless steel from literature. To what extent these differences in overstrength between austenitic and duplex can be confirmed by own experimental investigations has to be checked in the following investigations.

Table 4.2-1: Summary of the literature review regarding the tension resistance of stainless steel bolts (additionally added publications compared to [282] are marked in bold in the table)

Steel type	Property class acc. to EN ISO 3506-1	Corrosion class acc. to EN ISO 3506-1	Publication	Bolt type	Bolt geometry	Testing type (B= Bolt, BA = Bolting assembly)	Number of tests	$f_{ub,calc,As}$ [N/mm²]	$f_{ub,calc,shank}$ [N/mm²]	Mean $F_{max,0°}$ [kN]	Coefficient of variation $F_{max,0°}$	Overstrength ratio of Mean $F_{max,0°}$ / F_{mf}	Failure mode
Austenitic	PC 70	A2-70	**SCI** [272] (2007)	Partially threaded	M12×50	BA	1	747.7	-	63.0	-	1.068	T
		A4-70	**SCI** [266] (1990)	Fully threaded	M16×-	BA	6	689.4	-	108.0	1.85%	0.984	T
			Song et al. [5] (2020)	Fully threaded	M16×100	BA	3	732.1	-	114.7	1.12%	1.046	T
					M20×100	BA	3	796.2	-	194.9	0.30%	1.137	T
					M24×100	BA	3	824.4	-	290.6	0.85%	1.178	T
				Partially threaded	M20×100	BA	3	855.4	659.0[2)]	209.4	1.15%	1.222	S
	PC 80	A4-80		Fully threaded	M20×100	BA	3	832.7	-	204.0	1.44%	1.041	T
				Partially threaded	M20×100	BA	3	923.2	712.0[2)]	226.0	0.43%	1.154	S
			SCI [266] (1990)	Fully threaded	M16×-	BA	15	859.2	-	134.6	1.49%	1.074	T
				Fully threaded	M20[1)]×-	BA	13	873.4	-	213.8	0.94%	1.091	T
			Ryan [270] (2000)	Partially threaded	M12×-	BA	4	846.2	-	71.3	0.62%	1.058	-
					M16×-	BA	4	931.3	-	145.9	1.31%	1.163	-
					M20×-	BA	4	845.6	-	207.0	1.79%	1.057	-
			SCI [272] (2007)	Partially threaded	M12×50	BA	2	897.2	-	75.6	3.74%	1.121	T
	PC 8.8	A4-8.8	Song et al. [6] (2020)	Fully threaded	M20×140	BA	3	1029.0	-	251.9	0.15%	1.286	T
				Partially threaded	M20×140	BA	3	1057.6	824.8[2)]	258.9	0.08%	1.322	T
	PC 10.9	A4-10.9		Fully threaded	M20×140	BA	2	1074.4	-	263.0	2.82%	1.074	T
				Partially threaded	M20×140	BA	3	1098.9	925.8[2)]	269.0	0.18%	1.099	T
Duplex	PC 10.9	D6-10.9	Song et al. [6] (2020)	Fully threaded	M20×140	BA	3	1039.6	-	254.5	0.82%	1.040	T
				Partially threaded	M20×140	BA	3	1033.9	809.9[2)]	253.1	0.49%	1.034	T
	PC 12.9[3)]	D6-12.9		Fully threaded	M20×140	BA	3	1139.7	-	279.0	0.28%	0.949	T
				Partially threaded	M20×140	BA	3	1158.1	903.0[2)]	283.5	0.17%	0.964	T
Σ Total number of tensile tests on austenitic bolting assemblies							78	$F_{max,0°}$ / F_{mf} | min./max.				0.984/1.322	
Σ Total number of tensile tests on duplex bolting assemblies							12	$F_{max,0°}$ / F_{mf} | min./max.				0.949/1.040	
Σ Total number of tensile tests on bolting assemblies							**90**	$F_{max,0°}$ / F_{mf} | min./max.				0.949/1.322	

[1)] Tensile tests on M20 A4-80 bolts from supplier C are not considered as the bolts clearly fail the requirements of PC 80. | [2)] Tensile strength of the bolt shank $f_{ub,calc,shank}$ on the safe side taken from machined tensile specimens. | [3)] Resulting tensile strength $f_{ub,calc,mean}$ < nom. $f_{ub,12.9}$ = 1200 N/mm² and min. $R_{mf,12.9}$ = 1220 N/mm², therefore PC 12.9 could not be confirmed.

The graphical comparison of the experimental/nominal overstrength ratio of the bolt tension resistance in Figure 4.2-1 also highlights in red colour if the requirements of EN ISO 3506-1 of the minimum ultimate tensile load F_{mf} (shown as a dotted reference line) are not fulfilled.

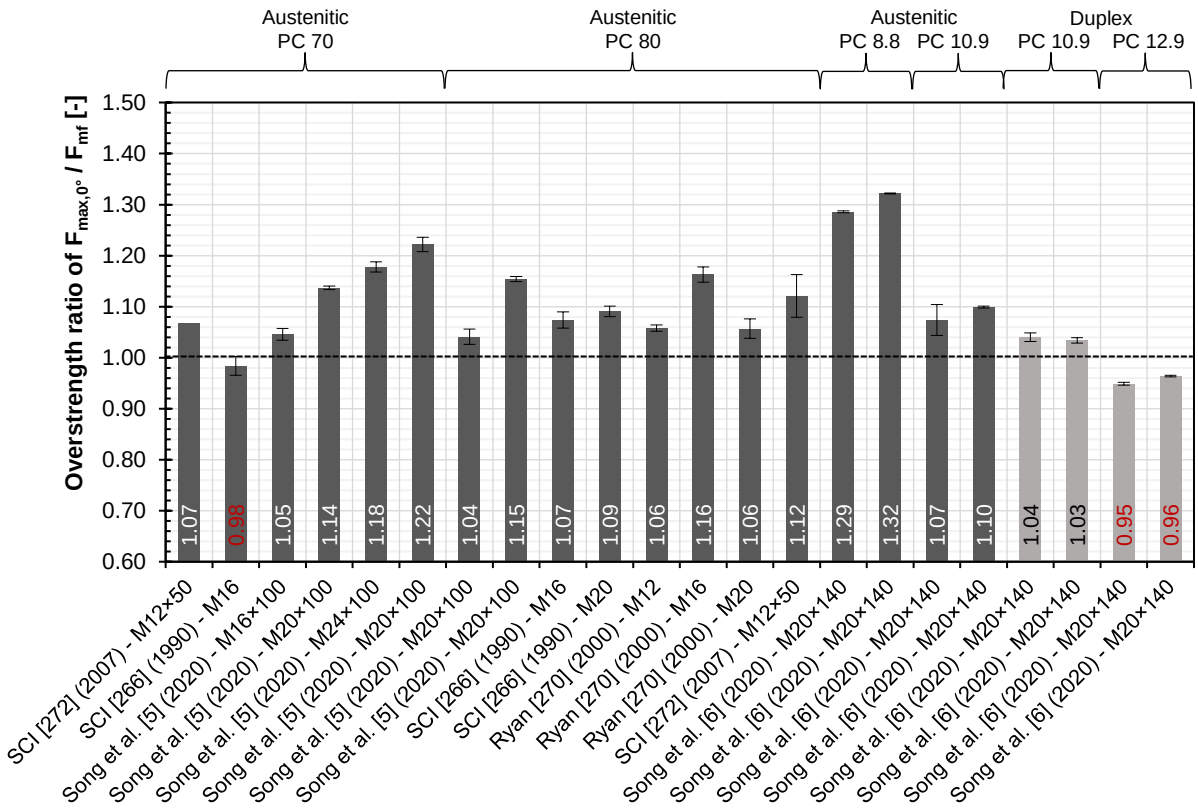


Figure 4.2-1: Overstrength ratios of the tested series from literature review regarding the tension resistance of stainless steel bolts

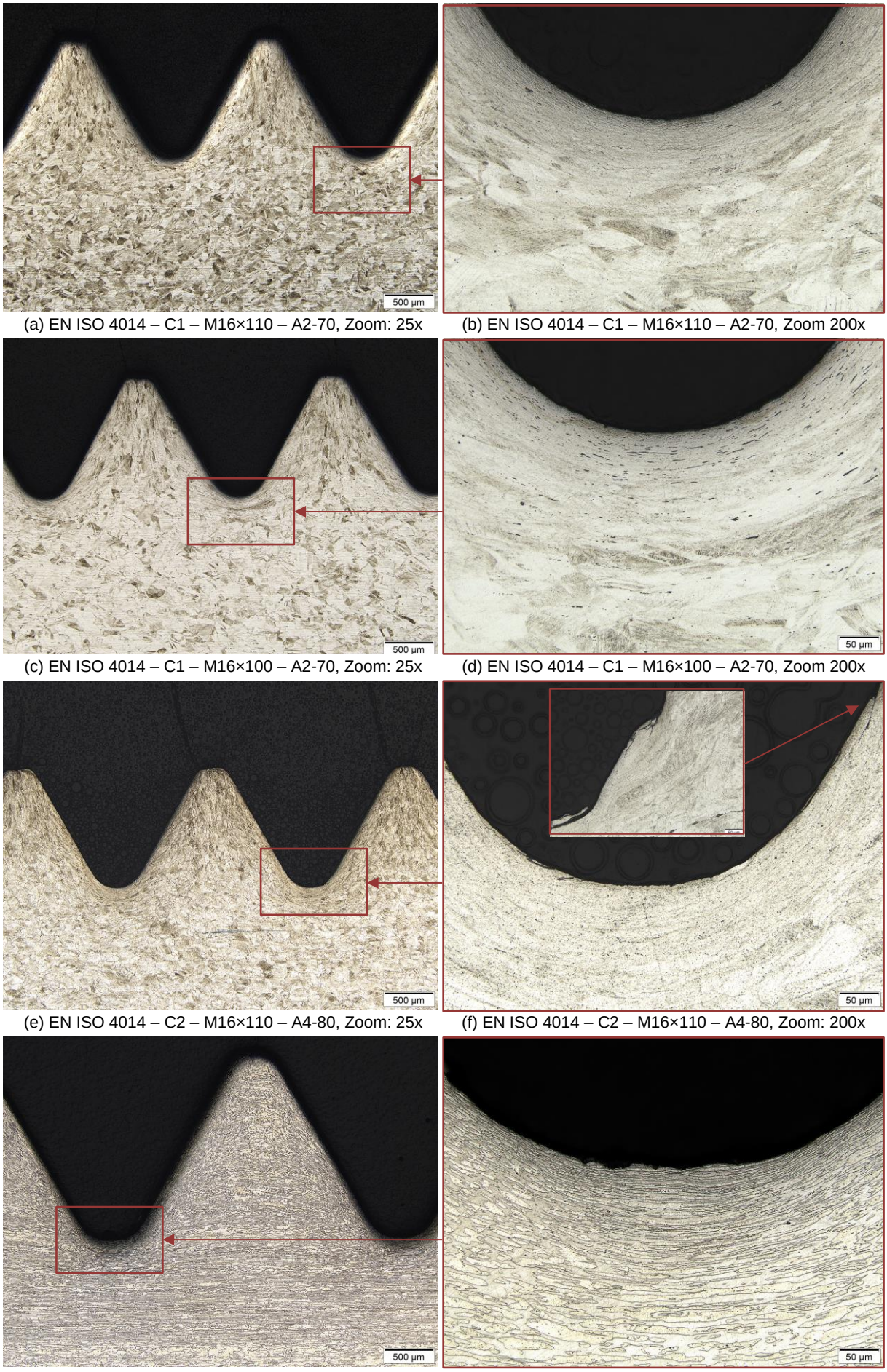
4.3 Characterisation of material and geometric parameters of the bolts

4.3.1 General

As preliminary work for the following experimental investigations, a characterisation of the material and geometric parameters of the bolts are required as input parameters of the reliability analysis in the term of material and geometrical basic variables. Therefore, a characterisation of the type of thread production (Chapter 4.3.2) and the relevant geometric parameters (Chapter 4.3.3) of the unthreaded and threaded part of bolts are carried out and complemented by a detailed statistical evaluation covering in advance all test specimens as partially and fully threaded austenitic and duplex stainless steel bolts for the tension, single-shear, double-shear and interaction tests.

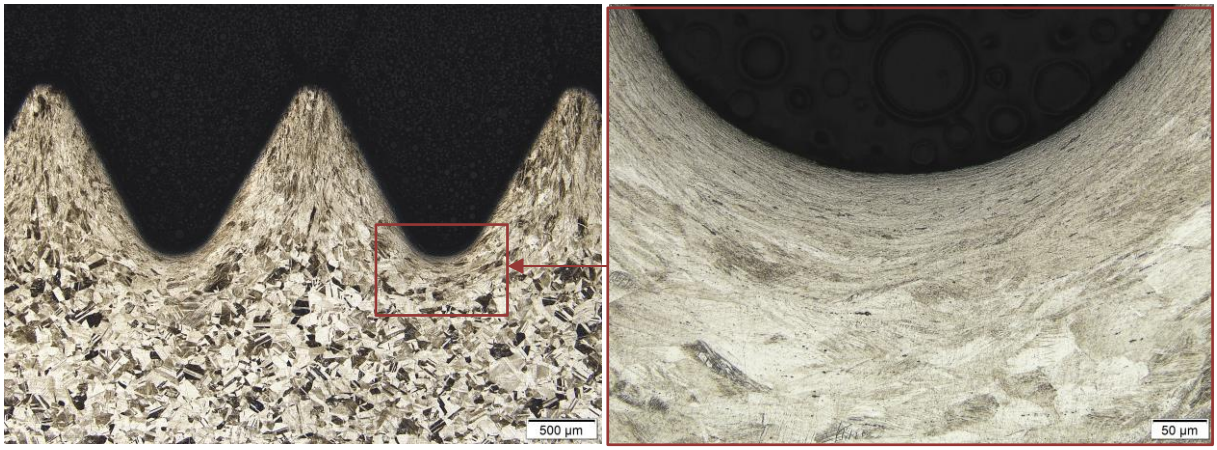
4.3.2 Determination of the thread production type

In order to be able to make a clear definition for each tested bolt series whether the threaded part was produced by cutting or rolling process, in the frame of [78], the bolt manufacturers, traders or distributors were contacted. If a clear specification of the type of thread production was not possible, microsections of the outstanding partially and fully threaded stainless steel bolts were made and evaluated regarding the thread production type. Selected microsections of partially and fully threaded austenitic and duplex bolts in different property classes are presented in Figure 4.3-1 and Figure 4.3-2.

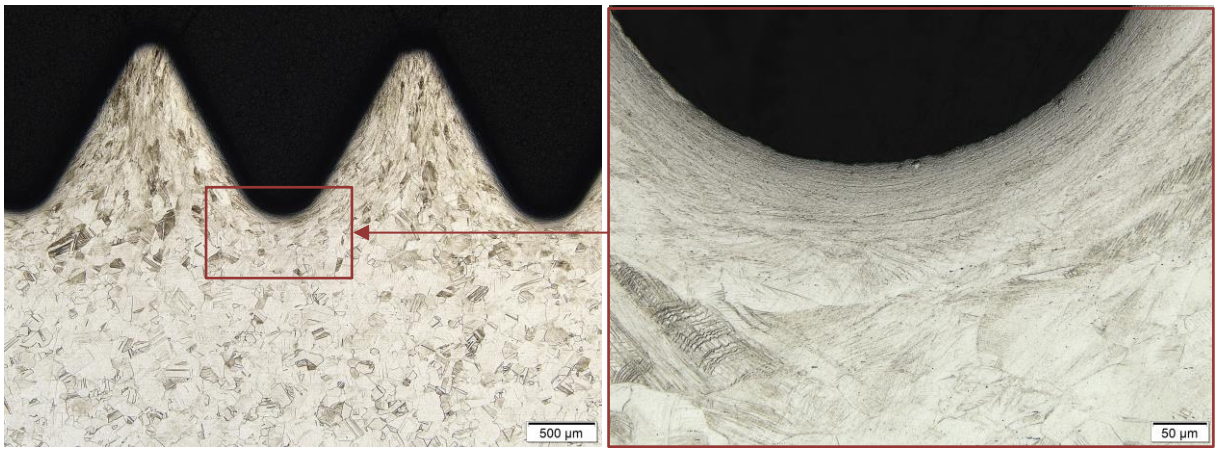


(a) EN ISO 4014 – C1 – M16×110 – A2-70, Zoom: 25x
(b) EN ISO 4014 – C1 – M16×110 – A2-70, Zoom 200x
(c) EN ISO 4014 – C1 – M16×100 – A2-70, Zoom: 25x
(d) EN ISO 4014 – C1 – M16×100 – A2-70, Zoom 200x
(e) EN ISO 4014 – C2 – M16×110 – A4-80, Zoom: 25x
(f) EN ISO 4014 – C2 – M16×110 – A4-80, Zoom: 200x
(g) EN ISO 4014 – C5 – M24×130 – D6-70, Zoom: 25x
(h) EN ISO 4014 – C5 – M24×130 – D6-70, Zoom: 200x

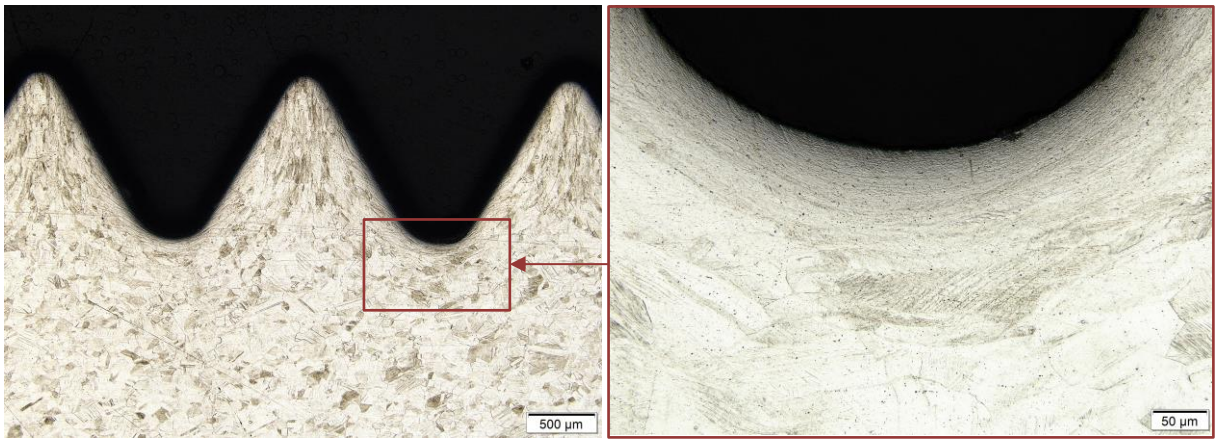
Figure 4.3-1: Microsections of partially threaded stainless steel bolts (P 1386 / IGF-No. 20651 N [78]); © UDE-IML



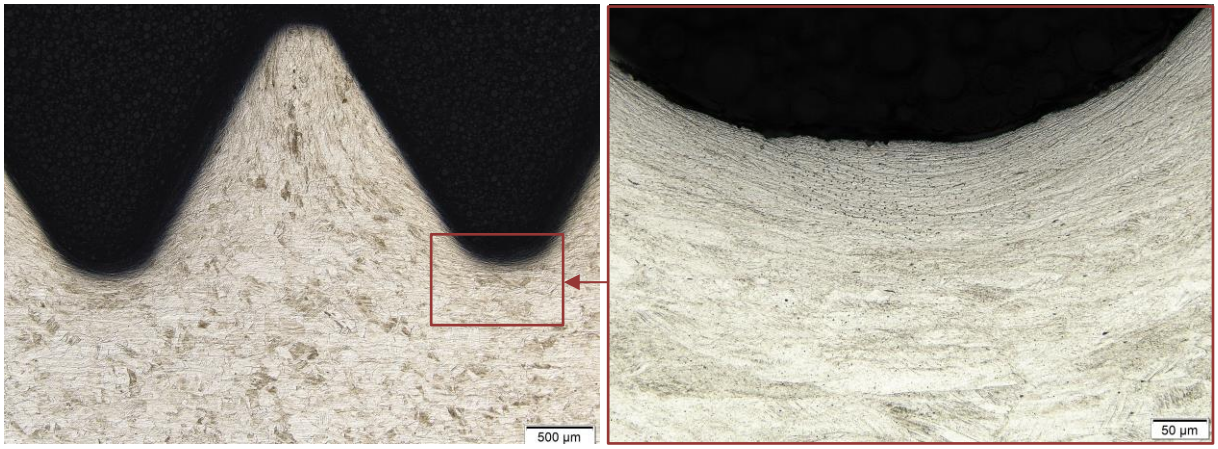
(a) EN ISO 4017 – C1 – M16×100 – A2-70, Zoom: 25x (b) EN ISO 4017 – C1 – M16×100 – A2-70, Zoom: 200x



(c) EN ISO 4017 – C2 – M16×100 – A4-70, Zoom: 25x (d) EN ISO 4017 – C2 – M16×100 – A2-80, Zoom: 200x



(e) EN ISO 4017 – C2 – M16×100 – A4-80, Zoom: 25x (f) EN ISO 4017 – C2 – M16×100 – A4-80, Zoom: 200x

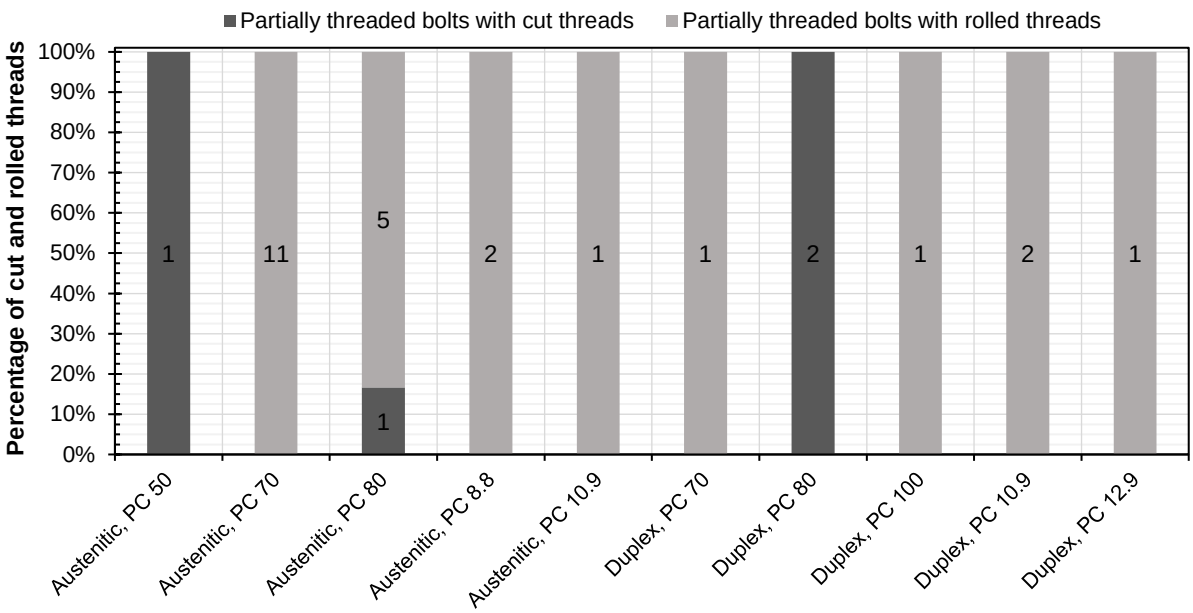


(g) EN ISO 4017 – C2 – M24×130 – A4-80, Zoom: 25x (h) EN ISO 4017 – C2 – M24×130 – A4-80, Zoom: 200x

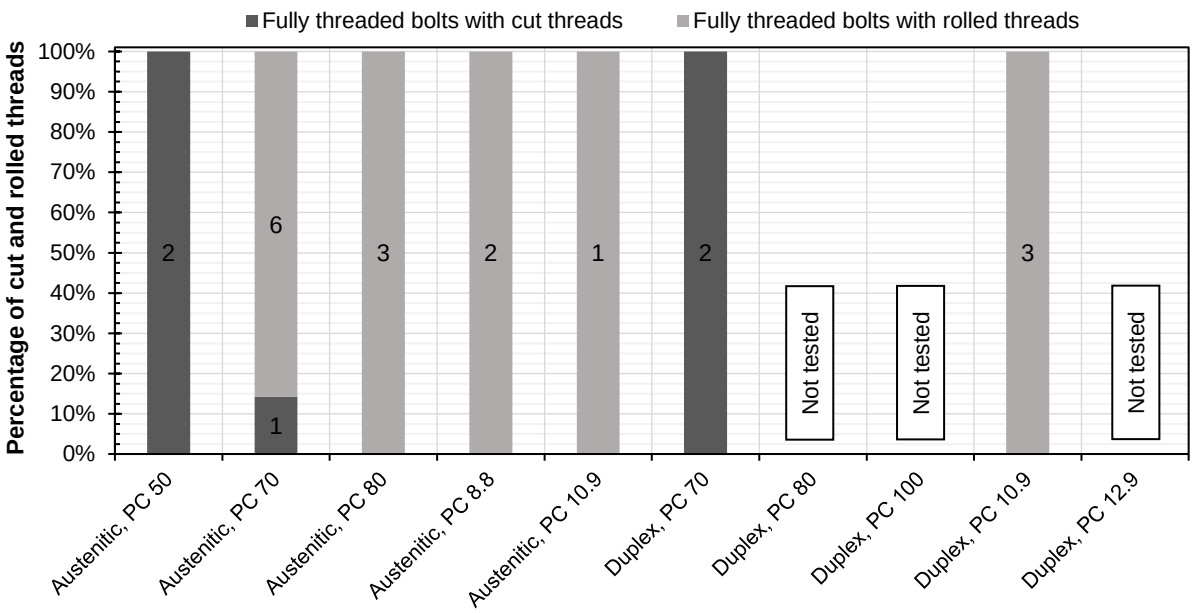
Figure 4.3-2: Microsections of fully threaded stainless steel bolts (P 1386 / IGF-No. 20651 N [78]); © UDE-IML

Although bolts made of stainless steel are produced on a much smaller scale compared to carbon steel bolts and often only produced as custom-made products, it could be shown that the majority of the bolts intended to be used for testing are made by rolling process. Beside the high dimensional accuracy of the rolled threads, cold rolling threads are also characterised by reduced notch sensitivity and show superior fatigue behaviour due to induced compressive stresses during the rolling process [63].

An overview of the tested bolt series and the related thread production type is given in [78]. Furthermore, in the following experimental investigations always the thread production type of each tested series is provided. Figure 4.3-3 shows a summary of all different bolt steel types and property classes to be tested in the following experimental investigations. In total, 28 configurations of partially threaded as well as 20 configurations of fully threaded austenitic and duplex stainless steel bolts were considered. Only a minority of four configurations of partially threaded bolts and five configurations of fully threaded bolts with cut threads were examined.



(a) Summary of partially threaded stainless steel bolt series with cut and rolled threads



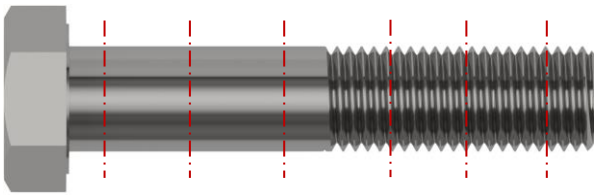
(b) Summary of fully threaded stainless steel bolt series with cut and rolled threads

Figure 4.3-3: Summary of partially and fully threaded stainless steel bolt series with cut and rolled threads

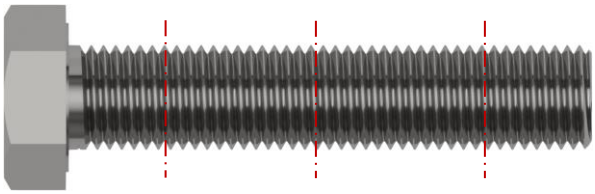
4.3.3 Measurement and statistical evaluation of main geometric parameters

For the interpretation of the test results, especially in the context of the shear capacity $F_{v,Rd}$ and for the determination of the resulting shear coefficients but also for the tension and interaction resistance, it is important to measure and quantify the material-specific and geometric variables according to the evaluated design approach in advance. While the tensile strength of austenitic and duplex stainless steel bolts as material-specific basic variable is determined and evaluated in a tensile test on the whole bolt (cf. Chapter 4.4.2) according to EN ISO 3506-1, the measurement and statistical evaluation of the main geometric bolt parameters are presented in the following. Compared to the evaluations regarding the geometrical parameters carried out in [164] and [282], the database was significantly extended and complemented by statistical in-depth analyses of the resulting measured cross-sectional areas A and A_s.

The measured geometrical bolt dimensions are in detail the diameter d of the unthreaded, shanked bolt part for calculating the gross cross-section A_{meas}, the basic pitch diameter of the external thread d_2, see ISO 724 [368], and the minor diameter of the external thread d_3, see ISO 724 and ISO 68-1 [369], for the calculation of the measured tensile stress area of the bolt $A_{s,meas}$. The basic variables of the geometrical dimensions have been measured with a digital caliper and micrometre gauges at several defined points of each partially or fully threaded bolt, schematically presented in Figure 4.3-4. In total, six individual values (as two measurements rotated by 90° at each of the three defined measurement points) are measured for each of the unthreaded, shanked and threaded part leading to $A_{meas,i}$ and $A_{s,meas,i.}$ of each bolt.



(a) Defined measurement points for the unthreaded and threaded part of partially threaded bolts



(b) Defined measurement points for the threaded part of fully threaded bolts

(c) Measurement by digital caliper and micrometre gauges

Figure 4.3-4: Definition of measurement points and measurement of the geometrical dimensions by digital caliper and micrometre gauges; © UDE-IML

The calculation of the gross cross-section $A_{meas,i}$ of the individual shank diameter $d = d_s$ of partially threaded bolts according to EN ISO 4014 and EN ISO 4762 as the basic variable of the geometrical dimensions was carried out by (Eq. 4.3-1).

$$A_{meas,i} = \frac{\pi \cdot d_{meas}^{2}}{4} \qquad \text{(Eq. 4.3-1)}$$

The calculation of the tensile stress area $A_{s,meas,i}$ for all partially threaded and full threaded bolts was calculated according to EN ISO 3506-1 by (Eq. 4.3-2).

$$A_{s,meas,i} = \frac{\pi}{4} \cdot \left(\frac{d_{2,meas} + d_{3,meas}}{2} \right)^2 \qquad \text{(Eq. 4.3-2)}$$

with

$d_{2,meas}$: measured basic pitch diameter of the external thread, see ISO 724, and

$d_{3,meas}$: measured minor diameter of the external thread, see ISO 724 and ISO 68-1.

Furthermore, a statistical evaluation of the measured cross-sectional areas A_{meas} and $A_{s,meas}$ is conducted and compared with the nominal values A_{nom} and $A_{s,nom}$. In order to evaluate the scattering between the nominal and measured geometrical dimensions, the "Least Squares" best-fit method following EN 1990, Annex D has been applied and the mean value correction factor b has been evaluated according to (Eq. 4.3-3) as the mean value correction factor b_A for the gross cross-section A and (Eq. 4.3-4) as the mean value correction factor b_{As} for the tensile stress area A_s:

$$b_A = \frac{\sum A_{meas,i} \cdot A_{nom}}{\sum A_{nom}^{\ 2}} \quad \text{as mean value correction factor } b_{A,} \qquad \text{(Eq. 4.3-3)}$$

$$b_{As} = \frac{\sum A_{s,meas,i} \cdot A_{s,nom}}{\sum A_{s,nom}^{\ 2}} \quad \text{as mean value correction factor } b_{As.} \qquad \text{(Eq. 4.3-4)}$$

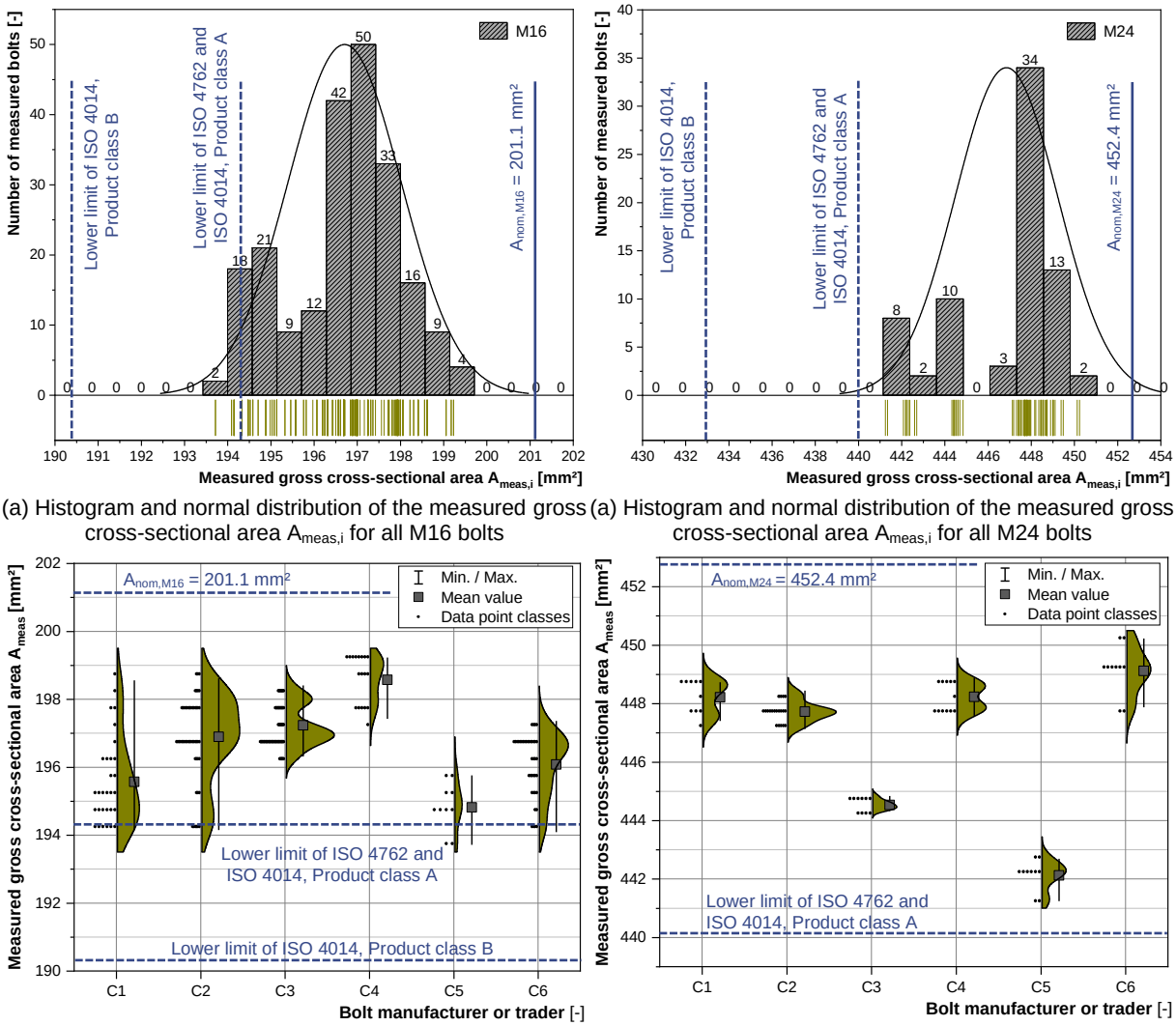
The results of the extended statistical evaluation of the scattering of the measured gross cross-section A_{meas} and the tensile stress area $A_{s,meas}$ for partially and threaded bolts (EN ISO 4014 and EN ISO 4762) and fully threaded bolts (EN ISO 4017) including the intended testing type and the mean value correction factors b_A and b_{As} are summarised in Table 4.3-2 (A_{meas}) and Table 4.3-2 ($A_{s,meas}$). Furthermore, the scatterings of the measured gross cross-section A and the tensile stress area A_s over all bolts were statistically evaluated and graphically presented in Figure 4.3-5 and Figure 4.3-6.

Table 4.3-1: Statistical evaluation of the measured gross cross-sectional area A_{meas} as geometrical basic variable

Gross cross-sectional area of EN ISO 4014 and EN ISO 4762 partially threaded bolts									
Testing type	Bolt diameter	Number of specimens	A_{nom} [mm²]	$A_{meas,mean}$ [mm²]	$\sigma^{1)}$ [mm²]	COV[2)] [%]	$\Delta A_{meas,mean}/A_{nom}$ [%]	b_A[3)]	b_A[3)]
Single-shear tests	M16	84	201.1	196.6	1.3	0.67	2.20	0.9780	0.9846
	M24	36	452.4	446.8	2.4	0.54	1.23	0.9846	
Double-shear tests	M16	48	201.1	197.0	0.9	0.46	2.00	0.9800	-
	M24	-	-	-	-	-	-	-	
Tensile tests acc. to 3506-1	M16	84	201.1	196.9	1.5	0.75	2.22	0.9778	0.9878
	M24	36	452.4	446.9	2.4	0.53	1.22	0.9878	
Total	**M16**	**216**	201.1	196.7	1.3	**0.67**	2.17	0.9783	0.9843
	M24	**72**	452.4	446.9	2.4	**0.53**	1.22	0.9843	

[1)] Standard deviation σ | [2)] Coefficient of variation (COV) | [3)] Mean value correction factor b of nominal and measured geometrical dimension A according to (Eq. 4.3-3).

The statistical evaluation over all austenitic and duplex stainless steel bolts show remarkably low coefficients of variation (COV) of less than 1 % for the measured gross cross-sectional area A_{meas} of the partially threaded bolts according to EN ISO 4014 and EN ISO 4762 (0.67 % for M16 and 0.53 % for M24) with a mean value correction factor b_{As} of 0.9843. As summarised in Table 4.3 2, the maximum difference between the measured gross cross-sectional areas area A_{meas} and the nominal gross cross-sectional area A_{nom} is about 2.22 % for M16 stainless steel bolts.



(a) Histogram and normal distribution of the measured gross cross-sectional area $A_{meas,i}$ for all M16 bolts

(a) Histogram and normal distribution of the measured gross cross-sectional area $A_{meas,i}$ for all M24 bolts

(c) Scatter plots of the measured gross cross-sectional area $A_{meas,i}$ of different bolt manufacters and traders for M16

(d) Scatter plots of the measured gross cross-sectional area $A_{meas,i}$ of different bolt manufacters and traders for M24

Figure 4.3-5: Visualisation of the scattering of the measured gross cross-sectional area A_{meas} for M16 (a, c) and M24 (b, d) partially threaded bolts

For M16 and M24 partially threaded bolts according to EN ISO 4014 and EN ISO 4762, the nominal gross cross-sectional areas of $A_{nom,M16}$ = 201.1 mm² and $A_{nom,M24}$ = 452.4 mm² are equal to the maximum allowed gross cross-sectional areas according to the product standards of the bolts. The minimum allowed gross cross-sectional area for M16 structural bolts is $A_{min,M16}$ = 190.4 mm² according to EN ISO 4014 (product class B) or $A_{min,M16}$ = 194.3 mm² for EN ISO 4014 (product class A) and EN ISO 4762 bolts. For M24 bolts, the minimum allowed gross cross-sectional area is in the amount of $A_{min,M24}$ = 433.0 mm² according to EN ISO 4014 (product class B) or $A_{min,M24}$ = 440.0 mm² for EN ISO 4014 (product class A) and EN ISO 4762 bolts. It can be seen in Figure 4.3-5 that all partially threaded bolts in bolt diameter M24 are fulfilling the requirements of the product standards regarding the gross cross-sectional area. Thus, the EN ISO 4014 bolts can be classified as bolts of product class A. On the contrary, some of the M16 partially threaded bolts slightly undercut the EN ISO 4014 product standard requirements regarding product class A and have to be classified as product class B. However, all EN ISO 4762 bolts fulfil the requirements of product class A.

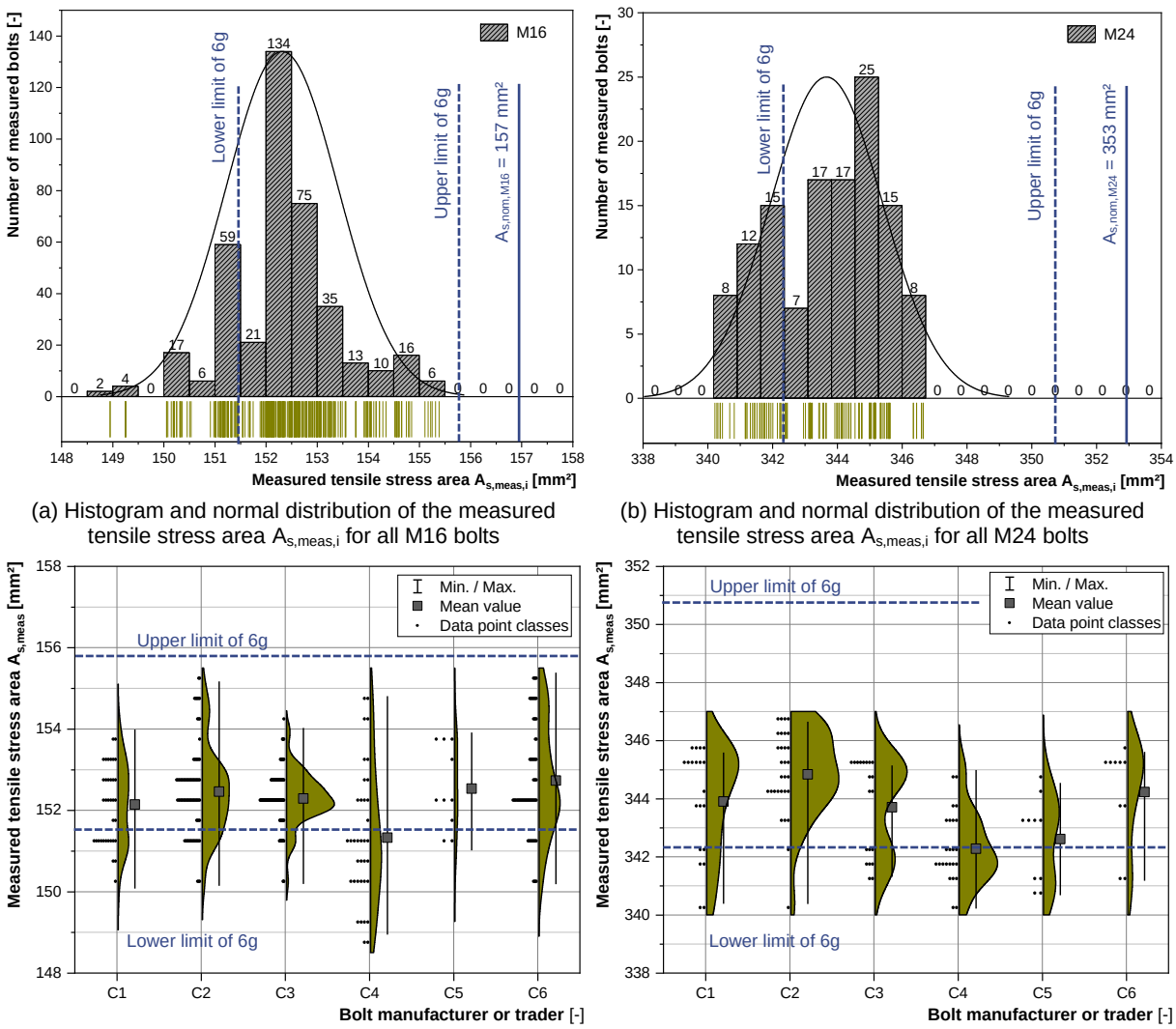
The practical implications are that reduced tension, shear and interaction resistances are presumably achieved for these bolts in the following experimental investigations, which is on the safe side and indicating a heterogeneous composition of the test specimens.

Table 4.3-2: Statistical evaluation of the measured tensile stress area $A_{s,meas}$ as geometrical basic variable

Tensile stress area of EN ISO 4014 and EN ISO 4762 partially threaded bolts									
Testing type	Bolt diameter	Number of specimens	$A_{s,nom}$ [mm²]	$A_{s,meas,mean}$ [mm²]	$\sigma^{1)}$ [mm²]	COV[2)] [%]	$\Delta A_{s,meas,mean}/A_{s,nom}$ [%]	b_{As}[3)]	b_{As}[3)]
Single-shear tests	M16	84	157	152.6	1.3	0.86	2.80	0.9720	0.9715
	M24	36	353	342.9	1.5	0.45	2.87	0.9713	
Double-shear tests	M16	48	157	152.5	1.0	0.63	2.90	0.9710	-
	M24	-	-	-	-	-	-	-	
Tensile tests acc. to 3506-1	M16	84	157	152.5	1.3	0.87	2.86	0.9714	0.9712
	M24	36	353	342.8	1.5	0.44	2.89	0.9711	
Total	**M16**	**216**	157	152.5	1.2	**0.82**	2.84	0.9716	0.9713
	M24	**72**	353	342.8	1.5	**0.44**	2.88	0.9712	
Tensile stress area of EN ISO 4017 fully threaded bolts									
Testing type	Bolt diameter	Number of specimens	$A_{s,nom}$ [mm²]	$A_{s,meas,mean}$ [mm²]	$\sigma^{1)}$ [mm²]	COV[2)] [%]	$\Delta A_{s,meas,mean}/A_{s,nom}$ [%]	b_{As}[3)]	b_{As}[3)]
Single-shear tests	M16	64	157	152.0	0.9	0.62	3.19	0.9681	0.9740
	M24	26	353	344.8	1.3	0.38	2.32	0.9768	
Double-shear tests	M16	54	157	152.2	0.3	0.21	3.06	0.9692	-
	M24	-	-	-	-	-	-	-	
Tensile tests acc. to 3506-1	M16	64	157	152.0	0.9	0.62	3.19	0.9681	0.9740
	M24	26	353	344.8	1.3	0.38	2.32	0.9768	
Total	**M16**	**128**	157	152.0	0.8	**0.53**	3.15	0.9685	0.9734
	M24	**52**	353	344.8	1.3	**0.38**	2.32	0.9768	
Statistical evaluation over all bolts									
Testing type	Bolt diameter	Number of specimens	$A_{s,nom}$ [mm²]	$A_{s,meas,mean}$ [mm²]	$\sigma^{1)}$ [mm²]	COV[2)] [%]	$\Delta A_{s,meas,mean}/A_{s,nom}$ [%]	b_{As}[3)]	b_{As}[3)]
Shear + tensile	**M16**	**398**	157	152.3	1.1	**0.72**	2.99	0.9701	0.9722
	M24	**124**	353	343.7	1.7	**0.50**	2.65	0.9735	

[1)] Standard deviation σ | [2)] Coefficient of variation (COV) | [3)] Mean value correction factor b of nominal and measured geometrical dimension A_s according to (Eq. 4.3-4).

In conclusion, the statistical evaluation of austenitic and duplex stainless steel bolts shows very small coefficients of variation (COV) of less than 1 % for the measured tensile stress area $A_{s,meas}$ of the partially threaded bolts according to EN ISO 4014 and EN ISO 4762 (0.82 % for M16 and 0.44 % for M24) and fully threaded bolts according to EN ISO 4017 (0.53 % for M16 and 0.38 % for M24). Over all partially and fully threaded stainless steel bolts, the coefficients of variation are about 0.72 % for M16 and 0.50 % for M24 with a mean value correction factor b_{As} of 0.9722. As it can be seen in Table 4.3-2, the maximum difference between the measured tensile stress area $A_{s,meas}$ and the nominal tensile stress area $A_{s,nom}$ is about 3.19 % for EN ISO 4017 fully threaded stainless steel bolts M16. In principle, the deviations result mainly from the tolerance class 6g of external threads (bolts) according to ISO 965-1, which was achieved for nearly all tested M16 stainless steel bolts with measured tensile stress areas of 151.5 mm² ≤ $A_{s,meas,mean,M16}$ = 152.3 mm² ≤ 155.8 mm² as well as for M24 bolts in the amount of 342.4 mm² ≤ $A_{s,meas,mean,M24}$ = 343.7 mm² ≤ 350.9 mm². The resulting scatterings of the measured tensile stress area $A_{s,meas}$ for bolt diameter M16 and M24 are graphically presented in Figure 4.3-6 as histograms and scatter plots.



(a) Histogram and normal distribution of the measured tensile stress area $A_{s,meas,i}$ for all M16 bolts

(b) Histogram and normal distribution of the measured tensile stress area $A_{s,meas,i}$ for all M24 bolts

(c) Scatter plots of the measured tensile stress area $A_{s,meas,i}$ of different bolt manufacturer and traders for M16

(d) Scatter plots of the measured tensile stress area $A_{s,meas,i}$ of different bolt manufacters and traders for M24

Figure 4.3-6: Visualisation of the scattering of the measured tensile stress area $A_{s,meas}$ for M16 and M24 partially and fully threaded bolts

It could be shown that partially undercutting of tolerance class 6g of bolt dimension M16 and M24 occurred, which mainly results from bolt manufacturer C4, see Figure 4.3-6 (c). These bolts were manufactured as special production only for the German research project FOSTA P 1386 / IGF-No. 20651 N. Nevertheless, also partially undercutting of the threaded part could be observed for other bolt manufacturers and traders. Nevertheless, the experimental results of these bolts achieved in the tension, shear and interaction tests are again on the safe side due to partially undercutting of the tensile stress areas.

However, due to the low scattering of the gross cross-sectional area A_{meas} and the measured tensile stress area $A_{s,meas}$, it was decided not to repeat the time-consuming procedure of measuring the geometrical bolt parameters for the tensile tests according to EN ISO 3506-1 subjected to low and elevated temperatures, tensile tests on bolting assemblies according to EN 15048-2 as well as interaction tests. However, to consider the scattering of the geometrical basic variables within the following reliability analyses according to EN 1990, Annex D for the tension, shear and interaction resistance of stainless steel bolts, a coefficient of variation of 1 % was assumed as maximum value on the clearly safe side for both the gross cross-section A and the tensile stress area A_s. Further information can be found in Chapter 4.7.5.

4.4 Experimental investigations: Tensile test programme and test procedures

4.4.1 General

The test programme and procedures of the experimental investigations regarding the tension resistance of austenitic and duplex stainless steel bolts are presented in the following. The main objectives are to extend the database for a more detailed and extended reliability analysis compared to [282] and to evaluate different aspects and differences of the tension resistance of stainless steel bolts in an in-depth analysis. The main results of the experimental investigations from the German research project FOSTA P 1386 / IGF-No. 20651 N [78] are presented and supplemented by new, independent research activities embedded in the thesis considering:

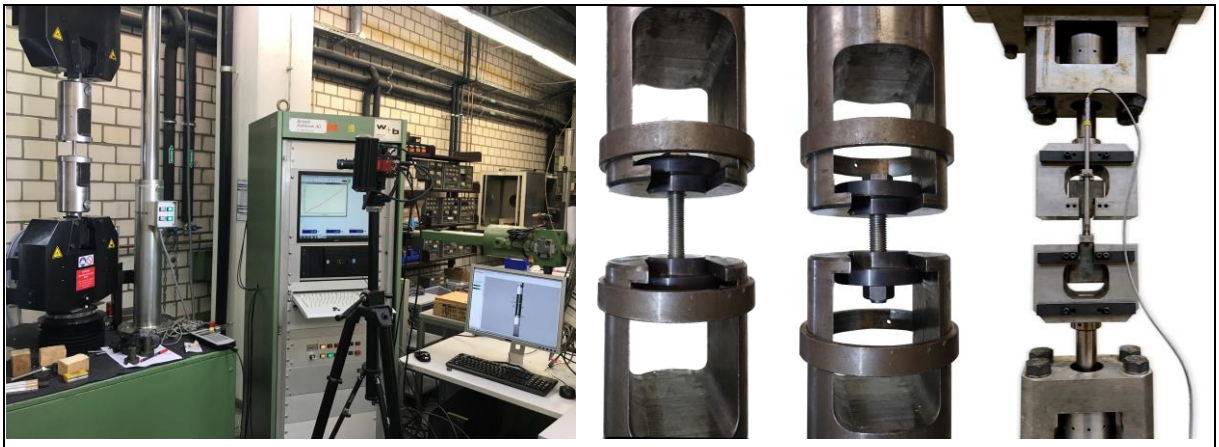
- Tensile tests on stainless steel bolts according to EN ISO 3506-1 (based on [78]),
- Tensile tests on bolting assemblies made of stainless steel according to EN 15048-2 (supplementary experimental investigations),
- Modified tensile tests on machined bolts to determine the tensile strength of the bolt shank $f_{ub,exp,shank}$ (based on [78]),
- Modified tensile tests exclusively on the threaded bolt part separated from the stainless steel bolts to determine the tensile strength of the bolt threads $f_{ub,exp,threads}$ (supplementary experimental investigations),
- Tensile coupon test specimens machined from M16 stainless steel bolts according to EN ISO 6892-1 to determine the tensile strength of the bolt core $f_{ub,exp,core}$ (supplementary experimental investigations),

4.4.2 Tensile tests on stainless steel bolts according to EN ISO 3506-1

In the framework of [78] and already published in [282], 120 tensile tests on the whole bolt with EN ISO 4014 and EN ISO 4762 bolts as well as 90 tensile tests with EN ISO 4017 bolts in bolt dimensions M16×100/110 and M24×130 were conducted.

The tensile tests were performed in accordance with EN ISO 3506-1, Clause 9.1 on the whole bolt in order to determine the mechanical properties of the bolts as the resulting tensile strength $R_{mf,exp}$ (= $f_{ub,exp}$), yield strength $R_{pf,exp}$ (= $f_{yb,exp}$) and elongation at fracture A. The 120 tensile tests with partially threaded EN ISO 4014 and EN ISO 4762 bolts cover austenitic (PC 50, 70, 80, 8.8 and 10.9), duplex (PC 70, 80, 100 and 12.9) and super duplex (only PC 10.9) stainless steel bolts, while the 90 tensile tests with fully threaded EN ISO 4017 bolts contain austenitic (PC 50, 70, 80, 8.8 and 10.9), lean duplex (PC 10.9), duplex (PC 70 and 10.9) as well as super duplex (PC 10.9) stainless steel. Each configuration includes at least three test specimens ($n \geq 3$) from different anonymised bolt manufacturers or traders (abbreviated as C1 to C6) with either rolled or cut bolt threads (cf. Chapter 4.3.2) to represent the current European market as realistic as possible. Detailed test matrixes of the tested austenitic/duplex bolts are given in Table B.1 and Table B.2 of Appendix B.

Two tensile test rigs for the experimental investigations into the tension resistance of austenitic and duplex stainless steel bolts for bolt diameters M16 and M24 were used both complying with the normative testing specifications given in EN ISO 3506-1, Clause 9, see Figure 4.4-1. All manual length measurements (clamping length L_2, length of thread engagement and free threaded length l_{th}) were carried out with a digital caliper with an accuracy of 0.01 mm, which is fulfilling the requirements of EN ISO 3506-1 of 0.05 mm or better.



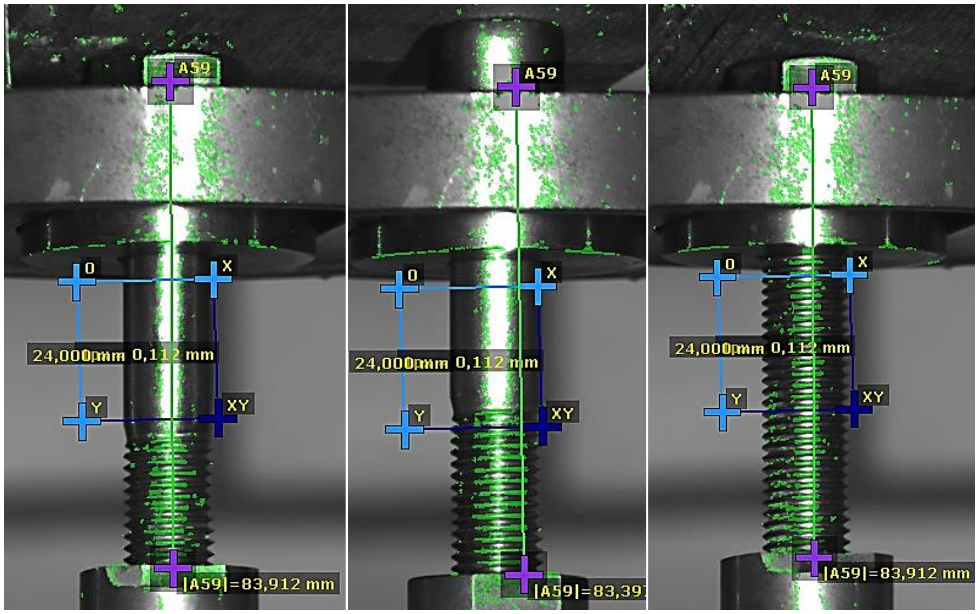
200 kN testing machine with Mercury VEX-50® video extensometer for EN ISO 3506-1 tensile tests	Tensile test rig M16 EN ISO 3506-1	Tensile test rig for M16 EN 15048-2	Tensile test rig M24 EN ISO 3506-1

Tensile test rig M16: Rigid and self-aligning	**Tensile test rig M24:** Rigid and self-aligning
Testing machine: Walter+Bai 200 kN servohydraulic static universal testing machine, Class 0	**Testing machine:** Schenk 1.0 MN servohydraulic static and dynamic universal testing machine, Class 0
Testing procedure: Displacement-controlled with a constant testing speed of 0.08 mm/s	**Testing procedure:** Displacement-controlled with a constant testing speed of 0.08 mm/s
Hardness of the adapters: 49.2 HRC ≥ 45 HRC	**Hardness of the adapters:** 50.3 HRC ≥ 45 HRC
Test adapter under the bolt head: Adapter discs with clearance hole 17.5 mm ≤ d_h = 17.55 mm ≤ 17.77 mm acc. to EN ISO 3506-1, Table 12	**Test adapter under the bolt head:** Block adapter with clearance hole 26.0 mm ≤ d_h = 26.18 mm ≤ 26.33 mm acc. to EN ISO 3506-1, Table 12
Threaded test adapter: Adapter discs with ISO metric coarse thread M16×2 in thread tolerance class 5H6G	**Threaded test adapter:** Block adapter with ISO metric coarse thread M24×3 in thread tolerance class 5H6G
Length of thread engagement: Chosen as 1d fulfilling 1d ± 1P acc. to EN ISO 3506-1	**Length of thread engagement:** Chosen as 1d fulfilling 1d ± 1P acc. to EN ISO 3506-1
Free threaded length l_{th}: Chosen as 1d fulfilling the requirements of EN ISO 3506-1	**Free threaded length l_{th}:** Chosen as 1d fulfilling the requirements of EN ISO 3506-1
Measurement system: High precision Mercury VEX-50® video extensometer	**Measurement system:** High-precision LVDT, adjusted with a micrometre gauge

Figure 4.4-1: Test rigs for tensile tests according to EN ISO 3506-1 (and EN 15048-2) for bolt dimension M16 (left) and M24 (right) according to P 1386 / IGF-No. 20651 N [78]; © UDE-IML

For the experimental programme, a 200 kN Walter+Bai servohydraulic static universal testing machine at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen, Germany, was used for performing tensile tests on the M16 partially (EN ISO 4014 and EN ISO 4762) and fully threaded (EN ISO 4017) austenitic and duplex stainless steel bolts. Following the testing requirements of EN ISO 3506-1, all tensile tests were conducted displacement-controlled with a constant testing speed of 0.08 mm/s till bolt fracture occurs, while the bolt elongation was measured and recorded during the whole test with a Mercury VEX-50® high-precision video extensometer. Additionally, for tensile tests on M24 bolts, the institute's own 1.0 MN Schenck servohydraulic static and dynamic universal testing machine was applied. These tensile tests were also performed displacement-controlled with a constant testing speed of 0.08 mm/s till bolt fracture using a high-precision linear variable differential transducers (LVDT) to measure the bolt elongation and continuously recorded with a Peekel Autosoft/Autolog 3000 data measuring system (new: Burster Präzisionsmesstechnik GmbH & Co. KG) during the whole test, see Figure 4.4-1. Both servohydraulic testing machines are fulfilling the requirements of Class 0 according to ISO 7500-1 [370].

The measurement of the bolt elongation for M16 bolts is exemplarily presented in Figure 4.4-2 for partially threaded bolts according to EN ISO 4014 (a) and EN ISO 4762 (b) as well as for fully threaded bolts according to EN ISO 4017 (c). The green line designated as "A59" is representing the clamping length L_2 and measuring the relative displacement between bolt head and beginning of the thread engagement during the whole tensile test.



(a) Tensile testing on M16 partially threaded EN ISO 4014 bolts

(b) Tensile testing on M16 partially threaded EN ISO 4762 bolts

(c) Tensile testing on M16 fully threaded EN ISO 4017 bolts

Figure 4.4-2: Measurement of the bolt elongation with Mercury VEX-50® video extensometer according to P 1386 / IGF-No. 20651 N [78]; © UDE-IML

4.4.3 Tensile tests on stainless steel bolting assemblies according to EN 15048-2

In order to extend the database for a more detailed statistical evaluation about the difference between the tension resistance of bolts tested formerly according to EN ISO 3506-1, Clause 9.1 on the whole bolt and the resulting tension resistance of the bolting assembly (as bolt and nut excluding washer), further tensile tests according to EN 15048-2, Clause 6 were carried out. In this way, not the pure mechanical properties of the stainless steel bolts were tested but the maximum achieved tension resistance of the bolting assemblies itself, which includes the mechanical properties of the bolt and the nut and their mutual load bearing behaviour. Therefore, in total 58 tensile tests with partially threaded austenitic (PC 70, 80, 8.8 and 10.9), duplex (PC 80 and 100) as well as super duplex bolting assemblies (only PC 10.9) were performed. Furthermore, in total 56 fully threaded austenitic (PC 50, 70, 80, 8.8 and 10.9), lean duplex (PC 10.9), duplex (PC 70 and 10.9) as well as super duplex bolting assemblies (PC 10.9) M16×100/110 were tested. The testing procedure is identical to that shown in Figure 4.4-1 but the threaded adapter is replaced by a second hardened test adapter under the nut with a thread projection of less or equal to 1P. However, only the maximum load $F_{bi,max}$ achieved in the tensile test was measured and evaluated.

Analogues to the tensile tests according to EN ISO 3506-1, each configuration includes at least three test specimens from different anonymised bolt manufacturers or traders. The detailed test matrixes of the tested austenitic and duplex stainless steel bolting assemblies are provided in Table B.3 and Table B.4 of Appendix B.

4.4.4 Tensile tests on machined bolts and the separated threaded bolt part to determine the tensile strength of the unthreaded and threaded parts

Predominantly austenitic bolts fail in the unthreaded bolt part due to the transformation of austenitic to forming induced martensitic material in the tensile cross-section during the rolling process, if finally the tension resistance of the threaded part is greater than the tension resistance of the unthreaded part, cf. Chapters 2.4.7 and 2.4.8. Consequently, a direct determination of the tensile strength of the unthreaded part $f_{ub,shank,i}$ based on the measured individual bolt geometry of the gross cross-sectional area $A_{meas,I}$ as well as the mean shank

tensile strength $f_{ub,shank,mean}$ of the tested series are possible whenever bolt failure occurs in the unthreaded part. The exact tensile strength $f_{ub,threads}$ of the threaded bolt part is unknown but it can be concluded that it is equal or even greater than R_{mf} determined in a tensile test according to EN ISO 3506-1. In order to gather more information on the exact tensile strength of the threaded bolt part $f_{ub,threads}$, additional tensile tests are conducted specifically on the threaded portion, which were separated from the stainless steel bolts.

In cases where the bolt failure occurs in the threaded part as the intended failure mechanism of carbon steel and duplex stainless steel bolts (but also occurring in some cases of austenitic bolts), a direct determination of the tensile strength of the unthreaded bolt part $f_{ub,shank}$ is not possible. The determined tensile strength in a tensile test according to EN ISO 3506-1 is nearly the exact tensile strength of the threaded part. To be precise, EN ISO 3506-1 always determines the tensile strength with the nominal tensile stress area $A_{s,nom}$ without considering the thread tolerance class which would lead to a smaller tensile stress area. Therefore, the tensile strength of the threaded part $f_{ub,threads}$ is on the safe side. However, additional tests on modified test specimens must be conducted in order to determine the unknown tensile strength of the unthreaded part $f_{ub,shank,i}$ and the mean shank tensile strength $f_{ub,shank,mean}$ of the tested series. Here, a simplification of $f_{ub,threads} \approx f_{ub,shank}$ is not possible particularly for austenitic bolts. Therefore, in [78], tensile tests on machined M16 and M24 bolts were conducted to determine the tensile strength of the unthreaded bolt part $f_{ub,exp,shank}$. In total, 33 tensile tests on bolts with machined bolt shank according to EN ISO 898-1, Clause 9.7.6 (regarding the geometry) and EN ISO 3506, Clause 9.3 (for the testing procedure for fasteners with reduced loadability) were conducted with at least three test specimens for each bolt series, see the detailed test matrix in Table B.5 of Appendix B, Figure 4.4-3 and Figure 4.4-4.

In order to enforce bolt failure in the unthreaded, shanked part, a reduced bolt shank diameter d_s slightly below the pitch thread diameter d_2 under consideration of the tolerance class 6g was selected for testing and results to a shank diameter of d_s = 14 mm < $d_{2,M16,6g,min}$ = 14.5 mm for M16 bolts and d_s = 21 mm < $d_{2,M24,6g,min}$ = 21.8 mm for M24 bolts, see Figure 4.4-3. Before testing, all M16 and M24 specimens were measured with a digital caliper.

(a) Machined bolt shank of a M16 EN ISO 4014 bolt (b) Machined bolt shank of a M16 EN ISO 4762 bolt

Figure 4.4-3: Machined bolt shank of EN ISO 4014 and EN ISO 4762 bolts according to P 1386 / IGF-No. 20651 N [78]; © UDE-IML

The testing procedure is identical to that already described in Chapter 4.4.2. However, only the tensile strength $f_{ub,exp,shank}$ can be determined according to EN ISO 3506-1, Clause 9.3.1. A direct determination of the yield strength and elongation at fracture is not possible. It is worth mentioning that by reducing the bolt shank diameter d_s, the more strain hardened outer area of the shank is removed, and a lower tensile strength $f_{ub,shank,exp}$ is achieved in the tensile test compared to the tensile strength achieved by the full, not machined unthreaded bolt part. Nevertheless, the tensile tests carried out with the reduced bolt shank provide tensile strengths $f_{ub,exp,shank}$ that are on the safe side. In order to quantify the error, additional circular Vickers (HV 10) hardness measurements according to EN ISO 6507-1 [209] of the cross-sectional shank area according to were carried out on austenitic bolts A4-80 and the different hardness areas were scaled with the measured tensile strength of tensile coupon test specimens to determine the mean shank tensile strength. This time-consuming procedure was preferred by Knobloch/Schmidt [171–173] and Renner/Lange [178–183, 235]. However, it could be shown

in [78] that $f_{ub,exp,shank}$ determined by bolts with reduced bolt shank diameter d_s had only slightly lower shank tensile strengths of 1.8 to 2.5 % compared to the scaled tensile strength by hardness measurements of the M16 and M24 bolts. Consequently, a simple reduction of the bolt diameter provides sufficiently accurate results on the safe side.

Furthermore, 21 tensile tests exclusively on the threaded bolt part of bolts in PC 70, 80 and 8.8 to determine the tensile strength of the bolt threads $f_{ub,threads}$, which are separated from the stainless steel bolts, were conducted. Only selected M16 bolt series are tested with at least three test specimens for each bolt series. The test matrix is presented in Table B.6 of Appendix B. The procedure for tensile tests on the separated threaded bolt part of EN ISO 4014 partially threaded M16 austenitic and duplex bolts are carried out according to the specifications of EN ISO 3506-1, Clause 9.1 as tensile tests on fully threaded studs, see Figure 4.4-4.

(a) Eamples of machined stainless and carbon steel bolts for tensile tests to determine $f_{ub,exp,shank}$	(b) Test rigs for tensile tests on the separated threaded bolt part

Testing specifications:
– **Tensile test rig M16:** Rigid and self-aligning
– **Testing machine:** Walter+Bai 200 kN servohydraulic static universal testing machine, Class 0
– **Testing procedure:** Displacement-controlled with a constant testing speed of 0.08 mm/s
– **Hardness of the threaded test adapters:** 49.2 HRC ≥ 45 HRC
– **Threaded test adapter:** Adapter discs with ISO metric coarse thread M16×2 in thread tolerance class 5H6G
– **Length of thread engagement:** Chosen as 1d - 1P acc. to EN ISO 3506-1
– **Free threaded length l_{th}:** Chosen as 1 d fulfilling the requirements of EN ISO 3506-1
– **Measurement system:** Mercury VEX-50® high-precision video extensometer

Figure 4.4-4: Test rigs for tensile tests according to EN ISO 3506-1 on machined bolts (a) and for the separated threaded bolt part (b) of stainless steel bolts; © UDE-IML

The testing requirement of a total stud length of ≥ 3.5 d = 3.5 · 16 mm = 56 mm according to EN ISO 3506-1 is not fulfilled. Thus, only the maximum load is measured for the determination of the tensile strength of the threaded bolt part $f_{ub,exp,threads}$. Only those austenitic and duplex bolts are considered which have a minimum thread length of 44 mm. Herein, the length of thread engagement in the threaded adapters is defined as 14 mm (1·d - 1·P) for both sides including the free threaded length l_{th} of minimum 1d. However, a length of thread engagement of 16 mm (1·d) is preferred to avoid overstressing of the paired threads, whenever feasible. In total, only seven austenitic stainless steel bolt series in PC 70, 80, 8.8 and 10.9 could fulfil these testing requirements.

4.4.5 Tensile coupon test specimens machined from stainless steel bolts according to EN ISO 6892-1

In order to investigate the effect of strain hardening as well as the transformation of austenitic to forming induced martensitic material between the bolt core and the threaded part on the load bearing capacity of austenitic and duplex stainless steel bolts, tensile coupon test specimens B8×40 in accordance with DIN 50125 [371] of selected six bolt series from PC 70, 80, 8.8 and 10.9 were produced by the mechanical workshop of University of Duisburg-Essen. In total, 27 tensile tests according to EN ISO 6892-1 [366] were carried out on tensile coupon test specimens B8×40 with three tests of each series, see Table B.7 of Appendix B.

Tensile coupon test specimens B8×40 according to DIN 50125 machined from stainless steel bolts were produced by the mechanical workshop of the University of Duisburg-Essen, see Figure 4.4-5. All tensile tests were carried out on the Walter+Bai 200 kN servohydraulic static universal testing machine according to Method B of EN ISO 6892-1, Clause 10.3.3. Therefore, a stress rate $\dot{R}$ of 25 N/mm² per second was chosen for all coupon specimens, which is in the middle range of the permissible stress rate between 6 and 60 N/mm² per second. After exceeding the yield point at 0.2 % non-proportional elongation, the tensile tests were performed displacement-controlled until failure. The displacement velocity v_c was estimated by (Eq. 4.4-1) according to EN ISO 6892-1 by the strain rate over the entire test length of $\dot{e}_{Lc}$ = 0.00417 s^{-1} resulting to a displacement of 12 mm/min for B8×40 tensile coupon test specimens.

$$v_c = L_c \cdot \dot{e}_{L_c} \qquad \text{(Eq. 4.4-1)}$$

with

L_c: test length of the specimen according to DIN 50125 of L_c = 48 mm for B8×40,

$\dot{e}_{Lc}$: estimated strain rate over the entire test length according to EN ISO 6892-1.

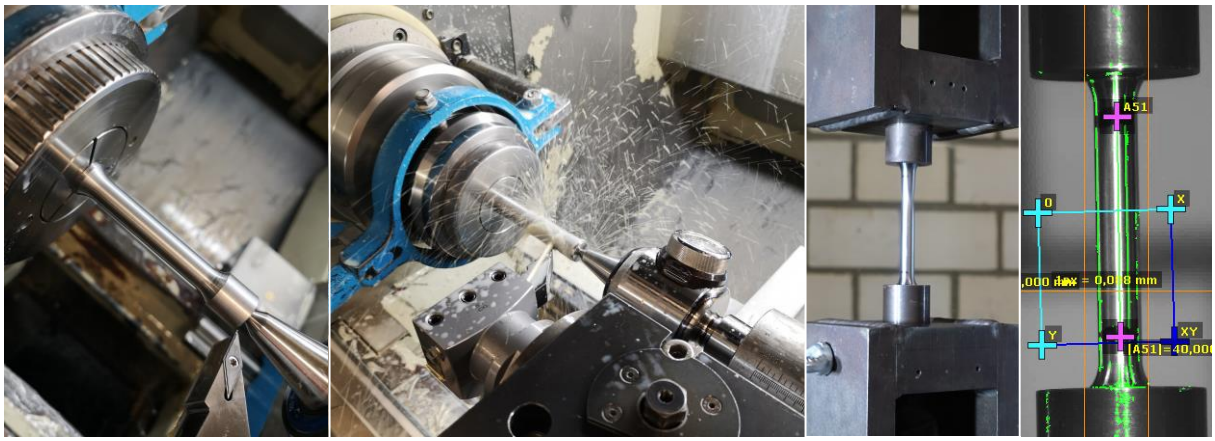


Figure 4.4-5: Production of B8×40 tensile test coupon specimens made from stainless steel bolts by the mechanical workshop of the University of Duisburg-Essen and tensile testing according to EN ISO 6892-1; © UDE-IML

4.5 Experimental investigations: Discussion of the tensile test results

4.5.1 General

A summary of all tensile test results of partially and fully threaded austenitic and duplex stainless steel bolts according to EN ISO 4014, EN ISO 4762 and EN ISO 4017 is summarised in Appendix D. Firstly, the evaluation of the tensile tests on bolts according to the specifications of EN ISO 3506-1 provides for each tested austenitic and duplex stainless steel bolt the maximum tensile load $F_{mf,exp}$ and the corresponding tensile strength $R_{mf,exp}$, the load $F_{pf,exp}$ at

0.2 % non-proportional elongation measured during testing and the corresponding proof stress $R_{pf,exp}$ as well as the measured elongation at fracture A_{exp}. Despite the already discussed different failure modes of austenitic and duplex stainless steel bolts (austenitic bolts generally tend to fail under pure tension in the unthreaded bolt part while duplex bolts fail in the free loaded threaded part), according to EN ISO 3506-1, Clause 9.1.5 and 9.1.6, the determination of the tensile strength $R_{mf,exp}$ and the yield strength $R_{pf,exp}$ is always based on the nominal tensile stress area $A_{s,nom}$ of the bolt, see (Eq. 4.5-1) to (Eq. 4.5-3):

$$R_{mf,exp} = f_{ub,exp} = \frac{F_{mf,exp}}{A_{s,nom}} \qquad \text{(Eq. 4.5-1)}$$

$$R_{pf,exp} = f_{yb,exp} = \frac{F_{pf,exp}}{A_{s,nom}} \qquad \text{(Eq. 4.5-2)}$$

with

$$A_{s,nom} = \frac{\pi}{4} \cdot \left(\frac{d_2 + d_3}{2} \right)^2 \qquad \text{(Eq. 4.5-3)}$$

with

d_2: basic pitch diameter of the external thread, see ISO 724, and

d_3: minor diameter of the external thread, see ISO 724 and ISO 68-1.

Secondly, the evaluation of the tensile tests on non-preloaded structural bolting assemblies according to the specifications of EN 15048-2, Clause 6.4 provides for each tested austenitic and duplex stainless steel bolting assembly the maximum tensile load $F_{bi,max,exp}$ and the corresponding tensile strength $f_{ub,exp,15048\text{-}2}$, see (Eq. 4.5-4). As stated in EN 15048-2, the resulting bolt elongation was not measured during testing.

$$f_{ub,exp,15048-2} = \frac{F_{bi,max,exp}}{A_{s,nom}} \qquad \text{(Eq. 4.5-4)}$$

Thirdly, the tensile strength $f_{ub,exp,shank}$ of the unthreaded, shanked part of a bolt is determined by (Eq. 4.5-5). However, only the tensile strength $f_{ub,exp,shank}$ can be determined based on the maximum tensile load $F_{bi,max,exp}$ and the measured reduced shank diameter $A_{ds,meas}$. A determination of the yield strength and elongation at fracture is not possible according to EN ISO 3506-1, Clause 9.3.1.

$$f_{ub,shank,exp} = \frac{F_{bi,max,exp}}{A_{ds,meas}} \qquad \text{(Eq. 4.5-5)}$$

Fourthly, the evaluation of the tensile tests on coupon specimens made from austenitic and duplex stainless steel bolts is based on EN ISO 6892-2. Before testing, the mean cross-sectional area $S_{0,meas}$ of each B8×40 tensile coupon test specimen was measured with a digital caliper at several defined points. Based on the maximum tensile load $F_{max,exp}$ observed in the tensile test, the resulting tensile strength $f_{ub,exp,6892\text{-}1}$ was determined, see (Eq. 4.5-6). The yield strength $f_{yb,exp,6892\text{-}1}$ is ascertained in the resulting stress-strain curve at 0.2 % non-proportional elongation as well as the elongation at fracture A_{exp}.

$$f_{ub,exp,6892-1} = \frac{F_{max,exp}}{S_{0,meas}} \qquad \text{(Eq. 4.5-6)}$$

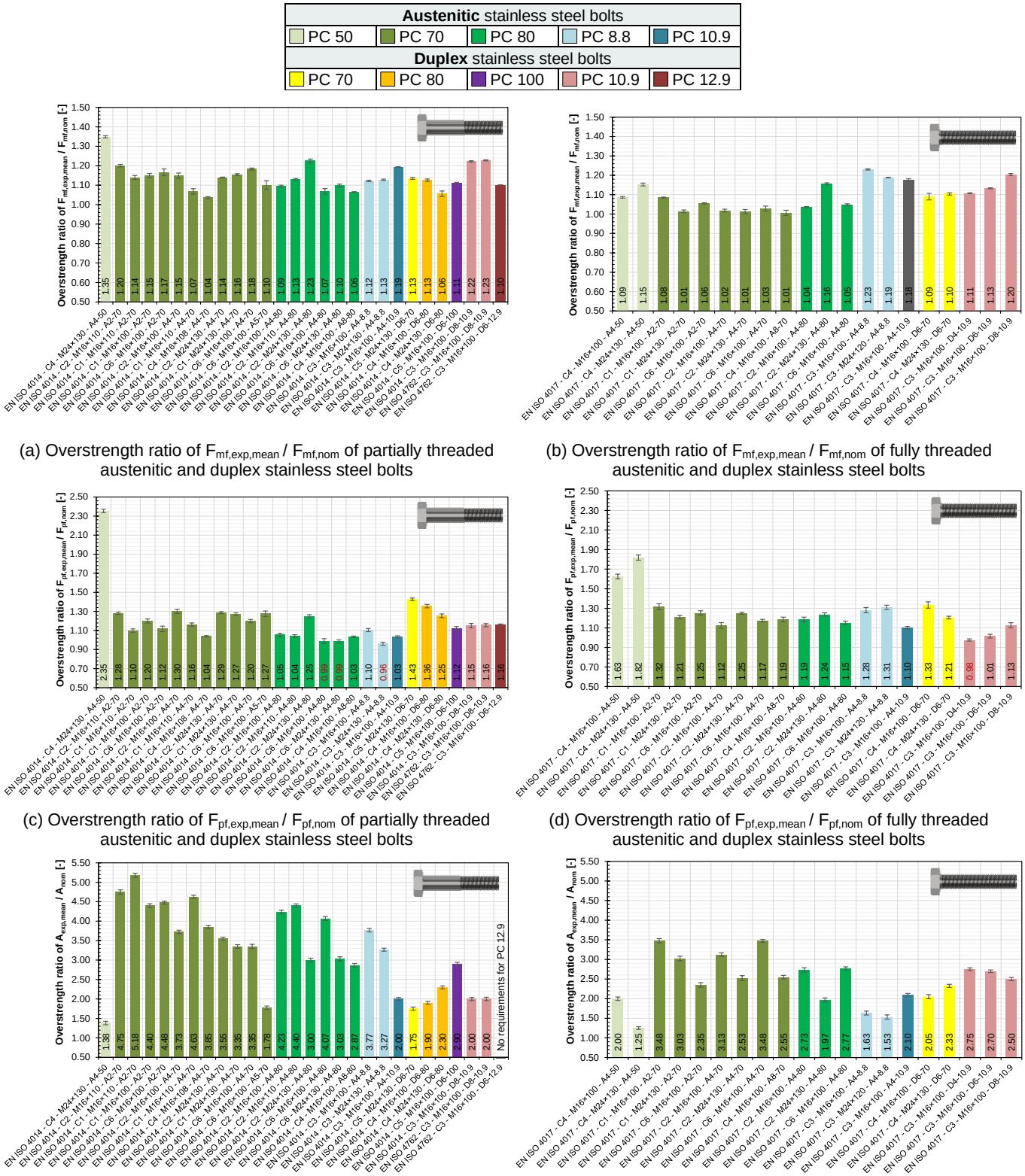
4.5.2 Comparison between partially and fully threaded stainless steel bolts in tensile tests according to EN ISO 3506-1

The results of the tensile tests on the whole bolt according to EN ISO 3506-1 achieved in [78] for partially and fully threaded austenitic/duplex stainless steel bolts were already discussed by Stranghöner/Abraham in [78] and [282] including the resulting load-bolt elongation curves of EN ISO 4014 and EN ISO 4762 partially and EN ISO 4017 fully threaded M16 bolts. It could be shown that the scattering of the mean maximum load $F_{mf,exp,mean}$ achieved in a tensile test on the whole bolt according to EN ISO 3506-1, Clause 9.1 and the corresponding tensile strength $R_{mf,exp,mean}$ (= $f_{ub,exp,mean}$) over all tested bolt series is remarkably low with coefficients of variation (COV) less than 2.2 %. Furthermore, the scattering of the proof load at the 0.2 % non-proportional elongation $F_{pf,exp,mean}$ and the corresponding yield strength $R_{pf,exp,mean}$ is only slightly larger with COV ≤ 3.3 %.

A graphical comparison of the resulting overstrength ratios of the experimental and nominal minimum ultimate tensile loads $F_{mf,exp,mean}$ / $F_{mf,nom}$, the experimental and nominal minimum proof loads at the 0.2 % non-proportional elongation $F_{pf,exp,mean}$ / $F_{pf,nom}$ as well as the experimental and nominal elongation at fracture $A_{exp,mean}$ / A_{nom} of all tested partially and fully threaded austenitic and duplex stainless steel bolt series is presented in Figure 4.5-1.

The overstrength ratios between the experimental mean maximum load $F_{mf,exp,mean}$ and the minimum ultimate tensile load $F_{mf,nom}$ of the tested partially threaded austenitic stainless steel bolts due to the varying degrees of transformation of austenitic to forming induced martensitic material are between 1.07 and 1.35. The majority of bolt failures of the 21 tested austenitic bolt series occurred in the unthreaded part of the bolt under tension loading. Only four austenitic bolt series showed failure in the threaded bolt part in the tensile tests due to less overstrength, one series each in PC 50 (A4, cut threads), PC 70 (A5, rolled threads), PC 80 (A8, cut threads) and PC 10.9 (A4, rolled threads). For duplex stainless steel bolts, the overstrength ratios of the tensile strength yield to values between 1.06 and 1.23 and failure always occurred in the threaded bolt part, as expected.

The findings were elucidated in [78] and [282], demonstrating that the experimental maximum tensile load $F_{mf,exp,mean}$ steady increases with increasing property class from PC 50 to PC 12.9, while the outstanding high ductility of the tested stainless steel bolts generally decreases. Particularly, partially threaded austenitic bolts of PC 70 and 80 show significantly pronounced ductility (as elongation of the unthreaded part caused by uniaxial tensile stresses), while the maximum tensile load $F_{mf,exp,mean}$ of austenitic and duplex bolts in PC 100, 10.9 and 12.9 generally drops off more rapidly compared to those of the lower property classes but still exceeding twice (and more) the normative requirements regarding the elongation at fracture, cf. [282]. The impact of the fracture location on the ductility of the austenitic bolts can exemplarily be shown for the partially threaded austenitic bolt series EN ISO 4014 – C4 – M24×130 – A4-50 (with $A_{exp,mean,A4\text{-}8.8}$ / A_{nom} = 1.38) and the tested series EN ISO 4014 – C6 – M16×100 – A5-70 (with $A_{exp,mean,A48.8}$ / A_{nom} = 1.76), which are showing significantly reduced bolt elongation compared to the austenitic bolts in PC 70 and PC 80 with bolt failure in the unthreaded (and from the perspective of fracture analysis unnotched) bolt part.



(a) Overstrength ratio of $F_{mf,exp,mean}$ / $F_{mf,nom}$ of partially threaded austenitic and duplex stainless steel bolts

(b) Overstrength ratio of $F_{mf,exp,mean}$ / $F_{mf,nom}$ of fully threaded austenitic and duplex stainless steel bolts

(c) Overstrength ratio of $F_{pf,exp,mean}$ / $F_{pf,nom}$ of partially threaded austenitic and duplex stainless steel bolts

(d) Overstrength ratio of $F_{pf,exp,mean}$ / $F_{pf,nom}$ of fully threaded austenitic and duplex stainless steel bolts

(e) Overstrength ratio of $A_{exp,mean}$ / A_{nom} of partially threaded austenitic and duplex stainless steel bolts

(f) Overstrength ratio of $A_{exp,mean}$ / A_{nom} of partially threaded austenitic and duplex stainless steel bolts

Figure 4.5-1: Graphical comparison of the overstrength ratios of partially and fully threaded austenitic and duplex stainless steel bolts achieved in [78]

The test results on fully threaded austenitic stainless steel bolts according to EN ISO 4017 show overstrength ratios $F_{mf,exp,mean}$ / $F_{mf,nom}$ between 1.01 and 1.23 and due to the stress triaxiality of the threaded bolt part are less pronounced compared to those achieved for the partially threaded EN ISO 4014 and EN ISO 4762 bolts. On the contrary, the overstrength ratios of the duplex stainless steel bolts are between 1.09 and 1.20, nearly comparable to the partially threaded bolts.

However, fully threaded duplex stainless steel bolts were only tested in PC 70 and 10.9. Again, a strongly pronounced ductility of austenitic and duplex stainless steel bolts of PC 70 and 80 is evident and the ductility generally decreases with increasing property class (with exception of austenitic bolts of PC 50). Furthermore, it can be seen that for the fully threaded bolts of PC 100 and 10.9 once the maximum tensile load $F_{mf,exp,mean}$ is exceeded, the load drops off more rapidly compared to those curves for bolts of lower property classes, cf. [282]. However, high ductility of the tested austenitic and duplex stainless steel bolts was always observed of $A_{exp,mean,A4\text{-}8.8} / A_{nom} = 1.53$ even to $A_{exp,mean,D4\text{-}10.9} / A_{nom} = 2.75$ exceeding significantly the normative requirements regarding the elongation at fracture. In general, the ductility of fully threaded austenitic and duplex stainless steel bolts in PC 70, 80 and 8.8 is lower compared to the partially threaded austenitic bolts but still outstanding in comparison to those made of carbon steel.

In conclusion, as evident from Figure 4.5-1, all normative requirements of the tensile test on the whole bolt according to EN ISO 3506-1 are achieved with the exception of the following tested austenitic and duplex series, which are all slightly undercutting the minimum proof load at the 0.2 % non-proportional elongation $F_{pf,nom}$:

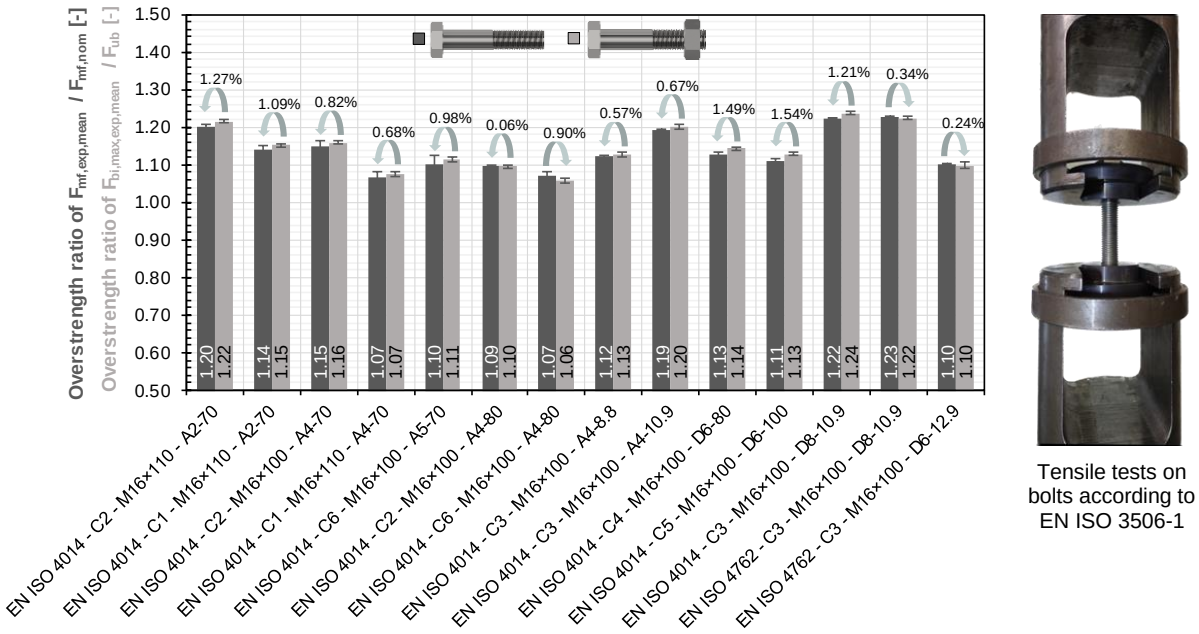
- EN ISO 4014 – C6 – M16×100 – A4-80 with $F_{pf,exp,mean} / F_{pf,nom} = 0.99$,
- EN ISO 4014 – C6 – M24×130 – A4-80 with $F_{pf,exp,mean} / F_{pf,nom} = 0.99$,
- EN ISO 4014 – C3 – M24×130 – A4-8.8 with $F_{pf,exp,mean} / F_{pf,nom} = 0.96$,
- EN ISO 4017 – C3 – M16×100 – D4-10.9 with $F_{pf,exp,mean} / F_{pf,nom} = 0.98$.

However, if the scatter of the test data in these series is taken into account, the normative requirement of $F_{pf,nom}$ is only partially not fulfilled for individual bolts within the tested series.

4.5.3 Comparison between tensile tests on bolts according to EN ISO 3506-1 and tensile tests on bolting assemblies according to EN 15048-2

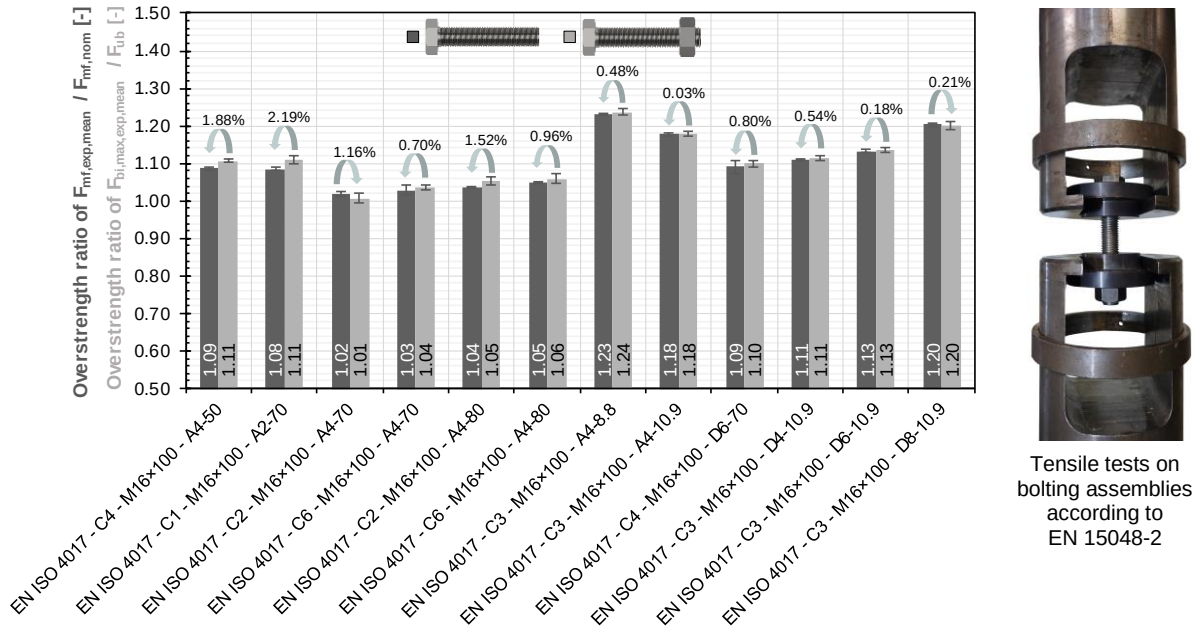
A comparison between the resulting overstrength ratios of the tensile tests on stainless steel bolts according to EN ISO 3506-1 ($F_{mf,exp,mean} / F_{mf,nom}$) and tensile tests on bolting assemblies (bolt + nut) according to EN 15048-2 ($F_{bi,max,exp,mean} / F_{ub}$) is presented in Figure 4.5-2.

It can be confirmed that the resulting tension resistance of the tested M16 partially and fully threaded austenitic and duplex stainless steel bolts and bolting assemblies is comparable with only minor differences with a maximum of 1.54 % (EN ISO 4014 – C5 – M16×100 – D6-100) and 2.19 % (EN ISO 4017 – C1 – M16×100 – A2-70). An in-depth analysis discerns a slight trend by 21 of 25 tested series that the maximum load achieved in a tensile test on stainless steel bolting assemblies according to EN 15048-2, Clause 6.4 is slightly higher but negligible compared to the maximum load observed in a tensile test on the individual bolt according to EN ISO 3506-1, which lies in the scatter of the test results and thus cannot be verified. Since failure of austenitic bolts mainly occurs in the unthreaded part, this experimental observation is consistent, as from mechanical point of view no effects like greater nut resilience or a slightly favourable load transfer may have a clear detectable impact here. It can be concluded that the differences between the testing procedures according to EN ISO 3506-1 and EN 15048-2 regarding the bolt tension resistance of austenitic and duplex stainless steel bolts and bolting assemblies are insignificant. Consequently, a statistical evaluation of the resulting partial safety factors γ_M* according to EN 1990, Annex D of the tension resistance $F_{t,Rd}$ extended to stainless steel bolts and bolting assemblies can be carried out, as presented in Chapter 4.7.7.



Tensile tests on bolts according to EN ISO 3506-1

(a) Comparison of the overstrength ratios between EN ISO 3506-1 and EN 15048-2 for partially threaded EN ISO 4014 and EN ISO 4762 austenitic and duplex bolts and bolting assemblies



Tensile tests on bolting assemblies according to EN 15048-2

(b) Comparison of the overstrength ratios between EN ISO 3506-1 and EN 15048-2 for fully threaded EN ISO 4017 austenitic and duplex bolts and bolting assemblies

Figure 4.5-2: Comparison of the ultimate overstrength ratios between EN ISO 3506-1 and EN 15048-2 for partially and fully threaded austenitic and duplex bolts and bolting assemblies

4.5.4 Comparison between the tensile strengths of the core, the unthreaded and the threaded part of a bolt

In order to gain a deeper understanding of the load bearing behaviour of austenitic and duplex stainless steel bolts under pure tensile loading and the associated role of the strain hardening during the plastic bolt forming and thread rolling process (cf. Chapter 2.4.8), a comparison between the resulting tensile strengths of the bolt core (represented and determined by B8×40 tensile coupon test specimens according to DIN 50125), the unthreaded and the threaded part of M16×100/110 partially and fully threaded bolts was conducted. A graphical comparison of the different nominal cross-sectional areas A (gross cross-sectional area), A_s (tensile stress area) and A_{core} (core area) of a partially and fully threaded stainless steel bolt is presented in

Figure 4.5-3. Furthermore, the positions of the tensile coupon test specimens in partially and fully threaded bolts are qualitatively defined.

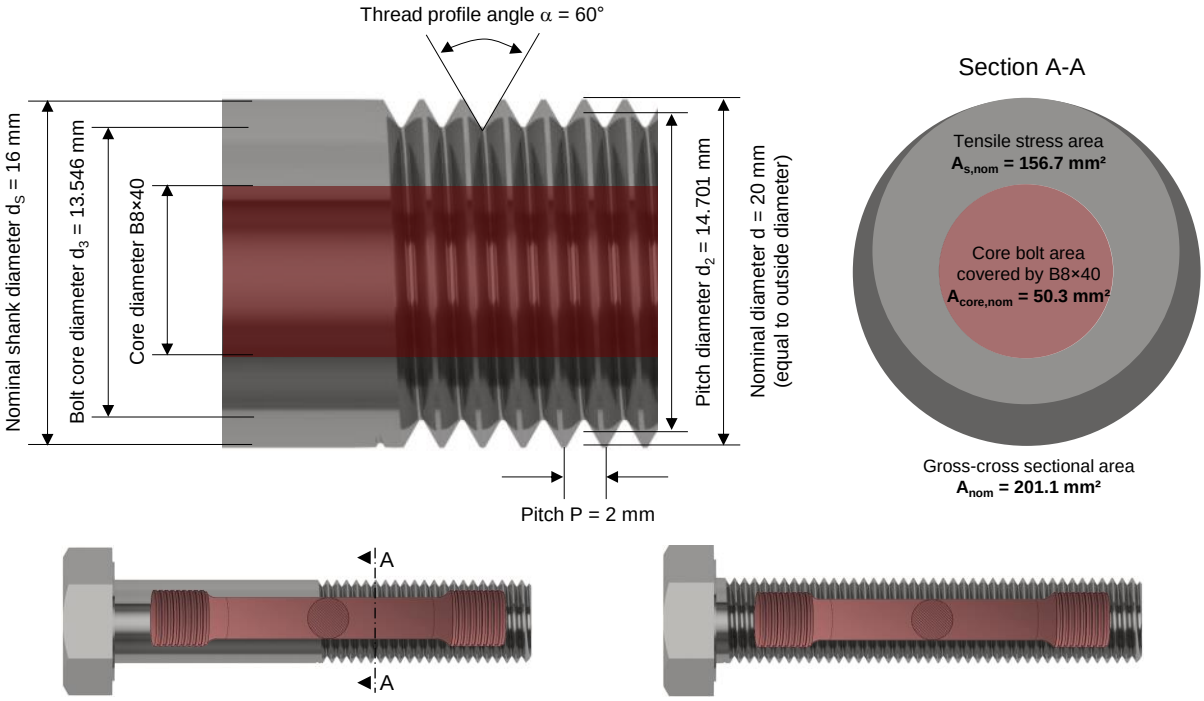


Figure 4.5-3: Comparison of the different investigated (nominal) cross-sectional areas of a partially and fully threaded stainless steel bolt for bolt dimensions M16×100 and M16×110

Due to the strain hardening during the plastic bolt forming and thread rolling process mentioned in [184, 276, 289], a non-homogeneous distribution of the tensile and yield strength in the unthreaded and threaded parts of austenitic stainless steel bolts could be confirmed. For duplex stainless steel bolts, a more homogenous distribution of the tensile and yield strength was assumed. However, for all tested duplex bolt series, always tensile failure occurred in the threads but different tensile strengths between the unthreaded and threaded part could be observed, particularly for PC 100 and 10.9. For instance, the EN ISO 4014 – C5 – M16×100 – D6-100 series shows for the threaded part $f_{ub,exp,mean}$ = 1111.8 N/mm² and for the unthreaded part $f_{ub,exp,shank,mean}$ = 876.2 N/mm². Consequently, for the tested duplex PC 100 bolt series, the threaded bolt part shows comparable to austenitic bolts significantly higher tensile strength compared to the unthreaded bolt part by a factor of 1.27. Additionally, the same observation was made for the tested high-strength duplex bolts in PC 10.9 and 12.9 with overstrength factors between 1.10 and 1.23 contradicting a more homogeneous strengths distribution of duplex bolts. Nevertheless, all tested duplex stainless steel bolts failed in the threaded part due to the smaller tensile stress area A_s compared to the gross cross-sectional area A.

A graphical comparison between the resulting tensile strengths of the core ($f_{ub,exp,core,mean}$), the unthreaded ($f_{ub,exp,shank,mean}$) and threaded part ($f_{ub,exp,threads,mean}$) of all tested partially threaded austenitic and duplex stainless steel bolts over all property classes is presented in Figure 4.5-4. The dark grey area indicates the (minimum) difference of the tensile strengths between the unthreaded and threaded part over all tested series. It is again worth mentioning that the exact tensile strength of the threaded bolt part $f_{ub,exp,threads}$ is always unknown if failure occurs in the unthreaded bolt part, which is generally the case for austenitic bolts. Therefore, it can be only stated that the tensile strength $f_{ub,exp}$ achieved in tensile tests on the whole bolt according to EN ISO 3506-1 is always smaller or equal to the real tensile strength of the threaded bolt part $f_{ub,exp,threads}$ on the safe side ($f_{ub,exp,3506\text{-}1} \leq f_{ub,exp,threads}$; (T)) Therefore, to get knowledge about the tensile strength of the bolt threads, additional tensile tests on separated threaded bolt parts (S) for selected series were conducted to determine the tensile strength of the bolt threads

$f_{ub,exp,threads}$, as outlined in Chapter 4.4.4. On the contrary, whenever failure occurs in the threaded part (e.g. for duplex bolts), the tensile strength determined in a tensile test according to EN ISO 3506-1 is equal to the tensile strength of the threaded part ($f_{ub,exp,3506\text{-}1} = f_{ub,exp,threads}$). In this case, the unknown tensile strengths of the unthreaded bolt part $f_{ub,exp,shank}$ were established by machined bolt shanks (M), as described in Chapter 4.4.4

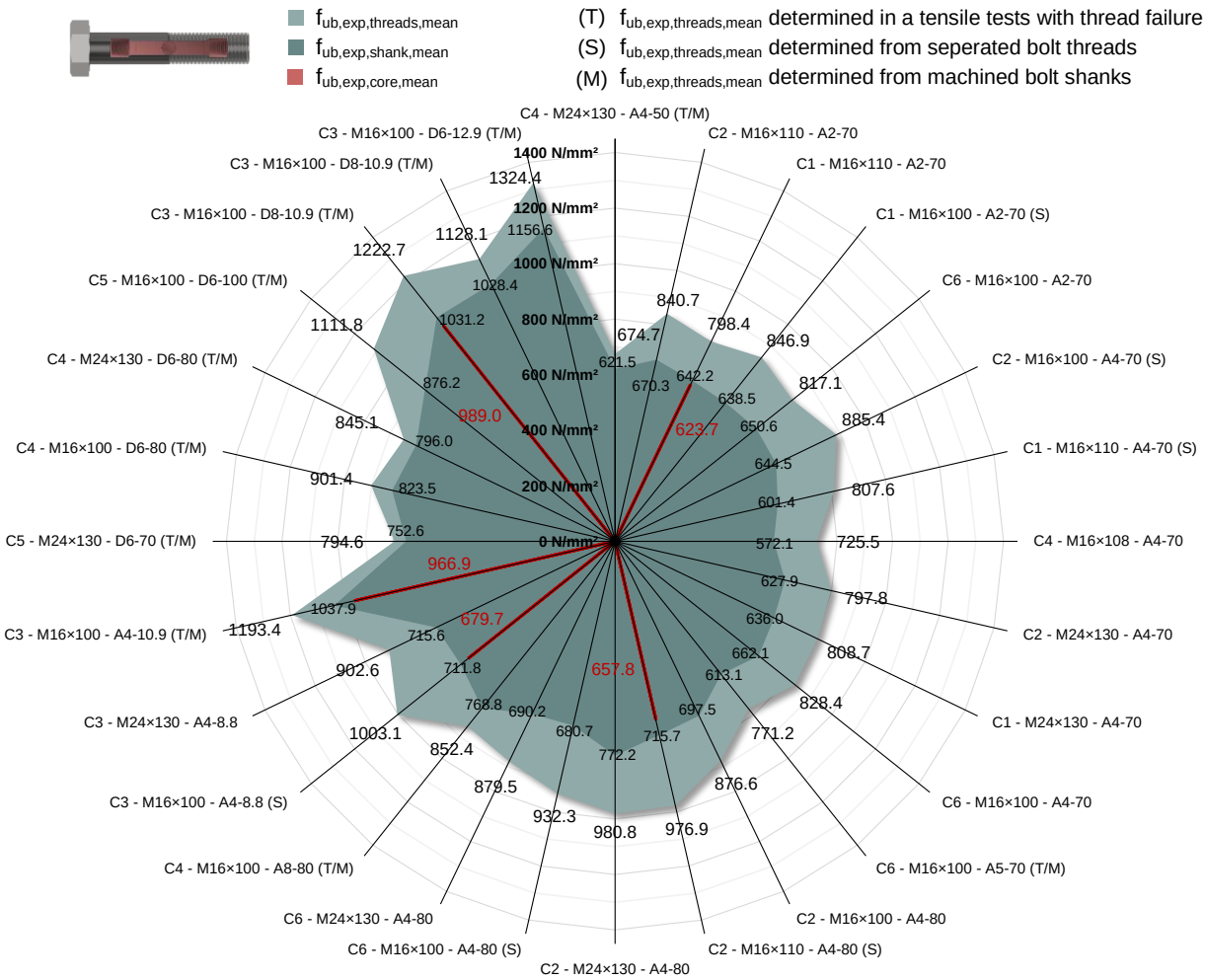


Figure 4.5-4: Comparison between the resulting tensile strengths of the core, the unthreaded and threaded part of partially threaded austenitic and duplex stainless steel bolts [unit: N/mm²]

As it can be seen in Figure 4.5-4, the tensile strengths of the threaded bolt part are always higher (indicated by the brighter coloured area) compared to the unthreaded part, especially for austenitic bolts (with exception of PC 50) and for duplex bolts in PC 100, 10.9 and 12.9. The "real" tensile strength of the threaded part of selected series could be determined in tests on separated threads showing increased tensile strengths between +5.13 % (EN ISO 4014 – C1 – M16×100 – A2-70 series) and +11.70 % (EN ISO 4014 – C3 – M16×100 – A4-8.8 series) compared to the calculated shank tensile strength according to EN ISO 3506-1. Finally, the pronounced transformation of austenitic to forming induced martensitic material in the threaded part of austenitic stainless steel bolts during the thread forming and rolling processes is reflected in the differences between the tensile strengths of the unthreaded and threaded bolt parts. However, in contrast to the revealed significant differences between the tensile strengths of the unthreaded and threaded bolt part, the disparities between the tensile strength of the machined bolt shank and the bolt core represented by B8×40 tensile coupon test specimens on five selected series, which are less distinct with a minimum ratio of $f_{ub,exp,shank,mean}$ / $f_{ub,exp,core,mean}$ = 1.03 (EN ISO 4014 – C1 – M16×110 – A2-70) and a maximum ratio of $f_{ub,exp,shank,mean}$ / $f_{ub,exp,core,mean}$ = 1.08 (EN ISO 4014 – C2 – M16×100 – A4-80), as presented in Figure 4.5-4.

The bolts from bolt producer C3 in PC 8.8 and 10.9 show strong overstrength of the bolt threads with $f_{ub,exp,threads,mean,8.8}$ = 1003.1 N/mm² and $f_{ub,exp,threads,mean,10.9}$ = 1193.4 N/mm², while the core and the unthreaded part are characterised by minor differences in the degree of strain hardening with $f_{ub,exp,shank,mean,8.8}$ = 711.8 N/mm² and $f_{ub,exp,core,mean,8.8}$ = 679.7 N/mm² for PC 8.8 as well as $f_{ub,exp,shank,mean,10.9}$ = 1037.9 N/mm² and $f_{ub,exp,core,mean,10.9}$ = 966.9 N/mm² for PC 10.9.

The above presented experimental investigations and evaluations confirm the results from Manninen and Söderman [211]. They concluded a parabolic yield strength distribution in the unthreaded and threaded bolt part with maximum values at the shank edges and bolt thread tooths. The impact of the thread rolling process on the strength distribution is consistent with other studies from literature on carbon steel bolts but can now be explicitly correlated with the pronounced strain hardening of austenitic bolts. However, without detailed microhardness measurements, no clear strength distribution can be determined quantitatively and qualitatively and the parabolic approach of Manninen and Söderman [211] cannot be verified. Nevertheless, the impact of the varying degrees of transformation of austenitic to forming induced martensitic material and cold working below the recrystallisation temperature is measurable in the core, shank and threads. Additionally, material-specific investigations are warranted for a more profound comprehension of material behaviour, characterisation of metal flow and the establishment of a material model.

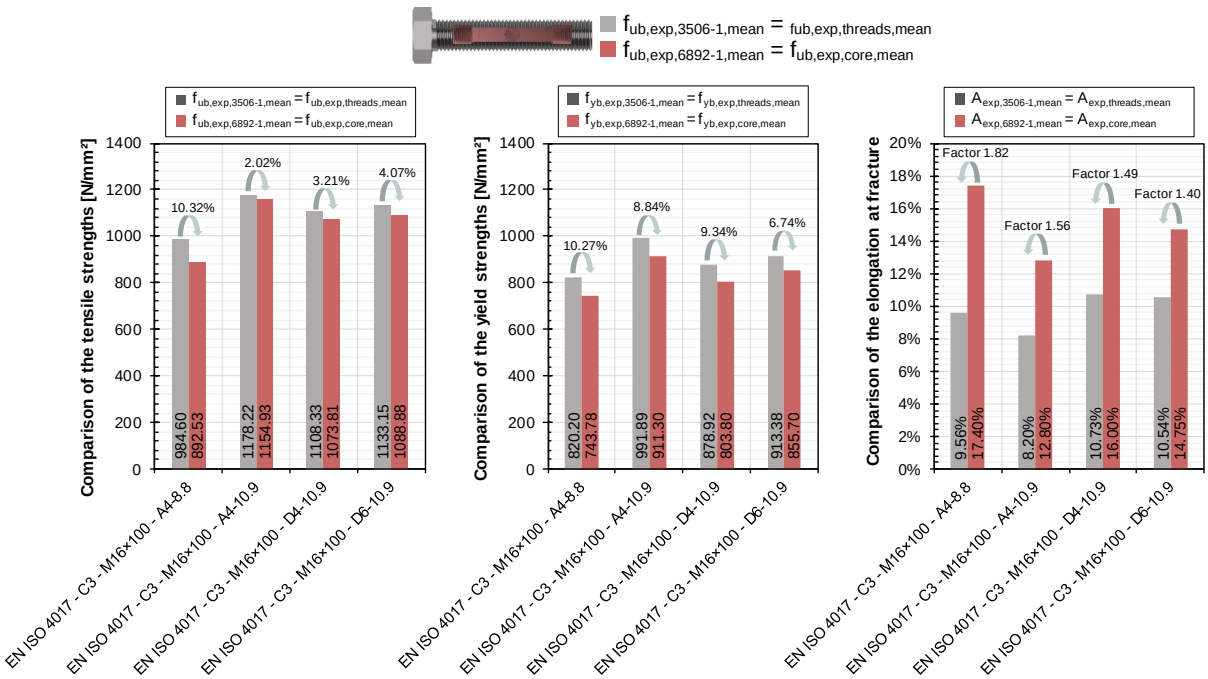


Figure 4.5-5: Comparison between the resulting tensile strengths of the core and the threaded part of fully threaded austenitic and duplex stainless steel bolts from bolt manufacturer C3

Furthermore, a graphical comparison between the tensile strengths of the core ($f_{ub,exp,core,mean}$) and the threaded part ($f_{ub,exp,3506-1,mean}$ = $f_{ub,exp,threads,mean}$) of selected fully threaded austenitic and duplex bolts from bolt manufacturer C3 is presented in Figure 4.5-5. As expected, the tensile strength of fully threaded austenitic and duplex stainless steel bolts is always higher compared to the tensile strength of the bolt core material covered by B8×40 tensile coupon test specimens between 2.02 % (A4-10.9) and 10.32 % (A4-8.8). These findings are consistent with the determined tensile strengths of the threaded part of partially threaded bolts. For instance, in the case of A4-8.8, there is an increase of +11.70 % for the tensile strength of the bolt threads ($f_{ub,exp,threads}$) in partially threaded bolts, as opposed to +10.32 % for fully threaded bolts. The same observation is made for the yield strength of the threaded bolt part ranging between 6.74 % (D6-10.9) and 10.27 % (A4-8.8) higher than the bolt core, see [211].

In contrast, the elongation at fracture shows highest values for the tensile coupon test specimens between 12.80 % (A4-10.9) up to 17.40 % (A4-8.8), while the related elongation of fully threaded bolts in a tensile test according to EN ISO 3506-1 is between 9.56 % (A4-8.8) and 10.73 % (D4-10.9). The highest difference of the elongation at fracture can be found for the EN ISO 4014 – C3 – M16×100 – A4-8.8 series with $A_{exp,core,mean}$ / $A_{exp,threads,mean}$ = 1.82. From mechanical point of view, the different ductility is understandable and consistent due to the uniaxial and uniform tensile strain and stress state of the B8×40 test specimens versus the multiaxial strain and stress-state in a highly notched threaded bolt geometry.

4.6 Proposed design approach for the tension resistance of stainless steel bolts

The presented experimental investigations and the literature review both present significant overstrength ratios of the tensile strength $f_{ub,exp}$ / $f_{ub,nom}$ both for the partially threaded bolts according to EN ISO 4014 and EN ISO 4762 and for the fully threaded bolts according to EN ISO 4017 made of austenitic and duplex stainless steel.

Consequently, in order to allow a more economical design of the tension resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolts, an increase of the reduction factor to k_2 = 1.0 (with the exception of countersunk bolts, which are not part of the investigations) was proposed by Stranghöner/Abraham in [78] and confirmed in [282] by a reliability analysis in accordance with EN 1990, Annex D to prove the resulting partial safety factors γ_M* against the recommended partial safety factor of γ_{M2} = 1.25 for determining the design resistance of cross-sections in tension and the design resistance of bolted and welded connections, see (Eq. 4.6-1).

$$F_{t,Rd} = \frac{k_2 \cdot f_{ub,nom} \cdot A_{s,nom}}{\gamma_{M2}} \xrightarrow[\text{with } \gamma_{M2}=1.25]{\text{with } k_2=1.0} F_{t,Rd} = \frac{f_{ub,nom} \cdot A_{s,nom}}{\gamma_{M2}} \qquad \text{(Eq. 4.6-1)}$$

The proposed design approach is following the “Approach 2” of the tension resistance of an individual bolt without reduction factor, as already comprehensively presented in Chapter 3.3.2 and Chapter 3.3.3. Herewith, a global harmonisation of the tension resistance of stainless steel bolts between the product standard EN ISO 3506-1 and the design standards like European EN 1993-1-4, North American ANSI/AISC 370, AISC Design Guide 27 and the newly revised SEI/ASCE 8 as well as Australian/New Zealand AS/NZS 4673 and more is intended.

The proposed new design rules for the tension resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolts were already successfully implemented in the revision of EN 1993-1-4, FprEN 1993-1-4, and the renewed abZ/aBG Z-30.3-6:2022 [81].

4.7 Reliability analysis of the tension resistance of stainless steel bolts

4.7.1 General

In general, EN 1990 provides all the principles and requirements for safety, serviceability and durability of structures that are common to all Eurocode parts. It is based on the concept of design according to limit states (ultimate limit state or serviceability) with partial safety factors.

Hence, in order to minimize the likelihood of structural failure and ensure a secure and dependable design throughout the entire operational period, it is imperative to introduce partial safety factors (γ_M and γ_M*) as numerical values. These factors are defined based on both experimental and nominal data, providing coverage for uncertainties in material properties (such as the overstrength of yield and tensile strength) and geometric characteristics (including tolerances in the thread rolling process). Additionally, they account for inaccuracies in the

derived design resistance function. For this, three partial safety factors, γ_{M0}, γ_{M1} and γ_{M2} are used for the design of stainless steel structural members according to EN 1993-1-4. The recommended values in EN 1993-1-4 are γ_{M0} = 1.1 (for cross-sectional checks), γ_{M1} = 1.1 (for member instability design checks) and γ_{M2} = 1.25, while γ_{M2} is of particular interest and always applied for determining the resistance of carbon and stainless steel cross-sections in tension as well as the resistance of bolted and welded connections.

The partial safety factors are fundamental in the Eurocode safety concept within the framework of a probabilistic reliability theory as an adopted first order reliability method ("FORM") are based on statistical evaluation according to EN 1990, Annex D of test data from experimental investigations. Consequently, both the partial safety factor (γ_M) and the calculated design resistance are based on experimental data, so that for each test different resistance values are calculated. However, in everyday engineering, nominal material parameters from standards like the nominal tensile strength f_{ub} of a bolt or the nominal tensile stress area A_s are used for determining the resistance. Therefore, in this case, γ_M* as partial safety factor strictly based on nominal parameters is of major importance and shall be used for design.

In the following, the safety assessment, fundamentals and methodology of determining partial safety factors according to EN 1990, Annex D are briefly summarised and further specified in Appendix E. Additionally, the input parameters and definition of resistance functions of the reliability analysis regarding the tension resistance of austenitic and duplex stainless steel bolts and bolting assemblies are pointed out. As a supplement to [78], [282], an additional reliability analysis according to EN 1990, Annex D is based on a significantly extended database by an updated literature review and further tensile tests on stainless steel bolts according to EN ISO 3506-1 and bolting assemblies according to EN 15048-2 (414 instead of 261 tensile tests are considered in the updated statistical evaluation including literature). Furthermore, the extended reliability analysis is complemented by in-depth analyses of the distribution of the resulting partial safety factors γ_M* in order to improve the reliability of the proposed design approach regarding the tension resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolts.

4.7.2 Safety assessment I: Fundamentals of the determination of partial safety factors according to EN 1990

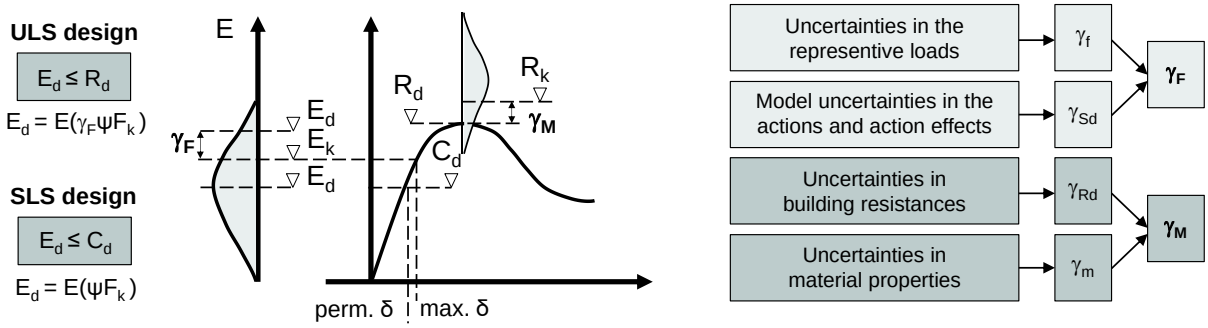
The verification methods of the Eurocodes are based on a semi-probabilistic design concept with partial safety factors in which the effect of an action E is compared with a resistance R, see Figure 4.7-1 (a). Based on EN 1990, Annex C, a design with partial safety factors means that for each design situation, the effect of the characteristic actions E_k or E is increased by a partial safety factor γ_F and the characteristic resistance R_k or the resistance C is reduced by a partial safety factor γ_M. It must be ensured that in all design situations none of the limit states (ultimate limit state (ULS) and serviceability limit state (SLS)) is exceeded when applying the design values for the effects of the actions E_d and for the design values of the resistances R_d, see (Eq. 4.7-1) and (Eq. 4.7-2).

$$E_k \times \gamma_F = E_d \leq R_d = \frac{R_k}{\gamma_M} \rightarrow \gamma_M = \frac{R_k}{R_d} \quad \text{(ULS)} \qquad \text{(Eq. 4.7-1)}$$

$$E \times \gamma_F = E_d \leq R_d = \frac{C}{\gamma_M} \quad \text{(SLS)} \qquad \text{(Eq. 4.7-2)}$$

The partial safety factor γ_M for the resistance can be distinguished into the partial safety factor γ_m considering material uncertainties and the partial safety factor γ_{Rd} considering inaccuracies in the resistance function itself, see Figure 4.7-1 (b). However, in the following the partial safety factor for the action effects γ_F is neglected; the focus will be exclusively on the resistance.

Furthermore, EN 1990 generally distinguishes between either a resistance model calculating the resistance values based on basic variables including their deviations and scattering in material strength and stiffness as well in geometrical properties, see EN 1990, Annex D.8, or single design properties, for example the tensile strength, see EN 1990, Annex D.7. Finally, if no resistance model is available, but a single parameter is determined from experimental investigations, the approach of γ_m is sufficient, see EN 1990, Annex D.7.



(a) Semi-probabilistic proof format of the Eurocode (b) Composition of the partial safety factors

Figure 4.7-1: Eurocode proof format and composition of the partial safety factors according to EN 1990, Annex C

In general, defined reliability of the load bearing capacity of a structure has to be observed during design. EN 1990 distinguishes between two probabilistic methods for the calibration of the partial safety factors. The first method is based on a completely probabilistic method (Level III) which, however, is rarely used. The completely probabilistic method requires a large statistical data set, which is often missing. The second method is the First Order Reliability Method (FORM) (Level II), which is based on a simplification that is mostly used to determine the partial safety factors. FORM is used in the frame of this PhD thesis to derive the partial safety factors. For both methods, the probability of failure P_f over a defined period is stored which can be linked to the reliability index β, see (Eq. 4.7-3).

$$P_f = P\left[\left(R - E\right) \leq 0\right] = \Phi(-\beta) \qquad \text{(Eq. 4.7-3)}$$

where Φ is the cumulative distribution function of the Gaussian normal distribution. The reliability index is assigned to the failure probabilities P_f according to EN 1990. Furthermore, a combined manner to determine reliability is considered insufficient. Consequently, EN 1990 separates the analysis with FORM regarding the sensitivity factors α_R and α_E, for action effects and resistances and action effects, see (Eq. 4.7-4) and (Eq. 4.7-5).

$$P\left(E > E_d\right) = \Phi\left(\alpha_E \beta\right) \qquad \text{(Eq. 4.7-4)}$$

$$P\left(R \leq R_d\right) = \Phi\left(\alpha_R \beta\right) \qquad \text{(Eq. 4.7-5)}$$

The sensitivity factors can be taken as α_R = + 0.8 and α_E = - 0.7, given that the proportion of the standard deviation of action effects σ_E and resistances σ_R equals $0.16 \leq \sigma_E / \sigma_R < 7.6$. If the described ratio cannot be satisfied, the sensitivity factors shall be taken as $\alpha = \pm 1.0$ for the variable with the higher standard deviation and $\alpha = \pm 0.4$ for the variable with the lower standard deviation. Considering the failure probability and the reliability index, structures are dimensioned in such a way that they only fail with a probability of P_f. Failure occurs when the loads exceed the ultimate material resistance.

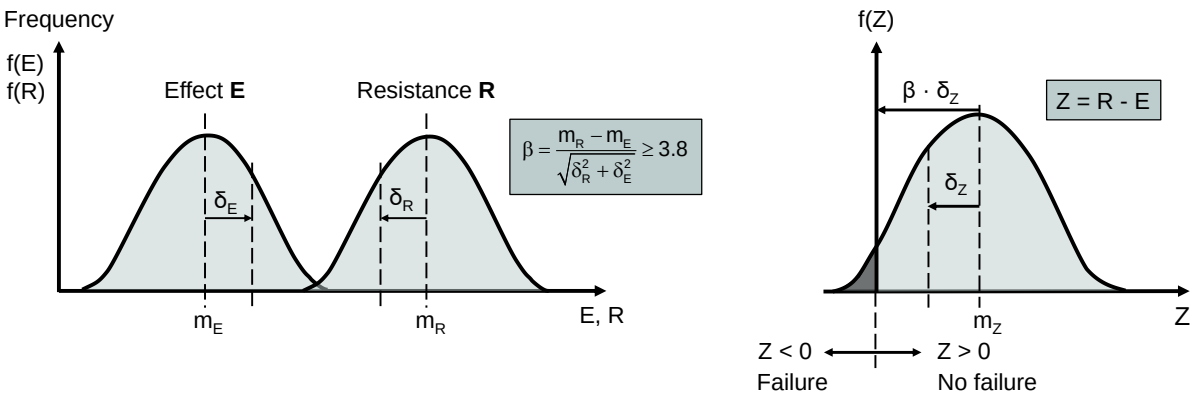
Table 4.7-1: Relationship between the failure probability P_f and the reliability index β according to EN 1990

P_f [-]	0.5	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
β [-]	0	1.28	2.32	3.09	3.72	4.27	4.75	5.20	5.61	6.00	6.36

In civil engineering, structures are designed with a chance to collapse, which is resembled by the failure probability. The target reliability index is linked to the consequence class defined in EN 1990, Annex C, which is linked to the reliability classes RC 1 to RC 3. The consequence classes (CC 1 to CC 3) define the consequences of a failing structure, where CC 3 resembles the worst consequences, e.g. collapsing grandstands, and CC 1 the less bad consequences, e.g. collapsing sheds. The higher the CC, the higher the reliability index used in structural engineering and the design. Typical building structures are linked to RC 2 with a uniform reliability index $\beta = \beta_{50} = 3.8$ for ultimate limit state design (on the contrary, the North American design standard ANSI/AISC 370 distinguishes between $\beta = 2.6$ for members and $\beta = 4.0$ for connections), a failure probability of $P_f = 7.0 \cdot 10^{-5}$ and a structure reference life span of 50 years. Considering the sensitivity factor $\alpha_R = +0.8$, the probability of failure equals roughly 0.1 %. RC 2 is the used reliability class in the frame of this thesis.

Figure 4.7-2 illustrates the relationship between the failure probability P_f, the reliability class β, the action effects E and the material resistance R. The ultimate limit state is reached when the action effects E equal the material resistance values R (E = R), illustrated by Z in the figure. Collapse occurs if E > R and thus Z = R - E < 0. Since the action effects and resistance values are based on statistical quantities, that are assumed to be normally distributed, Z is also normally distributed. In case of Z < 0 the respective probability of failure is given as a function of β, which is calculated according to (Eq. 4.7-6).

$$P_f = \int_{-\infty}^{Z=0} f(Z)\, dZ \qquad \text{(Eq. 4.7-6)}$$



(a) Reliability index β (b) Frequence distribution of structural failure

Figure 4.7-2: Relationship between the probability of failure P_f and the reliability index β, the action effects E and the material resistance R

Finally, the partial safety factor γ_M can be derived using experimentally measured values of basic variables by (Eq. 4.7-7):

$$\gamma_M = \frac{R_k}{R_d} \qquad \text{(Eq. 4.7-7)}$$

However, in everyday engineering, nominal values for base variables, such as tensile strength or the tensile stress area of a bolt A_s, are used to evaluate design resistances. Therefore, partial resistance factors based on nominal values are decisive, called γ_M*, see (Eq. 4.7-8).

$$\gamma_M{}^* = \frac{R_n}{R_d} \qquad \text{(Eq. 4.7-8)}$$

Additional information and studies regarding the reliability analysis of structural stainless steel design provisions can be found by Afshan et al. in [372]. Further guidance and practical

examples can be found by Gulvanessian in [373]. In addition, a discussion about the methods for deriving structural resistance design values assisted by testing methods according to ISO 2394 [374] and EN 1990 are provided by Yukun et al. [375].

4.7.3 Safety assessment II: Methodology of the determination of partial safety factors according to EN 1990, Annex D

The methodology of the determination of the partial safety factor γ_M* according to EN 1990, Annex D covering Method A (D.8.2) and Method B (D.8.3) is summarised in Figure 4.7-3. The detailed procedure with all relevant equations is presented in Appendix E.

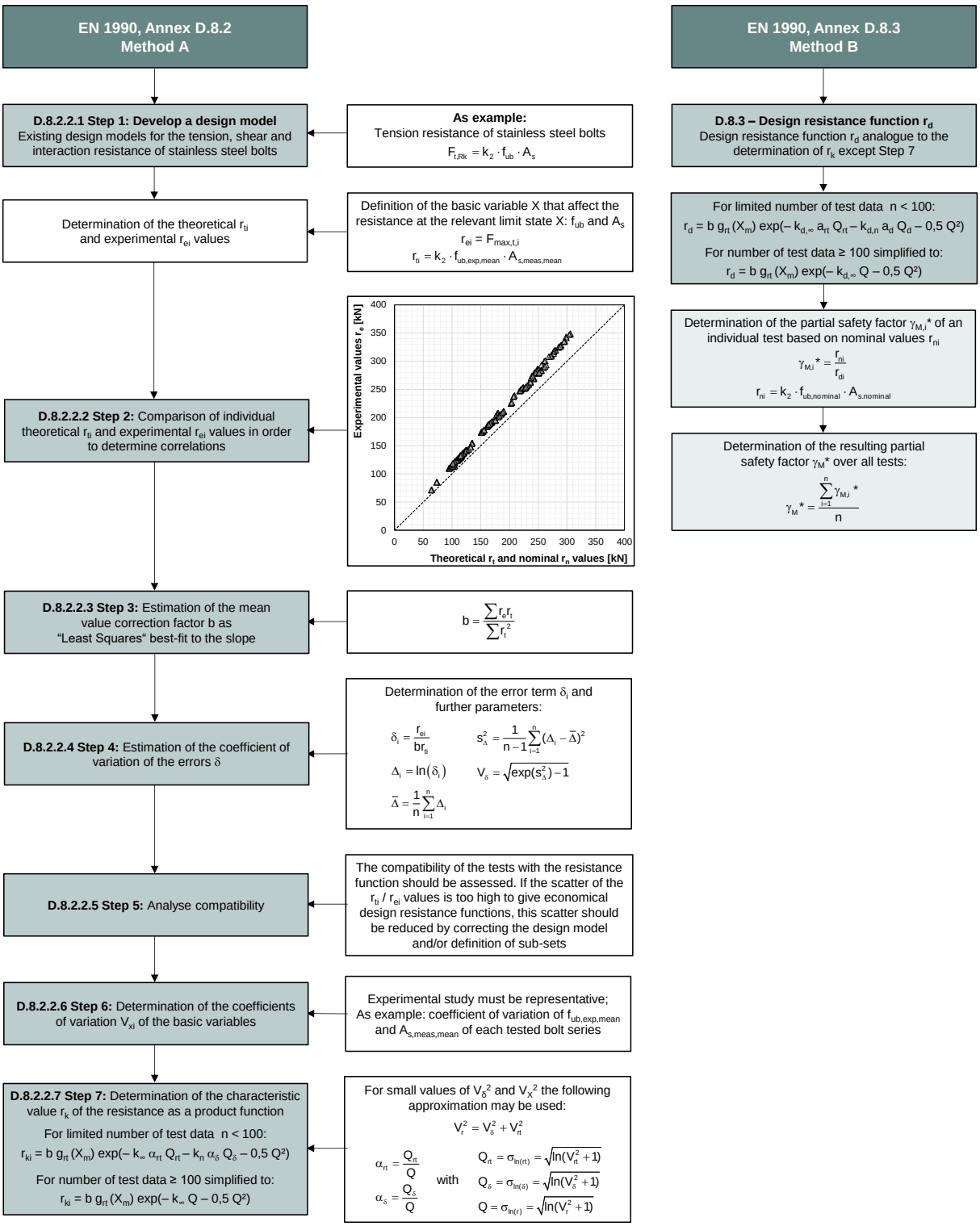


Figure 4.7-3: Flowchart of the determination of the partial safety factor γ_M* according to the methodology of EN 1990

4.7.4 Safety assessment III: Modified assessment criteria

In the methodology of the statistical evaluation according to EN 1990, Annex D, the resulting partial safety factors γ_M and γ_M* are to be understood as mean partial safety factors based on the resulting individual partial safety factors $\gamma_{M,i}$ and $\gamma_{M,i}$* of the defined test population (over all test results or subsets). These mean partial safety factors γ_M and γ_M* must be proved against the partial safety factors provided by the Eurocode, e.g. γ_{M2} = 1.25 for connections, in order to fulfill the safety requirements of the Eurocode. This implies that the limiting partial safety factors (γ_{M0}, γ_{M1}, γ_{M2}, γ_{M3} etc.) specified by the Eurocode can partially be exceeded by individual partial safety factors $\gamma_{M,i}$*, which are tolerated within the framework of this methodology. This partial overshooting of individual partial safety factors $\gamma_{M,i}$* is well-known in engineering and can be observed in reliability analysis for various structural applications like in steel and timber construction, concrete and composite construction and so on. Herein, the partial exceeding by individual partial safety factors $\gamma_{M,i}$* is an expression of the scattering of the test population. However, EN 1990, Annex D does not define any limiting criteria regarding the overshooting of individual partial safety factors. The standard merely states that *"the compatibility of the test population with the assumptions made in the resistance function should be assessed".* In order to reduce the scattering EN 1990, Annex D proposes to correct the design model to take into account parameters which had previously been ignored or to split the test population into subsets. Moreover, the "Designers' Guide to Eurocode: Basis of Structural Design EN 1990" by Gulvanessian et al. [373] gives further guidance and brief examples of the compatibility analysis of the test population, but no assessment criteria are mentioned here either.

However, Kruppa [376] (1999) proposed a methodology to check the accuracy of assessment methods of Eurocode-fire parts in the framework of CEN/TC 250 "Structural Eurocodes" in the "Horizontal Group Fire". The assessment criteria developed by Kruppa were recently applied by Kucukler [377] regarding the shear resistance and design of stainless steel plate girders in fire, and applied by Zhe Xing [378] dealing with the local buckling of stainless steel columns in fire. Although the criteria were developed by Kruppa [376] for the Eurocode fire design, they are going to be applied directly to partial safety factors in a modified and reformulated form within the scope of this thesis:

- **Criterion I (maximum error)**: The percentage of results on the unsafe side by more than 15 % of the reference result, which should be zero (Kruppa). Adaptoded to partial safety factors: The maximum observed individual partial safety factor $\gamma_{M,i}$* of a given test population should not exceed 15 % of the partial safety factor specified by the Eurocode like γ_{M0}, γ_{M1}, γ_{M2} etc.
- **Criterion II (maximum number of unsafe results)**: The percentage of results on the unsafe side, which should be less than 20 % (Kruppa). Adaptoded to partial safety factors: The percentage of individual partial safety factors $\gamma_{M,i}$* of a given test population exceeding the partial safety factor specified by the Eurocode (γ_{M0}, γ_{M1}, γ_{M2}, γ_{M3} etc.) should not exceed 20 %.
- **Criterion III (Plausibility check):** The mean value of all percentage differences between calculation results and reference result, which should be on the safe side and less than zero (Kruppa). Adaptoded to partial safety factors: The ratio of the individual nominal design r_{ni}/γ_{Mx} and the experimental r_{ei} results should be on the safe side by ≤ 1.

The modified safety assessment criteria I, II and III will be applied in all following reliability analyses of the tension, shear and interaction resistance of stainless and carbon steel bolts in the frame of this thesis. Furthermore, an illustration of the modified assessment criteria is presented in Table 4.7-2.

Table 4.7-2: Assessment criteria by Kruppa for the Eurocode fire design applied to partial safety factors in an adapted and reformulated form for bolted connections with $\gamma_{Mx} = \gamma_{M2}$

Criterion I Maximum error	**Criterion II** Maximum number of unsafe results	**Criterion III** Plausibility check
Max $\gamma_{M,i}^* \leq 1.15 \cdot \gamma_{M2}$	$(\sum \gamma_{M,i}^* > \gamma_{M2}) \leq 20$ %	$(r_{ni}/\gamma_{M2}) / r_{ei} \leq 1$

4.7.5 Input parameters and definition of resistance functions of the reliability analysis

4.7.5.1 General

The input parameters and definition of resistance functions for the tension resistance $F_{t,Rd}$ of stainless steel bolts are outlined in the following. In addition, to check whether the precondition of the reliability analysis according to EN 1990, Annex D regarding normal distribution or log-normal distribution of the material and geometrical basic variables is fulfilled, the distribution of the measured variables is examined in detail by supplementary statistical methods.

4.7.5.2 Input parameters and definition of resistance functions

According to the design rule of EN 1993-1-4, the theoretical resistance function r_t of the tension resistance of stainless steel bolts is based on the experimentally determined tensile strength $f_{ub,exp}$ including overstrength as the material basic variable and the measured tensile stress area $A_{s,meas}$ as the geometrical basic variable of every individual bolt both as independent basic variables $\underline{X}_{exp}$ and can be reformulated to (Eq. 4.7-9).

$$r_t = g_{rt}(\underline{X}_{exp}) = F_{t,Rk} = k_2 \cdot f_{ub,exp} \cdot A_{s,meas} \qquad \text{(Eq. 4.7-9)}$$

Analogues to this, (Eq. 4.7-10) provides the nominal resistance function r_n of the tension resistance of stainless steel bolts considering basic variables $\underline{X}_{nom}$ based on the nominal tensile strength $f_{ub,nom}$ as the material basic variable and the nominal tensile stress area $A_{s,nom}$ as the geometrical basic variable of every individual bolt.

$$r_n = g_{rt}(\underline{X}_{nom}) = k_2 \cdot f_{ub,nom} \cdot A_{s,nom} \qquad \text{(Eq. 4.7-10)}$$

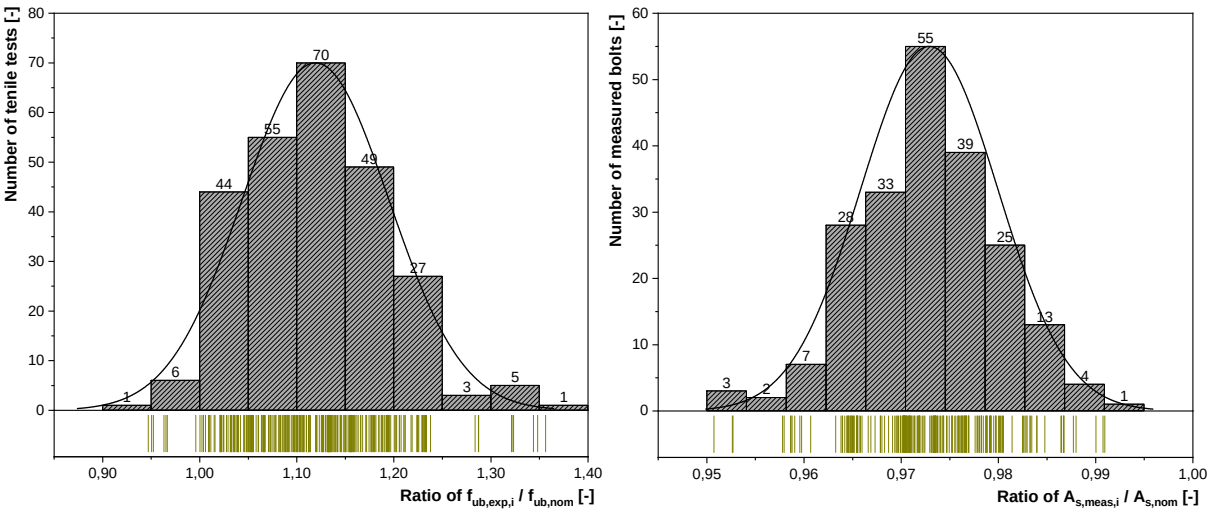
On the contrary, for both equations the reduction factor k_2 is part of the theoretical and nominal resistance functions itself and not a basic variable and has been increased in the following reliability analysis from $k_2 = 0.9$ (as normatively given k_2 value according to EN 1993-1-4 and adopted from EN 1993-1-8) to $k_2 = 1.0$, $k_2 = 1.1$ and even $k_2 = 1.2$ in order to evaluate the different resulting partial safety factors γ_M* according to EN 1990, Annex D.

As already pointed out, it is of major importance that the scattering of the basic variables $\underline{X}$ of the investigated resistance function must be respected in the reliability analysis. Therefore, the coefficients of variation (COV) V_{Xi} of the basic variables $f_{ub,exp}$ and $A_{s,meas}$ as input data were determined from the experimental test data for each individual tested bolt. The scattering of the tensile strength $f_{ub,exp,mean}$ of each bolt series in a tensile test according to EN ISO 3506-1 is in most cases small with coefficients of variation (COV) clearly below 1 %, but in some cases also higher with a maximum COV of 2.2 % (EN ISO 4014 – C6 – M16×100 – A5-70 series). Therefore, it was decided in the frame of [164] and [282] to choose a COV ($f_{ub,exp}$) of 3 % for the scattering of the tensile strength over all tested bolt series as a maximum value clearly on the safe side. The scattering of the measured tensile stress area $A_{s,meas}$ is very remarkably small with a COV below 1 %, see [78] and [164, 282]. Consequently, a maximum COV (A_s) of 1 % was chosen on the safe side for all tested series.

In order to classify and evaluate the chosen coefficients of variation: Afshan et al. [372] performed a reliability analysis of structural stainless steel design provisions and assumed a COV (f_{ub}) of 3.5 % and a COV of the bolt geometry of 5.0 %. However, due to the absence of suitable statistical data on stainless steel bolts during the publication, the statistical parameters used for the analysis presented were based on those of the stainless steel sheet/plate products. As part of the normative process of the revision of DIN 18800-1:1988-03 [379] and the draft of Eurocode 3 [380], Valtinat et al. [381] conducted a meta-analysis on the shear resistance of carbon steel bolts.The meta-analysis includes scatter data of COV (f_{ub}) = 7.0 % and COV (A_s) = 1.0 %, but without any further information about the reliability of these values. The background document for the revision of EN 1993-1-8 from 2004 adopted the coefficients of variation on the safe side. However, in the frame of the German research project FOSTA P 1386 / IGF-No. 20651 N and the extended statistical evaluation presented in Chapter 4.3.3, it could be shown that resulting COVs are remarkable low and the minor scattering should also be integrated in the reliability analysis to represent the European market as realistic as possible but still on the safe side by choosing maximum COV-values.

4.7.5.3 Normal distribution of the experimental tensile strength $f_{ub,exp}$ and measured tensile stress area $A_{s,meas}$

In order to prove that the test population according to EN 1990, Clause D.8.2.2.6 (Step 6) is representative, the histograms and normal distribution of the determined tensile strength of bolt ratios of $f_{ub,exp}$ / $f_{ub,nom}$ and the measured tensile stress area ratios of bolts $A_{s,meas}$ / $A_{s,nom}$ are presented in Figure 4.7-4. It can be seen for both basic variables that the available test data is normally distributed and representative. The requirement of normal or log-normal distributed variables is also defined in Clause D.8.2.1 of EN 1990.



(a) Histogram and normal distribution of the experimentally determined tensile strength of bolts $f_{ub,exp}$

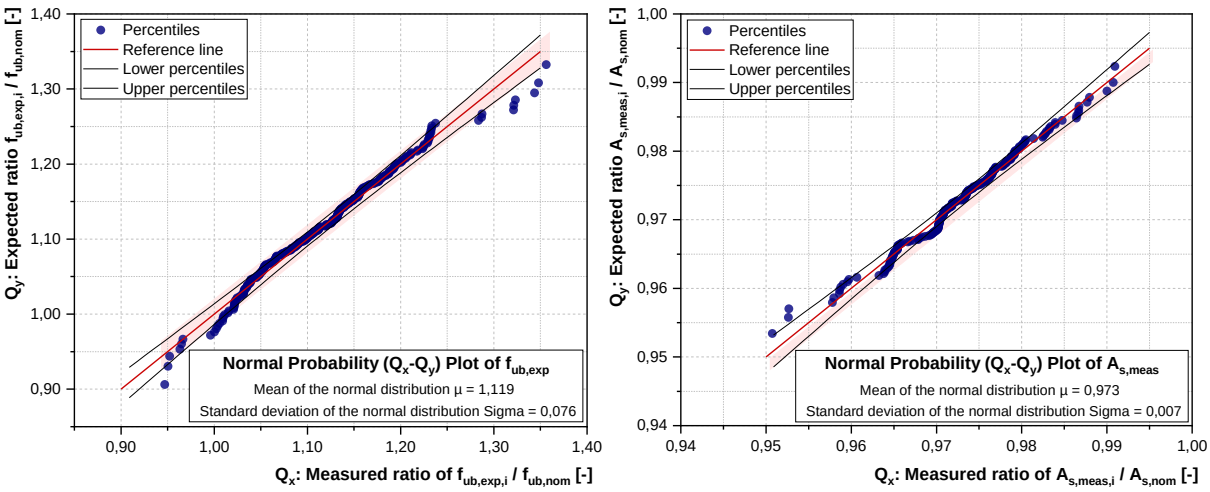
(b) Histogram and normal distribution of the measured tensile stress area of bolts $A_{s,meas}$

Figure 4.7-4: Histograms of the basic variables $f_{ub,exp}$ and $A_{s,meas}$ to visualise the normal distribution

In order to prove normal distribution of the test population of the experimental tensile strength $f_{ub,exp}$ and the measured tensile stress area of bolts $A_{s,meas}$, analytic tests like the Kolmogorov-Smirnov test [382, 383], Lilliefors test [384] and Shapiro-Wilk [385–388] test for normality are applied as supplementary statistical methods. The chosen normality tests are suitable for smaller samples and can be applied to all scale levels. In particular, they are largely robust in contrast to other test procedures (e.g. the Anderson-Darling [389] or Chen-Shapiro test [390]) so that smaller deviations from the normal distribution do not directly lead to the rejection of the normal distribution. The Lilliefors test is another modification of the Kolmogorov-Smirnov test and can be applied to normal distributions with unknown mean and standard deviation.

Beside the purely analytical tests, the normal distribution of the test population can be visualised in probability plots or Q-Q diagrams, which depict the expected quantiles and the measured quantiles, see [391]. The results of selected analytic tests for normality as well as the Q-Q diagrams for the measured basic variables $f_{ub,exp}$ (a, c) and $A_{s,meas}$ (b, d) are presented in Figure 4.7-5. The mathematical background of these analytic tests is not outlined in the frame of this thesis. For further information, reference is made to Lantz [392] regarding statistical significance as well as the references of the analytic tests given above.

Based on the analytic tests for normality, the histograms and the normal probability (Q_x-Q_y) plots, it can be shown that the measured experimental tensile strength $f_{ub,exp}$ and the measured tensile stress area of bolts $A_{s,meas}$ are normally distributed. As visualised in Figure 4.7-5, the main percentiles are following the normal distribution reference line with only minor deviations. However, around low or high ratios, the scattering of the percentiles around the reference lines is increasing. Nevertheless, it can be shown that the measured basic variables are following Gaussian normality and therefore, the methodology of EN 1990, Annex D can be applied.



(a) Normal probability (Q_x-Q_y) plot of $f_{ub,exp}$ (b) Normal probability (Q_x-Q_y) plot of $A_{s,meas}$

Kolmogorov-Smirnov test	Lilliefors test	Kolmogorov-Smirnov test	Shapiro-Wilk test
Statistic: K = 0.045	Statistic: K = 0.045	Statistic: K = 0.080	Statistic: K = 0.987
p-value: 0.688	p-value: 0.222	p-value: 0.132	p-value: 0.055
Decision at 5 % level: Normal distribution cannot be rejected ✓	Decision at 5 % level: Normal distribution cannot be rejected ✓	Decision at 5 % level: Normal distribution cannot be rejected ✓	Decision at 5 % level: Normal distribution cannot be rejected ✓

(c) Analytic test results for normal distribution of $f_{ub,exp}$ (d) Analytic test results for normal distribution of $A_{s,meas}$

Figure 4.7-5: Normal probability (Q_x-Q_y) plots and analytic tests for normality of the variables $f_{ub,exp}$ and $A_{s,meas}$

4.7.6 Results of the reliability analysis for tensile tests according to EN ISO 3506-1

A summary of the results of the reliability analysis for the tension resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolts based on tensile tests on the whole bolt according to EN ISO 3506-1 including literature data is presented in Table 4.7-3. In the reliability analysis of FOSTA P 1386 / IGF-No. 20651 N, the reduction factor k_2 according to EN 1993-1-4 was increased from k_2 = 0.9 to k_2 = 1.0 (as proposed approach for FprEN 1993-1-4) and k_2 =1.1. However, in the frame of this thesis, an increased dataset of in total 210 tensile tests according to EN ISO 3506-1 and 90 tensile tests from literature became available for the statistical evaluation including even k_2 =1.2. For this large number of available tensile tests (n ≥ 100), the simplified formula for obtaining the design value r_d given in (Eq. E.12) was applied with a fractile factor of $k_{d,n}$ = 3.04 for an infinite number of tests.

As a supplement to [282], the resulting partial safety factors γ_M* in Table 4.7-3 are separately evaluated in subsets for each steel grade (austenitic/duplex), each bolt property class and

finally over all bolts for an in-depth analysis of the distribution of the resulting partial safety factors γ_M*. The determined partial safety factors γ_M* are in all subsets and over all bolts even for k_2 = 1.2 below γ_{M2} = 1.25 on the safe side except for duplex bolts in PC 12.9 with k_2 = 1.2 leading to γ_M* = 1.33 > γ_{M2} = 1.25. However, in one duplex PC 12.9 bolt series, the normative requirements are not fulfilled with $f_{ub,exp,mean}$ = 1157.1 N/mm² < $f_{ub,12.9,nom}$ = 1200 N/mm² leading to high γ_M* values.

Table 4.7-3: Summary of the reliability analysis for the tension resistance of austenitic and duplex stainless steel bolts based on tensile tests acc. to EN ISO 3506-1 including literature data with maximum COV (f_{ub}) = 3 % and maximum COV (A_s) = 1 %

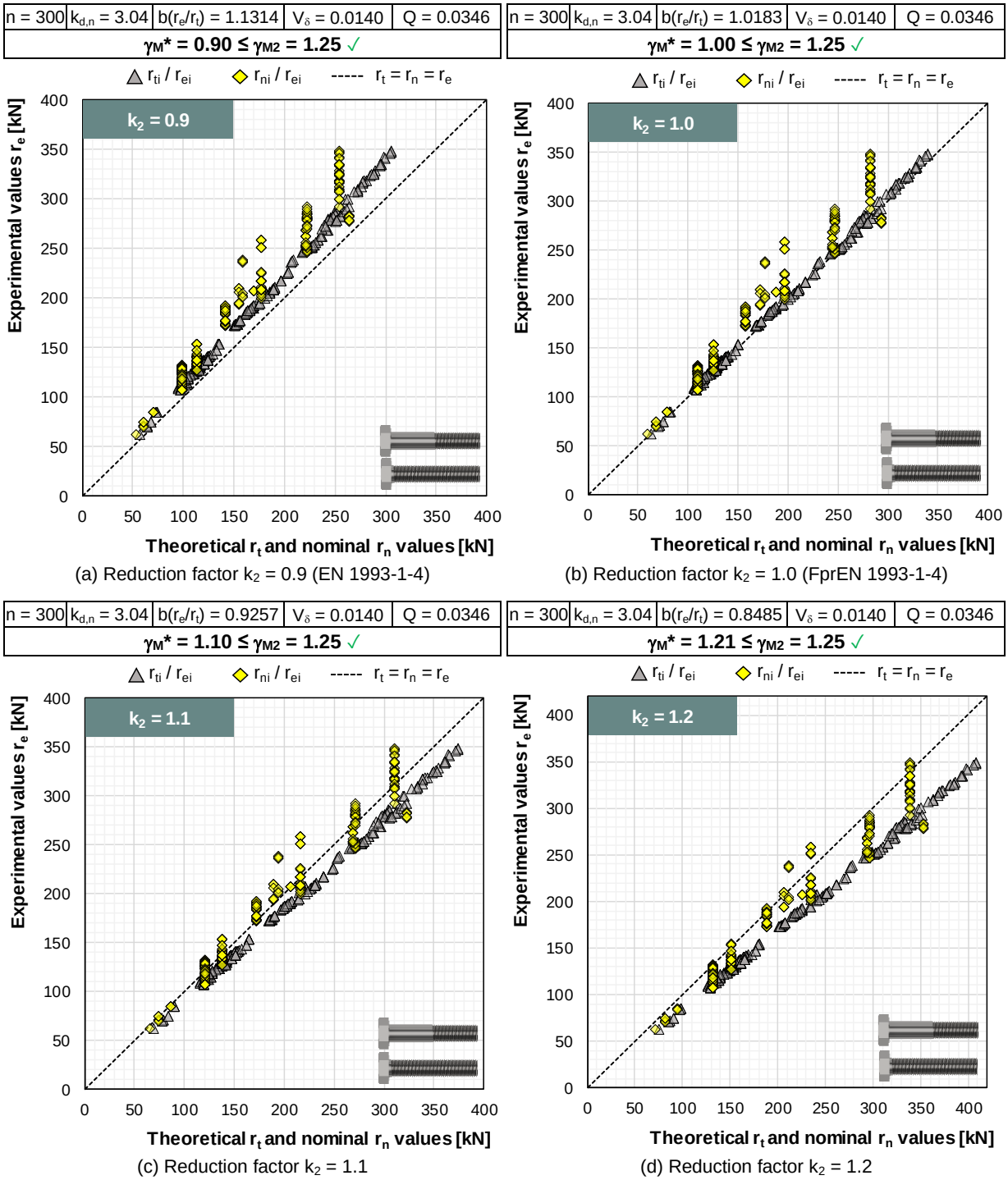
Steel grade	PC	Number of tests	k_2 = 0.9			k_2 = 1.0			k_2 = 1.1			k_2 = 1.2		
			γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]
Austenitic	PC 50	9	0.84			0.93			1.03			1.12		
	PC 70	105	0.92			1.02			1.12			1.22		
	PC 80	91	0.91	0.90		1.01	1.00		1.11	1.10		1.22	1.20	
	PC 8.8	24	0.83			0.92			1.02			1.11		
	PC 10.9	13	0.88		**0.90**	0.98		**1.00**	1.08		**1.10**	1.17		**1.21**
Duplex	PC 70	11	0.90			1.00			1.10			1.20		
	PC 80	6	0.91			1.01			1.11			1.21		
	PC 100	5	0.89	0.91		0.99	1.01		1.09	1.11		1.19	1.21	
	PC 10.9	30	0.90			1.00			1.10			1.20		
	PC 12.9[1)]	6	0.99			1.10			1.22			1.33		

[1)] In one of two duplex series, PC 12.9 was not achieved with $f_{ub,exp,mean}$ = 1157.1 N/mm² < $f_{ub,12.9,nom}$ = 1200 N/mm² leading to high γ_M* values.

Furthermore, an extended comparison of the experimental and theoretical values (r_e/r_t) as well as experimental and nominal values (r_e/r_n) for austenitic and duplex stainless steel bolts with k_2 = 0.9 / 1.0 / 1.1 / 1.2 is provided in Figure 4.7-6.

As summarised, the mean value correction factor for a reduction factor of k_2 = 1.0 is about $b(r_e/r_t)$ = 1.0183 showing a very good agreement between the data points of the theoretical r_{ti} and experimental r_{ei} tension resistance of each tested austenitic and duplex stainless steel bolts lying on the angle bisector and indicating remarkably low scattering. For k_2 = 0.9, the r_{ti} / r_{ei} data points lie above the angle bisector with $b(r_e/r_t)$ = 1.1314 on the safe but noneconomical side. On the contrary, the r_{ti} / r_{ei} data points shift below the angle bisector with $b(r_e/r_t)$ = 0.9257 for k_2 = 1.1 and $b(r_e/r_t)$ = 0.8485 for k_2 = 1.2. Nevertheless, the resulting partial safety factors γ_M* over all bolts are still below γ_{M2} = 1.25 for connections.

It can be concluded that the resistance function with k_2 = 1.0 seems to be most suitable to describe the tension resistance of austenitic and duplex stainless steel bolts and still includes sufficient safety reserves against bolt overstressing and failure. As already pointed out in [282], since the scope of the experimental investigations is large but of course still limited in order to reflect all European and German market variations of austenitic and duplex stainless steel bolts and to consider unfavourable but non-negligible prying effects, eccentricity, bending of the bolt and/or imperfections, it was decided in the frame of the German research project FOSTA P 1386 / IGF-No. 20651 N and further studies to suggest an increase of the tension resistance of a stainless steel bolt with k_2 = 1.0 and not higher. The proposed design is already implemented in the revision of EN 1993-1-4, FprEN 1993-1-4, and the updated German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022. Furthermore, a harmonisation of the tension resistance of stainless steel bolts between European EN 1993-1-4 and EN ISO 3506-1 design and product standards, North American ANSI/AISC 370, AISC Design Guide 27 and SEI/ASCE 8 and Australian/New Zealand AS/NZS 4673 and other standards was intended.



(a) Reduction factor k_2 = 0.9 (EN 1993-1-4)

(b) Reduction factor k_2 = 1.0 (FprEN 1993-1-4)

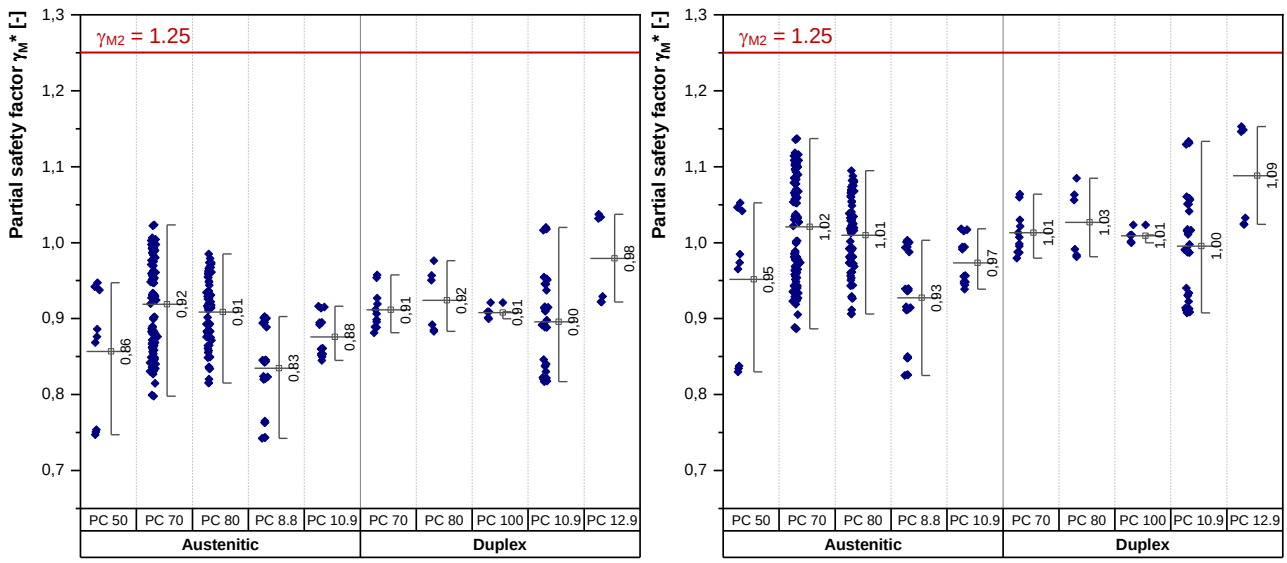
(c) Reduction factor k_2 = 1.1

(d) Reduction factor k_2 = 1.2

Figure 4.7-6: Comparison of the experimental r_e and theoretical r_t/nominal r_n tension resistances for austenitic and duplex stainless steel bolts) based on tensile tests on bolts according to EN ISO 3506-1 including literature data

In order to visualise the distribution of the resulting individual partial safety factors $\gamma_{M,i}$* over all austenitic and duplex stainless steel bolts across all investigated bolt property classes for k_2 = 0.9 and k_2 = 1.0, the individual data points of each tested bolt including literature data are summarised graphically in Figure 4.7-7 including plots of the range and resulting partial safety factor mean values γ_M*. In both cases it can be shown that all individual partial safety factors $\gamma_{M,i}$* are clearly below γ_{M2} = 1.25 in all investigated property classes.

Since the individual partial safety factors $\gamma_{M,i}$* are not exceeding γ_{M2} = 1.25, a further evaluation according to modified assesment criteria (see Chapter 4.7.4) is not imperative.



(a) Distribution of γ_M* for each bolt property class with k_2 = 0.9 based on the reliability analysis over all bolts

(b) Distribution of γ_M* for each bolt property class with k_2 = 1.0 based on the reliability analysis over all bolts

Figure 4.7-7: Distribution of the partial safety factors γ_M* of austenitic and duplex stainless steel bolts for each property class with k_2 = 1.0 and k_2 = 1.1 based on the tensile tests according to EN ISO 3506-1 including literature data

4.7.7 Results of the reliability analysis for tensile tests on bolts according to EN ISO 3506-1 and bolting assemblies according to EN 15048-2

In order to extend the database for a more detailed and statistical evaluation of the tension resistance of austenitic and duplex stainless steel bolts, the tensile tests on bolts according to EN ISO 3506-1 are complemented by tensile tests on bolting assemblies (as bolt and nut excluding washer) according to the specifications given in EN 15048-2. It must be mentioned that the tension resistance of stainless steel bolts always has to be determined according to EN ISO 3506-1 on the whole bolt. However, in a steel structure, bolts are generally installed with nuts (and washers) so that the tension resistance of the bolting assembly becomes decisive. In order to cover also this (more practical and realistic) case, the reliability analysis is extended by the additionally performed tensile tests according to EN 15048-2 on M16 austenitic and duplex stainless steel bolting assemblies. In total, 210 tensile tests on bolts according to EN ISO 3506-1 and 114 tensile tests on bolting assemblies according to EN 15048-2 (see Chapter 4.5.3) as well as 90 tensile tests from literature review are considered in the reliability analysis leading to an increased data set of 414 tensile tests compared to 261 tests presented in [282].

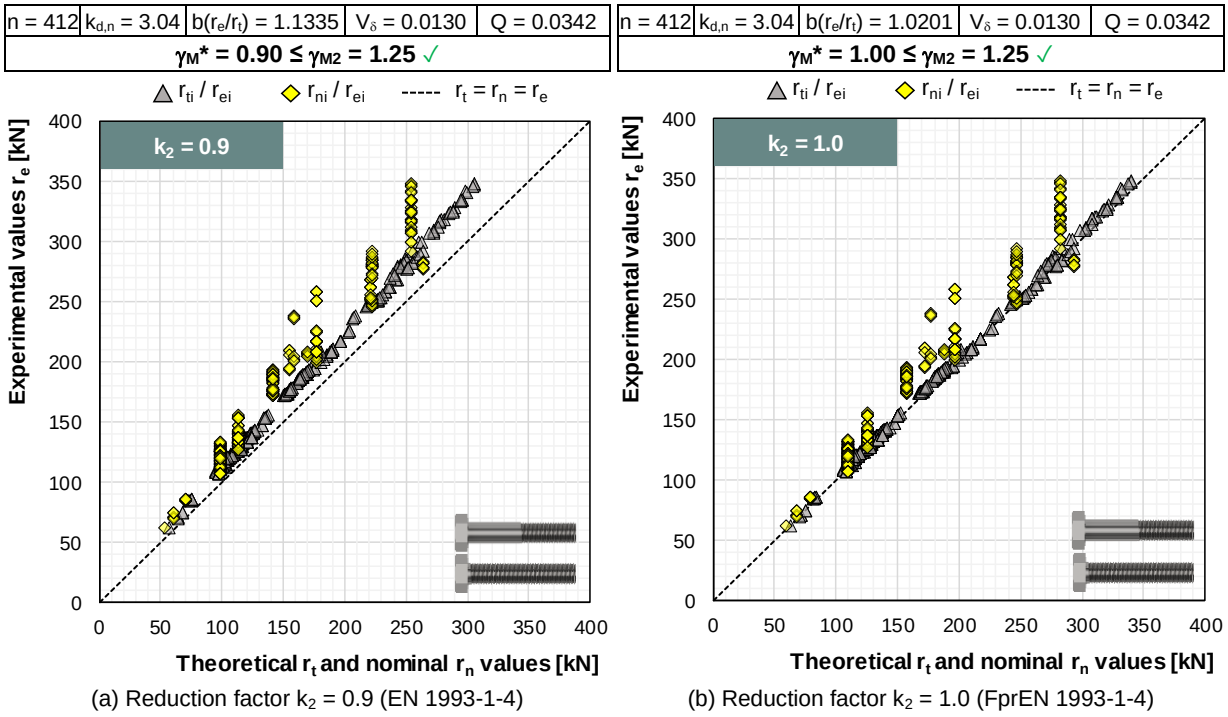
A summary of the results of the extended reliability analysis for the tension resistance of austenitic and duplex stainless steel bolts and bolting assemblies including literature data is presented in Table 4.7-4 in defined subsets and over all tests. For the reliability analysis of the stainless steel bolting assemblies tested according to the specifications of EN 15048-2, also a maximum COV (f_{ub}) = 3 % and maximum COV (A_s) = 1 % was applied with a fractile factor of $k_{d,n}$ = 3.04 for an infinite number of tests. Analogues to the reliability analysis presented above on austenitic and duplex stainless steel bolts according to EN ISO 3506-1, the determined partial safety factors γ_M* are in all subsets and over all bolts and bolting assemblies even for k_2 = 1.2 below γ_{M2} = 1.25 on the safe side (again except for duplex bolts in PC 12.9 with k_2 = 1.2 leading to γ_M* = 1.29 > γ_{M2} = 1.25). In general, it can be concluded that the resulting partial safety factors γ_M* based on a test population covering stainless steel bolts and bolting assemblies are equal or partially slightly lower in the second decimal compared to the γ_M* values only based on tensile tests according to EN ISO 3506-1 on the whole bolt.

Table 4.7-4: Summary of the reliability analysis of the tension resistance for austenitic and duplex stainless steel bolts and bolting assemblies including literature data with maximum COV (f_{ub}) = 3 % and maximum COV (A_s) = 1 %

Steel grade	PC	Number of tests	k_2 = 0.9			k_2 = 1.0			k_2 = 1.1			k_2 = 1.2		
			γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]
Austenitic	PC 50	12	0.86			0.95			1.05			1.14		
	PC 70	145	0.91			1.01			1.11			1.22		
	PC 80	111	0.92	0.90		1.02	1.00		1.12	1.10		1.22	1.20	
	PC 8.8	32	0.83			0.93			1.02			1.11		
	PC 10.9	21	0.87			0.96			1.06			1.15		
					0.90			**1.00**			**1.10**			**1.20**
Duplex	PC 70	14	0.90			1.00			1.10			1.21		
	PC 80	9	0.89			0.99			1.09			1.19		
	PC 100	10	0.89	0.89		0.98	0.99		1.08	1.09		1.18	1.19	
	PC 10.9	51	0.88			0.98			1.07			1.17		
	PC 12.9[1)]	9	0.97			1.07			1.18			1.29		

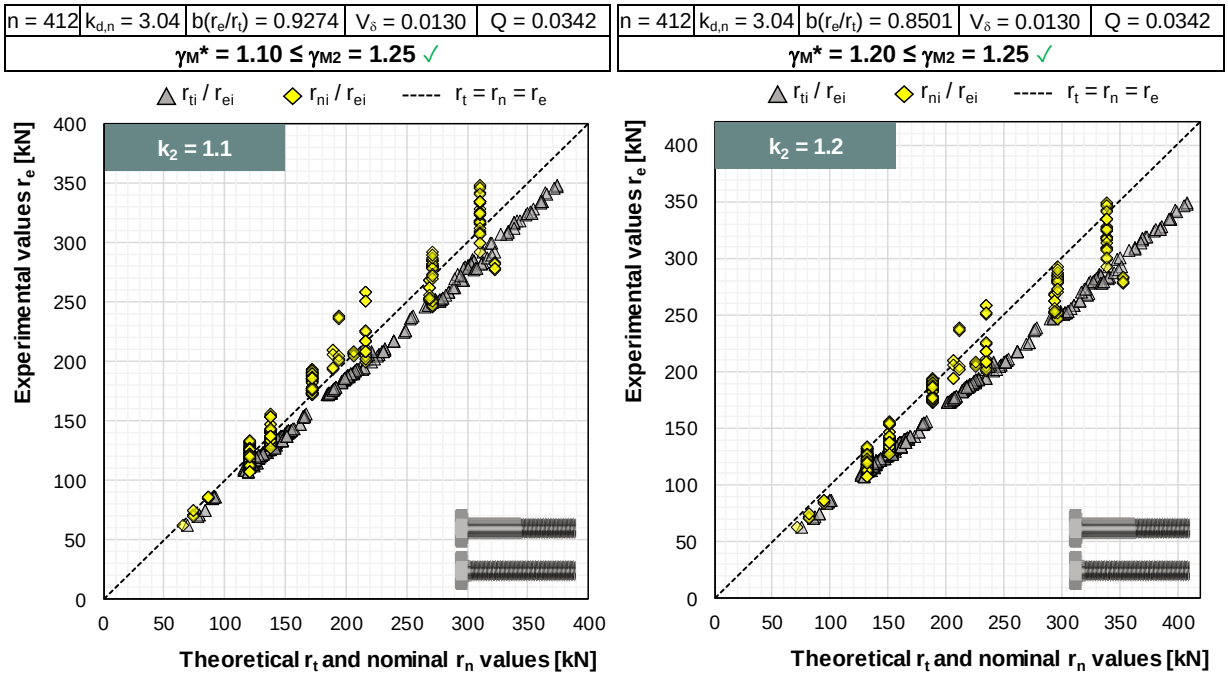
[1)] In one of two duplex series, PC 12.9 was not achieved with $f_{ub,exp,mean}$ = 1157.1 N/mm² < $f_{ub,12.9,nom}$ = 1200 N/mm² leading to high γ_M* values.

In order to allow an in-depth analysis, an extended comparison of the experimental and theoretical values (r_e/r_t) as well as experimental and nominal values (r_e/r_n) for austenitic and duplex stainless steel bolts with k_2 = 0.9 / 1.0 / 1.1 / 1.2 is provided in Figure 4.7-8. The mean value correction factor b for k_2 = 1.0 is about b(r_e/r_t) = 1.0201 (instead of 1.0183) showing again a very good agreement between the data points of the theoretical r_{ti} and experimental r_{ei} tension resistance of each tested austenitic and duplex stainless steel bolts. Thus, the resistance function with k_2 = 1.0 seems to be most suitable to describe the tension resistance of stainless steel bolts and bolting assemblies including sufficient safety reserves. For a reduction factor of k_2 = 0.9, the r_{ti} / r_{ei} data points lie above the angle bisector with b(r_e/r_t) = 1.1335 (instead of b(r_e/r_t) = 1.1314) on the safe but noneconomical side. In contrast, the r_{ti} / r_{ei} data points shift below the angle bisector with b(r_e/r_t) = 0.9274 (instead of b(r_e/r_t) = 0.9257) for k_2 = 1.1 and b(r_e/r_t) = 0.8501 (instead of b(r_e/r_t) = 0.8485) for k_2 = 1.2.



(a) Reduction factor k_2 = 0.9 (EN 1993-1-4) (b) Reduction factor k_2 = 1.0 (FprEN 1993-1-4)

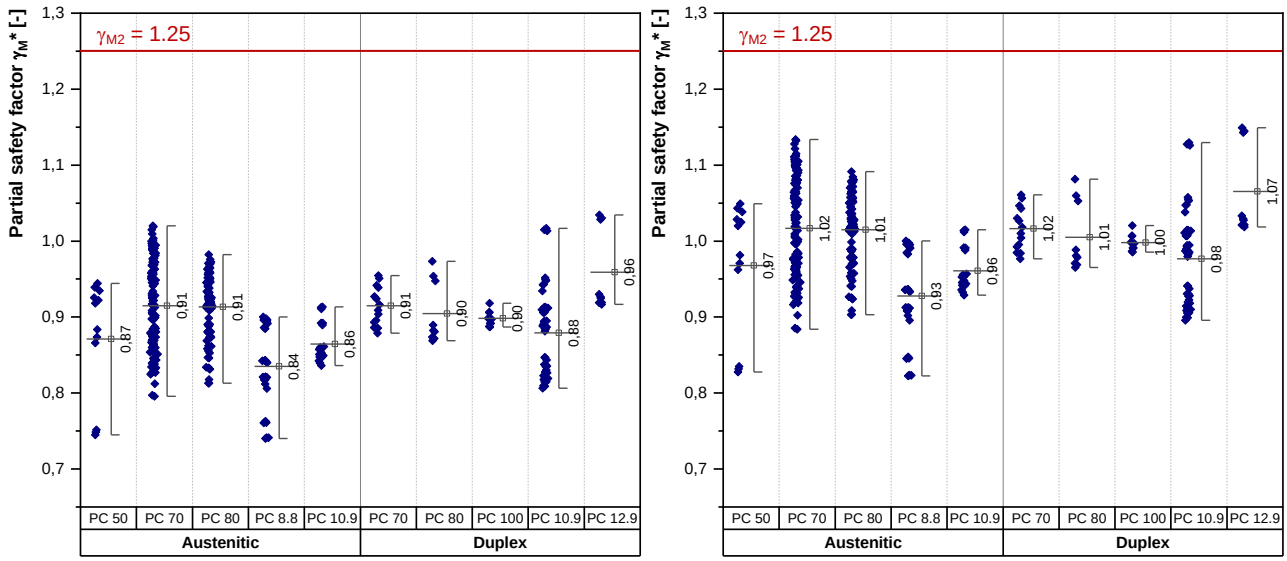
Figure 4.7-8: Comparison of the experimental r_e and theoretical r_t/nominal r_n tension resistances for austenitic and duplex stainless steel bolts based on tensile tests on bolts according to EN ISO 3506-1 and bolting assemblies according to EN 15048-2 including literature data



(c) Reduction factor k_2 = 1.1 (d) Reduction factor k_2 = 1.2

Figure 4.7-8: Comparison of the experimental r_e and theoretical r_t/nominal r_n tension resistances for austenitic and duplex stainless steel bolts based on tensile tests on bolts according to EN ISO 3506-1 and bolting assemblies according to EN 15048-2 including literature data (Cont.)

The distribution of the resulting individual partial safety factors $\gamma_{M,i}$* over all austenitic and duplex stainless steel bolts and bolting assemblies across all investigated property classes for k_2 = 0.9 and k_2 = 1.0 including literature are summarised graphically in Figure 4.7-9 in conjunction with range plots and resulting partial safety factor mean values γ_M*. Analogues to the results from the tensile tests according to EN ISO 3506-1, it can be shown that for k_2 = 0.9 and k_2 = 1.0 all individual partial safety factors $\gamma_{M,i}$* of the bolts and bolting assemblies are clearly below γ_{M2} = 1.25 in all investigated property classes and indicate sufficient safety reserves to cover bending and prying action effects caused by eccentricity and imperfections. Again, a further safety assesment is not necessary.



(a) Distribution of γ_M* for each bolt property class with k_2 = 0.9 based on the reliability analysis over all bolts and assemblies

(b) Distribution of γ_M* for each bolt property class with k_2 = 1.0 based on the reliability analysis over all bolts and assemblies

Figure 4.7-9: Distribution of the partial safety factors γ_M* of austenitic and duplex stainless steel bolts for each property class with k_2 = 1.0 and k_2 = 1.1 based on the tensile tests on bolts according to EN ISO 3506-1 and bolting assemblies according to EN 15048-2 including literature data

4.8 Summary and conclusions

An overview of the experimental investigations and statistical evaluations conducted in the German research project FOSTA P 1386 / IGF-No. 20651 N were briefly presented and complemented by additional experimental investigations in order to extend the database for an extended statistical evaluation according to EN 1990, Annex D. The supplementary experimental investigations covered tensile tests on austenitic and duplex stainless steel bolting assemblies according to EN 15048-2 (for the purpose of an informative comparison with tensile test results from bolts), tensile coupon test specimens machined from M16 stainless steel bolts according to EN ISO 6892-1

It could be shown that the overstrength ratios between the experimental mean maximum load $F_{mf,exp,mean}$ and the minimum ultimate tensile load $F_{mf,nom}$ of the tested partially threaded austenitic stainless steel bolts are due to the varying degrees of strain hardening and transformation of austenitic to forming induced martensitic material between 1.07 and 1.35 and between 1.06 and 1.23 for duplex bolts. Fully threaded austenitic stainless steel bolts according to EN ISO 4017 show overstrength ratios between 1.01 and 1.23 and are less pronounced, while duplex stainless steel bolts show overstrength ratios between 1.09 and 1.20 nearly comparable to the partially threaded bolts. Furthermore, a comparison between tensile tests on bolts according to EN ISO 3506-1 and tensile tests on bolting assemblies according to EN 15048-2 showed that the differences between both tensile testing procedures and the resulting tension resistances between austenitic and duplex stainless steel bolts and bolting assemblies are negligible.

Due to a transformation of austenitic to forming induced martensitic material in the tensile cross-section originating from the thread rolling process with a larger hardness and higher strength in the border of the cross-section of the threads, a non-homogeneous distribution of the tensile and yield strength in the unthreaded and threaded parts of austenitic and even duplex stainless steel bolts could be confirmed. The main failure mode of austenitic bolts was positioned in the unthreaded bolt part, while all duplex bolts and only a few austenitic bolt series failed in the threaded part. Based on the experimental investigations and the observed overstrength ratios, an increase of the reduction factor of k_2 up to $k_2 = 1.0$ according to the design of EN 1993-1-4 was already proposed in [78, 282].

Finally, based on the extended database of 375 tensile tests including literature data, a reliability analysis according to EN 1990, Annex D was conducted to verify the resulting partial safety factors γ_M* of the proposed design approach for the tension resistance of stainless steel bolts with $k_2 = 1.0$ against the partial safety factor $\gamma_{M2} = 1.25$ for connections. It could be shown that due to overstrength of the austenitic and duplex stainless steel bolts in conjunction with low scattering of the test results and geometrical properties all individual partial safety factors $\gamma_{M,i}$* are clearly below $\gamma_{M2} = 1.25$ on the safe side in all investigated property classes and over all stainless steel bolts and bolting assemblies (even by increasing to $k_2 = 1.1$). Therefore, it can be concluded that the proposed design approach for the tension resistance of austenitic and duplex stainless steel bolts is fulfilling the safety requirements of the Eurocode. Further analyses based on Kruppa and modified assesment criteria were therefore not necessary. Furthermore, a harmonisation of the tension resistance of stainless steel bolts between European EN 1993-1-4 and EN ISO 3506-1 design and product standards, North American ANSI/AISC 370, AISC Design Guide 27 and SEI/ASCE 8 and Australian/New Zealand AS/NZS 4673 and other standards is accomplished. The proposed design is already implemented in the revision of EN 1993-1-4 and abZ/aBG Z-30.3-6:2022.

5 Shear resistance of stainless steel bolts and bolting assemblies

5.1 General

An overview of the experimental investigations including an extended literature review is given in Chapter 5 and complemented by statistical evaluations according to EN 1990, Annex D [79] regarding the shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolts and bolting assemblies. Since the testing programmes, procedures, main test results and the statistical evaluations of the German research project FOSTA P 1386 / IGF-No. 20651 N [78] and further research activities have already been published by Stranghöner/Abraham [164, 283, 362, 364], they are only briefly outlined.

Analogues to the investigations into the tension resistance $F_{t,Rd}$ of stainless steel bolts and bolting assemblies, supplementary experimental investigations were carried out beyond the scope of the German research project and complemented by an extended literature review to expand the database. The new investigations include studies into the load bearing behaviour and differences between the shear resistance of austenitic and duplex stainless steel bolts and bolting assemblies achieved by single-shear testing and double-shear testing. For this reason, the shear test procedures and specifications of different standards are briefly introduced and discussed regarding the findings about the shear resistance of carbon and stainless steel bolts summarised in Chapter 2.5. In addition, the impact of skewing and possible misalignments of the bolt during testing is analysed by numerical FEM investigations.

In order to identify the key parameters and the correlations between the tensile and shear strength of austenitic and duplex stainless steel bolts, direct and indirect multi-step pathway and correlation analyses are conducted. Additionally, based on an extended literature review (considering 102 instead of 51 shear test results) and an extended database by 132 new double-shear tests on stainless steel bolts and bolting assemblies, reliability analyses according to EN 1990, Annex D are conducted to re-validate the proposed shear resistance and new shear coefficients α against the partial safety factor of γ_{M2} = 1.25 for connections. The statistical evaluations are complemented by distribution analyses of the resulting partial safety factors γ_M* and safety assessments to improve the reliability of the proposed design approach for the shear resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolts.

Finally, Chapter 5 is summarised and conclusions regarding the shear resistance $F_{v,Rd}$ of stainless steel bolts and bolting assemblies are drawn. The proposed new design rules for the shear resistance of austenitic and duplex stainless steel bolts were already implemented in FprEN 1993-1-4 [80] and German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022 [81].

5.2 Existing studies into the shear resistance of stainless steel bolts

As already discussed in Chapter 2.5, a great variety of research into non-preloaded stainless steel bolted connections is available but mainly focuses exclusively on the bearing and net section failure behaviour of plates made of austenitic or duplex stainless steel. As only a few studies exist on the shear load bearing behaviour of austenitic and duplex stainless steel bolts, systematic experimental investigations were conducted in [78]. Only those test data from publications are considered which give a direct contribution to the shear resistance of stainless steel bolts and bolting assemblies and where a clear description of the test procedure and the mechanical properties of the bolts is provided. Compared to [164], the shear testing database from the literature review is doubled to 102 shear test results (instead of 51 shear tests) in

order to improve the representativity and reliability of the statistical evaluation. The following briefly outlines the existing studies into the shear resistance of austenitic and duplex stainless steel bolts.

First, a limited test programme was conducted by the Steel Construction Institute (SCI) [266] in 1990 covering double-shear tests on fully threaded austenitic A4-70 (M16) and A4-80 (M16, M20) stainless steel bolting assemblies. In total, 30 double-shear tests were conducted. Analogues to the investigations into the bolt tension resistance, the M20 A4-80 series from bolt supplier C was not considered for the following investigations since the normative required minimum ultimate tensile load F_{mf} is not achieved with clear undercutting of approximately -19 %. The resulting experimental shear/tensile strength ratios of the double-shear tests with both shear planes in the threaded part are α = 0.63 (M16 A4-70), α = 0.66 (M16 A4-80) and α = 0.62 (M20 A4-80).

In the framework of the ECSC project 7210-SA/327, Ryan [270] reported further three double-shear tests on partially threaded austenitic stainless steel bolts in PC A4-80 of each bolt diameter/length M12×40, M16×50 and M20×50 resulting in average ratios of the shear/tensile strength to α = 0.69 (M12), α = 0.66 (M16) and α = 0.62 (M20). In 2007, the Steel Construction Institute [272] conducted a small amount of double-shear tests in the European “Stainless steel in fire (SSIF)” research project. Nevertheless, the double-shear tests on partially threaded M12×50 A2-70 and A4-80 austenitic stainless steel bolting assemblies at room temperature are considered in the following investigations.

Beside the investigations into the tension and interaction resistance, Song et al. [5, 6] carried out additionally single-/double-shear tests on partially threaded (M20, EN ISO 4014) and fully threaded (M16/M20/M24, EN ISO 4017) austenitic (1.4401, A4-70, A4-80 and 1.4432, PC 8.8 and 10.9) and duplex stainless steel bolting assemblies (1.4462, PC 10.9 and 12.9). However, the resulting shear coefficients were not determined by Song et al. If the shear/tensile strengths are evaluated following the design of EN 1993-1-4 and focusing on single-shear tests, the following shear coefficients α result for the case that the unthreaded part of a bolt is in the shear plane for austenitic bolts: 0.64 (PC 70), 0.62 (PC 80), 0.59 (PC 8.8) and 0.60 (PC 10.9), and for duplex bolts: 0.60 (PC 10.9) and 0.59 (PC 12.9). For the loading case that the threaded part of a bolt is positioned in the shear plane, for austenitic stainless steel bolts, the shear coefficients α result to 0.66 to 0.72 (PC 70) (indicating decreasing shear coefficients α if the bolt diameter is increased from M16 to M24, which also can be observed in the investigations of Ryan [270]), 0.67 (PC 80), 0.64 (PC 8.8) and 0.63 (PC 10.9), and for duplex stainless steel bolts, the shear coefficients α result to 0.68 (PC 10.9 and 12.9).

The experimental investigations from Song et al. [5] allow a comparison between the resulting shear resistances of partially and fully threaded M20 austenitic stainless steel bolts in PC 70 and 80 tested in single-shear and double-shear testing procedures. The loading blocks for both single-shear and double-shear testing were made of Q&T 80 as a quenched and tempered high-strength carbon steel material according to AS/NZS 3597 [393] with a defined grip length of 100 mm. Based on the test results from Song et al. [5, 6], the shear resistance per shear plane of bolts tested in the double-shear test rig was always slightly smaller compared to the shear resistance achieved in single-shear tests. The smallest deviation of the resulting shear resistance of a bolt per shear plane between single-shear and double-shear testing is 1.34 % for M20 A4-80 bolting assemblies with unthreaded part in the shear plane, while the largest deviation is in the amount of 3.91 % for M20 A4-80 bolting assemblies with threaded part in the shear plane.

Table 5.2-1: Summary of the literature review regarding the shear resistance of stainless steel bolts (additionally added publications compared to [164] are marked in bold in the table)

Steel type	Property class acc. to EN ISO 3506-1	Corrosion class acc. to EN ISO 3506-1	Publication	Testing procedure	Bolt position of the shear plane	Bolt geometry	Testing type (B= Bolt, BA = Bolting assembly)	Number of tensile tests	$f_{ub,calc,As}$ [N/mm²]	$f_{ub,calc,shank}$ [N/mm²]	Mean $F_{max,0°}$ [kN]	Overstrength ratio of Mean $F_{max,0°}$ / F_{mf}	Number of shear tests	Mean shear resistance per plane $F_{max,90°}$ [kN]	Mean shear coefficient $\alpha_{EC3-1-4,calc,mean}$ [-] [4]
Austenitic	PC 70	A2-70	**SCI [272] (2007)**	**Double-shear**	Shank + Threads	M12×50	BA	1	747.7	-	63.0	1.068	1	43.7	0.52[5]
		A4-70	**SCI [266] (1990)**	**Double-shear**	Threads + Threads	M16×-	BA	6	689.4	-	108.0	0.984	2	68.3	0.63
			Song et al. [5] (2020)	Single-shear	Threads	M16×100	BA	3	732.1	-	114.7	1.046	3	82.6	0.72
						M20×100	BA	3	796.2	-	194.9	1.137	3	137.4	0.70
						M24×100	BA	3	824.4	-	290.6	1.178	3	192.5	0.66
					Shank	M20×100	BA	3	855.4	659.0[2]	209.4	1.222	3	170.8	0.64
				Double-shear	Threads + Threads	M20×100	BA	3	796.2	-	194.9	1.137	3	132.7	0.68
					Shank + Shank	M20×100	BA	3	855.4	659.0[2]	209.4	1.222	3	168.5	0.63
	PC 80	A4-80		Single-shear	Threads	M20×100	BA	3	833.4	-	204.0	1.041	3	138.1	0.67
					Shank	M20×100	BA	3	923.2	712.0[2]	226.0	1.154	3	178.9	0.62
				Double-shear	Threads+ Threads	M20×100	BA	3	833.4	-	204.0	1.041	3	132.7	0.65
					Shank + Shank	M20×100	BA	3	923.2	712.0[2]	226.0	1.154	3	172.6	0.59
			SCI [266] (1990)	**Double-shear**	Threads + Threads	M16×-	BA	15	859.2	-	134.6	1.074	12	88.4	0.66
						M20[1]×-	BA	13	873.4	-	213.8	1.091	16	131.9	0.62
			Ryan [270] (2000)	Double-shear	Shank + Threads	M12×-	BA	4	846.2	-	71.3	1.058	3	49.5	0.69
						M16×-	BA	4	931.3	-	145.9	1.163	3	95.8	0.66
						M20×-	BA	4	845.6	-	207.0	1.057	3	128.7	0.62
			SCI [272] (2007)	**Double-shear**	Shank + Threads	M12×50	BA	2	897.2	-	75.6	1.121	1	53.0	0.61[5]
	PC 8.8	A4-8.8	Song et al. [6] (2020)	Single-shear	Threads	M20×140	BA	3	1029.0	-	251.9	1.286	3	160.3	0.64
					Shank	M20×140	BA	3	1057.6	824.8[2]	258.9	1.322	3	195.7	0.59
	PC 10.9	A4-10.9			Threads	M20×140	BA	2	1074.4	-	263.0	1.074	3	165.5	0.63
					Shank	M20×140	BA	3	1098.9	925.8[2]	269.0	1.099	3	205.4	0.60
Duplex	PC 10.9	D6-10.9	Song et al. [6] (2020)	Single-shear	Threads	M20×140	BA	3	1039.6	-	254.5	1.040	3	172.7	0.68
					Shank	M20×140	BA	3	1033.9	809.9[2]	253.1	1.034	3	195.3	0.60
	PC 12.9[3]	D6-12.9			Threads	M20×140	BA	3	1139.7	-	279.0	0.949	3	189.0	0.68
					Shank	M20×140	BA	3	1158.1	903.0[2]	283.5	0.964	3	213.4	0.59
Σ Total number of shear tests on austenitic bolts								90	$\alpha_{EC3-1-4,calc,mean}$ | min./max.					0.52/0.72	
Σ Total number of shear tests on duplex bolts								12	$\alpha_{EC3-1-4,calc,mean}$ | min./max.					0.59/0.68	
Σ Total number of shear tests on bolts								**102**	$\alpha_{EC3-1-4,calc,mean}$ | min./max.					0.52/0.72	

[1] Shear tests on M20 A4-80 bolts from supplier C are not considered as the bolts clearly fail the requirements of PC 80. | [2] Tensile strength of the bolt shank $f_{ub,calc,shank}$ on the safe side from machined tensile specimens. | [3] Resulting tensile strength $f_{ub,calc,mean}$ < nom. $f_{ub,12.9}$ = 1200 N/mm² and min. $R_{m,12.9}$ = 1220 N/mm², PC 12.9 could not be confirmed. | [4] The shear coefficients $\alpha_{EC3-1-4,calc,mean}$ = Mean $F_{max,90°}$ / ($f_{ub,calc,As}$ · (A or A_s)) are determined as characteristic values according to the design rules of EN 1993-1-4, see (Eq. 3.4-3). | [5] The shear coefficient α for the case that the unthreaded and threaded part of a bolt are in the shear plane is determined as an average value of both loading cases.

The load-deformation curves of the tested bolting assemblies are very similar and the authors report neither bending or prying action effects nor damages of the hole bearing or test rigs caused by the high hardness of the austenitic threads. However, this contradicts the studies of Dörre et al. [175] into the shear resistance of carbon steel bolts, which identified single-shear testing in their experimental investigations as the more critical case. This needs to be further examined in the following investigations.

Furthermore, Dünkel [289] stated that the normative regulations for the shear coefficients of austenitic stainless steel bolts in PC 50, 70 and 80 from the German national annex of EN 1993-1-4, DIN EN 1993-1-4/NA [71], were only roughly estimated on the basis of the investigations of Thomala [169] from 1984. However, only a limited number of double-shear tests on cold-formed unnotched steel bars of A2 (1.4303) and A4 (1.4401) material were carried out, and it remained uncertain to what extent a direct transferability to partially or fully threaded bolts is possible. Consequently, the test results of [169] were not considered in [164] and in the following investigations.

5.3 Experimental investigations: Shear test programme

5.3.1 General

The test programme of the experimental investigations into the bolt shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolts and bolting assemblies are provided in the following. The main results of the experimental studies in the framework of the German research project FOSTA P 1386 / IGF-No. 20651 N are summarised and complemented by new, independent research activities embedded in the thesis considering:

- Single-shear tests on stainless steel bolting assemblies (based on [78]), and
- Double-shear tests on stainless steel bolts and bolting assemblies with and without nut to investigate the load bearing behaviour under different testing conditions (supplementary experimental investigations).

5.3.2 Single-shear tests on stainless steel bolting assemblies

In total, 120 single-shear tests on austenitic and duplex stainless steel bolts with unthreaded part in the shear plane (partially threaded EN ISO 4014 [119] or EN ISO 4762 [120] bolts with EN ISO 4032 [394] nuts) complemented by 90 single-shear tests with threaded bolt part in the shear plane (fully threaded EN ISO 4017 [121] bolts with EN ISO 4032 nuts) in bolt dimensions M16×100/110 and M24×130 were conducted and statistically evaluated. The 120 single-shear tests on partially threaded EN ISO 4014 and EN ISO 4762 bolts cover austenitic (PC 50, 70, 80, 8.8 and 10.9), duplex (PC 70, 80, 100, 12.9) and super duplex (only PC 10.9) stainless steel bolts, while the 90 single-shear tests on fully threaded EN ISO 4017 bolts contain austenitic (PC 50, 70, 80, 8.8 and 10.9), lean duplex (PC 10.9), duplex (PC 70 and 10.9) as well as super duplex (PC 10.9) grades. Analogues to the experimental investigations into the tension resistance of stainless steel bolts, each configuration includes at least three specimens from different anonymised bolt manufacturers or traders (abbreviated as C1 to C6) with either rolled or cut threads to represent the current European market as realistic as possible.

The detailed test matrixes of the tested austenitic and duplex stainless steel bolting assemblies are presented in Table B.8 and Table B.9 of Appendix B.

5.3.3 Double-shear tests on stainless steel bolts and bolting assemblies

An experimental investigation into the double-shear resistance of M16×100 partially and fully threaded austenitic and duplex stainless steel bolts and bolting assemblies is carried out in order to get deeper knowledge about the different load bearing characteristics of bolts subjected to single- or double-shear loading. Therefore, the loading cases “unthreaded bolt part in the shear planes” (a), “threaded bolt part in the shear planes” (b) and a combination of “unthreaded and threaded bolt part in the shear planes” (c) are covered in the experimental investigations.

Furthermore, double-shear tests on austenitic and duplex stainless steel bolts tested with or without EN ISO 4032 nuts are conducted to determine the load bearing and possibly stabilising effect of the ISO hexagon nut. In this way, the resulting shear resistance of stainless steel bolts and bolting assemblies and possible supporting effects of the nuts can be compared directly. All single-shear tests are carried out with a nominal bolt hole diameter of $d_{h,nom}$ = 17 mm for the purpose a practicable installation situation for testing with as little hole clearance as possible to reduce misalignments of the bolt or bolting assembly. To ensure direct comparability, special hardened adapters with a hole diameter of $d_{h,nom}$ = 17 mm are applied for double-shear testing. As a second parameter, the influence of the hole clearance in the M16 double-shear test rig is investigated. Therefore, hardened adapters with bolt holes of $d_{h,nom}$ = 16 mm produced in ISO tolerance field H8 (+27 μm, -0 mm) according to EN ISO 286-1 [395] and EN ISO 286-2 [396] are applied to intentionally avoid misalignments of the bolt or bolting assembly during testing. Thus, the influence of possible inclination or misalignments of the bolts or bolting assemblies which are possibly increasing the shear cross-sectional area during testing will be explicitly considered and systematically investigated.

In total, 162 double-shear tests were conducted as a supplement to [164] in the frame of this thesis. A detailed overview of the test matrixes for the previously described loading cases is provided in Table B.10 (a), Table B.11 (b) and Table B.12 (c) of Appendix B:

5.4 Experimental investigations: Shear test procedures and testing specifications

5.4.1 General

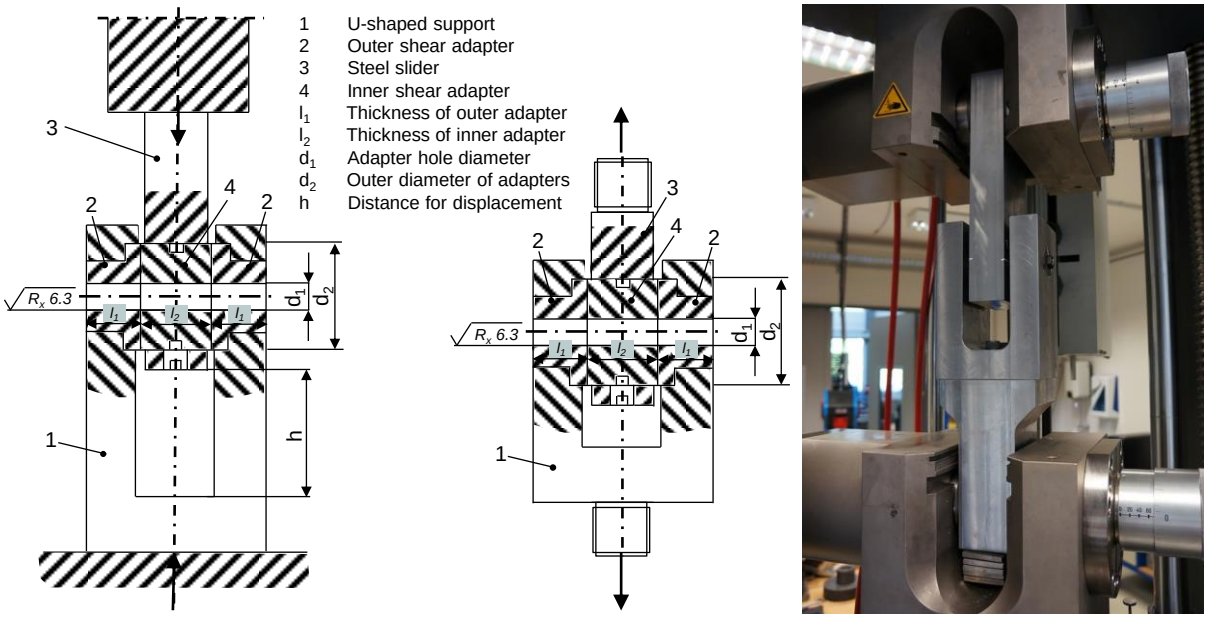
The test procedure and testing specifications of the single-shear and double-shear tests under standard condition and under low and elevated temperatures on austenitic and duplex stainless steel bolts and bolting assemblies are summarised in the following. Furthermore, selected active and withdrawn single- and double-shear testing procedures and specifications from Germany, Europe and North America are introduced. Finally, hardened single-shear test rigs were developed in the German research project FOSTA P 1386 / IGF-No. 20651 N and complemented by a special developed double-shear test rig for bolts and bolting assemblies in the frame of this thesis.

5.4.2 Existing shear testing procedures and specifications

In Europe, the mechanical properties of fasteners are defined in EN ISO 898-1 [76] for carbon steel and alloy steel and in EN ISO 3506-1 [73] for stainless steel. Nevertheless, both standards do not outline any requirements for either the bolt shear strength or the prescribed test method to be employed. Furthermore, EN 15048-1 [75] defines that non-preloaded bolting assemblies may be used in connections that are subjected to tensile and/or shear loading and that the unthreaded part is decisive for the ability of the bolting assembly to withstand shear stress. Neither the requirements for shear strength nor the specified test methods are outlined.

To give guidance, the German VDI Guideline 2230 Part 1 [167], Clause 5.5.6.1 recommends the determination of the shear resistance of bolts in a double-shear test rig according to the withdrawn and not replaced German testing standard DIN 50141 [262] “Testing of metals; Shear test” from 1982 and the still active German aviation standard LN 65150 [263] “Testing of metallic materials; double shear test of screws and bolt” from 1977. DIN 50141 explicitly refers to cylindrical specimens between d_0 = 2 mm and d_0 = 25 mm up to a maximum tensile strength of 1300 N/mm² but does not address to bolts directly. The withdrawn standard proposed double-shear test rigs for the application in compression or tension testing machines, see Figure 5.4-1, as well as three test rig sizes: Size 1 for 2 mm ≤ d_0 ≤ 8 mm, Size 2 for 10 mm ≤ d_0 ≤ 16 mm and Size 3 for 18 mm ≤ d_0 ≤ 25 mm). The testing speed is defined as 10 N/mm². Furthermore, the hardness of the outer and inner shear adapters (see Figure 5.4-1, Pos. 2 and 4) are defined by ≥ 700 HV 30 (≈ HRC 60) and the main geometrical parameters of the shear test rigs are provided in DIN 50141 including the ISO tolerance fields (H8 for Size 2 and 3, H11 or H12 for Size 1) according to EN ISO 286-1 [395] and EN ISO 286-2 [396].

Dörre et al. [175] (2019) examined the DIN 50141 testing procedure in the framework of own experimental investigations on bolts instead of cylindrical specimens (deviating from the scope of DIN 50141). They raised criticism regarding the lack of definition for a maximum distance between the inner and outer shear adapters so that an unrestrained gap in the shear planes may result, see Figure 5.4-1, Pos. 2 and 4. Since no detailed information is given on the material and the required stiffness of the double-shear test rigs and particularly the U-shaped support, prying effects and out-of-plane deformation may result during testing leading again to gap formation. Dörre et al. [175] point out that even a minor gap between the shear plates during testing might accumulate bolt material in the shear plane, which can lead to erroneously higher shear resistance of bolts. Additionally, potential misalignments of the bolt or bolting assemblies during testing, arising from the tolerances of the adapter clearance hole, can result in an increased shear cross-sectional area and higher shear resistance results.



(a) Double-shear test rig for the application in compression testing machines according to DIN 50141

(b) Double-shear test rig for the application in tension testing machines according to DIN 50141

(c) Example of double-shear test rig by Dörre et al. [175] at Fraunhofer IGP, Rostock

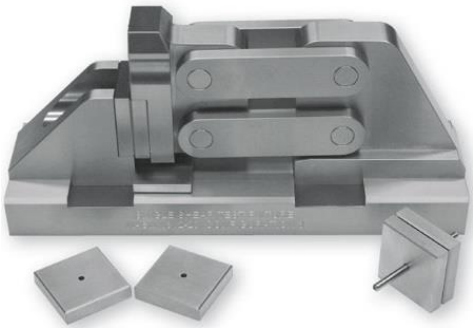
Figure 5.4-1: Double-shear test rigs for the application in compression (a) or tension (b) testing machines according to DIN 50141 and example of a double-shear test rig by Dörre et al. [175] (c; © Fraunhofer IGP Rostock, Germany)

As summarised in Chapter 2.5, it is worth mentioning that, Wallart and Fischer [220] (1964) found that the resulting shear strength of carbon steel bolts tested under tension was 6 to 13 % lower compared to shear tests under compression caused by the lap plate prying mechanism

and the uneven bearing deformations of the tested bolt. Consequently, shear testing of bolts and bolting assemblies in tension test rigs is more conservative and on the safe side, which is not explicitly considered or even stated in DIN 50141. It may be noted that the impact of the testing procedure under compression or tension can also be overserved for preloaded bolted shear connections. For example, the determination of the slip factor for slip-resistant connections as preloaded category B/C shear connections according to EN 1090, Annex G is based on quasi-static tension testing procedure, while the North American Research Council on Structural Connections (RCSC) determines the slip factor either in static compression tests (leading to higher experimental slip factors compared to the EN 1090 procedure) or tension creep tests. Further explanations regarding the impact of the compression or tensile testing procedure on preloaded bolted shear connections can be found in [397], [398] and [399].

In the North American region, standards regarding single-shear and double-shear testing of fasteners are available from ASTM (American Society for Testing and Materials) and NASM (National Aerospace Standard by the Aerospace Industries Association (AIA/NAS)), which are briefly outlined in the following. The corresponding test rigs presented in Figure 5.4-2 are commercially available from testing machine manufacturers. However, separate test rigs must always be used for each bolt diameter and each bolt length. Generally, single-shear test rigs are available for shear tension testing, while double-shear test rigs are available for shear compression testing. Here, ASTM F 606/F 606M [400] from 2021 defines the standard test methods for determining the mechanical properties of externally and internally threaded fasteners. Clause 3.8 deals with single-shear testing as self-aligning tension type fixture (see Figure 5.4-2 (a)) and recommends *"a suitable jig or nut"* to prevent separating of the hardened shear planes during testing. The testing speed should not be less than 6 mm/min and not greater than 12 mm/min. The maximum load applied to the specimen, coincident with or prior to bolt failure, shall be recorded as the shear strength of the bolt. ASTM F 606/ F 606M notes that single-shear tests are primarily used for bolts from M12 up to M25 and for general use MIL-STD-1312/NASM 1312 Method 20 [401] (single-shear test rig under compression testing, see Figure 5.4-2 (b)) or MIL-STD-1312/NASM 1312 Method 13 [402] (double-shear test rig as compression fixture, Figure 5.4-2 (c)) are recommended.

(a) Single-shear test rig as tension type fixture according to ASTM F606/606M-21; © Instron GmbH



(b) Single-shear test rig as compression type fixture according to MIL-STD 1312-20 and NASM 1312-20 (Method 20), Sheet 13; © Don Adams

(c) Double-shear test rig as compression type fixture according to MIL-STD 1312-13 and NASM 1312-13 (Method 13); © Instron GmbH

Figure 5.4-2: Single-shear and double-shear tests according to different North American testing standards

Both MIL-STD-1312/NASM 1312 specifications for Method 20 and 13 focus on determining the bolt shear resistance either of the unthreaded or threaded bolt part without any nut. A combination of the unthreaded and threaded bolt parts in the shear planes is not intended. While loading rates and geometrical parameters are specified in the standards, there is a

notable absence of general information regarding the material composition of the test rigs. Regarding the impact of compression shear testing in contrast to tension shear testing, no further information is given in the standards about preventing misalignments of the bolt during testing, which are to be expected due to the lack of fixation of the bolt ends. The German aviation standard LN 65150 from 1977, which is still active and recommended by VDI 2230 Part 1 for shear testing of bolts, is based on the double-shear test specification of MIL-STD-1312/NASM 1312 Method 13 for bolts M4 to M24 including defined load-controlled testing speeds.

Finally, a completely different approach regarding the determination of the pure shear strength of bolts determined from torsional testing without any adverse and disturbing influences due to possible misalignments of the bolt, prying and bending effects or accumulation of bolt material in the gap between the shear adapters is proposed by Dünkel [289]. Thomala [169] and Bittner [403] found in their studies only slightly differences between the torsional strength and the shear strength of a steel bar. Therefore, Dünkel proposes to conduct torsion tests on unthreaded steel bars instead of single-/double-shear tests in order to determine the pure shear strength of a bolt material. That should be investigated in future studies.

5.4.3 Development of test rigs and testing specifications for pure single-shear and single-shear interaction tests on stainless steel bolts and bolting assemblies

In FOSTA P 1386 / IGF-No. 20651 N, individual single-shear and single-shear interaction test rigs for loading angles of 15°, 30°, 45° and 67.5° were developed for the project that are as simple and massive as possible to efficiently perform the large number of tests. All single-shear test rigs were cut out of a plate of 42CrMo4 heat-treatable alloyed steel of steel grade 1.7225 according to EN ISO 683-2 [404] and fabricated by the mechanical workshop of the University of Duisburg-Essen, see Figure 5.4-3.

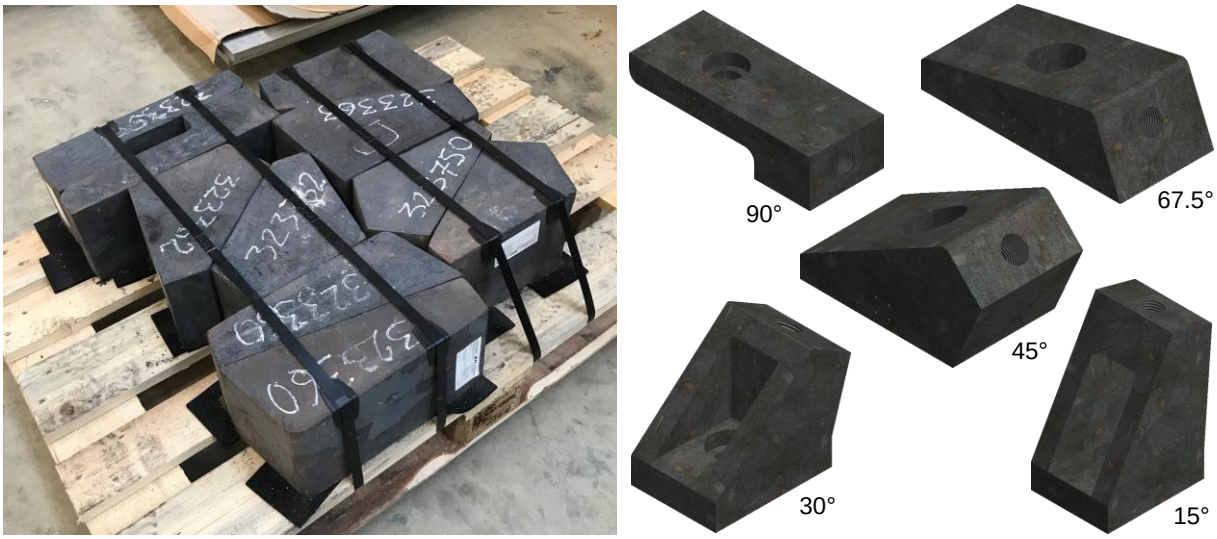


Figure 5.4-3: Single-shear and single-shear interaction test rigs made of pre-cut 42CrMo4 heat-treatable alloyed steel (1.7225) according to EN ISO 638-2

All test rigs were special hardened with a Rockwell hardness of about 55 HRC with additionally hardened inserts as shear adapters of about 58 HRC to avoid any plastic deformations and negative influences like yawning gaps in the shear plane due to testing, see Figure 5.4-4. The inserts are pressed into the test rig for a perfect fit but interchangeable to allow the application of different bolt diameters and bolt/clamping lengths within the same test rig. Particularly the strongly austenitic strain-hardened bolt threads defined by high hardness (cf. Chapter 2.4.8) represent a severe challenge for the hole bearing of the inserts and require a well-suited choice

of adapter material with explicit high hardness. All testing specifications for single-shear testing are summarised in Figure 5.4-4. Technical drawings of the rigs are presented in Appendix F.

Pure single-shear test rig: Upper and lower special hardened test components

Testing machine: Schenk / ZwickRoell 1.0 MN servohydraulic static and dynamic universal testing machine, Class 0

Testing procedure: Displacement-controlled with a constant testing speed of 0.08 mm/s in tensile direction analogues to the tensile tests presented in Chapter 4

Hardness of the test rig: ≈ 55 HRC

Hardness of the interchangeable inserts as shear adapters: ≈ 58 HRC for M16 and M24

Measurement system: ZwickRoell testing software + Peekel Autosoft/Autolog 3000 data measuring system (new: Burster Präzisionsmesstechnik GmbH & Co. KG); Continuously recording of machine load and machine stroke

Position of the shear planes: 40 mm for M16	Position of the shear planes: 50 mm for M24

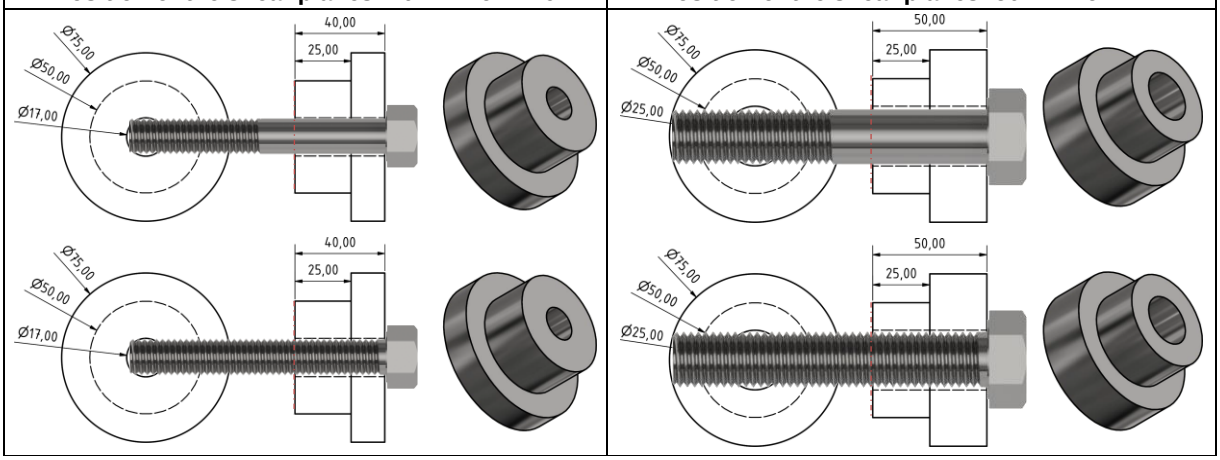
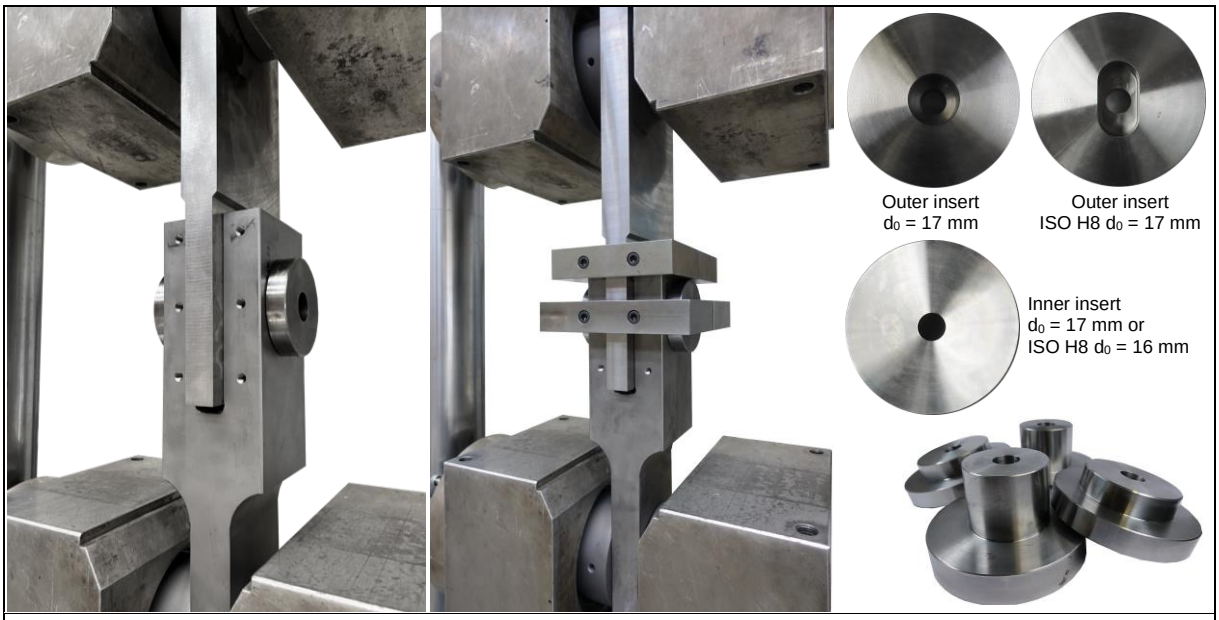


Figure 5.4-4: Test rig for pure single-shear testing for bolt dimension M16×100 and M24×130

All single-shear tests on EN ISO 4014/EN ISO 4762 partially threaded (representing the loading case “unthreaded bolt part in the shear plane”) and EN ISO 4017 fully threaded (representing the loading case “threaded bolt part in the shear plane”) austenitic and duplex stainless steel bolts paired with EN ISO 4032 nuts were performed displacement-controlled as tension procedure with a constant testing speed of 0.08 mm/s in the 1.0 MN servohydraulic static and dynamic universal testing machine of UDE-IML till bolt shear failure occurs. The machine load and stroke are continuously recorded.

5.4.4 Development of a test rig and testing specifications for pure double-shear on stainless steel bolts and bolting assemblies

In the framework of this thesis, supplementary experimental investigations on the double-shear load bearing behaviour of M16 austenitic and duplex stainless steel bolts and bolting assemblies were conducted. Therefore, a M16 test rig for double-shear tests was developed. To increase the stiffness of the test rig to avoid any yawning of the forked test part and resulting gap formation in the shear planes during testing, in total, four steel clamps that fit closely to the test rig were produced. The technical drawings of the double-shear test rig are attached in Appendix F and the testing specifications are summarised in Figure 5.4-5.



Double-shear test rig: Forked test part with outer inserts and slider with inner insert

Testing machine: Schenk / ZwickRoell 1.0 MN servohydraulic static and dynamic universal testing machine, Class 0

Testing procedure: Displacement-controlled with a constant testing speed of 0.08 mm/s in tensile direction analogues to the tensile tests in Chapter 4 and single-shear tests

Hardness of the test rig: ≈ 57 HRC

Hardness of the interchangeable inserts as shear adapters: ≈ 61 HRC for outer and inner inserts

Measurement system: ZwickRoell testing software + Peekel Autosoft/Autolog 3000 data measuring system (new: Burster Präzisionsmesstechnik GmbH & Co. KG); Continuously recording of machine load and machine stroke

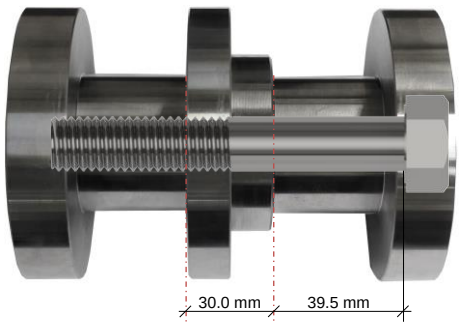
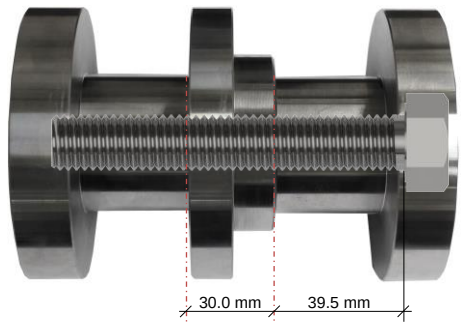
Position of the shear planes for EN ISO 4014/4762 partially threaded M16×100 bolts	**Position of the shear planes for** EN ISO 4017 fully threaded M16×100 bolts
	

Figure 5.4-5: Test rig for double-shear tests for bolt dimension M16×100 as supplementary investigations

The clamps also act as securing elements during testing. As already presented in Figure 3.4-1, the loading cases “unthreaded bolt part in the shear planes” (c), “threaded bolt part in the shear planes” (c) and a combination of “unthreaded and threaded bolt part in the shear planes” (d) are covered in the experimental investigations.

5.5 Experimental investigations: Discussion of the shear test results

5.5.1 General

A comprehensive overview of all single-/double-shear test results of partially threaded bolts according to EN ISO 4014 and EN ISO 4762 (representing the loading case “unthreaded bolt part in the shear plane”) and fully threaded austenitic and duplex stainless steel bolts according to EN ISO 4017 (representing the loading case “threaded bolt part in the shear plane”) is summarised in Appendix D including the mechanical properties determined in tensile tests according to EN ISO 3506-1, see Chapter 4. Furthermore, all considered test data from the extended literature review are summarised in Appendix C.

According to the European design rules for the design shear resistance $F_{v,Rd}$ of a stainless steel bolt according to EN 1993-1-4 (“EC-3”), the experimental individual shear coefficients $\alpha_{EC\text{-}3,exp,i}$ have been determined under consideration of the experimental mean tensile strength $f_{ub,exp,mean}$ (= $R_{mf,mean}$ according to EN ISO 3506-1) of the whole tested bolt series and the experimental individual shear stress $\tau_{ub,exp,i}$ of each tested bolt depending on the position of the shear plane, see (Eq. 5.5-1) to (Eq. 5.5-3):

$$\alpha_{EC-3,exp,i} = \frac{\tau_{ub,exp,i}}{f_{ub,exp,mean}} \qquad \text{(Eq. 5.5-1)}$$

with

$$\tau_{ub,exp,i} = \frac{\text{Max } F_{v,exp,i}}{A_{meas,i}} \quad \text{for “unthreaded bolt part in the shear plane”} \qquad \text{(Eq. 5.5-2)}$$

$$\tau_{ub,exp,i} = \frac{\text{Max } F_{v,exp,i}}{A_{s,meas,i}} \quad \text{for “threaded bolt part in the shear plane”} \qquad \text{(Eq. 5.5-3)}$$

It is worth mentioning that according to EN ISO 3506-1, Clause 9.1.5, the tensile strength $f_{ub,exp}$ has to be determined always under consideration of the nominal tensile stress area $A_{s,nom}$, regardless of whether the bolt failure occurs in the unthreaded or threaded bolt part, see explanations in Chapter 2.4.7. Consequently, the normative regulations lead to some special characteristics regarding the shear resistance of austenitic and duplex stainless steel bolts $F_{v,Rd}$, which have to be clarified in the following from mechanical point of view:

- For austenitic partially threaded bolts according to EN ISO 4014 and EN ISO 4762 with bolt failure in the unthreaded part A under pure tensile loading (as the general case), the ultimate tensile load $F_{mf,exp}$ of the bolt shank is directly known but the experimental tensile strength $f_{ub,exp}$ is always based on the tensile stress area $A_{s,nom}$. Thus, if shear failure of the bolt takes place in the unthreaded part A, the product of $f_{ub,exp,mean} \cdot A_{meas,i}$ by (Eq. 5.5-1) and (Eq. 5.5-2) is overestimating the tension resistance of the bolt shank and consequently the experimental shear coefficient $\alpha_{EC\text{-}3,exp,i}$ as the ratio of the experimental bolt shear and tension resistance is reduced compared to the “real physical” shear coefficient $\alpha_{phys,exp,i}$ of the bolt shank material, see (Eq. 5.5-4).

$$\alpha_{phys,exp,i} = \frac{\tau_{ub,exp,i}}{f_{ub,exp,shank,mean}} = \frac{\text{Max } F_{v,exp,i}}{\underbrace{f_{ub,exp,shank,mean} \cdot A_{meas,i}}_{= f_{ub,exp,mean} \cdot A_{s,nom} = F_{mf,exp,mean}}} = \frac{\text{Max } F_{v,exp,i}}{F_{mf,exp,mean}} \qquad \text{(Eq. 5.5-4)}$$

- For austenitic or duplex partially threaded stainless steel bolts according to EN ISO 4014 and EN ISO 4762 with bolt failure in the threaded part A_s under pure tensile loading, the ultimate tensile load $F_{mf,exp}$ of the bolt threads is directly known but the tensile strength of

the unthreaded bolt part $f_{ub,exp,shank}$ is always unknown and cannot be derived directly from testing. Again, an overestimation of the tension resistance of the bolt shank results according to the EC-3 approach and the experimental shear coefficient $\alpha_{EC\text{-}3,exp,i}$ is lower compared to the "real physical" shear coefficient $\alpha_{phys,exp,i}$ of the bolt shank material, see (Eq. 5.5-5). In order to determine the physical shear coefficient $\alpha_{ultimate,phys,exp,i}$ of the bolt shank material, the tensile strength of the bolt shank was determined by tensile tests on special machined bolts, see Chapter 4.4.4.

$$\alpha_{phys,exp,i} = \frac{\tau_{ub,exp,i}}{f_{ub,exp,shank,mean}} = \frac{\text{Max } F_{v,exp,i}}{f_{ub,exp,shank,mean} \cdot A_{meas,i}} \qquad \text{(Eq. 5.5-5)}$$

- For austenitic or duplex fully threaded bolts according to EN ISO 4017 bolt failure under tensile or shear loading always occurs in the threaded bolt part (tensile stress area A_s). Therefore, the experimental shear coefficient $\alpha_{EC\text{-}3,exp,i}$ according to EN 1993-1-4 is equal to the "real physical" shear coefficient $\alpha_{phys,exp,i}$ of the bolt threads material, see (Eq. 5.5-6).

$$\alpha_{EC3-,exp,i} = \alpha_{phys,exp,i} = \frac{\tau_{ub,exp,i}}{f_{ub,exp,mean}} = \frac{\text{Max } F_{v,exp,i}}{\underbrace{f_{ub,exp,mean} \cdot A_{s,meas,i}}_{F_{mf,exp,mean}}} = \frac{\text{Max } F_{v,exp,i}}{F_{mf,exp,mean}} \qquad \text{(Eq. 5.5-6)}$$

For the sake of comparability, the experimental shear coefficients $\alpha_{EC\text{-}3,exp,i}$ and the physical shear coefficients $\alpha_{phys,exp,i}$ are discussed in the following chapters. As discussed in [78] and [164], the experimental mean shear coefficients $\alpha_{EC\text{-}3,exp,mean}$ were rounded up to $\alpha_{proposed}$ and statistically checked in a reliability analyses according to EN 1990, Annex D against the partial safety factor γ_{M2} = 1.25 for connections. If the safety requirements of the Eurocode are not fulfilled, the resulting experimental mean shear coefficients $\alpha_{EC\text{-}3,exp,mean}$ were rounded down to $\alpha_{proposed}$. The leading objective was to achieve higher and more economical shear coefficients α combined with "Ease of Use" for daily engineering in line with the European design approach. Thus, bolt property classes were summarised as far as possible and the differentiation of shear coefficients α between the unthreaded or threaded bolt part in the shear plane is dispensed.

5.5.2 Experimental comparison between the single-shear and double-shear resistance of stainless steel bolts

The bolt shear resistances of M16×100 EN ISO 4014 partially and EN ISO 4017 fully threaded austenitic/duplex bolts with different PC and testing configurations are shown in Figure 5.5-1 (PC 70 and 80) and Figure 5.5-2 (PC 8.8 and 10.9). The following configurations were tested:

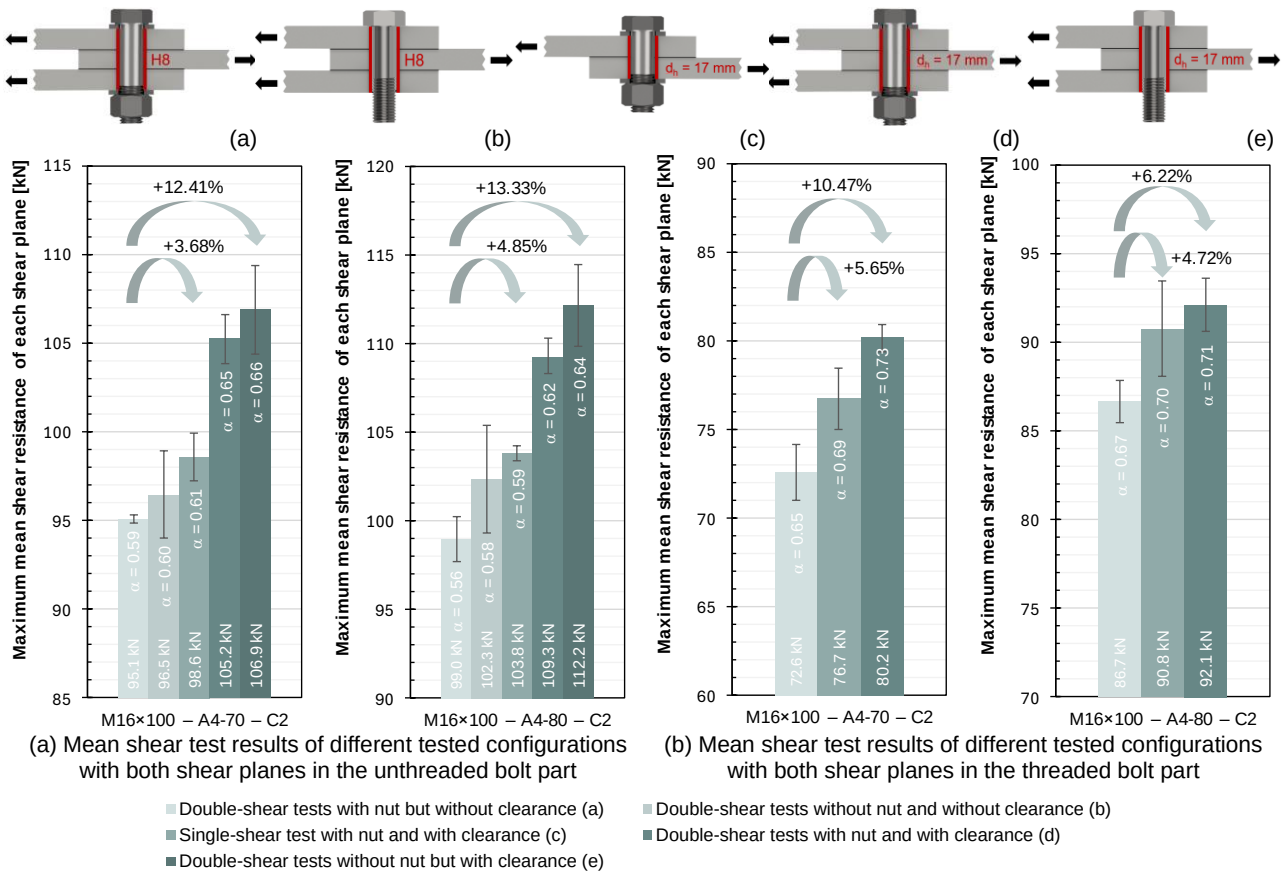
(a) Double-shear tests on bolting assemblies with hexagon nut but without hole clearance by shear adapters with nominal bolt holes of $d_{h,nom}$ = 16 mm in ISO tolerance field H8 (+27 μm, -0 mm) according to EN ISO 286-1 [395] and EN ISO 286-2 [396],

(b) Double-shear tests on bolts without hexagon nut and no hole clearance realised by shear adapters with nominal bolt holes of $d_{h,nom}$ = 16 mm produced in ISO tolerance field H8 in order to investigate the stabilising effect of the nut,

(c) Single-shear tests on bolting assemblies with shear adapters with $d_{h,nom}$ = 17 mm,

(d) Double-shear tests on bolting assemblies with a hexagon nut and shear adapters with a bolt hole diameter of $d_{h,nom}$ = 17 mm, and

(e) Double-shear tests on bolts without hexagon nut and with adapters produced with a hole diameter of $d_{h,nom}$ = 17 mm to investigate the nut's stabilising effect.



(a) Mean shear test results of different tested configurations with both shear planes in the unthreaded bolt part

(b) Mean shear test results of different tested configurations with both shear planes in the threaded bolt part

Figure 5.5-1: Comparison of mean shear test results of different tested configurations on stainless steel bolts and bolting assemblies in PC 70 and 80 with both shear planes in the unthreaded or threaded bolt part

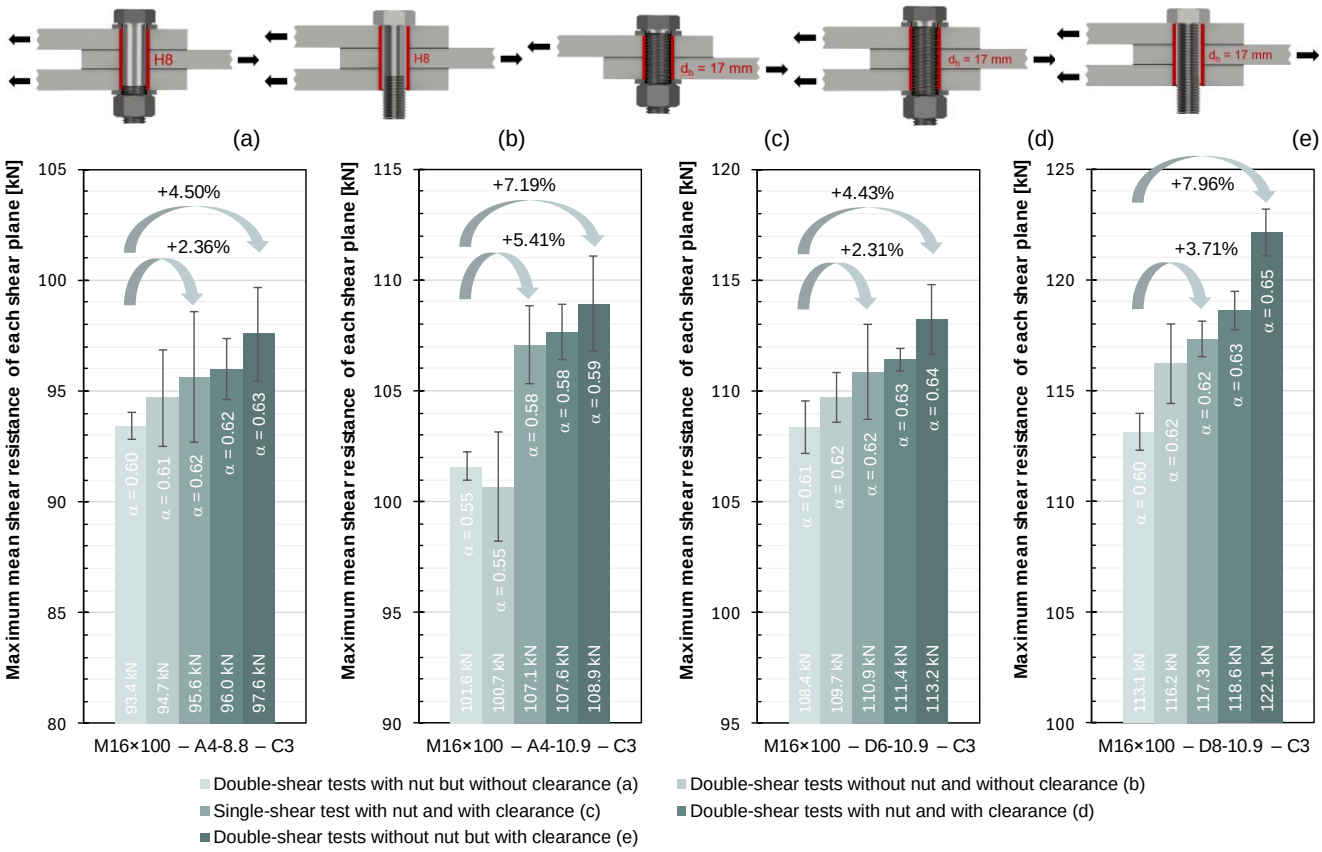


Figure 5.5-2: Comparison of mean shear test results of different tested configurations on stainless steel bolts and bolting assemblies in PC 8.8 and 10.9 with both shear planes in the threaded bolt part

The findings of the experimental investigation into the single- and double-shear resistance of M16×100 partially and fully threaded austenitic and duplex stainless steel bolts and bolting assemblies in different testing conditions can be summarised as follows:

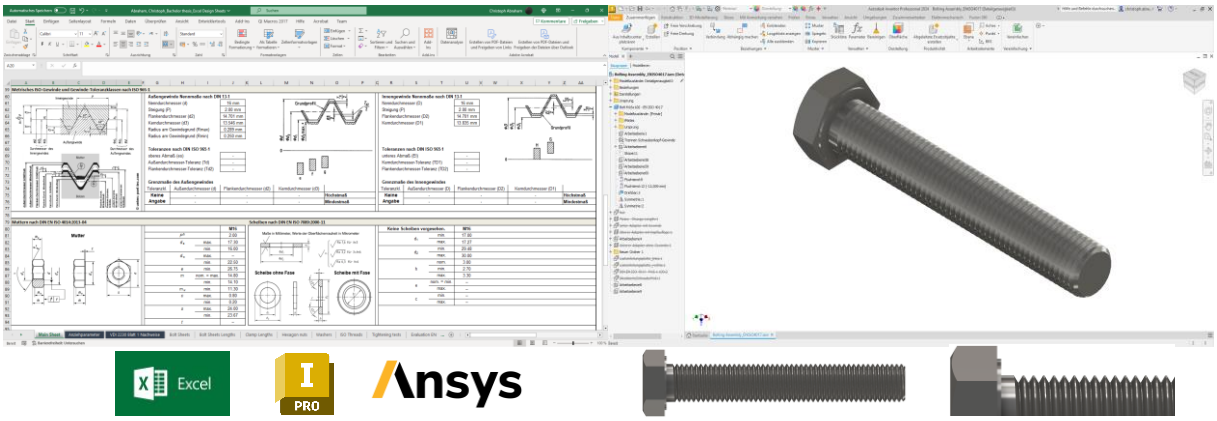
- The lowest bolt shear resistance across all tested partially and fully threaded bolt series is always achieved by double-shear tests on bolting assemblies with EN ISO 4032 hexagon nut and hardened adapters with nominal bolt holes of $d_{h,nom}$ = 16 mm in ISO tolerance field H8 (+27 μm, -0 mm). Since the limited bolt hole clearance largely prevents the bolting assemblies from being misaligned during shear testing, consequently no increased cross-sectional area and no increased bolt shear resistance per each shear plane results. The hexagon nut also helps to stabilise the bolt under loading impact and counteracts possible misalignment. This could also be verified in numerical FEM analyses, see Chapter 5.5.3.
- If the bolt hole clearance is maintained in double-shear tests with $d_{h,nom}$ = 16 mm produced in ISO tolerance field H8 but the austenitic or duplex stainless steel bolt is tested without a nut, the elimination of the stabilising nut effect leads to a slight misalignment and thus to an increased cross-sectional area in the shear planes, which ultimately results in a slightly increased mean bolt shear resistance with a maximum of +3.3 % for each shear plane (with the exception of EN ISO 4017 – M16×100 – A4-10.9 series). Depending on how the bolt aligns itself under load, different shear resistances can be observed within a series, which are generally accompanied by increased scattering.
- Single-shear testing on bolting assemblies with nut and a bolt hole diameter of d_h = 17 mm leads to a further increase of the bolt shear resistance, as the increased hole clearance allows the bolt to be inclined and consequently, an increased cross-sectional area in the shear plane results under loading, which can only be stabilised to a certain extent by the nut. This could be confirmed in all tested partially and fully threaded austenitic and duplex bolt series, but the difference lies mostly within the range of scattering (except for EN ISO 4017 – M16×100 – A4-10.9 series) and is thus negligible, which is an important finding regarding the design of these connections. The practical implication is that shear testing can be conducted in a simplified manner, utilising single-shear instead of double-shear, without imposing more stringent requirements on the hole diameter, see Chapter 8.
- If a bolt hole diameter of d_h = 17 mm is applied in double-shear testing of an austenitic or duplex bolting assembly, a further increase of the resulting shear resistance for each shear plane is observed for all tested series between +0.4 % and +6.7 %. The load-increasing effect resulting from skewing or misalignments, leading to increased cross-sectional areas, seems to exacerbate unfavourably under double-shear loading. Moreover, when the stabilising nut is removed during testing, there is a general tendency for slightly higher bolt resistances per shear plane, typically accompanied by increased scattering.

Finally, it can be concluded that depending on the bolt's specific alignment in the bolt hole and considering the extraordinarily high deformation capacity of austenitic/duplex stainless steel, the maximum load bearing shear capacities achieved in tests can exhibit noticeable variations. However, single-shear testing under normal conditions with a hole diameter of d_h = 17 mm leads to lower bolt shear resistances for each shear plane on the safe side compared to double-shear testing under the same clearance. The application of shear adapters with $d_{h,nom}$ = 16 mm in ISO tolerance field H8 leads to measurably lower shear capacities, which lie with the exception of one tested series within the range of scattering and is therefore negligible.

5.5.3 Numerical comparison between the single-shear and double-shear resistance of stainless steel bolts

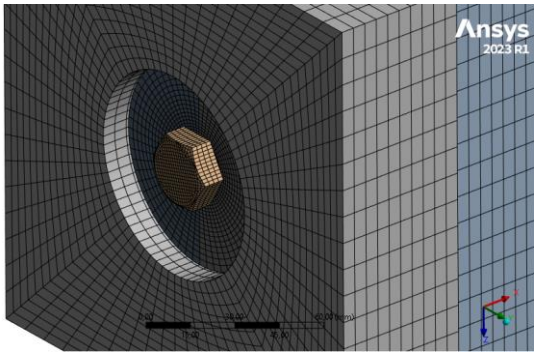
In order to analyse the experimental results and to illustrate possible misalignments of bolting assemblies under the pure single-shear loading with different bolt hole clearances, numerical FEM investigations based on experimentally determined nonlinear material parameters were carried out for selected bolt series and exemplarily presented for the partially threaded EN ISO 4014 – C3 – M16×100 – A4-8.8 series in Figure 5.5-3. The 3D FE models were established in ANSYS® Workbench [405] within [78] and further improved in this thesis to investigate the load bearing behaviour and setting motions of the bolt or bolting assembly under loading at different bolt hole clearances. Here, a fully threaded bolting assembly with helical structures mesh (for the case “threaded bolt part in the shear plane”) and a simplified non-threaded bolting assembly (for the case “unthreaded bolt part in the shear plane”) were developed, see Figure 5.5-3 (a) to (f).

In contrast to [78] and most of the studies from literature (e.g. [5, 6, 236, 237, 250]), the bonded contacts between the bolt head or nut and shear inserts are replaced by rough type contacts so that the bolt can move naturally in the hole clearance, see Figure 5.5-3 (f). The applied displacement in each time step was significantly reduced to 0.05 mm to achieve equilibrium in a quasi-static structural-mechanical analysis. At the same time, the maximum iteration number was increased to 100 for each step. The computer effort is high but makes it possible to prove that the bolt or bolting assembly under pure shear undergoes skewing and misalignments to varying degrees with increasing bolt hole clearance, which finally enlarges the shear resistance of the bolt due to the increased cross-section in the shear plane, see Figure 5.5-3 (g) to (h). In particular, the slight inclination of the bolt head and the nut, as presented in Figure 5.5-3 (g) for 1 mm hole clearance, contradicts the assumption of constant and uniform bolt support during testing. Additionally, it can be demonstrated that a force reaction occurs under pure shear, deviating from the anticipated pure shear loading at 90°. This deviation is attributed to the bolt's misalignment, the nut's support effect causing additional tension stress, and, ultimately, the disparate stiffness of the bolt in the longitudinal and transverse directions. Therefore, even under pure shear loading, the uniaxial shear stress changes to a complex triaxial stress state depending on the final position of the bolt in the hole clearance. If the bolt head and the nut are fixed in the numerical model, skewing or possible misalignments of the bolt in the hole clearance cannot be adequately detected. However, as the resulting error made in neglecting misalignments is small, this can certainly be tolerated depending on the intended FEM application.

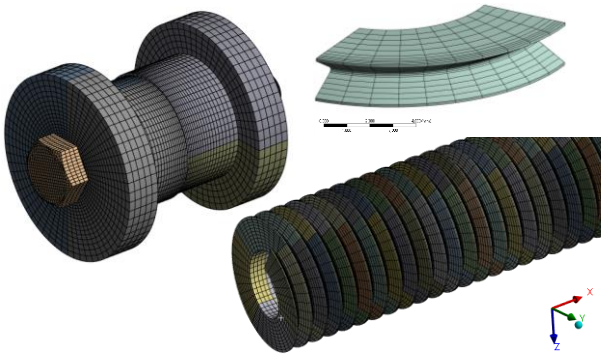


(a) Excel-Inventor-ANSYS Workbench Interface (b) Excel parametrised bolt geometry in Autodesk Inventor

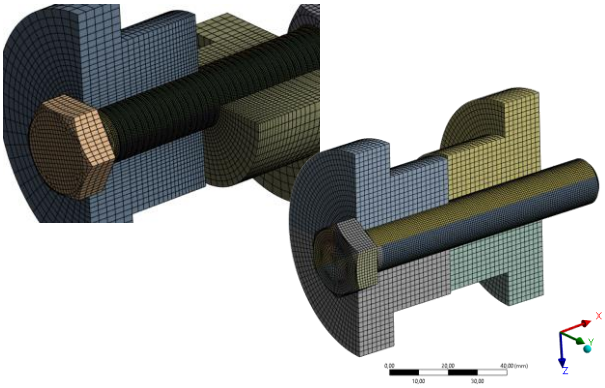
Figure 5.5-3: Developed numerical 3D fully threaded and simplfied non-threaded FE hexagon bolt models including geometry interface, meshing, boundary conditions and resulting deformations under different bolt hole clearances



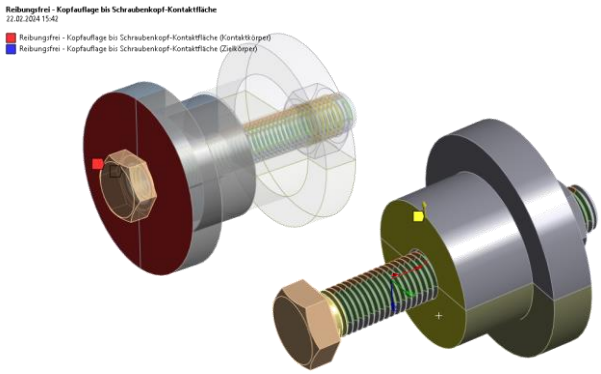
(c) Main FEM model and submodelling process



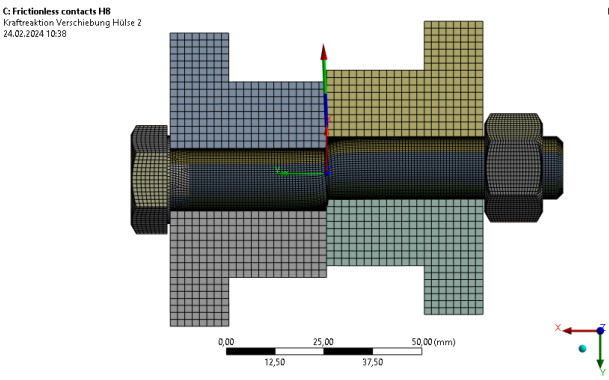
(d) Structured mesh for shear inserts and bolt threads



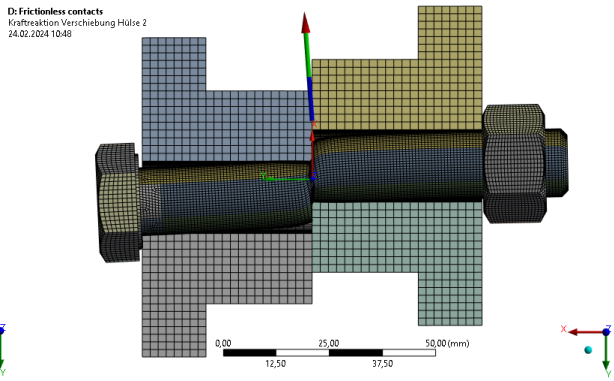
(e) Fully threaded and simplified FE bolt models



(f) Definition of frictionless contacts and shear displacement



(g) Deformation and resulting reaction force from ISO tolerance H8 hole clearance at 4 mm shear displacement



(h) Deformation and resulting reaction force from 1 mm hole clearance at 6 mm shear displacement

Figure 5.5-3: Developed numerical 3D fully threaded and simplified non-threaded FE hexagon bolt models including geometry interface, meshing, boundary conditions and resulting deformations under different bolt hole clearances (Cont.)

5.5.4 Comparison between physical shear coefficients and design shear coefficients α according to the Eurocode approach

As stated in Chapter 5.5.1, it must be distinguished between shear coefficients as measurable physical material parameter defined as the ratio of shear and tensile strength, and between shear coefficients that are adapted to fit in a design concept, for instance, the shear coefficients α for stainless steel bolts according to EN 1993-1-4 or α_v for carbon steel bolts according to EN 1993-1-8. For comparison, the minimum, mean and maximum experimental shear coefficients according to the Eurocode and as physical parameter determined according to (Eq. 5.5-4) and (Eq. 5.5-5) are summarised for the unthreaded bolt part in Table 5.5-1. Since for austenitic or duplex fully threaded bolts failure under tensile or shear loading always occurs in the threaded part (tensile stress area A_s), the experimental shear coefficient $\alpha_{EC\text{-}3,exp}$ according to EN 1993-1-4 is equal to the physical shear coefficient $\alpha_{phys,exp}$ of the bolt threads, see (Eq. 5.5-6), and therefore not presented in the following.

Table 5.5-1: Comparison between physical shear coefficients and design shear coefficients α based on [164] and supplementary experimental investigations

Unthreaded bolt part in the shear plane				
Bolt property class	**α acc. to the Eurocode design approach**		**α as physical material parameter**	
	Austenitic $\alpha_{EC\text{-}3,min/mean/max}$ **[-]**	**Duplex** $\alpha_{EC\text{-}3,min/mean/max}$ **[-]**	**Austenitic** $\alpha_{phys,min/mean/max}$ **[-]**	**Duplex** $\alpha_{phys,min/mean/max}$ **[-]**
PC 50	0.72 / **0.73** / 0.73	-[2)]	0.78 / **0.79** / 0.80	-[2)]
PC 70	0.62 / **0.64** / 0.68	0.72 / **0.72** / 0.72	0.77 / **0.81** / 0.86	0.75 / **0.75** / 0.76
PC 80	0.57 / **0.61** / 0.64	0.66 / **0.68** / 0.69	0.68 / **0.77** / 0.84	0.72 / **0.73** / 0.74
PC 100	-	0.57 / **0.57** / 0.57	-	0.71 / **0.72** / 0.73
PC 8.8[1)]	0.57 / **0.58** / 0.59	-	0.71 / **0.73** / 0.75	-
PC 10.9[1)]	0.53 / **0.54** / 0.54	0.56 / **0.57** / 0.57	0.61 / **0.62** / 0.63	0.66 / **0.68** / 0.69
PC 12.9[1)]	-	0.57 / **0.58** / 0.58	-	0.66/ **0.66** / 0.66

[1)] Not yet covered by EN ISO 3506-1 and EN ISO 3506-2 but already available on the European market. | [2)] PC 50 does not exist for duplex stainless steel bolts according to EN ISO 3506-1.

As expected, it can be seen in Table 5.5-1 that all experimentally determined physical shear coefficients are higher compared to the α-values determined according to EN 1993-1-4 and FprEN 1993-1-4. Higher shear coefficients are consistent with the findings on the distribution of tensile strengths in the unthreaded and threaded bolt part, see Chapter 4.5.4, to the extent that the tensile strength $f_{ub,exp,shank}$ in the unthreaded part is lower due to the less pronounced transformation of austenitic to forming induced martensitic material. The product of $f_{ub,exp,shank}$ and measured gross cross-sectional area A_{meas} is always smaller than $f_{ub,exp}$ based on the threaded bolt part, which must be considered in the design according to (pr)EN 1993-1-4. Consequently, a simple conversion of the design shear coefficients α to physical shear coefficients by the ratio A/A_s is not possible due to the inhomogeneous strength distribution in stainless steel bolts. Here, the high experimentally determined physical shear coefficients are about ≈ 0.80 for austenitic bolts in PC 50, 70 and 80 and confirm the proposed shear strength ratios provided by the German VDI 2230 Part 1 Guideline for (solution-annealed) austenitic stainless steel.

Additionally, the shear coefficients of M16 fully threaded austenitic and duplex stainless steel bolting assemblies under different temperatures (-40 °C and +110 °C) were determined experimentally on a small scale as tentative tests. However, no differences regarding the resulting tensile/shear strength ratio were found, as expected. An in-depth analysis of the test results in the frame of design standards for high and low temperatures and fire resistance was not carried out here.

5.6 Pathway and correlation analyses between the bolt tensile and shear strength

5.6.1 General

A pathway or pathway analysis model is a statistical framework used to represent and analyse the relationships among various defined variables in a complex system and their mutual influence. In pathway analysis, variables are depicted as nodes and arrows or paths represent the relationships between variables. These paths indicate the hypothesised causal or associative connections between variables. Pathway models allow testing and refining theoretical models of how variables interact and influence each other, providing insights into the underlying mechanisms driving observed data patterns. Pathway models are commonly used in fields such as psychology, sociology, epidemiology, and economics to investigate complex relationships and inform theory development [406] but can also be applied in engineering to allow a deeper analysis of achieved test data and their interpretation regarding

their mutual effects on system behaviour, for instance, the relationship(s) between tensile and shear strength of austenitic and duplex stainless steel bolts

The Pearson correlation, first developed by Karl Pearson in 1895, is a statistical technique used to quantify the degree of linear correlation between two variables. It is defined as the covariance ratio to the product of their standard deviations. The Pearson correlation coefficient r ranges from [-1, 1], with the sign indicating the direction of the relationship: A Pearson correlation coefficient of +1 shows a perfectly positive linear relationship between two variables, -1 means a perfectly negative linear relationship and 0 indicates that no linear relationship between two variables exists. Furthermore, the strength of the relationship is commonly categorised as “weak” ($0.1 < |r| < 0.3$), “moderate” ($0.3 < |r| < 0.5$) or “strong” ($|r| > 0.5$), although these limits may vary across disciplines [407]. Assessing the confidence of a relationship between two variables involves considering the Pearson correlation coefficient r and the significance level, typically represented by the p-value. The p-value in the range from [0, 1] indicates the probability of observing the data if the null hypothesis (that means no relationship between the investigated variables exists) is true. A p-value below 0.05 is commonly interpreted as evidence to reject the null hypothesis. It is worth mentioning that the Pearson correlation assesses only the strength of a univariate relationship; hence, mechanistic variable equations are often substituted into the overall pathway equations.

5.6.2 Pathway analysis

In the following, a pathway analysis is conducted for the main parameters as tensile strength and shear strength separated for the unthreaded or threaded bolt part in the shear plane under consideration of the bolt diameter, bolt hole clearance, bolt property class and steel grade (austenitic or duplex grades). The pathway diagrams are presented in Figure 5.6-1.

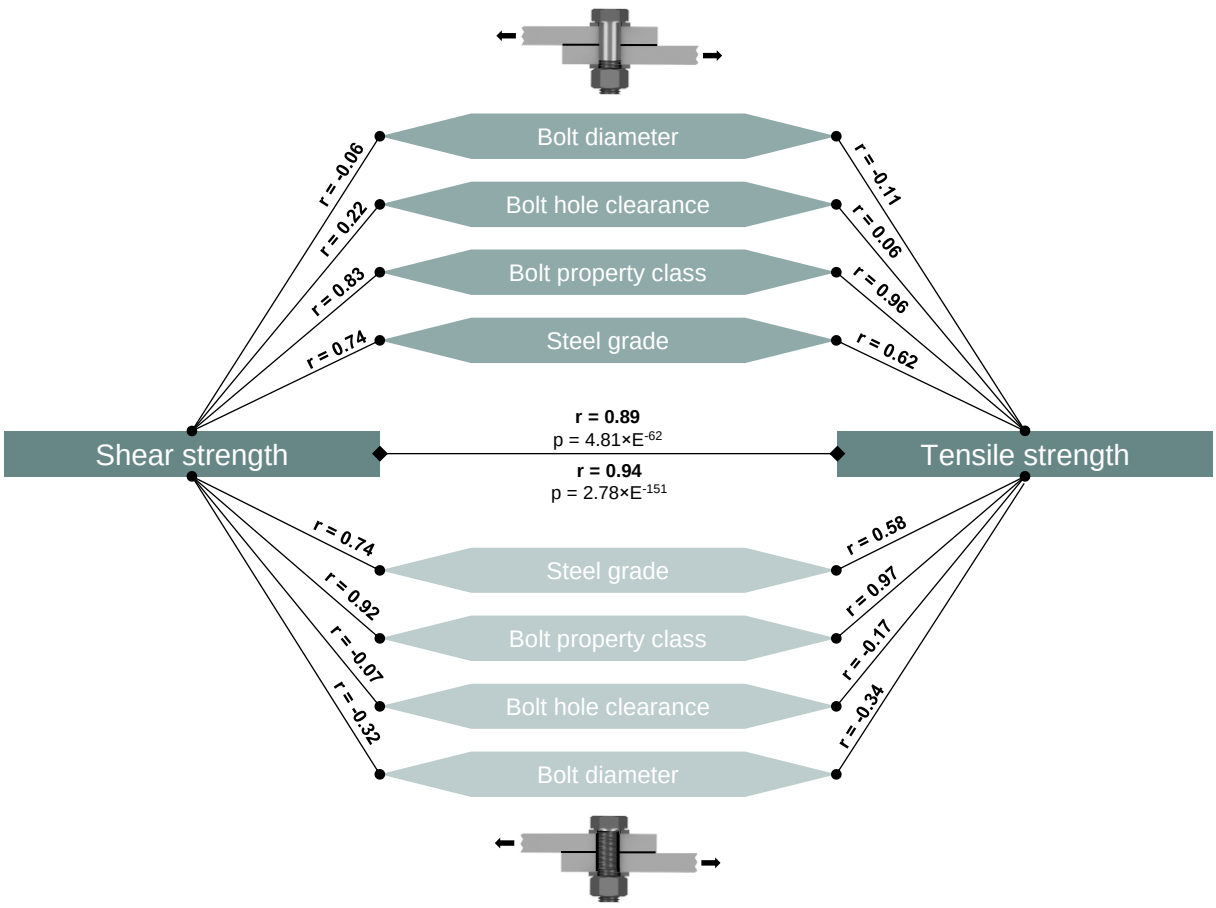


Figure 5.6-1: Pathway diagrams for the tensile strength and shear strength separated for the unthreaded (above) or threaded (below) bolt part in the shear plane

For both paths (unthreaded or threaded bolt part in the shear plane) a direct positive correlation between the tensile strength and shear strength exists (r = 0.89 for the unthreaded part and r = 0.94 for the threaded part) accompanied by indirect strong correlations of the bolt property class and steel grade. However, the indirect correlations stemming from bolt diameter and bolt hole clearance, concerning their impact on the relationship between tensile strength and shear strength, are relatively weak.

Interestingly, the "unthreaded bolt part in the shear plane" shows no (r < 0.10) or only a weak correlation (0.10 < | r | < 0.30) between bolt diameter, bolt hole clearance, shear strength and tensile strength, while the "threaded bolt part in the shear plane" exhibit at least a moderate (0.3 < | r | < 0.5) correlation with the bolt diameter with r = 0.34 to tensile and r = 0.32 to shear strength. Further experimental investigations on different bolt diameters are recommended to investigate whether this finding from the pathway analysis can be confirmed or rejected.

A detailed overview of all investigated parameters including Pearson correlation coefficients r and p-values is presented in Figure 5.6-2 as correlation colour plots for the unthreaded (right) or threaded (left) bolt part in the shear plane.

Figure 5.6-2: Correlation colour plots of all investigated parameters separated for the unthreaded (right) or threaded (left) bolt part in the shear plane

The pathway analyses in Table 5.5.1 offer insight into the direct and indirect multi-step pathways connecting the tensile and shear strength of stainless steel bolts, incorporating intermediate parameters such as "bolt property class" and "steel grade". Here, alongside the direct path from tensile strength (TSG) to shear strength (SSG), two indirect pathways are explored:

- “tensile strength (TSG) to steel grade (SG)” accompanied by “steel grade (SG) to shear strength (SSG)”, and

- "tensile strength (TSG) to property class (PC)" followed by "property class (PC) to shear strength (SSG)".

All equations were derived based on the best-fitted polynomial functions using stepwise regression models applied to the measured data.

Finally, graphical comparisons of the direct and indirect pathways between tensile strength and shear strength, based on the equations provided in Table 5.6-1 are shown in Figure 5.6-3 for stainless steel bolts with unthreaded part in the shear plane and in Figure 5.6-4 for stainless steel bolts with threaded part in the shear plane.

Table 5.6-1: Direct and multistep pathway equations for the tensile and shear strength of stainless steel bolts

Path	Unthreaded bolt part in the shear plane	Threaded bolt part in the shear plane
Direct path	***Tensile strength (TSG) to shear strength:*** (SSG)SSG = 1.4771E-06 · TSG^3 - 0.0041 · TSG^2 + 4.0152 · TSG + 845.293	***Tensile strength (TSG) to shear strength:*** SSG = 5.6838E-07 · TSG^3 - 0.0013 · TSG^2 + 1.3476 · TSG + 27.614
Indirect path 1	***Tensile strength (TSG) to steel grade (SG):*** SG = -2.1810E-08 · TSG^3 + 7.2290E-05 · TSG^2 - 0.0737 · TSG + 24.947 ***Steel grade (SG) to shear strength (SSG):*** SSG = 7.8806 · SG^2 + 15.974 · SG + 505.615 ***Tensile strength (TSG) to shear strength (SSG):*** SSG = 3.7485E-15 · TSG^6 - 2.4849E-11 · TSG^5 + 6.6525E-08 · TSG^4 - 9.2924E-05 · TSG^3 - 0.0724 · TSG^2 - 30.166 · TSG + 5808.723	***Tensile strength (TSG) to steel grade (SG):*** SG = 3.0946E-08 · TSG^3 - 7.2511E-05 · TSG^2 + 0.0558 · TSG + 13.034 ***Steel grade (SG) to shear strength (SSG):*** SSG = 6.7132 · SG^2 + 90.723 · SG + 518.901 ***Tensile strength (TSG) to shear strength (SSG):*** SSG = -6.4289E-15 · TSG^6 + 3.0128E-11 · TSG^5 - 5.8500E-08 · TSG^4 + 6.2589E-05 · TSG^3 - 0.0402 · TSG^2 + 14.8385 · TSG + 1804.032
Indirect path 2	***Tensile strength (TSG) to property class (PC):*** PC = -2.3125E-09· TSG^3 + 5.9621E-06 · TSG^2 + 0.0045 · TSG - 4.0612 ***Property class (PC) to shear strength (SSG):*** SSG = 0.9490 · PC^2 - 7.4053 · PC + 511.011 ***Tensile strength (TSG) to shear strength (SSG):*** SSG = 3.1813E-17 · TSG^6 - 1.6404E-13 · TSG^5 + 8.9044E-11 · TSG^4 - 4.4450E-07 · TSG^3 - 0.0002 · TSG^2 - 0.2480 · TSG + 639.206	***Tensile strength (TSG) to property class (PC):*** PC = -3.1903E-08· TSG^3 + 8.9643E-05 · TSG^2 - 0.0730 · TSG +19.824 ***Property class (PC) to shear strength (SSG):*** SSG = 0.2180 · PC^2 + 744.8211· PC + 448.774 ***Tensile strength (TSG) to shear strength (SSG):*** SSG = 2.2192E-16 · TSG^6 – 1.2471E-12 · TSG^5 + 2.7674E-09 · TSG^4 – 4.5583E-06 · TSG^3 - 0.0060 · TSG^2 - 3.9015 · TSG + 1422.972

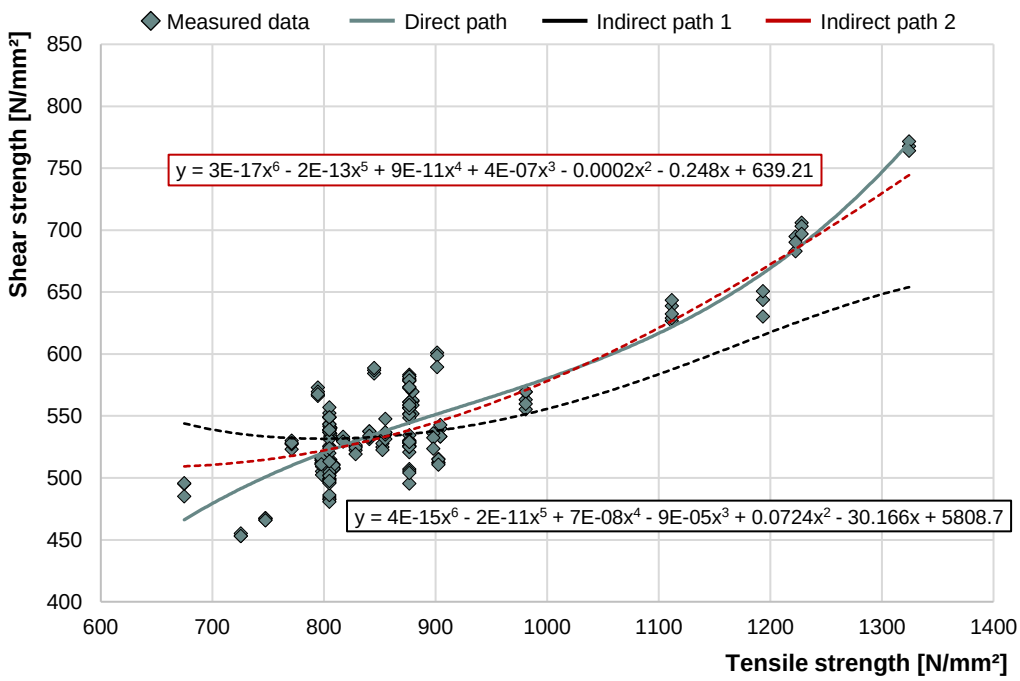


Figure 5.6-3: Direct and indirect multi-step pathway diagram for stainless steel bolts with unthreaded bolt part in the shear plane

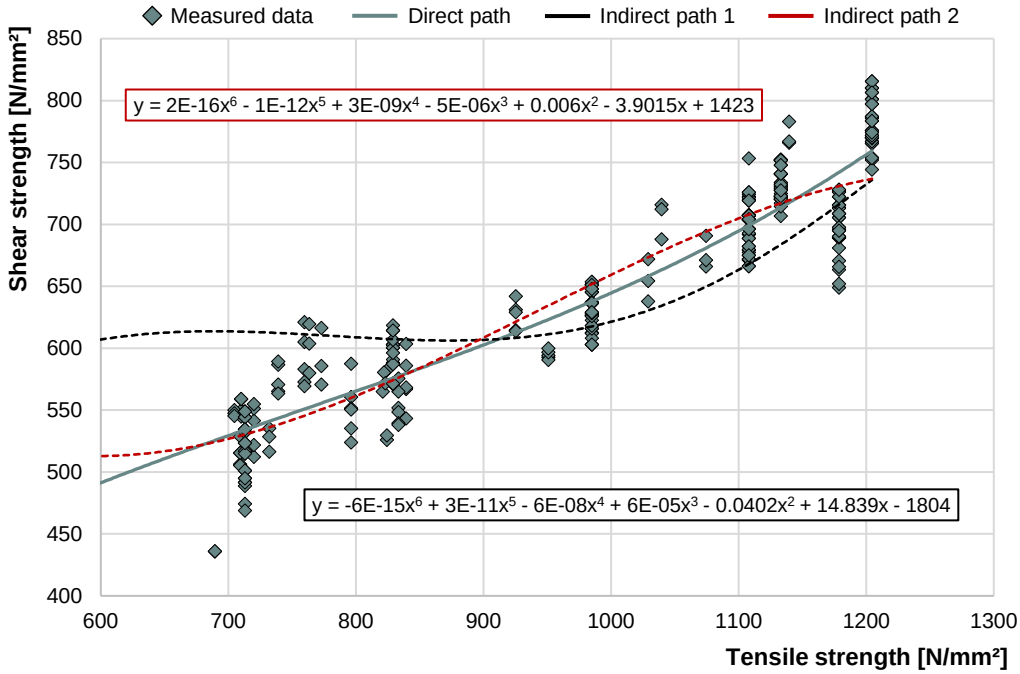


Figure 5.6-4: Direct and indirect multi-step pathway diagram for stainless steel bolts with threaded bolt part in the shear plane

Considering Figure 5.6-3 and Figure 5.6-4, it can be concluded that:

- For the unthreaded bolt part in the shear plane, the relationship between tensile strength and shear strength can also be determined by *Indirect Path 2* as "tensile strength to property class" combined with "property class to shear strength". The indirect path curve shows good agreement, especially between tensile strength values of 800 to 1250 N/mm^2, in the relevant range comparable to the direct path TSG to SSG.
- Also, for bolts with threaded bolt part in the shear plane, the relationship between tensile strength and shear strength can be calculated by *Indirect Path 2* as "tensile strength to property class" combined with "property class to shear strength". The indirect path curve shows again favourable agreement, especially for tensile strengths falling within the range of 700 to 900 N/mm².

5.6.3 Correlation between the bolt tensile strength and shear coefficient α

In order to illustrate the correlation between the individual bolt tensile strength $f_{ub,exp,i}$ and the resulting individual shear coefficient $\alpha_{exp,i}$ according to EN 1993-1-4 across all investigated steel grades and bolt property classes, all single-shear and double-shear test data for the unthreaded and threaded bolt part in the shear plane including histograms are summarised in Figure 5.6-5. It can be seen for the unthreaded and threaded bolt part in the shear plane that with increasing bolt tensile strength $f_{ub,exp,i}$ the resulting shear coefficient $\alpha_{exp,i}$ continuously decreases. It is striking that firstly the α-values of all duplex bolts in all property classes are above Thomalla's trendline [169], which was determined experimentally on unnotched austenitic 1.4401 and 1.4303 stainless steel samples as the lower limit line. Secondly, all austenitic stainless steel bolts with threaded part in the shear plane are above the trendline, while austenitic bolts with unthreaded part in the shear plane are mainly below Thomalla's trendline (with the exception of austenitic bolts in PC 10.9). Therefore, it can be concluded that duplex bolts with threaded part in the shear plane allow to utilise the highest shear coefficients followed by austenitic bolts with threaded bolt part in the shear plane. The lowest shear

coefficients are achieved by austenitic stainless steel bolts with unthreaded bolt part in the shear plane.

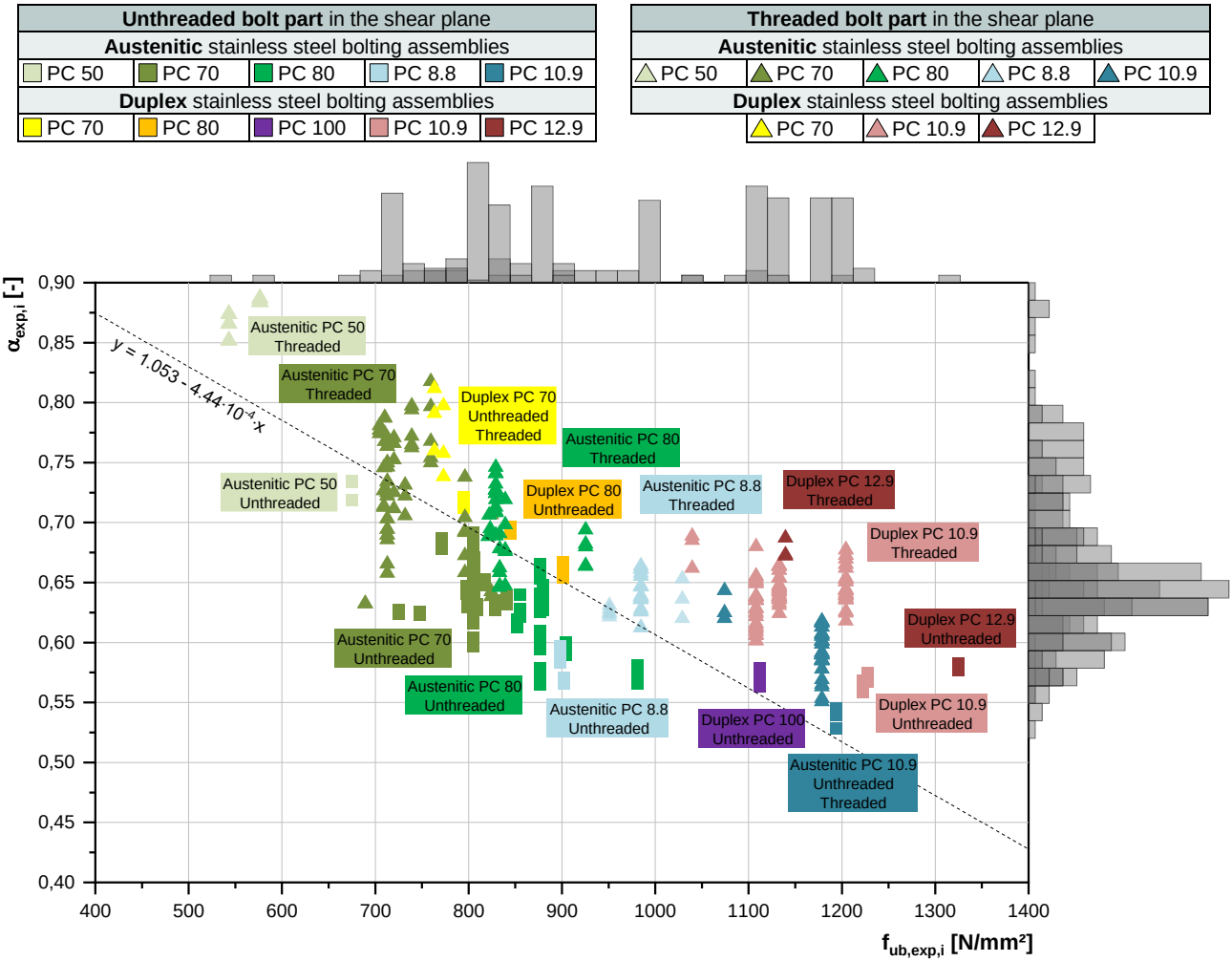


Figure 5.6-5: Correlation between the tensile strength $f_{ub,exp,i}$ and shear coefficients $\alpha_{exp,i}$ according to EN 1993-1-4 for austenitic and duplex bolts with unthreaded or threaded part in the shear plane based on [164] and supplementary tests

5.7 Proposed design approach for the shear resistance of stainless steel bolts

Based on the experimental investigations and statistical evaluations according to EN 1990, Annex D in P 1386 / IGF-No. 20651 N and further studies conducted at UDE-IML, finally new and more economical (higher) shear coefficients α could be proposed, see [78] and [164], and already implemented in FprEN 1993-1-4 and the German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022 [81], which are both following the European (and not German) design approach (as Approach 1, see Chapter 3.4) equal to the design of carbon steel bolts according to EN 1993-1-8 and EN 1993-1-8:2024: the shear resistance of an individual bolt per shear plane is defined as the product of a shear coefficient α, the nominal tensile strength $f_{ub,nom}$ and either the nominal gross cross-sectional area of the unthreaded part A_{nom} or the nominal tensile stress area $A_{s,nom}$ of a bolt depending on the position of the shear plane in the unthreaded or threaded part of a bolt, see (Eq. 5.7-1).

$$\overbrace{F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A}{\gamma_{M2}}}^{\text{Bolt shank in the shear plane}} \quad \text{or} \quad \overbrace{F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A_s}{\gamma_{M2}}}^{\text{Bolt threads in the shear plane}} \qquad \text{(Eq. 5.7-1)}$$

In the frame of this thesis, the supplementary experimental investigations and the extended literature review also confirm that higher and more economical shear coefficients α can be

proposed and that in principle single-shear bolted connections are representing the adverse condition. Finally, higher and more economical shear coefficients α could be proposed for austenitic and duplex stainless steel bolts in PC 50, 70, 80 and 100 for FprEN 1993-1-4. In this thesis, the proposed shear coefficients α are also expanded to PC 8.8, 10.9 and 12.9 as an amendment for further revisions of EN 1993-1-4 and EN ISO 3506-1. As already mentioned, stainless steel bolting assemblies with mechanical properties comparable to PC 8.8, 10.9 (and even 12.9) for carbon steel bolting assemblies already exist on the market and fulfil the normative requirements of EN 15048-1, although not yet covered by EN ISO 3506-1 and /-2.

The proposed shear coefficients α for the determination of the shear resistance of austenitic and duplex stainless steel bolts are summarised in Table 5.7-1.

Table 5.7-1: Proposed shear coefficients α for prEN 1993-1-1 for the determination of the shear resistance of austenitic and duplex stainless steel bolts based on [164]

Unthreaded or threaded bolt part in the shear plane			
Implemented in	**Property class**	**Austenitic α [-]**	**Duplex α [-]**
FprEN 1993-1-4 [80] **+ abZ/aBG Z-30.3-6 from 2022** [81]	**PC 50**	**0.8**	**-**[2)]
	PC 70	**0.7**	**0.8**
	PC 80	**0.7**	**0.7**
	PC 100	**0.6**	**0.6**
Proposed for future revisions (informative)	PC 8.8[1)]	0.7	0.7
	PC 10.9[1)]	0.6	0.6
	PC 12.9[1)]	0.6	0.6

[1)] Not proposed for FprEN 1993-1-4 as not yet covered by EN ISO 3506-1 and EN ISO 3506-2 but already available on the European market. | [2)] PC 50 does not exist for duplex stainless steel bolts according to EN ISO 3506-1.

In the following, the proposed shear coefficients α are statistically re-verified in extended reliability analyses including supplementary test data according to EN 1990, Annex D and complemented by an in-depth evaluation of the resulting partial safety factors γ_M*.

5.8 Reliability analysis of the shear resistance of stainless steel bolts

5.8.1 General

As already stated, the determination of partial safety factors γ_M* according to EN 1990, Annex D for the shear resistance of austenitic and duplex stainless steel bolting assemblies was already carried out by Stranghöner/Abraham in [164]. This statistical evaluation is based on single-shear testing of stainless steel bolting assemblies and a literature review conducted in the German research project FOSTA P 1386 / IGF-No. 20651 N and further research. In this thesis, additional 132 double-shear tests on stainless steel bolts and bolting assemblies as well as an extended literature review of 102 instead of 51 shear test results are carried out. Therefore, the extended database requires a statistical re-verification within a new reliability analysis of the proposed more economical shear coefficients α (including PC 8.8, 10.9 and 12.9) presented in Table 5.7-1 against the partial safety factor of γ_{M2} = 1.25 for connections.

Therefore, the input parameters and definition of the theoretical r_t and nominal r_n resistance functions of the reliability analysis regarding the shear resistance of austenitic and duplex stainless steel bolts for the current design rules of EN 1993-1-4, the German national annex DIN EN 1993-1-4/NA, FprEN 1993-1-4 and abZ/aBG Z-30.3-6 are pointed out. Only those test data were used for the reliability analysis which specifies the testing procedure and provides the individual test results. Studies that only provide mean values are not used in the statistical

evaluation. Furthermore, the additional experimental investigations into the double-shear load bearing behaviour of stainless steel bolts are also considered in the statistical re-verification. Analogues to the tension resistance of stainless steel bolts, the extended statistical evaluations of the bolt shear resistance are complemented by in-depth analyses of the distribution of the resulting partial safety factors γ_M* over all property classes to improve the reliability of the proposed design approach for the shear resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolts. The results of the reliability analyses are compared with the already published statistical evaluation by Stranghöner/Abraham [164].

5.8.2 Input parameters and definition of resistance functions of the reliability analysis

5.8.2.1 General

The input parameters and definition of resistance functions for the shear resistance $F_{t,Rd}$ of stainless steel bolts are outlined in the following. To examine whether the requirement of the reliability analysis according to EN 1990, Annex D regarding normal distribution or log-normal distribution of the gross cross-sectional area A_{meas} as the geometrical basic variable is fulfilled, the distribution type is examined. The tensile strength $f_{ub,exp}$ and the measured tensile stress area of bolts $A_{s,meas}$ are already confirmed as normally distributed, see Chapter 4.7.5.3.

5.8.2.2 Input parameters and definition of resistance functions

According to the proposed design rules of FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022, the theoretical resistance function r_t of the shear resistance of austenitic and duplex stainless steel bolts must be distinguished between the unthreaded or threaded bolt part in the shear plane. The theoretical resistance function r_t of the shear resistance of stainless steel bolts with unthreaded part in the shear plane can be reformulated to (Eq. 5.8-1):

$$r_t = g_{rt}(\underline{X}_{exp}) = F_{v,Rk} = \alpha \cdot f_{ub,exp} \cdot A_{meas} \qquad \text{(Eq. 5.8-1)}$$

If the threaded part of a bolt is not excluded from the shear plane, r_t is based on the tensile strength $f_{ub,exp}$ as the material basic variable and the measured tensile stress area $A_{s,meas}$ as the geometrical basic variable of every individual bolt, both regarded as independent basic variables $\underline{X}_{exp}$ reformulated to (Eq. 5.8-2):

$$r_t = g_{rt}(\underline{X}_{exp}) = F_{v,Rk} = \alpha \cdot f_{ub,exp} \cdot A_{s,meas} \qquad \text{(Eq. 5.8-2)}$$

However, in a single- or double-shear test, the individual measured tensile strength of the stainless steel bolt $f_{ub,exp,i}$ is unknown, and only the mean tensile strength $f_{ub,exp,mean}$ of the whole tested bolt series is known from tensile tests on the whole bolt according to EN ISO 3506-1. For this reason, $f_{ub,exp}$ from (Eq. 5.8-1) and (Eq. 5.8-2) has to be taken as a mean value of the experimentally determined tensile strength from each bolt series, which, however, results to uncertainties in the determined individual shear coefficients $\alpha_{exp,i}$. Furthermore, the question arises if there is a linear dependency between the shear and tensile strength. This is of major relevance, as the choice of a method for the statistical evaluation and, finally, the suitability of the reliability analysis according to EN 1990, Annex D depends on it. To answer this question, two studies are emphasized in the following:

Firstly, Knobloch [173] from the former Department of Steel Construction at the University of Essen, now the Institute for Metal and Lightweight Structures at the University of Duisburg-Essen (UDE-IML), Germany, analysed the correlations between shear, tensile and yield strength and elongation at fracture with stochastic methods and confirmed a “tight” positive linear relationship between shear and tensile strength of ductile metallic materials with a Pearson correlation coefficient of $r > 0.95$ (cf. [174] and Chapter 2.4.5). Secondly, Dörre et al. [175] investigated the resulting ratios of shear and tensile strength of carbon steel bolts in various property classes and performed single-shear and tensile tests on the same bolt with specially prepared specimens. Based on 84 tensile tests on special machined tensile specimens and 84 single-shear tests, again a tight Pearson correlation coefficient of $r > 0.989$ could be determined confirming a direct positive linear dependence. Thus, the methodology of EN 1990, Annex D can be applied. In addition, it should be noted that the scatter in the tensile tests on stainless steel bolts is generally very low. Therefore, applying the mean value of the tensile strength $f_{ub,exp,mean}$ instead of the individual values $f_{ub,exp,i}$ leads to minor errors, which can be neglected within the statistical investigations.

The nominal resistance functions r_n of the shear resistance of stainless steel bolts considering basic variables $\underline{X}_{nom}$ based on the nominal tensile strength $f_{ub,nom}$ as the material basic variable and the nominal gross cross-sectional area A_{nom} or the tensile stress area $A_{s,nom}$ as the geometrical basic variables of every individual bolt are presented in (Eq. 5.8-3) and (Eq. 5.8-4):

$$r_t = g_{rt}(\underline{X}_{nom}) = \alpha \cdot f_{ub,nom} \cdot A_{nom} \qquad \text{(Eq. 5.8-3)}$$

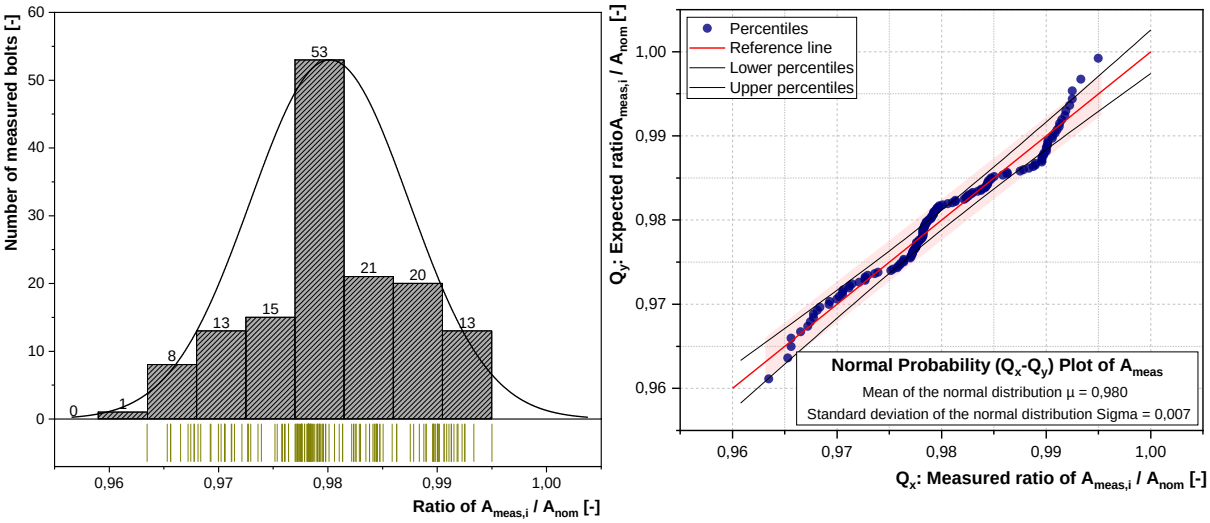
$$r_t = g_{rt}(\underline{X}_{nom}) = \alpha \cdot f_{ub,nom} \cdot A_{s,nom} \qquad \text{(Eq. 5.8-4)}$$

The shear coefficients α (here defined as design value and not as purely physical parameter) are part of the theoretical and nominal resistance functions itself and not a basic variable. In order to evaluate the different resulting partial safety factors γ_M* according to EN 1990, Annex D of the shear resistance $F_{v,Rd}$, the shear coefficients α of EN 1993-1-4, the German national annex DIN EN 1993-1-4/NA and the proposed shear coefficients for FprEN 1993-1-4/abZ Z-30.3-6:2022 [81] were implemented in the reliability analyses. However, the equations (Eq. 5.8-1) and (Eq. 5.8-3) cannot be applied according to the design rule of DIN EN 1993-1-4/NA as the design is always based on the tensile stress area A_s (as Approach 2, see Chapter 3.4). However, the lower shear resistance of austenitic bolts is compensated by higher shear coefficients which are based on the studies of Thomala [169] on unnotched bolt material bars tested in double-shear.

Analogues to the reliability analysis of the tension resistance of stainless steel bolts presented in Chapter 4, the coefficients of variation V_{Xi} of each basic variable are determined from the experimental test data. Under the assumption that the coefficient of variation of errors V_δ for the measured cross-section areas A_{meas} and $A_{s,meas}$ and the experimental determined tensile strength $f_{ub,exp,mean}$ are implicitly considered and therefore the scatterings are represented in the test results, the additional coefficients of variation for each basic variable V_{Xi} have not been taken into account in [78] and [164]. Here, V_{rt} has been neglected ($V_r^2 = V_\delta^2$) and was only considered for the tests from literature as no measured geometrical data were available. Furthermore, it was stated by Stranghöner/Abraham [164] that the influence of the scattering of both input variables on the determination of the partial safety factor has been checked and it could be confirmed that their influence is negligible. However, in the frame of this thesis, the scattering of each basic variable V_{Xi} is explicitly considered in the reliability analyses for direct comparison. Therefore, a maximum material specific COV (f_{ub}) of 3 % and a maximum geometrical COV (A; A_s) of 1 % are implemented in the reliability analysis on the safe side for all tested series.

5.8.2.3 Normal distribution of the gross cross-sectional area A_{meas}

In order to confirm a normal distribution of the test population of the measured gross cross-sectional area A_{meas}, histograms (a), the normal probability (Q_x-Q_y) plot (b) and the results of two analytic tests for normality (c) are presented in Figure 5.8-1. Finally, a normal distribution cannot be rejected by the Kolmogorov-Smirnov and D'Agostino K_2 test at 5 % level and therefore the methodology of EN 1990, Annex D can be applied. For information purposes: The more deviation-sensitive Lilliefors and Shapiro-Wilk analytic tests failed. As visualised in Figure 5.8-1, the percentiles follow the normal distribution reference line wavelike between the lower and upper percentiles with higher deviations than the percentiles of the measured basic variables $f_{ub,exp}$ and $A_{s,meas}$, see Figure 4.7-5.



(a) Histogram and normal distribution of the measured gross cross-sectional area area of bolts A_{meas}

(b) Normal probability (Q_x-Q_y) plot of A_{meas}

Shapiro-Wilk test	Lilliefors test	Kolmogorov-Smirnov test	D'Agostino K^2 test
Statistic: K =0.967	Statistic: K = 0.107	Statistic: K = 0.107	Statistic: K = 4.281
p-value: 0.002	p-value: 0.001	p-value: 0.071	p-value: 0.118
Decision at 5 % level: Normal distribution is rejected ↯	Decision at 5 % level: Normal distribution is rejected ↯	Decision at 5 % level: Normal distribution cannot be rejected ✓	Decision at 5 % level: Normal distribution cannot be rejected ✓

(c) Analytic test results for normal distribution of A_{meas}

Figure 5.8-1: Normal probability (Q_x-Q_y) plots and analytic tests for normality of the variable A_{meas}

5.8.3 Results of the reliability analysis for the unthreaded bolt part in the shear plane based on single-/double-shear testing and extended literature review

A comprehensive summary of the resulting partial safety factors γ_M* of the statistical re-verification and extended reliability analysis for the shear resistance of austenitic and duplex stainless steel bolts with unthreaded bolt part in the shear plane is presented in Table 5.8-1. The resulting partial safety factors γ_M* of the defined subsets of each individual bolt property class (PC 50 to 12.9), steel grades (austenitic and duplex) and different standards (EN 1993-1-4, DIN EN 1993-1-4/NA and FprEN 1993-1-4 / abZ/aBG Z-30.3-6:2022) are contrasted to the resulting partial safety factors γ_M* over all bolts and bolting assemblies. In total, 169 shear tests were considered for FprEN 1993-1-4 instead of 138 tests from [164].The proposed shear coefficients α for PC 8.8, 10.9 and 12.9 are considered in the statistical evaluation for these types of bolts (although not implemented in FprEN 1993-1-4 or abZ/aBG Z-30.3-6:2022) to ensure a completely statistical evaluation for the structural engineer.

For EN 1993-1-4 and DIN EN 1993-1-4/NA, the test data decreases to 132 shear tests due to a normative lack of shear coefficients α for stainless steel bolts in PC 100, 8.8, 10.9 and 12.9. Thus, for this large number of available single-/double shear tests ($n \geq 100$), the simplified formula for obtaining the design value r_d given in (Eq. E.12) is applied with a fractile factor of $k_{d,n} = 3.04$ for an infinite number of tests over all bolts, property classes and steel grades.

It can be seen in Table 5.8-1 that the resulting partial safety factors γ_M* for the shear resistance of stainless steel bolts with unthreaded bolt part in the shear plane are in all subsets (property classes and steel grades) and over all bolts below $\gamma_{M2} = 1.25$ on the safe side. Additionally, the approaches of FprEN 1993-1-4 and abZ Z-30.3-6:2022 show γ_M* values between γ_M* = 0.88 (PC 50) and γ_M* = 1.21 (PC 80) for austenitic and between γ_M* = 1.01 (PC 10.9) and γ_M* = 1.08 (PC 70 and 12.9) for duplex stainless steel bolts. Over all austenitic and bolts in all bolt property classes the reliability analysis results to a partial safety factor of γ_M* = 1.18 ≤ γ_{M2} = 1.25. Thus, the safety requirements of the Eurocode are fulfilled for the proposed FprEN 1993-1-4 approach regarding the determination of the shear resistance $F_{v,Rd}$ for stainless steel bolts with unthreaded bolt part in the shear plane for FprEN 1993-1-4 and abZ Z-30.3-6:2022.

Table 5.8-1: Summary of the reliability analysis of the shear resistance for austenitic and duplex stainless steel bolts and bolting assemblies including extended literature data for the unthreaded part in the shear plane with maximum COV (f_{ub}) = 3 % and maximum COV (A; A_s) = 1 %

Steel grade	PC	Number of tests	EN 1993-1-4				DIN EN 1993-1-4/NA				FprEN 1993-1-4/abZ Z-30.3-6			
			α	γM* [-]	γM* [-]	γM* [-]	α	γM* [-]	γM* [-]	γM* [-]	α	γM* [-]	γM* [-]	γM* [-]
Austenitic	PC 50	3	0.6	0.66	1.00	**1.00**	0.75	0.64	0.87	**1.05**	0.8	0.88	1.18	**1.18**
	PC 70	74	0.6	0.93			0.68	0.82			0.7	1.09		
	PC 80	44	0.6	1.04			0.68	0.92			0.7	1.21		
	PC 8.8	11	-[1)]	-[1)]			-[1)]	-[1)]			0.7	1.15		
	PC 10.9	6	-[1)]	-[1)]			-[1)]	-[1)]			0.6	1.11		
Duplex	PC 70	5	0.6	0.81	0.89		0.5	0.52	0.58		0.8	1.08	1.10	
	PC 80	6	0.6	0.90			0.5	0.60			0.7	1.05		
	PC 100	5	-[1)]	-[1)]			-[1)]	-[1)]			0.6	1.05		
	PC 10.9	9	-[1)]	-[1)]			-[1)]	-[1)]			0.6	1.01		
	PC 12.9[2)]	6	-[1)]	-[1)]			-[1)]	-[1)]			0.6	1.08		

[1)] According to EN 1993-1-4 and DIN EN 1993-1-4/NA, no shear coefficients α are given for PC 100, 8.8, 10.9 and 12.9. | [2)] In one of two duplex series from literature, PC 12.9 was not achieved with $f_{ub,exp,mean}$ = 1157.1 N/mm² < $f_{ub,12.9,nom}$ = 1200 N/mm² leading to high γ_M* values.

The conservatism of the EN 1993-1-4 and DIN EN 1993-1-4/NA design rules are obvious with a resulting partial safety factor of γ_M* = 1.00 for the European EN 1993-1-4 and γ_M* = 1.05 for the German national annex DIN EN 1993-1-4/NA. In particular, the property class subsets of these standards exhibit striking low γ_M* values between 0.66 ≤ γ_M* ≤ 1.04 for EN 1993-1-4 and 0.52 ≤ γ_M* ≤ 0.92 for DIN EN 1993-1-4/NA. If the bolt PC 80 and 8.8 as well as PC 100 and 10.9 are summarised to one PC group each, the resulting partial safety factors are presented in Table 5.8-2 and the different resulting γ_M* values compared to the results of Table 5.8-1 are highlighted in colour.

At this point, the question arises how generally low partial safety factors γ_M* of the bolt property classes PC 50, 70, 80 and 8.8 (0.52 ≤ γ_M* ≤ 0.93) can lead to a comparatively high partial safety factor over all bolts to γ_M* = 1.06 for the German national annex DIN EN 1993-1-4/NA, which is also higher compared to γ_M* = 1.02 over all bolts for EN 1993-1-4 consisting of also higher partial safety factors γ_M* for each property class.

Table 5.8-2: Summary of the reliability analysis of the shear resistance for austenitic and duplex stainless steel bolts and bolting assemblies including extended literature data for the unthreaded part in the shear plane with maximum COV (f_{ub}) = 3 % and maximum COV (A; A_s) = 1 % summarising PC 80/8.8 as well as PC 100/10.9 to one PC group each

Steel grade	PC	Number of tests	EN 1993-1-4				DIN EN 1993-1-4/NA				FprEN 1993-1-4/abZ Z-30.3-6			
			α	γ_M* [-]	γ_M* [-]	γ_M* [-]	α	γ_M* [-]	γ_M* [-]	γ_M* [-]	α	γ_M* [-]	γ_M* [-]	γ_M* [-]
Austenitic	PC 50	3	0.6	0.66	1.02	**1.02**	0.75	0.64	0.89	**1.06**	0.8	0.88	1.18	**1.18**
	PC 70	74	0.6	0.93			0.68	0.82			0.7	1.09		
	PC 80	55	0.6[1)]	1.06			0.68[1)]	0.93			0.7	1.23		
	PC 8.8													
	PC 10.9	6	-[1)]	-[1)]			-[1)]	-[1)]			0.6	1.11		
Duplex	PC 70	5	0.6	0.81	0.89		0.5	0.52	0.58		0.8	1.08	1.10	
	PC 80	6	0.6	0.90			0.5	0.60			0.7	1.05		
	PC 100	14	-[1)]	-[1)]			-[1)]	-[1)]			0.6	1.03		
	PC 10.9													
	PC 12.9[2)]	6	-[1)]	-[1)]			-[1)]	-[1)]			0.6	1.08		

[1)] According to EN 1993-1-4 and DIN EN 1993-1-4/NA, no shear coefficients α are given for PC 100, 8.8, 10.9 and 12.9. Nevertheless, PC 8.8 was included into PC 80 and PC 10.9 was included into PC 100 in the frame of this statistical evaluation. | [2)] In one of two duplex series from literature, PC 12.9 was not achieved with $f_{ub,exp,mean}$ = 1157.1 N/mm² < $f_{ub,12.9,nom}$ = 1200 N/mm² leading to high γ_M* values.

An explanation for this phenomenon is presented as a schematic overview in Figure 5.8-2. It can be shown that the simplified design resistance value r_d (Eq. E.12) for n ≥ 100 is depending on the mean value correction factor b (describing the variation between r_{ei} and r_{ti}), the scattering value Q (which is in principle based on the error term δ_I representing the mean value correction factor b as well as r_{ei} and r_{ti}) and the coefficients of variation of the basic variables V_{Xi}, see highlighted terms in Figure 5.8-2.

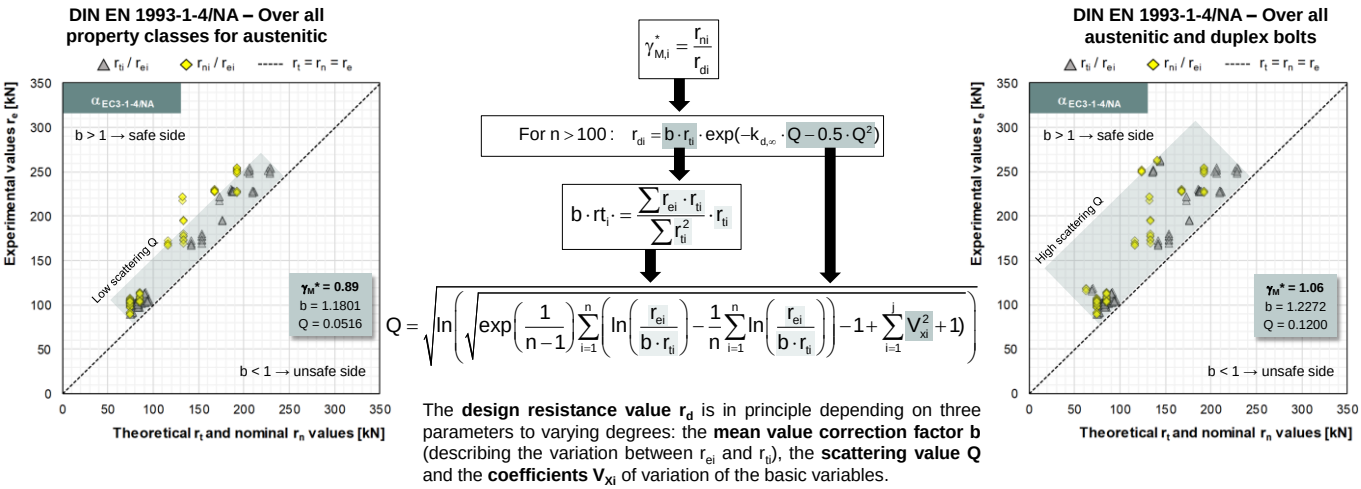


Figure 5.8-2: Main influencing parameters for the design resistance value r_d according to EN 1990, Annex D

In the case of austenitic stainless steel bolts in PC 50, 70, 80 and 8.8 according to the design of DIN EN 1993-1-4/NA, the mean value correction factor b is about 1.1801 with a scattering Q of 0.0516 resulting to a low partial safety factor of γ_M* = 0.89. On the contrary, if all austenitic and duplex stainless steel bolts are considered, the mean value correction factor b increases slightly from 1.1801 to 1.2272 (by factor ≈ 1.04) which indicates an approach more on the safe side with b > 1. Furthermore, a higher b value corresponds to a higher design resistance value r_d and finally a lower partial safety factor γ_M* (as ratio of the nominal resistance value r_n and design resistance value r_d). However, in this example, the scattering Q significantly increases from Q = 0.0516 to Q = 0.1200 (by factor ≈ 2.33) in the statistical evaluation over all austenitic and duplex bolts so that the simplified design resistance value r_d (Eq. E.12) for n ≥ 100 is finally decreasing under consideration of the negative exponential function terms. It can be seen that

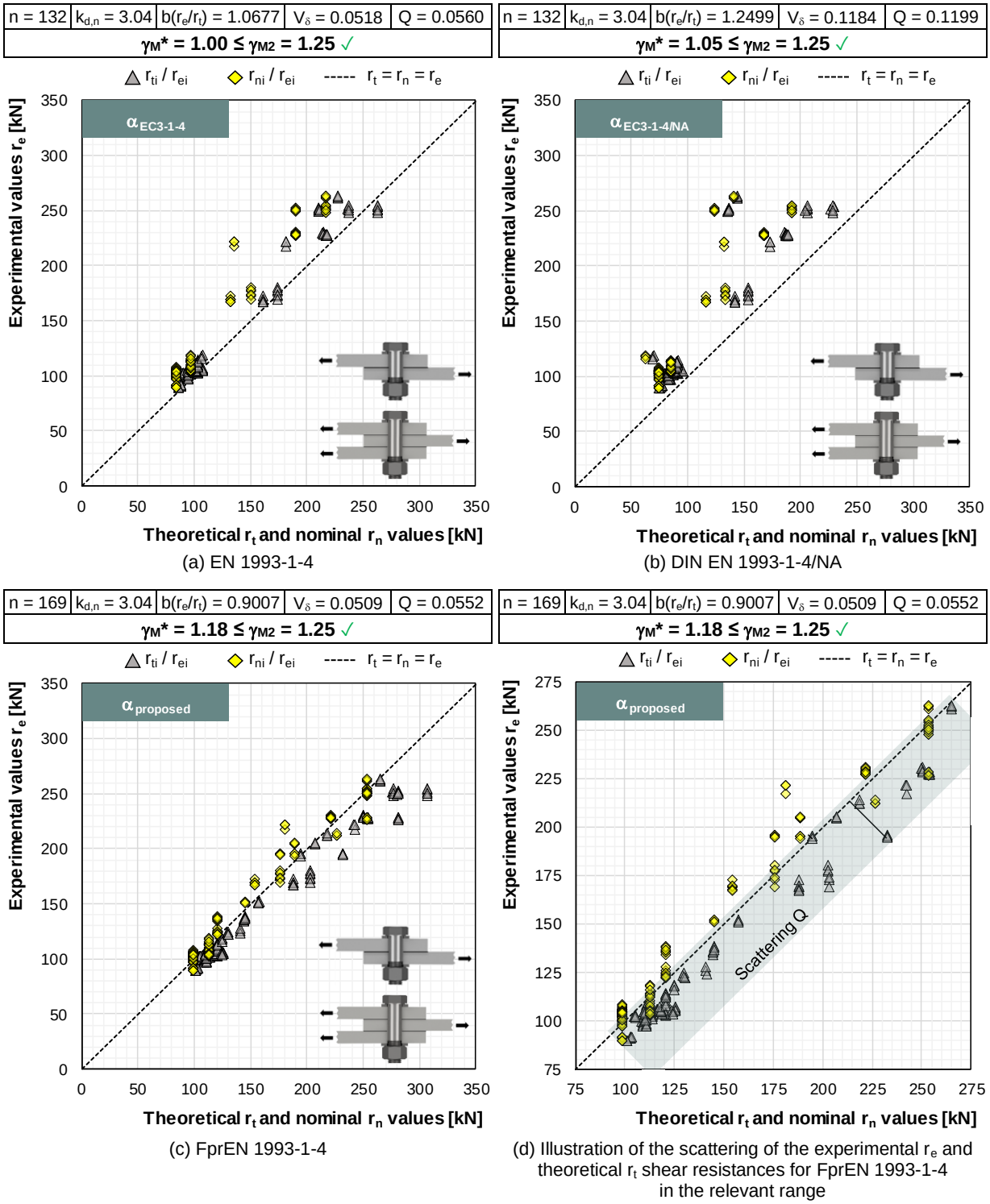
despite the higher mean value correction factor b (indicating a safe approach), the resulting partial safety factor γ_M* is finally increasing due the impact of the scattering parameter Q in (Eq. E.12). Therefore, it can be concluded in principle that γ_M* is determined by three parameters (b, Q, V_{Xi}) as multifactorial, which can collaborate or act in opposition.

A comparison of the experimental and theoretical values (r_e/r_t) as well as experimental and nominal values (r_e/r_n) for the shear resistance of austenitic and duplex stainless steel bolts based on the design of EN 1993-1-4 (a), the German national annex DIN EN 1993-1-4/NA (b) and FprEN 1993-1-4/abZ Z-30.3-6:2022 (c) is provided in Figure 5.8-3. In addition, the main parameters of the statistical evaluations according to EN 1990, Annex D are provided to allow direct comparisons of the mean value correction factor b and the scattering parameters V_δ (informative) and Q for the simplified design resistance value r_d. Furthermore, an illustration of the scattering of the experimental r_e and theoretical r_t shear resistances in the relevant range for FprEN 1993-1-4 and abZ Z-30.3-6:2022 is presented in Figure 5.8-3 (d).

The mean value correction factor b for the shear resistance of austenitic and duplex stainless steel bolts of the current EN 1993-1-4 is about $b(r_e/r_t) = 1.0677$ with a scattering of Q = 0.0560 and $V_\delta = 0.0518$. The r_e/r_t values are mainly on or above or only partially below the angle bisector. However, all r_e/r_n values lie above the angle bisector on the safe but also non-economical side. In addition to the relatively low scattering of the theoretical values, the high scattering of the experimental and nominal values r_e/r_n is striking. The greatest difference of the r_e/r_n values is detected for M24×130 A4-50 austenitic bolts tested only in single-shear due to the comparatively low shear coefficient α of 0.6 for bolts with significant high ductility and plastic deformation capacity. For the statistical evaluation of DIN EN 1993-1-4/NA, all r_e/r_t and r_e/r_n values are above the angle bisector with a mean value correction factor of $b(r_e/r_t) = 1.2499$ with a high scattering of Q = 0.1199 and $V_\delta = 0.1184$.

The major differences in the shear resistance of the r_e/r_t and r_e/r_n values are mainly based on duplex stainless steel bolts, which are defined by a low shear coefficient of $\alpha = 0.5$ always based on the tensile stress area A_s even if bolt shear failure occurs in the unthreaded part. Consequently, the approach of the German national annex DIN EN 1993-1-4/NA seems not suitable to describe the shear resistance $F_{v,Rd}$ of austenitic and particularly duplex stainless steel bolts appropriately. Finally, the proposed approach for the shear resistance $F_{v,Rd}$ of stainless steel bolts with unthreaded part in the shear plane according to FprEN 1993-1-4 and abZ Z-30.3-6:2022 shows a mean value correction factor $b < 1$ of $b(r_e/r_t) = 0.9007$. The scattering of the r_e/r_t values is in the amount of Q = 0.0552 and $V_\delta = 0.0509$ both slightly lower compared to EN 1993-1-4. The r_e/r_t values are mainly on or below the angle bisector, see Figure 5.8-3 (c) and (d), while the experimental/nominal r_e/r_n data points lie mainly on the angle bisector with the exception of M24×130 A4-50 austenitic stainless steel bolts, which are showing the highest deviation on the safe side despite the increased shear coefficient of $\alpha = 0.80$ still underestimating the shear resistance of these bolts in the statistical evaluation only on the basis of experimental/nominal values.

It can be concluded that based on a comparison of the experimental r_e and theoretical r_t/nominal r_n shear resistances for both austenitic and duplex bolts and bolting assemblies the proposed and already implemented approach for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022 with higher shear coefficients α seems to be most suitable to describe the more economical shear resistance of austenitic and duplex bolts with unthreaded part in the shear plane.



(a) EN 1993-1-4

(b) DIN EN 1993-1-4/NA

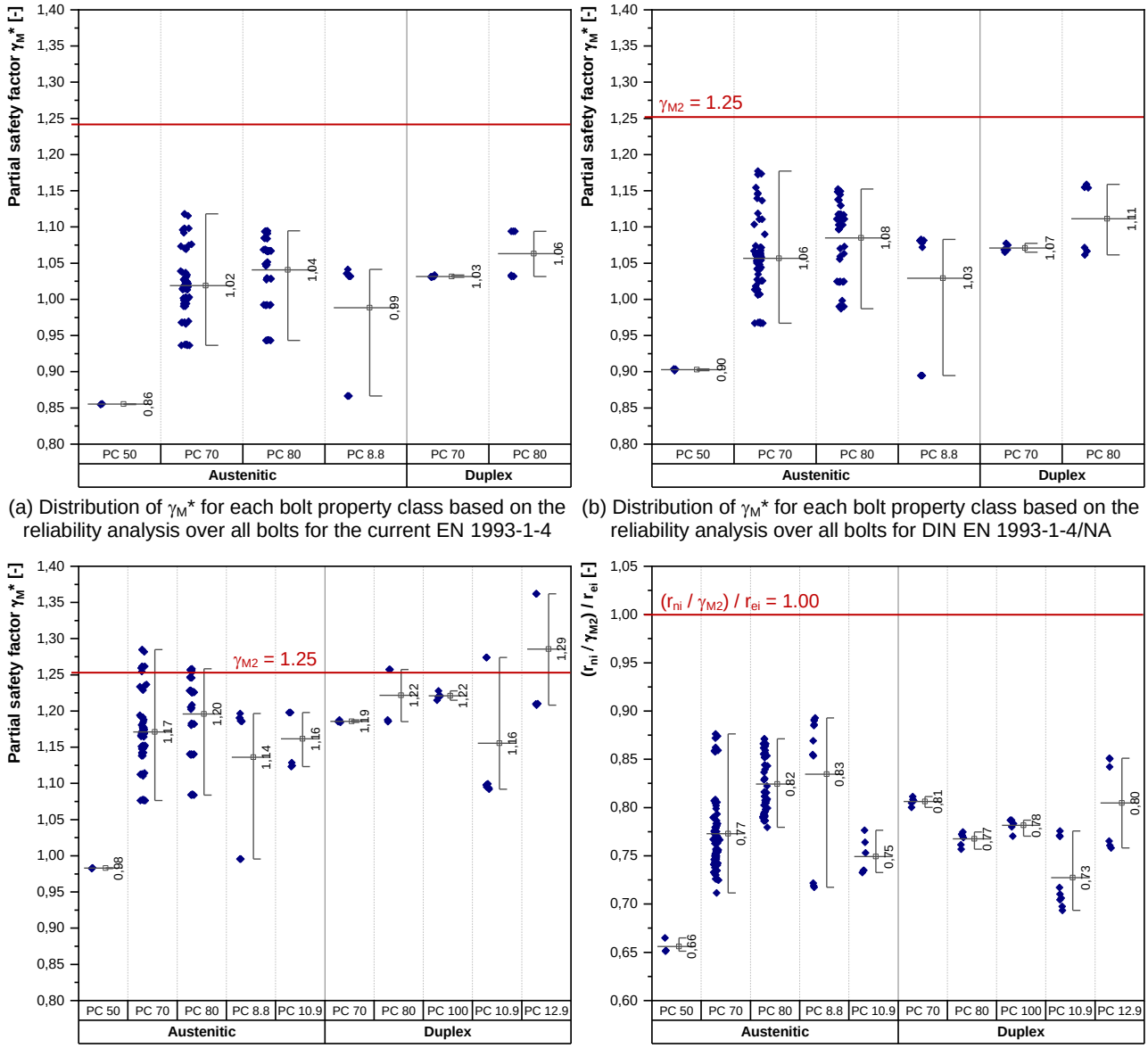
(c) FprEN 1993-1-4

(d) Illustration of the scattering of the experimental r_e and theoretical r_t shear resistances for FprEN 1993-1-4 in the relevant range

Figure 5.8-3: Comparison of the experimental r_e and theoretical r_t/nominal r_n shear resistances for austenitic and duplex stainless steel bolts and bolting assemblies including literature data for the unthreaded part in the shear plane

In order to visualise the distribution of the resulting individual partial safety factors $\gamma_{M,i}$* for the design rules of EN 1993-1-4 (a), DIN EN 1993-1-4/NA (b) and FprEN 1993-1-4 (c) over all investigated austenitic and duplex bolts across all bolt property classes, the individual data points of each tested bolt including extended literature data are summarised graphically in Figure 5.8-4. Plots of the range and resulting partial safety factor mean values γ_M* based on the reliability analysis over all bolts are informatively included (which can not be compared with the partial safety factors γ_M* from the subsets given in Table 5.8-1 and Table 5.8-2).

It can be proven that all resulting individual partial safety factors $\gamma_{M,i}$* for EN 1993-1-4 and the German national annex DIN EN 1993-1-4/NA are clearly below γ_{M2} = 1.25. However, the proposed and already implemented approach for FprEN 1993-1-4 shows partially $\gamma_{M,i}$* values which are exceeding γ_{M2} = 1.25, while the mean partial safety factors γ_M* for all property class with exception for duplex bolts in PC 12.9 are below γ_{M2} = 1.25. In one of two duplex stainless steel bolt series from literature, PC 12.9 (not implemented in FprEN 1993-1-4) was not achieved with $f_{ub,exp,mean}$ = 1157.1 N/mm² < $f_{ub,12.9,nom}$ = 1200 N/mm² leading to high γ_M* values over all bolts, while the subset of duplex PC 12.9 is fulfilling the safety requirements, see Table 5.8-1 and Table 5.8-2.



(a) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for the current EN 1993-1-4

(b) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for DIN EN 1993-1-4/NA

(c) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for FprEN 1993-1-4

(d) Distribution of the ratio of the individual nominal design r_{ni}/γ_{M2} and experimental r_{ei} results for FprEN 1993-1-4

Figure 5.8-4: Distribution of the partial safety factors γ_M* of austenitic and duplex stainless steel bolts for each property class for the shear resistance with unthreaded bolt part in the shear plane

In order to assess the quality of the design approach of EN 1993-1-4, DIN EN 1993-1-4/NA and the proposed approach for FprEN 1993-1-4 and to check if partially exceeding of γ_{M2} may be critical, the modified safety assessment criteria (see Chapter 4.7.4) are applied.

It could be proven in a plausibility check (as criterion III) in Figure 5.8-4 (d) that all nominal design values (r_{ni}/γ_{M2}) for prEN 1993-1-4 are clearly below the experimental resistances r_{ei} and that always sufficient safety reserves are guaranteed. A summary of the evaluation based on the modified criteria is presented in Table 5.8-3. Here, it can be confirmed that all criteria are fulfilled for EN 1993-1-4, DIN EN 1993-1-4/NA and the proposed approach of FprEN 1993-1-4 for the shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolts.

Table 5.8-3: Evaluation of the reliability analysis for the shear resistance of stainless steel bolts for EN 1993-1-4, DIN EN 1993-1-4/NA and FprEN 1993-1-4 according to the modified safety assessment criteria

Evaluation criteria (Chapter 4.7.4)		EN 1993-1-4	DIN EN 1993-1-4/NA	FprEN 1993-1-4
I	Maximum error ≤ 1.15 · γ_{M2}	1.09 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.16 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.36 ≤ 1.15 · γ_{M2} = 1.44 ✓
II	Maximum number of unsafe results ≤ 20 %	0 % ≤ 20 % ✓	0 % ≤ 20 % ✓	13.0 % ≤ 20 % ✓
III	Plausibility check	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.00 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.00 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.00 ✓

5.8.4 Results of the reliability analysis for the threaded bolt part in the shear plane based on single-/double-shear testing and extended literature review

A summary of the resulting partial safety factors γ_M* of the extended reliability analysis for the shear resistance of austenitic and duplex stainless steel bolts with threaded bolt part in the shear plane is presented in Table 5.8-4. Analogues to the results from the reliability analysis of the unthreaded part, again the resulting partial safety factors γ_M* of the defined subsets of individual property classes (PC 50 to 12.9), steel grades (austenitic/duplex) and different standards (EN 1993-1-4, DIN EN 1993-1-4/NA and FprEN 1993-1-4 / abZ Z-30.3-6:2022) are contrasted to the resulting partial safety factors γ_M* over all bolts and bolting assemblies. For this large number of available single-/double shear tests (n ≥ 100), the simplified formula for obtaining the design value r_d given in (Eq. E.12) was applied with a fractile factor of $k_{d,n}$ = 3.04 for an infinite number of tests over all bolts and for all property classes and steel grade subsets.

Table 5.8-4: Summary of the reliability analysis of the shear resistance for austenitic and duplex stainless steel bolts and bolting assemblies including extended literature data for the threaded part in the shear plane with maximum COV (f_{ub}) = 3 % and maximum COV (A_s) = 1 %

Steel grade	PC	Number of tests	EN 1993-1-4				DIN EN 1993-1-4/NA				FprEN 1993-1-4/abZ Z-30.3-6			
			α	γ_M* [-]	γ_M* [-]	γ_M* [-]	α	γ_M* [-]	γ_M* [-]	γ_M* [-]	α	γ_M* [-]	γ_M* [-]	γ_M* [-]
Austenitic	PC 50	6	0.5	0.57	0.87	0.86	0.75	0.85	1.14	1.29	0.8	0.91	1.18	1.15
	PC 70	52	0.5	0.82			0.68	1.12			0.7	1.15		
	PC 80	26	0.5	0.81			0.68	1.10			0.7	1.14		
	PC 8.8	28	-[1)]	-[1)]			-[1)]	-[1)]			0.7	1.02		
	PC 10.9	18	-[1)]	-[1)]			-[1)]	-[1)]			0.6	0.97		
Duplex	PC 70	6	0.5	0.70	0.70		0.5	0.70	0.70		0.8	1.12	1.00	
	PC 80	-[2)]	0.5	-[2)]			0.5	-[2)]			0.7	-[2)]		
	PC 100	-[2)]	-[1)]	-[1)]			-[1)]	-[1)]			0.6	-[2)]		
	PC 10.9	53	-[1)]	-[1)]			-[1)]	-[1)]			0.6	0.93		
	PC 12.9[3)]	3	-[1)]	-[1)]			-[1)]	-[1)]			0.6	1.01		

[1)] According to EN 1993-1-4 and DIN EN 1993-1-4/NA, no shear coefficients α are given for PC 100, 8.8, 10.9 and 12.9. | [2)] No shear tests were conducted for duplex bolts in PC 80 and PC 100. | [3)] In the duplex bolt series from literature, the requirements of PC 12.9 were not achieved with $f_{ub,exp,mean}$ = 1139.7 N/mm² < $f_{ub,12.9,nom}$ = 1200 N/mm².

Table 5.8-4 shows that the resulting partial safety factors γ_M* for the shear resistance $F_{v,Rd}$ of stainless steel bolts with threaded part in the shear plane are in all subsets (property classes and steel grades) and over all bolts for EN 1993-1-4 and FprEN 1993-1-4 / abZ Z-30.3-6 below γ_{M2} = 1.25 on the safe side.

Due to a constant shear coefficient α = 0.5 for all property classes (PC 50, 70 and 80), the current EN 1993-1-4 approach leads to generally low partial safety factors γ_M* below 0.90 on the non-economical safe side. In contrast, the proposed higher shear coefficients α for FprEN 1993-1-4 generally lead to increased γ_M* values between γ_M* = 0.88 (austenitic, PC 50) and γ_M* = 1.21 (austenitic, PC 70). In addition, the reliability analyses over all austenitic stainless steel bolts with threaded part in the shear plane lead to a partial safety factor of γ_M* = 1.18, while all duplex bolts result to γ_M* = 1.00. However, it is worth mentioning that no duplex bolts or bolting assemblies in PC 80 and 100 were available for testing and consequently missing in the statistical evaluation. Nevertheless, the safety requirements of the Eurocode are fulfilled for the proposed FprEN 1993-1-4 approach regarding the determination of the shear resistance $F_{v,Rd}$ for stainless steel bolts with threaded bolt part in the shear plane for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022. Consequently, also a more economical design for the shear resistance of the threaded bolt part is possible with unified shear coefficients α for both the unthreaded and threaded bolt part.

If the bolt PC 80 and 8.8 as well as PC 100 and 10.9 are summarised to each one PC group, the resulting partial safety factors are presented in Table 5.8-5 and the different resulting γ_M* values compared to the results of Table 5.8-4 are highlighted in colour.

Table 5.8-5: Summary of the reliability analysis of the shear resistance for austenitic and duplex stainless steel bolts and bolting assemblies including extended literature data for the threaded part in the shear plane with maximum COV (f_{ub}) = 3 % and maximum COV (A_s) = 1 % summarising PC 80/8.8 as well as PC 100/10.9 to one PC group each

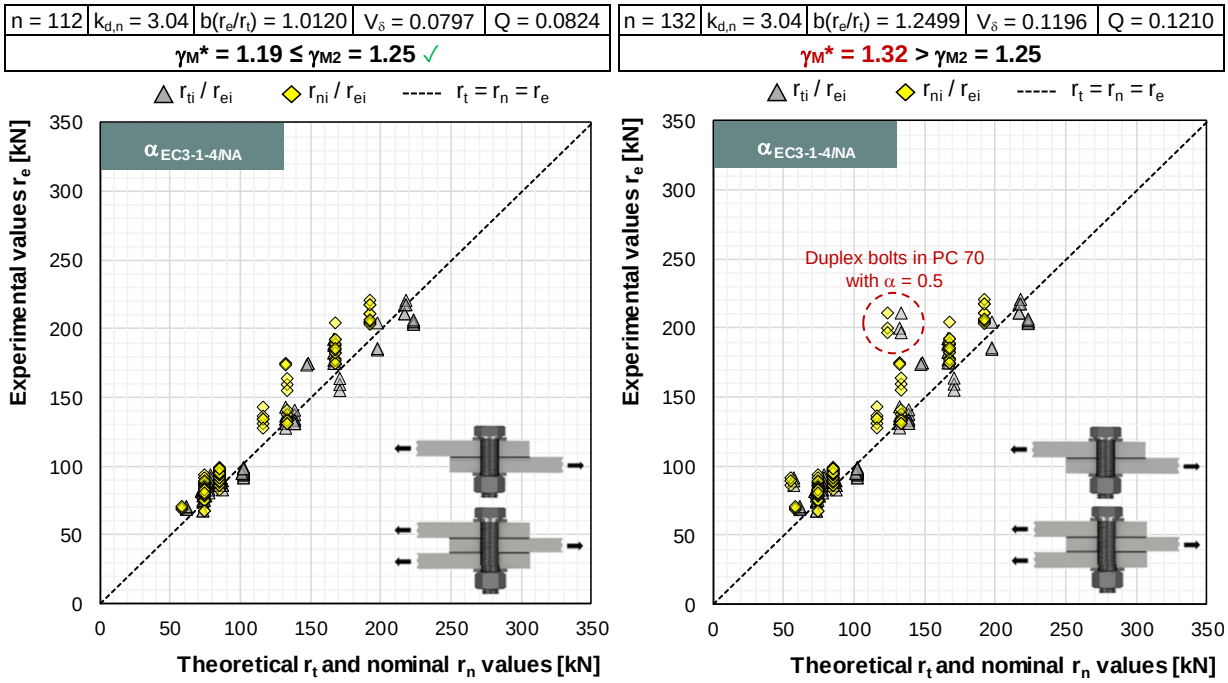
Steel grade	PC	Number of tests	EN 1993-1-4				DIN EN 1993-1-4/NA				FprEN 1993-1-4/abZ Z-30.3-6			
			α	γ_M* [-]	γ_M* [-]	γ_M* [-]	α	γ_M* [-]	γ_M* [-]	γ_M* [-]	α	γ_M* [-]	γ_M* [-]	γ_M* [-]
Austenitic	PC 50	6	0.5	0.57	0.90	**0.90**	0.75	0.85	1.19	**1.32**	0.8	0.91	1.18	**1.15**
	PC 70	52	0.5	0.82			0.68	1.12			0.7	1.15		
	PC 80	54	0.5[1)]	0.81			0.68[1)]	1.10			0.7	1.13		
	PC 8.8													
	PC 10.9	18	-[1)]	-[1)]			-[1)]	-[1)]			0.6	0.97		
Duplex	PC 70	6	0.5	0.70	0.70		0.5	0.70	0.70		0.8	1.12	1.00	
	PC 80	-[2)]	0.5	-[2)]			0.5	-[2)]			0.7	-[2)]		
	PC 100	53[2)]	-[1)]	-[1)]			-[1)]	-[1)]			0.6	0.93[2)]		
	PC 10.9													
	PC 12.9[3)]	3	-[1)]	-[1)]			-[1)]	-[1)]			0.6	1.01		

[1)] According to EN 1993-1-4 and DIN EN 1993-1-4/NA, no shear coefficients α are given for PC 100, 8.8, 10.9 and 12.9. Nevertheless, PC 8.8 was included into PC 80 and PC 10.9 included into PC 100 in the statistical evaluation. | [2)] No shear tests were conducted for duplex bolts in PC 80 and 100. | [3)] In the series from literature, PC 12.9 was not achieved with $f_{ub,exp,mean}$ = 1139.7 N/mm² < $f_{ub,12.9,nom}$ = 1200 N/mm².

However, it is striking that in Table 5.8-4 and Table 5.8-5 both for DIN EN 1993-1-4/NA partial safety factors of γ_M* = 1.29 or even 1.32 exceeding γ_{M2} = 1.25, which are not fulfilling the safety requirements of the Eurocode. However, if the test population is split into austenitic and duplex bolts (as recommended by EN 1990, Annex D, Clause D.8.2.2.5 if the scattering of r_{ei} and r_{ti} is too high), then γ_{M2} = 1.25 is achieved with γ_M* = 1.19 for all austenitic and γ_M* = 0.70 for all duplex bolts. Here, an in-depth view of the r_e/r_t and r_e/r_n values shown in Figure 5.8-5 reveals that the implementation of the duplex stainless steel bolts with α = 0.5 for PC 70 leads to high scattering of V_δ = 0.1196 (from V_δ = 0.0797 for austenitic stainless steel bolts) and Q = 0.1210 (from Q = 0.0824 for austenitic bolts). Despite a significantly increased mean value correction factor $b(r_e/r_t)$ = 1.2499 on the safe side (instead of 1.0120 for all austenitic bolts), γ_M* over all austenitic and duplex bolts also increases to γ_M* = 1.32 > γ_{M2} = 1.25.

A comparison of the experimental and theoretical values (r_e/r_t) as well as experimental and nominal values (r_e/r_n) for the shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolts based on the design of EN 1993-1-4 (a), the German national annex DIN EN 1993-1-4/NA (b),

FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022 (c) is summarised in Figure 5.8-6 including the main results and parameters of the statistical evaluations.



(a) DIN EN 1993-1-4/NA – All austenitic bolts (b) DIN EN 1993-1-4/NA – All austenitic and duplex bolts

Figure 5.8-5: Comparison of the experimental r_e and theoretical r_t/nominal r_n bolt shear resistances according to DIN EN 1993-1-4/NA austenitic (a) or austenitic and duplex bolts (b) over PC 50, 70, 80 and 8.8

It can be seen that the mean value correction factor b for the shear resistance of austenitic and duplex stainless steel bolts of EN 1993-1-4 is in the amount of $b(r_e/r_t) = 1.4404$ with a scattering of $Q = 0.0789$ and $V_\delta = 0.0817$ resulting to a partial safety factor γ_M* of 0.86 significantly on the safe but non-economical side. Consequently, the r_e/r_t values are clearly above the angle bisector. On the contrary, the proposed approach for the shear resistance of austenitic and duplex bolts with threaded bolt part in the shear plane for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022 show a mean value correction factor b of $b(r_e/r_t) = 1.0080$ slightly greater than 1. The experimental and theoretical values (r_e/r_t) are distributed above, below and on the bisector angle, while most of the experimental and nominal values (r_e/r_n) lie on or above the bisector angle. The scattering of the r_e/r_t values is in the amount of $Q = 0.0714$ and $V_\delta = 0.0745$ and therefore slightly greater compared to the proposed approach for the unthreaded part with $Q = 0.0509$ and $V_\delta = 0.0552$ for all partially threaded austenitic and duplex bolts.

The scattering of the experimental and theoretical shear resistances (r_e/r_t) in the relevant range for FprEN 1993-1-4 and abZ Z-30.3-6:2022 is presented in Figure 5.8-6 (d).

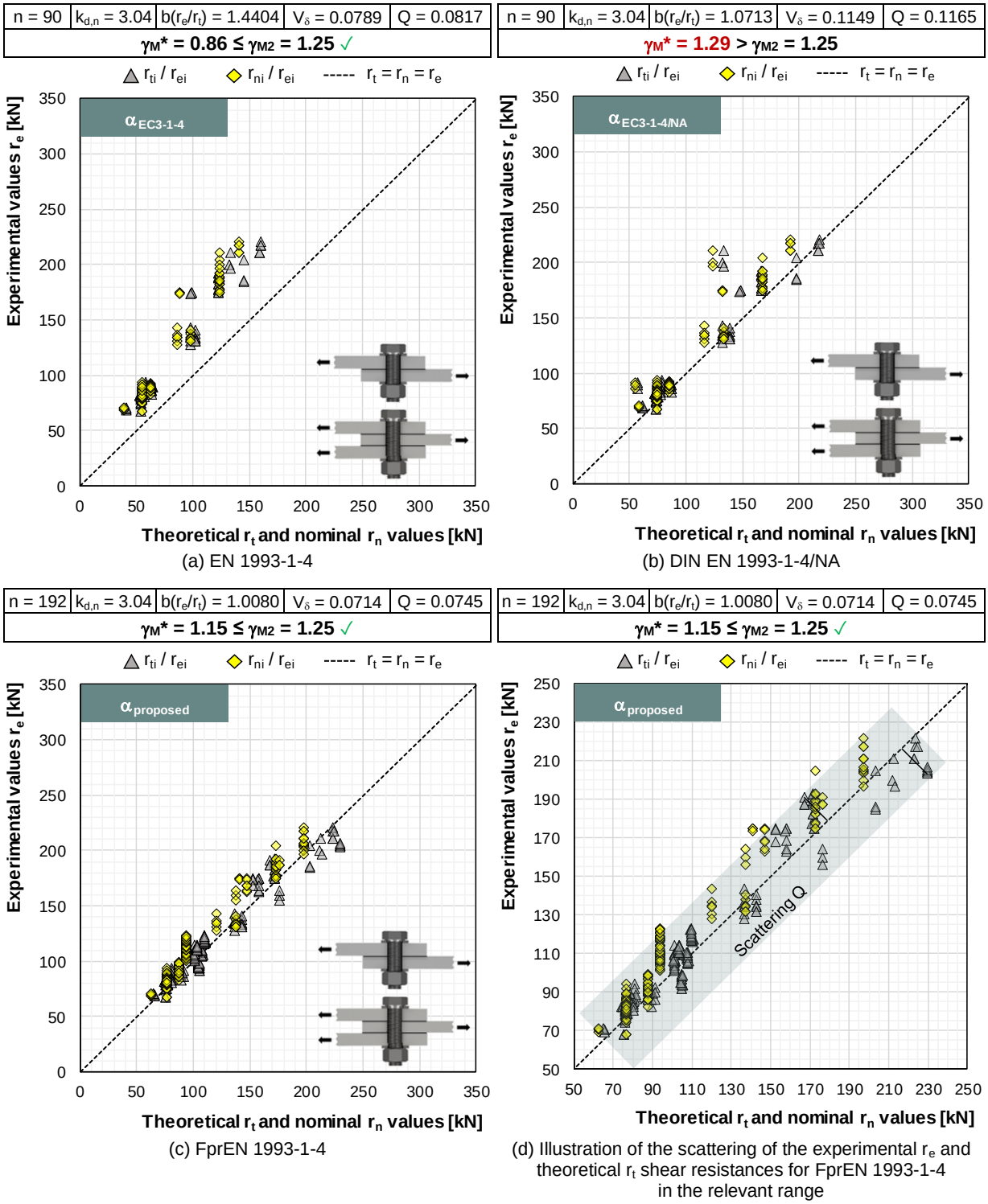
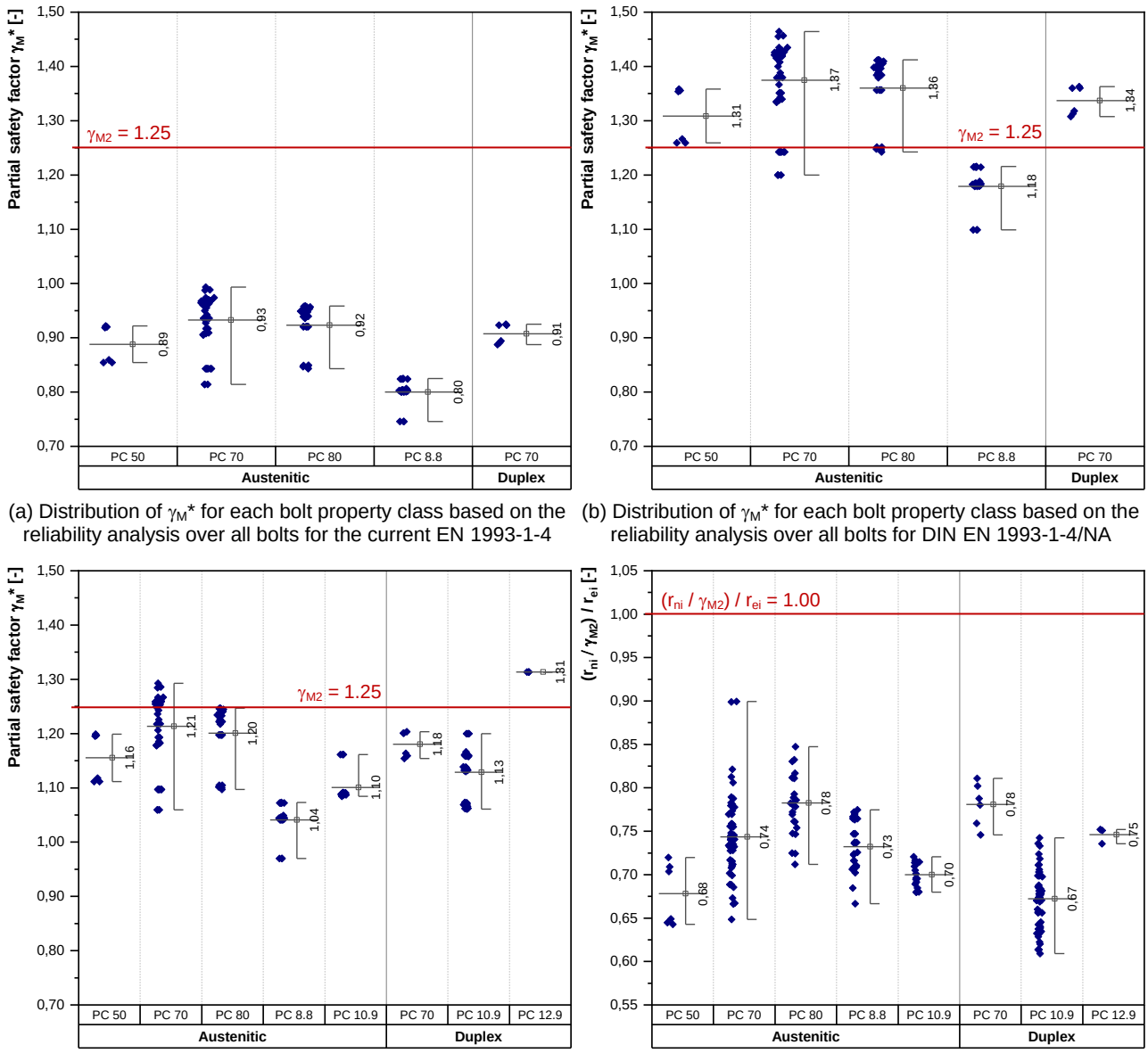


Figure 5.8-6: Comparison of the experimental r_e and theoretical r_t/nominal r_n shear resistances for austenitic and duplex stainless steel bolts and bolting assemblies including literature data for the threaded part in the shear plane

The distribution of the resulting individual partial safety factors $\gamma_{M,i}$* for the shear resistance of bolts with threaded part in the shear plane for EN 1993-1-4 (a), DIN EN 1993-1-4/NA (b) and FprEN 1993-1-4 (c) over all austenitic and duplex bolts across all investigated property classes including extended literature data are summarised graphically in Figure 5.8-7. The plots of the range and resulting partial safety factor mean values γ_M* are again based on the reliability analysis over all bolts.

For the design approach of EN 1993-1-4, all individual partial safety factors $\gamma_{M,i}$* are clearly below γ_{M2} = 1.25, while the German national annex DIN EN 19931-4/NA is clearly failing the safety requirements of the Eurocode in a statistical evaluation over all bolts without any

subsets due to high scattering with exception of bolts in PC 8.8 (if treated like PC 80 bolts). Finally, the proposed and already implemented approach for FprEN 1993-1-4 shows partially $\gamma_{M,i}$* values which are exceeding γ_{M2} = 1.25, while the mean partial safety factors γ_M* for all property class with exception for duplex bolts in PC 12.9 are below γ_{M2} = 1.25. However, the duplex bolt series from literature in PC 12.9 (which is not implemented in FprEN 1993-1-4) was not fulfilling the requirements of $f_{ub,exp,mean}$ = 1139.7 N/mm² < $f_{ub,12.9,nom}$ = 1200 N/mm² leading to high γ_M* values over all bolts, while, on the contrary, the subset of duplex PC 12.9 is fulfilling the safety requirements, see Table 5.8-4.



(a) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for the current EN 1993-1-4

(b) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for DIN EN 1993-1-4/NA

(c) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for FprEN 1993-1-4

(d) Distribution of the ratio of the individual nominal design r_{ni}/γ_{M2} and experimental r_{ei} results for FprEN 1993-1-4

Figure 5.8-7: Distribution of the partial safety factors γ_M* of austenitic and duplex stainless steel bolts for each property class for the shear resistance with threaded bolt part in the shear plane

In order to assess the quality of the design approaches of EN 1993-1-4, DIN EN 1993-1-4/NA and the proposed approach for FprEN 1993-1-4, analogues to the evaluation of the unthreaded bolt part in the shear plane, the modified assessment criteria are applied, see Table 5.8-6 and Figure 5.8-7 (d).

It can be confirmed that all assessment criteria are fulfilled for EN 1993-1-4 and the proposed and more economical approach for FprEN 1993-1-4 regarding the shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolts. As already discussed, the German approach of

DIN EN 1993-1-4/NA is not fulfilling the safety requirements of γ_{M2} = 1.25 of the Eurocode over all austenitic and duplex steel bolts. Furthermore, if the test population is split into austenitic and duplex bolts, the criterion of maximum number of unsafe results ≤ 20 % (criterion II) of is achieved by duplex bolts with 0 % unsafe results, while the subset of austenitic stainless steel bolts again failed by 38.4 % unsafe results due to the impact of the overstrength of PC 8.8 resulting in higher scattering and finally higher individual partial safety factors $\gamma_{M,i}$*, see Figure 5.8-5. It can be concluded that the proposed approach for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022 fully achieve the requirements of the Eurocode and further assessment criteria for the shear resistance of stainless steel bolts $F_{v,Rd}$ with shear plane in the unthreaded or threaded part.

Table 5.8-6: Evaluation of the reliability analysis for the shear resistance of stainless steel bolts for EN 1993-1-4, DIN EN 1993-1-4/NA and FprEN 1993-1-4 according to the modified safety assessment criteria

Evaluation criteria (Chapter 4.7.4)		EN 1993-1-4	DIN EN 1993-1-4/NA	FprEN 1993-1-4
I	Maximum error ≤ 1.15 · γ_{M2}	0.99 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.39 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.31 ≤ 1.15 · γ_{M2} = 1.44 ✓
II	Maximum number of unsafe results ≤ 20 %	0 % ≤ 20 % ✓	77.8 % ≤ 20 % ↯	14.6 % ≤ 20 % ✓
III	Plausibility check	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.00 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.00 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.00 ✓

5.9 Summary and conclusions

An overview of the experimental investigations, including an extended literature review, was given in Chapter 5 and complemented by statistical evaluations according to EN 1990, Annex D regarding the shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolts and bolting assemblies.

It could be shown that:

- Depending on the bolt's specific alignment in the bolt hole clearance and considering the extraordinarily high deformation capacity of austenitic/duplex stainless steel, the maximum load bearing shear capacities achieved in tests can vary measurably. However, single-shear testing under normal conditions with a hole diameter of d_h = 17 mm leads to lower bolt shear resistances for each shear plane on the safe side compared to double-shear testing under the same clearance. The application of hardened shear adapters with $d_{h,nom}$ = 16 mm in ISO tolerance field H8 leads to measurably lower shear capacities, which, except for one tested series, fall within the range of scattering and are therefore negligible.
- Skewing and possible misalignments of the bolt during shear testing could be demonstrated in numerical investigations, leading to an increased cross-sectional area and higher shear resistance of bolts.
- A simple conversion of the design shear coefficients α to physical shear coefficients for bolts with unthreaded bolt part in the shear plane by the ratio A/A_s is impossible due to the inhomogeneous strength distribution in stainless steel bolts. The high experimentally determined physical shear coefficients of about ≈ 0.80 for austenitic bolts in PC 50, 70 and 80 again reveal the conservativism of EN 1993-1-4 and DIN EN 1993-1-4/NA approaches but confirm the proposed shear strength ratios provided by the German VDI 2230 Part 1 Guideline for (solution-annealed) austenitic stainless steel.
- For the unthreaded or threaded bolt part in the shear plane, a direct positive correlation between the tensile strength and shear strength exists (r = 0.89 for the unthreaded part and r = 0.94 for the threaded part) accompanied by indirect strong correlations of the bolt

property class and steel grade. However, the indirect correlations stemming from bolt diameter and bolt hole clearance are relatively weaker concerning their impact on the relationship between tensile strength and shear strength.

- Based on the pathway analysis, the relationship between tensile strength and shear strength can also be determined by *Indirect Path 2* as “tensile strength to property class” combined with “property class to shear strength”. The indirect path curve shows good agreement in the relevant range comparable to the direct path of tensile strength to shear strength.
- Therefore, it can be confirmed in an extended reliability analysis according to EN 1990, Annex D that the proposed approach for FprEN 1993-1-4 regarding the shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolts with new and more economic shear coefficients α fulfils the safety requirements of the Eurocode with $\gamma_M^* = 1.18$ for the unthreaded bolt part and $\gamma_M^* = 1.15$ for the threaded bolt part in the shear plane based. The extended reliability analysis for statistical re-verification is based on a significantly expanded database and complemented by a modified safety assessment criteria.

6 Interaction behaviour of stainless steel bolting assemblies

6.1 General

An overview of the experimental investigations and statistical evaluations according to EN 1990, Annex D [79], including the proposed new and more economical design approaches for the revision of EN 1993-1-4 regarding the interaction resistance of austenitic and duplex stainless steel bolting assemblies were already provided in [78] and [282]. These investigations were embedded in [78] and further independent research activities conducted at UDE-IML. In the frame of this thesis, analyses of the interaction test results regarding the load bearing capacity of the unthreaded and threaded bolt part in the shear plane of the stainless steel bolting assemblies are carried out. Furthermore, the suitability of different European and North American bolt interaction design approaches from standards and the ongoing normative process is investigated to describe the interaction resistance of austenitic and duplex stainless steel bolting assemblies. Here, the reliability analysis according to EN 1990, Annex D is extended to allow an in-depth analysis of the distribution of the resulting partial safety factors γ_M* across all property classes, different shear plane positions and loading angles compared to other interaction design approaches to underline the suitability of the proposed bolt interaction approach by Stranghöner/Abraham for FprEN 1993-1-4 [80].

6.2 Existing studies into the interaction resistance of stainless steel bolts

As only a few studies are available explicitly dealing with the resulting pure tension and pure shear resistance of bolts and bolting assemblies made of austenitic and duplex stainless steel, experimental investigations into the interaction resistance of stainless steel bolted connections have been very limited. Therefore, systematic experimental investigations were conducted to close this gap of knowledge and to characterise for the first time the load bearing behaviour of austenitic and duplex partially and fully threaded stainless steel bolts in various property classes. Analogues to the tension resistance (Chapter 4) and shear resistance (Chapter 5) of stainless steel bolts and bolting assemblies, only test data from literature are included if they directly contribute to the interaction resistance. The selection is based on clear descriptions of the test procedure and the mechanical properties of the bolts, as summarised in Table 6.2-1. All applied test data from literature are summarised in Appendix C.

In order to get a first insight into the interaction behaviour of stainless steel bolts subjected to combined tension and shear loading, the Steel Construction Institute (SCI) carried out a limited test programme on the interaction resistance of fully threaded austenitic M20 A4-80 stainless steel bolting assemblies in 1990 [266]. In total, 15 interaction tests were conducted under a loading angle of 45°. Again, the M20 A4-80 series from bolt supplier C (consisting of only two interaction tests) is not considered for the following investigations since the normative required minimum ultimate tensile load F_{mf} of the bolts is not achieved. It could be shown that the bilinear bolt interaction of EN 1993-1-4 clearly underestimates the interaction resistance of austenitic M20 A4-80 bolts, see [266]. However, these 13 interaction tests are not added to the reliability analysis already conducted in [282] due to a lack of testing specifications and mechanical properties of the tested bolts.

Furthermore, Song et al. [5, 6] carried out single-shear interaction tests on partially threaded (M20, EN ISO 4014) and fully threaded (M16/M20/M24, EN ISO 4017) austenitic (1.4401, A4-70, A4-80 and 1.4432, PC 8.8 and 10.9) and duplex stainless steel bolting assemblies (1.4462, PC 10.9 and 12.9). The test rig of Song et al. is based on NASM 1312 Method 2 but modified for larger bolt diameters and a loading angle of 67.5° (instead of 60° and 75°). Based on the

experimental investigations and evaluations, the quadratic interaction approach of AS 4100 (and DIN 18800-1) has been retained. Finally, Song et al. [5, 6] show that the design according to EN 1993-1-4 is clearly on the safe side for the threaded and unthreaded part of an austenitic or duplex stainless steel bolt in the shear plane.

Table 6.2-1: Summary of the literature review regarding the single-shear interaction resistance of stainless steel bolts

Steel type	Property class acc. to EN ISO 3506-1	Corrosion class acc. to EN ISO 3506-1	Publication	Bolt position of the shear plane	Bolt geometry	Testing type (B= Bolt, BA = Bolting assembly)	Number of tests	$f_{ub,calc,As}$ [N/mm²]	$f_{ub,calc,shank}$ [N/mm²]	Mean $F_{max,0°}$ [kN]	Mean $F_{max,15°}$ [kN]	Mean $F_{max,30°}$ [kN]	Mean $F_{max,45°}$ [kN]	Mean $F_{max,67.5°}$ [kN]	Mean $F_{max,90°}$ [kN]
Austenitic	PC 70	A4-70	Song et al. [5] (2020)	Threads	M16×100	BA	8	732.1	-	114.7	114.3	108.4	98.9	83.8	82.6
					M20×100	BA	8	796.2	-	194.9	192.2	178.7	162.1	136.1	137.4
					M24×100	BA	8	824.4	-	290.6	283.3	260.6	234.3	193.2	192.5
				Shank	M20×100	BA	8	855.4	659.0[2)]	209.4	205.1	197.3	178.3	166.7	170.8
	PC 80	A4-80		Threads	M20×100	BA	8	833.4	-	204.0	192.2	176.8	160.7	136.4	138.1
				Shank	M20×100	BA	8	923.2	712.0[2)]	226.0	221.4	207.6	191.1	174.1	178.9
			SCI[3)] [266] (1990)	Threads	M20[1)]×-	BA	13	873.4	-	213.8	-	-	165.5	-	131.9
	PC 8.8	A4-8.8	Song et al. [6] (2020)	Threads	M20×140	BA	8	1029.0	-	251.9	232.7	207.9	181.9	165.1	160.3
				Shank	M20×140	BA	8	1057.6	824.8[2)]	258.9	252.7	230.3	205.7	190.6	195.7
	PC 10.9	A4-10.9		Threads	M20×140	BA	8	1074.4	-	263.0	242.2	217.1	185.9	164.7	165.5
				Shank	M20×140	BA	8	1098.9	925.8[2)]	269.0	272.2	248.8	220.1	193.8	205.4
Duplex	PC 10.9	D6-10.9	Song et al. [6] (2020)	Threads	M20×140	BA	8	1039.6	-	254.5	236.5	212.5	191.5	168.4	172.7
				Shank	M20×140	BA	8	1033.9	809.9[2)]	253.1	245.4	232.7	210.0	189.6	195.3
	PC 12.9[4)]	D6-12.9		Threads	M20×140	BA	8	1139.7	-	279.0	269.6	240.3	214.5	185.4	189.0
				Shank	M20×140	BA	8	1158.1	903.0[2)]	283.5	277.0	254.1	231.9	209.1	213.4
Σ Total number of interaction tests on austenitic bolting assemblies									93						
Σ Total number of interaction tests on duplex bolting assemblies									32						
Σ Total number of interaction tests on bolting assemblies									125						

[1)] Shear and interaction tests on M20 A4-80 bolts from supplier C are not considered as the bolts clearly fail the requirements of PC 80. | [2)] Tensile strength of the bolt shank $f_{ub,calc,shank}$ on the safe side taken from machined tensile specimens. | [3)] Interaction test results not added to the reliability analysis due to a lack of testing specifications and mechanical properties of the bolts. | [4)] Resulting tensile strength of the tested bolts according to Song et al. with $f_{ub,calc,mean}$ < nom. $f_{ub,12.9}$ = 1200 N/mm² and min. $R_{m,12.9}$ = 1220 N/mm², therefore PC 12.9 could not be confirmed.

6.3 Experimental investigations: Interaction test programme and test procedures

6.3.1 General

As a supplement to the experimental investigations regarding the tension and shear resistance of austenitic and duplex stainless steel bolts and bolting assemblies already presented in Chapter 4 and Chapter 5, the interaction resistance of stainless steel bolting assemblies was systematically investigated in FOSTA P 1386 / IGF-No. 20651 N [78]. In total, 408 single-shear interaction tests with unthreaded bolt part in the shear plane (partially threaded EN ISO 4014 [119] or EN ISO 4762 [120] bolts with EN ISO 4032 [394] nuts) as well as 382 single-shear interaction tests with threaded bolt part in the shear plane (fully threaded EN ISO 4017 bolts with EN ISO 4032 nuts) in bolt dimensions M16×100/110 and M24×130 were performed. Austenitic (PC 50, 70, 80, 8.8 and 10.9), lean duplex (PC 10.9), duplex

(PC 70 and 10.9), as well as super duplex (PC 10.9) stainless steel grades and bolt property classes were considered in the experimental investigations. Detailed test matrixes of the single-shear interaction tests on austenitic/duplex stainless steel bolting assemblies are presented in Table B.13 (unthreaded bolt part in the shear plane) and Table B.14 (threaded bolt part in the shear plane) of Appendix B. The main test results were already published in [78] and [164]. No further interaction tests on stainless steel bolts are conducted in this thesis.

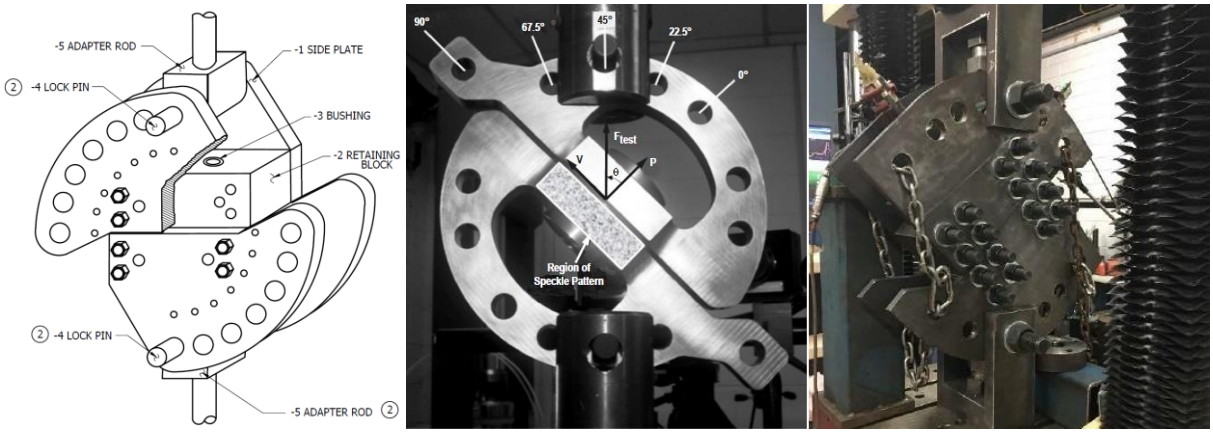
At first, an overview of existing interaction test procedures on bolts/fasteners in European and North American standardisation is introduced. Secondly, the developed test procedure and testing specification for the single-shear interaction tests on austenitic and duplex stainless steel bolting assemblies carried out in P 1386 / IGF-No. 20651 N are briefly summarised.

6.3.2 Existing interaction test procedures and specifications

Unfortunately, in German or European standardisation, no testing method is identified that deals with interaction tests to investigate the load bearing behaviour of bolts/fasteners subjected to combined tension and shear. For example, EN ISO 3506-1 [73] deals with the mechanical properties of corrosion-resistant stainless steel fastemers but defines neither further requirements regarding the shear and interaction resistance of bolts nor suitable testing methods to determine these mechanical bolt properties.

However, the North American Aerospace Industries Association (AIA/NAS) published, most recently, the revised NASM 1312 Method 2 [408] testing standard for fasteners in January 2023. This standard is focused on “the interaction test for a complete fastener system is a method for determining the properties of the fastener system under combined tension and shear loading for any configuration of installed fastener system” and replacing the old superseded military standard MIL-STD-1312-2 [409] from 1997 (the first version of MIL-STD-1312-2 refers even back to May 1967). The interaction test rig of NASM 1312 Method 2 is adapted from the experimental investigations from Chesson et al. [264], [221] (1964, 1965), Bilderbeek [222] (1971) as well as Shakir-Khalil and Ho [225] (1979) and further modified over time for the specific requirements and the intended application in aerospace for bolts up to M12 (≈ 0.5 inch). The single-shear interaction test rig consists of four metal quarter discs with U-shaped retaining metal blocks in between and a bushing for the tested bolting assembly, see Figure 6.3-1 (a). It is designed as a tension test rig and allows testing of different loading angles in 15° increments: 0° (as pure tension loading), 15°, 30°, 45°, 60°, 75° and 90° (as pure shear loading). However, it is stated in NASM 1312 Method 2, Clause 4.1.1 that the test rig for *“larger fasteners shall be proportionately larger but similar in shape and design, and equivalent in dimensional control”*. Consequently, applying the testing standard for bolts > M12 is, in principle, possible. Table 1 of NASM 1312 Method 2 defines loading rates up to 1.5 inch specimens. The geometry of the bushing, which represents an insert adapter for the bolt or bolting assembly during testing, is specified in Figure 4 of NASM 1312 Method 2 but without any clear definition of the hole diameter or tolerances, which must be specified “in accordance with part tested”. Thus, specific requirements for the hole clearance are not defined. Furthermore, the standard does not specify the material used for the rig (only the material thickness of 0.5 inch is defined).

The single-shear interaction test rig of NASM 1312 Method 2 was also adapted for the studies of Steeve and Wingate [273] (2012) on 3/8-inch bolts (≈ M10) of type NAS1956C14 with precipitation hardening austenitic stainless steel alloy type 660, see Figure 6.3-1 (b), as well as the studies from Song et al. on M20 austenitic [5] and austenitic/duplex [6] stainless steel bolts, see Figure 6.3-1 (c). In each case, the main construction principle is identical.



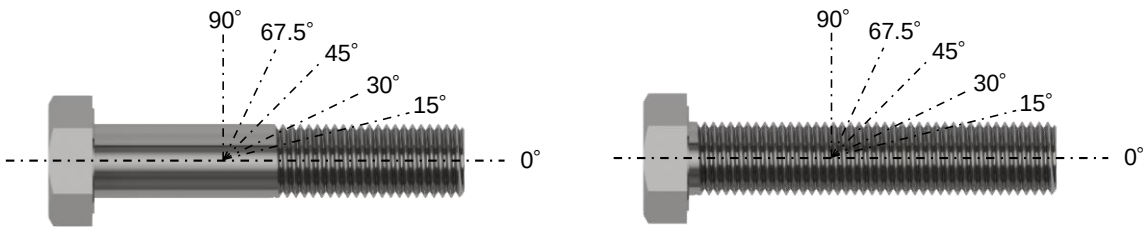
(a) Single-shear interaction test rig acc. to NASM 1312 Method 2 [408] (b) Single-shear interaction test rig by Steeve and Wingate [273] (c) Single-shear interaction test rig by Song et. al. [5, 6]

Figure 6.3-1: Single-shear interaction test rigs according to NASM 1312 Method 2 and modifications of the interaction test rig by Steeve and Wingate [273] as well as Song et. al. [5, 6]

6.3.3 Test procedure and testing specification for single-shear interaction tests on stainless steel bolting assemblies

The development of the massive single-shear interaction test rigs was already presented in Chapter 5.4.3. A pair of individual massive test rigs for each investigated loading angle was developed as an alternative testing approach compared to NASM 1312 Method 2 and manufacture by the mechanical workshop of the University of Duisburg-Essen. All test rigs were hardened with a Rockwell hardness of about 55 HRC with additionally hardened inserts as shear adapters of about 58 HRC. The interchangeable adapter inserts initially developed for the single-shear tests were reused and pressed into the interaction test rigs for a perfect fit to allow testing of different bolt diameters and lengths within the same test rig.

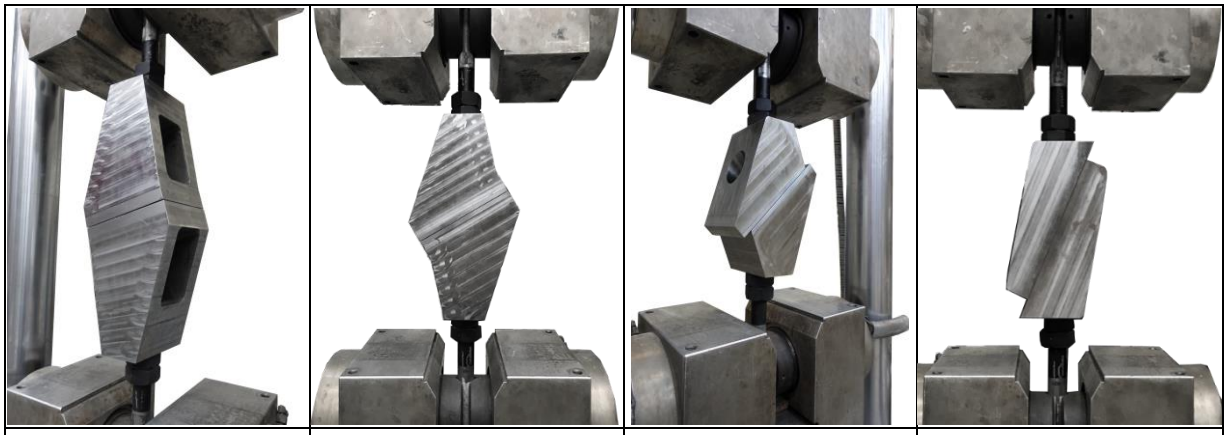
All interaction tests for EN ISO 4014/4762 partially threaded (“unthreaded bolt part in the shear plane”) and EN ISO 4017 fully threaded (“threaded bolt part in the shear plane”) austenitic and duplex bolts were paired with EN ISO 4032 nuts. The tests were performed displacement-controlled as tension rigs with a constant testing speed of 0.08 mm/s (analogues to the pure tensile and pure single-shear and double-shear tests) in the 1.0 MN servohydraulic static and dynamic universal testing machine of UDE-IML till bolt failure occurs. In order to investigate the combined load bearing behaviour of stainless steel bolting assemblies comprehensively, different ratios of tension and shear under loading angles of 15°, 30°, 45° and 67.5° were tested. The definition of the tested loading angles of partially and fully threaded bolts relative to the bolt longitudinal axis is presented in Figure 6.3-2.



(a) Definition of loading angles for partially threaded bolts according to EN ISO 4014/4762 (representing the loading case “unthreaded bolt part in the shear plane”) (b) Definition of loading angles for fully threaded bolts according to EN ISO 4017 (representing the loading case “threaded bolt part in the shear plane”)

Figure 6.3-2: Definition of loading angles for partially and fully threaded bolts and bolting assemblies

The testing specifications are summarised in Figure 6.3-3. Further information about the interaction test rigs are given in [78] and [282]; see also Appendix F.



(a) Test rig M16/M24 for 15° interaction tests	(b) Test rig M16/M24 for 30° interaction tests	(c) Test rig M16/M24 for 45° interaction tests	(d) Test rig M16/M24 for 67.5° interaction tests

Single-shear interaction test rigs: Upper and lower special hardened test components

Testing machine: Schenk / ZwickRoell 1.0 MN servohydraulic static and dynamic universal testing machine, Class 0

Testing procedure: Displacement-controlled with a constant testing speed of 0.08 mm/s in tensile direction analogues to the tensile and shear tests presented in Chapters 4 and 5

Hardness of the test rig: ≈ 55 HRC

Hardness of the interchangeable inserts as shear adapters: ≈ 58 HRC for M16 and M24

Measurement system: ZwickRoell testing software + Peekel Autosoft/Autolog 3000 data measuring system (new: Burster Präzisionsmesstechnik GmbH & Co. KG); Continuously recording of machine load and machine stroke

Position of the shear planes: 40 mm for M16	Position of the shear planes: 50 mm for M24

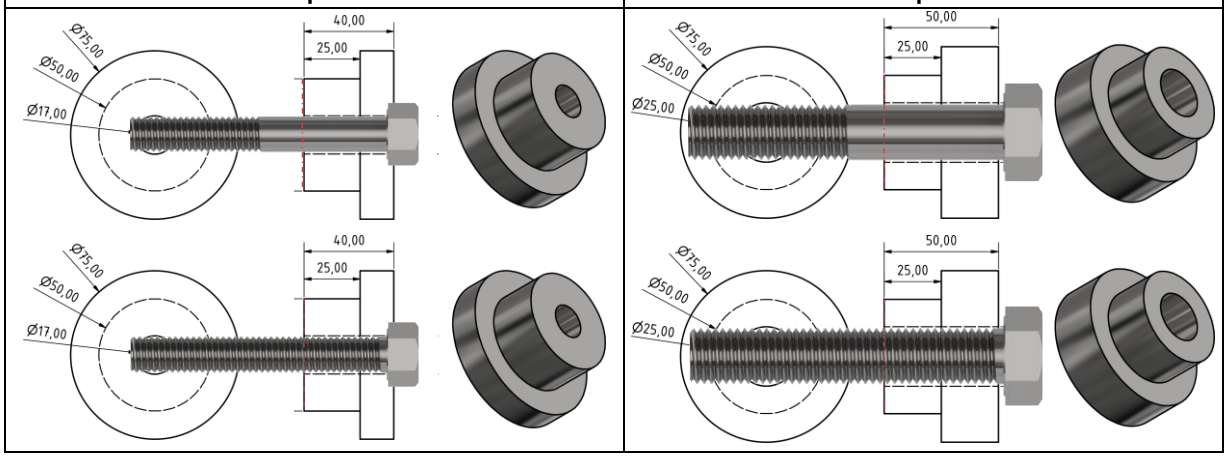


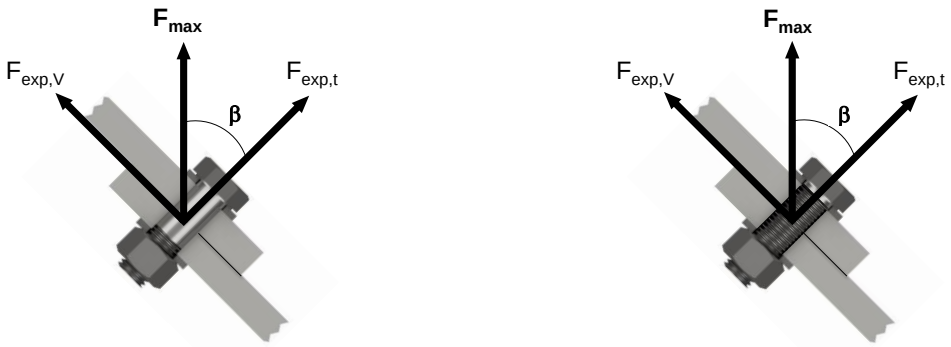
Figure 6.3-3: Test rigs single-shear interaction tests for bolt dimension M16 and M24 developed in the frame of the German research project FOSTA P 1386 / IGF-No. 20651 N [78]

6.4 Experimental investigations: Discussion of the interaction test results

6.4.1 General

A comprehensive overview of all single-shear interaction test results of partially threaded bolts according to EN ISO 4014 and EN ISO 4762 (representing the loading case “unthreaded bolt part in the shear plane”) and fully threaded austenitic and duplex stainless steel bolts according to EN ISO 4017 (representing the loading case “threaded bolt part in the shear plane”) is summarised in Appendix D including the results of the tensile tests and single-/double-shear tests of the tested bolt series. Furthermore, the results from the literature review are summarised in Appendix C.

The maximum load F_{max} achieved in an interaction test under different loading angles β can be divided into a tension load component $F_{exp,t}$ and shear load component $F_{exp,V}$, see Figure 6.4-1 for the unthreaded (a) or threaded (b) bolt part in the shear plane. This resolution of forces is based on the simplified assumption that the global loading angle β of the bolted connection also corresponds to the resulting multiaxial stress state in the bolt, as it is the standard case in the background of North American and European standardisation and literature. Herein, the load bearing behaviour of non-preloaded bolted tension/shear connections made of carbon and stainless steel with oversized round holes, short and long slotted holes will be investigated systematically.



(a) Resolution of forces for partially threaded bolts acc. to EN ISO 4014/4762 representing the loading case "unthreaded bolt part in the shear plane"

(b) Resolution of forces for fully threaded bolts acc. to EN ISO 4017 representing the loading case "threaded bolt part in the shear plane"

Figure 6.4-1: Resolution of the maximum interaction load F_{max} achieved in testing into a tension $F_{exp,t}$ and shear component $F_{exp,V}$ for stainless steel bolting assemblies depending on the loading angle β

As already stated in Chapter 3.5, in principle, two types of bolt interaction diagrams are possible for partially threaded structural bolts according to EN ISO 4014/4762 representing the loading case "unthreaded bolt part in the shear plane": Since carbon steel and duplex stainless steel bolts fail under pure tension loading in the free loaded bolt threads due to the smaller cross-sectional area of the threaded bolt part as the intended failure mechanism for structural bolts ($A_s/A \approx 0.78$ for bolt dimensions M12 to M36), the mean tension resistance of the threaded part here defined as mean $F_{exp,0°,As}$ is often preferred in the diagrams. In the case of bolting assemblies made of stainless steel, however, the mean tension resistance defined here as mean $F_{exp,0°,A}$ of the unthreaded bolt part (as gross cross-sectional area A) is preferred for a deeper understanding of the combined load bearing resistance of stainless steel bolts.

Particularly in the case of partially threaded bolts made of austenitic stainless steel with high forming induced martensitic material of the threaded part due to the thread rolling process, exploitation of the tensile strength of the unthreaded bolt part (as gross cross-sectional area A) can be observed. Consequently, $F_{exp,0°,A}$ can be directly used for evaluation. Whereas, in the case of duplex stainless steel bolts according to EN ISO 4014 and EN ISO 4762 (as well as some austenitic bolt series), the failure always occurs in the freely loaded bolt threads. In this case, the (higher but not useable) tension resistance of the unthreaded part must be determined experimentally by specific tensile tests on machined bolts as presented in Chapter 4.4.4 in order to determine the tensile strength of the unthreaded bolt part $f_{ub,exp,shank}$. Finally, the tension resistance of the unthreaded bolt part can be calculated by $F_{exp,0°,A} = f_{ub,exp,shank} \cdot A_{nom}$.

This type of interaction diagram allows to show the different failure mechanisms of stainless steel bolts in a more applicable way and consistently ensures that both the tension and shear resistances refer to the resistance of the unthreaded bolt part A, see (Eq. 6.4-1) for the x-axis and (Eq. 6.4-2) for the definition of the y-axis.

$$\frac{F_{exp,V,i}}{\text{mean}\,F_{exp,90°,A}} = \frac{F_{max,i} \cdot \sin(\beta)}{\text{mean}\,F_{exp,90°,A}} \quad \text{for the x-axis,} \qquad \text{(Eq. 6.4-1)}$$

$$\frac{F_{exp,t,i}}{\text{mean}\,F_{exp,0°,A}} = \frac{F_{max,i} \cdot \cos(\beta)}{\text{mean}\,F_{exp,0°,A}} \quad \text{for the y-axis.} \qquad \text{(Eq. 6.4-2)}$$

In the case of the threaded bolt part in the shear plane, the individual shear load $F_{exp,V,i}$ always refers to the mean shear resistance defined as mean $F_{exp,90°,As}$ of the whole series (determined by single-shear testing in the frame of this thesis). In contrast, the individual tensile load $F_{exp,t,i}$ refers to the mean tension resistance defined as mean $F_{exp,0°,As}$ (determined by tensile tests according to EN ISO 3506-1), see (Eq. 6.4-3) for the x-axis and (Eq. 6.4-4) for the y-axis. Consequently, the tension and shear resistances are referred to the threaded bolt part by the tensile stress area A_s and the tensile strength $f_{ub,exp,threads} = f_{ub,exp}$.

$$\frac{F_{exp,V,i}}{\text{mean}\,F_{exp,90°,As}} = \frac{F_{max,i} \cdot \sin(\beta)}{\text{mean}\,F_{exp,90°,As}} \quad \text{for the x-axis,} \qquad \text{(Eq. 6.4-3)}$$

$$\frac{F_{exp,t,i}}{\text{mean}\,F_{exp,0°,As}} = \frac{F_{max,i} \cdot \cos(\beta)}{\text{mean}\,F_{exp,0°,As}} = \frac{F_{max,i} \cdot \cos(\beta)}{f_{ub,exp,shank} \cdot A_{nom}} \quad \text{for the y-axis.} \qquad \text{(Eq. 6.4-4)}$$

6.4.2 Results and evaluation of the interaction resistance of stainless steel bolting assemblies with unthreaded bolt part in the shear plane

As discussed comprehensively in [78] and [282], the results and evaluation of the single-shear interaction tests of austenitic and duplex stainless steel bolting assemblies with unthreaded bolt part in the shear plane can be summarised into three main findings:

- The load-displacement curves of the EN ISO 4014 and EN ISO 4762 partially threaded austenitic and duplex stainless steel bolting assemblies show – as expected – a tendency that the maximum load F_{max} observed in the single-shear interaction tests accompanied by the bolt elongation/ductility decrease with increasing loading angle from 0° (pure tension) to 90° (pure shear),
- a slightly higher maximum load F_{max} is partially achieved for tested bolting assemblies in PC 50, 70 and 80 under a loading angle of 15°, which was also observed in the experimental studies from Song et al. [5, 6] for carbon steel bolting assembles in PC 8.8 [5], austenitic stainless steel bolting assemblies in PC 8.8 and 10.9 [6], as well as for carbon steel bolting assemblies in the studies of Renner/Lange [178, 180, 182, 410]. The additionally activated shear components due to slight skewing of the bolt during testing connected with still high tension resistance of the carbon or stainless steel bolts seem to explain this special load bearing behaviour under loading angles of 15°,
- the bolt failure location is changing for partially threaded duplex bolts (and for austenitic bolts if bolt failure occurs in the threaded part under pure tension) from the threaded part under pure tension of 0° to the unthreaded bolt part under loading angles of 15° or 30°. Consequently, this characteristic must be considered in the design of bolted connections subjected to combined tension and shear loading.

Exemplary representations of load-deformation curves of the interaction tests on austenitic and duplex stainless steel bolting assemblies with unthreaded bolt part in the shear plane are visualised in [78] and [282]. Furthermore, a comparative graphical representation of selected European, German and North American design concepts for the interaction resistance of stainless steel bolting assemblies, as well as approaches from literature including all test

results for the loading case “unthreaded bolt part in the shear plane” is shown in Figure 6.4-2. A detailed explanation of the interaction equations is presented in Chapter 3.5. The proposed interaction equation by Stranghöner/Abraham for FprEN 1993-1-4 and the German technical approval abZ/aBG Z-30.3-6:2022 (Eq. 3.5-5) is implemented in Figure 6.4-2. Furthermore, the results of the literature review are added. The following briefly discusses the results of the graphical comparison of the interaction tests and the suitability of the different interaction approaches, which were outlined in 3.5.

An evaluation of the experimental test results and those from the literature review reveals that the bilinear interaction approach according to EN 1993-1-4 and particularly the German national annex DIN EN 1993-1-4/NA significantly underestimates the combined load bearing capacity of austenitic and duplex stainless steel bolting assemblies if the unthreaded part is in the shear plane. Both interaction approaches are too conservative and fail to describe the interaction resistance of stainless steel bolting assemblies. The interaction equation by Može, see (Eq. 3.5-21) and (Eq. 3.5-22), which is a modification of the approach by Renner/Lange ((Eq. 3.5-17) and (Eq. 3.5-18)) by a reduction factor of 0.9 for the tension component, generally leads to higher interaction resistance of bolts compared to the bilinear interaction equation according to EN 1993-1-4 but still underestimates the load bearing capacity of austenitic and duplex stainless steel bolting assemblies. On the contrary, the quadratic approach of the withdrawn German DIN 18800-1 overestimates the interaction resistance, particularly under a loading angle of 67.5° with high shear loading. Analogues to the quadratic interaction approach, the trilinear North American interaction equation according to AISC 360, AISC 370 and the AISC Design Guide 27 (2nd Edition) shows generally a better agreement with the test results and those from the literature review but significantly overestimates the interaction resistance with high shear components like under a loading angle of 67.5°. All data points lie below the trilinear interaction curve on the unsafe side.

Finally, it can be concluded that mainly all data points lie between the quadratic interaction of DIN 18800-1 and the interaction approach of Renner/Lange (which was developed for carbon steel bolts using an exponent of 1.5 instead of 2), particularly for those bolting assemblies tested under loading angles with higher shear components like 45° and 67.5°. Therefore, the proposed interaction approach by Stranghöner/Abraham for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022 adapts the quadratic interaction approach by Knobloch/Schmidt with an exponent of 1.7; see Chapter 6.5 for further explanations and discussion. It becomes evident that high tension resistances exist, particularly for austenitic bolts under loading angles of 15° and 30°, which usually fail in the unthreaded part. The data points of the duplex bolts tend to be lower than those of the austenitic bolts. In addition to the graphical comparison, the suitability of the different interaction equations and critical undercutting of the interaction curves (particularly bolting assemblies in PC 10.9 and 12.9) was checked in a statistical evaluation according to EN 1990, Annex D in [282].

In the framework of this thesis, the statistical evaluations of the interaction resistance of stainless steel bolting assemblies with unthreaded bolt part in the shear plane are extended and complemented by analyses regarding the reliability of the proposed interaction equation for FprEN 1993-1-4.

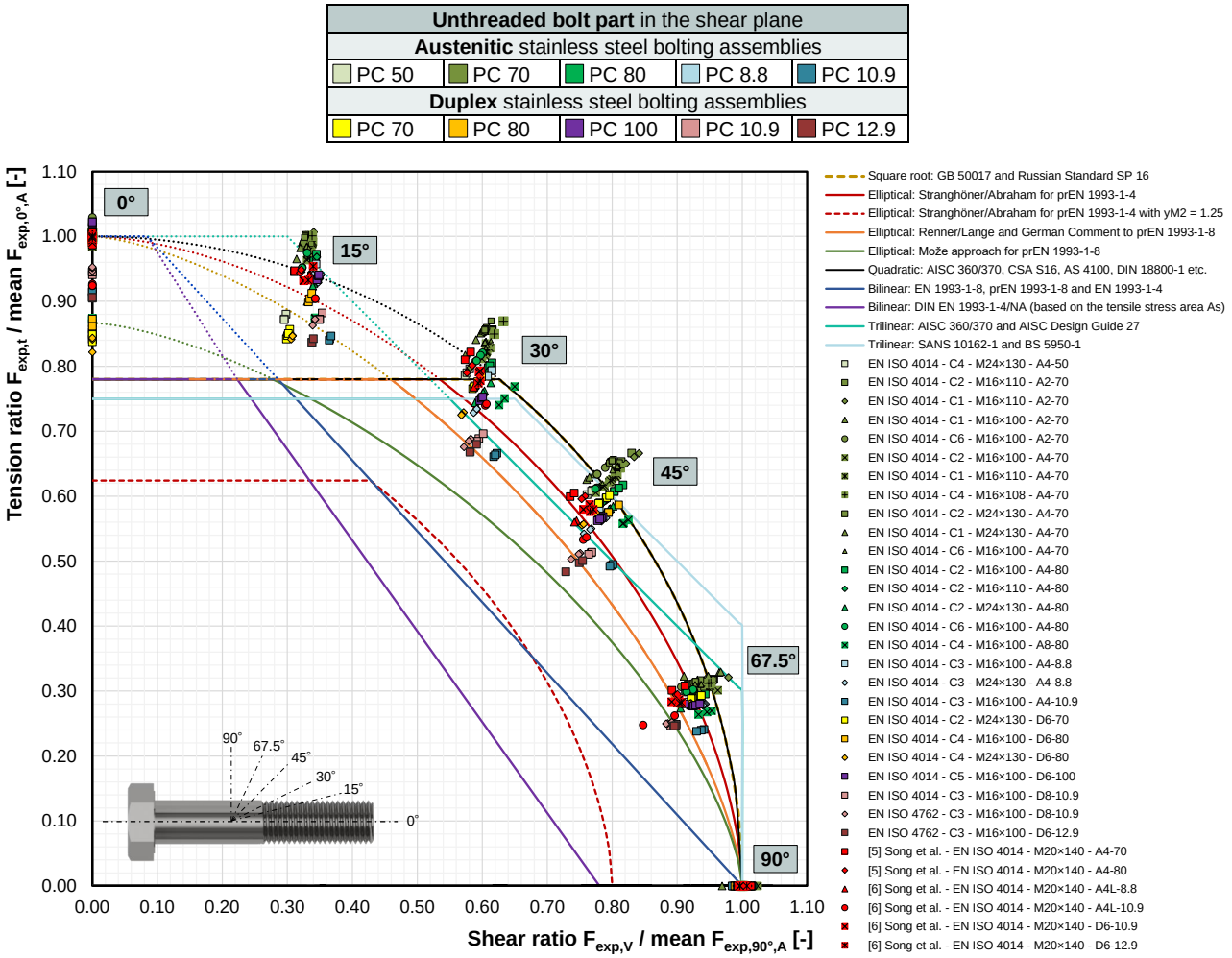


Figure 6.4-2: Results of the experimental tests and those from the literature review for interaction of austenitic and duplex stainless steel bolting assemblies with unthreaded bolt part in the shear plane

Typical fracture patterns of partially threaded austenitic and duplex stainless steel bolts tested under different loading angles in single-shear test rigs are presented in Figure 6.4-3 and show the strong pronounced ductility of stainless steel bolts.

(a) Fracture patterns of austenitic stainless steel bolts, here: EN ISO 4014 – C1 – M16×100 – A4-80

(b) Fracture patterns of duplex stainless steel bolts, here: EN ISO 4014 – C6 – M16×100 – D6-100

Figure 6.4-3: Typical fracture patterns of austenitic and duplex stainless steel bolts tested under different loading angles in single-shear test rigs with unthreaded bolt part in the shear plane; © UDE-IML

6.4.3 Results and evaluation of the interaction resistance of stainless steel bolting assemblies with threaded bolt part in the shear plane

The results and evaluation of the single-shear interaction tests of austenitic and duplex bolting assemblies with threaded bolt part in the shear plane were already discussed in detail in [78] and [282] and can be summarised into three main findings:

- Analogues to the interaction tests of stainless steel bolting assemblies with unthreaded bolt part in the shear plane, the interaction tests on fully threaded austenitic and duplex bolting assemblies according to EN ISO 4017 show that with increasing shear load, the maximum load F_{max} in the interaction test and the bolt elongation/ductility decrease,
- a slightly higher maximum load F_{max} is again partially achieved for tested austenitic and duplex bolting assemblies in PC 70 under a loading angle of 15°,
- bolt failure occurs always in the threaded bolt part. Shear failure of the bolt head or failure by stripping of the paired threads between the bolt and nut never occurred.

Again, load-deformation curves of the interaction tests on austenitic and duplex stainless steel bolting assemblies with threaded bolt part in the shear plane are presented in [78] and [282].

Moreover, a comparative graphical representation of selected European, German and North American design concepts for the interaction resistance of stainless steel bolting assemblies, as well as approaches from literature including all test results for the loading case “threaded bolt part in the shear plane” is visualised in Figure 6.4-4. Herein, the proposed interaction by Stranghöner/Abraham for FprEN 1993-1-4 and the German national technical approval/General construction technique permit abZ/aBG Z 30.3-6:2022 and the literature review results are implemented.

As already stated in [282], the graphical evaluation in Figure 6.4-4 shows that undercutting the quadratic interaction curve according to the withdrawn DIN 18800-1 can be confirmed for bolt property classes up to PC 80 for all loading angles. Analogues to the interaction tests with unthreaded bolt part in the shear plane, the trilinear North American interaction equation according to AISC 360, AISC 370 and the AISC Design Guide 27 (2nd Edition) significantly overestimates the interaction resistance with high shear components under a loading angle of 67.5°. For bolts subjected to high shear loading, all data points lie below the trilinear interaction curve on the unsafe side. On the contrary, the interaction approach of Renner/Lange marks the lower limit line of the data points except for high shear load components under 67.5°. In contrast, the approach of Može (both interaction equations were developed for bolted connections made of carbon steel) allows to activate more shear resistance. However, the approach of Može cannot appropriately describe higher tension components under a loading angle of 15°. The bilinear approach of EN 1993-1-4 and DIN EN 1993-1-4/NA shows a better fitting on the safe side (with partially undercutting the interaction curve under a loading angle of 15°). Nevertheless, the bilinear interaction equation can still not consider higher shear components at loading angles of 30° and 45°. Based on the graphical comparison, a new interaction approach between the quadratic interaction of DIN 18800-1 and the interaction approach of Renner/Lange was proposed by Stranghöner/Abraham for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022. For further explanations and discussion, see Chapter 6.5.

Again, the suitability of the different interaction equations and possibly critical undercutting of the interaction curves was checked in a statistical evaluation according to EN 1990, Annex D in [282] and complemented analyses of the resulting partial safety factors γ_M*.

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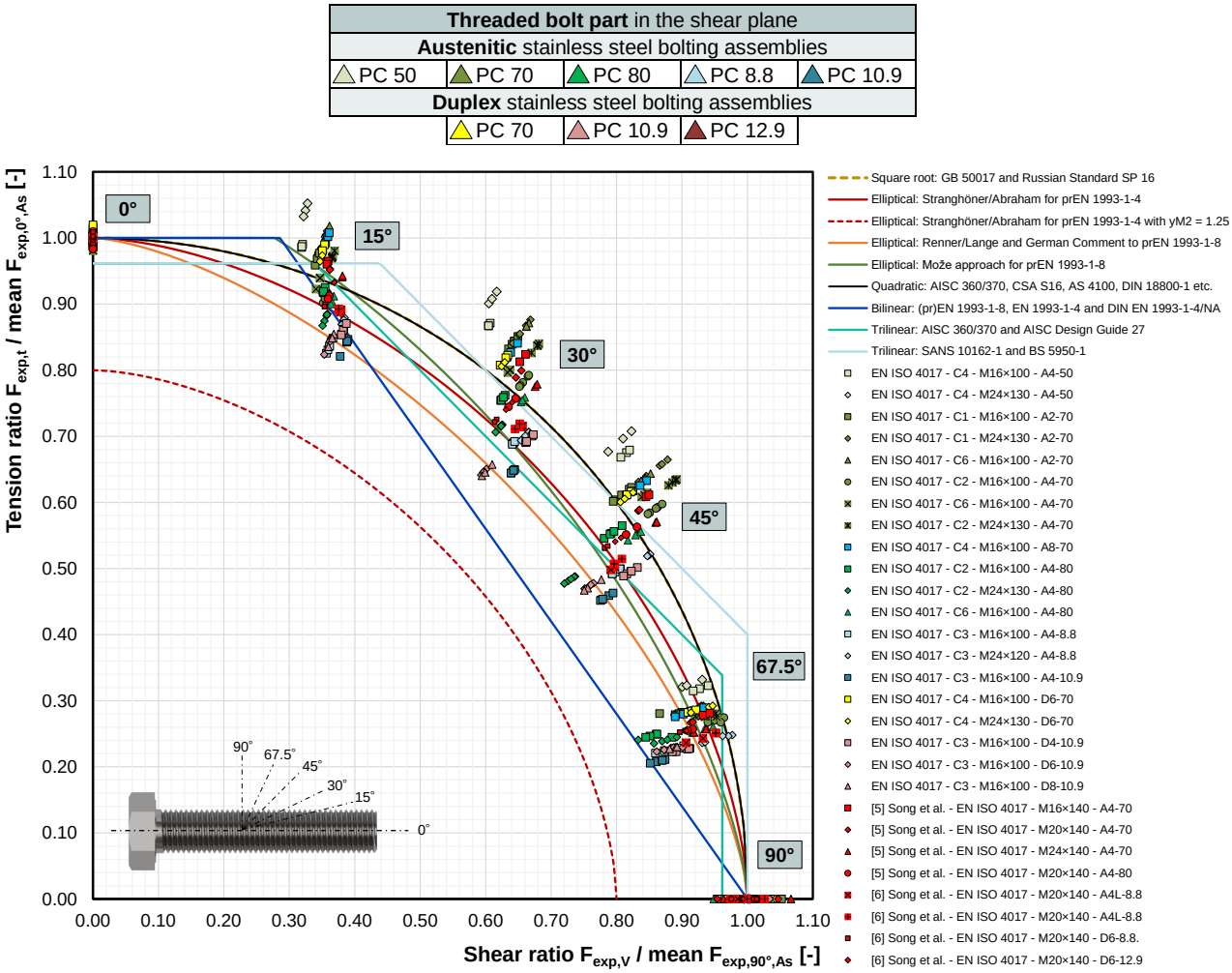


Figure 6.4-4: Results of the experimental tests and those from the literature review for interaction of austenitic and duplex stainless steel bolting assemblies with unthreaded bolt part in the shear plane

Typical fracture patterns of fully threaded austenitic and duplex stainless steel bolts tested under loading angles of 0° (pure tension), 15°, 30°, 45°, 67.5° and 90° (pure shear) in single-shear test rigs are presented in Figure 6.4-5. The strong, pronounced ductility of stainless steel bolts is again evident as an important characteristic of bolted connections made of austenitic and duplex steel.

(a) Fracture patterns of austenitic stainless steel bolts, here: EN ISO 4017 – C4 – M16×100 – A4-50

(b) Fracture patterns of duplex stainless steel bolts, here: EN ISO 4017 – C4 – M16×100 – D6-80

Figure 6.4-5: Typical fracture patterns of austenitic and duplex stainless steel bolts tested under different loading angles in single-shear test rigs with threaded bolt part in the shear plane; © UDE-IML

6.5 Proposed design approach for the interaction resistance of stainless steel bolting assemblies

6.5.1 General

Based on the experimental investigations and further research activities conducted at UDE-IML, new and more economical design approaches for the revision of EN 1993-1-4 regarding the interaction resistance of austenitic and duplex bolting assemblies were proposed and already published in [78] (as the first interaction design approaches) and [282] (as the second and final interaction design approaches).

For this purpose, the increased tension resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolts is considered with the proposed k_2-factor of k_2 =1.0 (except countersunk bolts, which are not part of the investigations) as described in Chapter 4.6. Additionally, the shear resistance $F_{v,Rd}$ of stainless steel bolts has to be determined with the proposed higher and more economical shear coefficients α for FprEN 1993-1-4; see Chapter 4.6. Finally, the proposed design equations for the interaction resistance of austenitic and duplex stainless steel bolts have been implemented in the revision of EN 1993-1-4, FprEN 1993-1-4, and the updated abZ/aBG Z-30.3-6:2022, see (Eq. 6.5-1) for “unthreaded bolt part in the shear plane” under consideration of $A/A_s \approx 1.25$ (as mean ratio value of the nominal gross cross-sectional area A and nominal tensile stress area A_s for bolt dimensions M12 to M36) and (Eq. 6.5-2) for “threaded bolt part in the shear plane”.

$$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^{1.7} + \left(\frac{F_{t,Ed}}{1.25 \cdot F_{t,Rd}}\right)^{1.7} \leq 1.0 \quad \text{but } F_{t,Ed}/F_{t,Rd} \leq 1.0 \qquad \text{(Eq. 6.5-1)}$$

$$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^{1.7} + \left(\frac{F_{t,Ed}}{F_{t,Rd}}\right)^{1.7} \leq 1.0 \qquad \text{(Eq. 6.5-2)}$$

The bolt interaction equations of (Eq. 6.5-1) and (Eq. 6.5-2) with an exponent of 1.7 were already proposed slightly modified by Knobloch/Schmidt [171] in 1987 for the interaction resistance of carbon steel bolts in the revision process of DIN 18800-1. However, at that time, the equations with an exponent of 1.7 were rejected as being too conservative for the design of carbon steel bolts under combined tension and shear loading. Knobloch specifies in his PhD thesis [173] that more experimental data and further statistical evaluations were required for a conclusive statement regarding the interaction behaviour of carbon steel bolts.

As discussed and presented before, the quadratic interaction approach overestimates the load bearing capacity of austenitic and duplex stainless steel bolting assemblies. The extent to which a possible adjustment of the shear coefficients α contributes to the suitability of the quadratic interaction is not investigated further here. However, since the category A bearing type connection has the most prominent part in steel construction, higher shear coefficients, as proposed for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022, are more important for the design of the pure shear resistance of bolted connections $F_{v,Rd}$ compared to a quadratic interaction resistance at the expense of the pure bolt shear resistance with reduced shear coefficients α.

6.5.2 Discussion of the proposed interaction resistance of stainless steel bolting assemblies with unthreaded part in the shear plane

As defined in (Eq. 6.5-1) for “unthreaded bolt part in the shear plane”, the first term considers the shear resistance $F_{v,Rd}$ of stainless steel bolts based on the nominal unthreaded gross cross-sectional area A_{nom} complying with the European design of EN 1993-1-8 and EN 1993-1-4.

The second term considers the tension component, which is always based on the nominal tensile stress area $A_{s,nom}$. As the ratio between the nominal gross cross-sectional area of the shank A_{nom} and the nominal tensile stress area $A_{s,nom}$ of a bolt is about $A/A_s \approx 1.28$, the gross cross-sectional area of the bolt shank can be considered as $A_{nom} = 1.25 \cdot A_{s,nom}$ on the safe side. For the sake of improved comparability, the proposed interaction equation of (Eq. 6.5-1) for "unthreaded bolt part in the shear plane" is graphically presented in Figure 6.4-2 in red colour and lies between the quadratic approach of DIN 18800-1 and the statistically not verified approach of Renner/Lange for carbon steel bolts but far above the bilinear interaction approach of the current EN 1993-1-8 and EN 1993-1-4.

The different bolt failure types (see Chapter 2.4.7) under tensile load of austenitic (failure either in the unthreaded or threaded bolt part) and duplex (failure always occurs in the threaded part) are implemented in the proposed interaction approach by Stranghöner/Abraham [282] with the condition $F_{t,Ed} \leq F_{t,Rd}$. Herewith, it is always ensured that the minimum ultimate tensile load F_{mf} specified in EN ISO 3506-1 is not once exceeded (in this way, the increase of the tension resistance to $k_2 = 1.0$ is reasonable). F_{mf} is determined in a tensile test on the whole bolt and indicates the failure load of the "weaker" part of the bolt: either the unthreaded (A) or threaded (A_s) part. Consequently, the failure mode of stainless steel bolts is considered by $f_{ub} \cdot A_s$, even if the bolt failure location is changing from the threaded to the unthreaded bolt part (for example, under a loading angle of 15° or 30°, as discussed in Chapter 6.4.2). In principle, two interaction curves of the proposed interaction by Stranghöner/Abraham are possible; see Figure 6.4-2: If the bolt failure occurs in the threaded part (duplex bolts), the tension resistance of the unthreaded bolt part is higher but cannot be activated, and an upper tension plateau is formed in the ratio $A_s/A \approx 0.78$. In contrast, if failure occurs in the unthreaded bolt part, the higher tension resistance of the bolt shank can be utilised, and the interaction curve is continued till F_{mf}.

6.5.3 Discussion of the proposed interaction resistance of stainless steel bolting assemblies with threaded part in the shear plane

As defined in (Eq. 6.5-2) for the loading case of "threaded bolt part in the shear plane", both the shear resistance $F_{v,Rd}$ and the tension resistance $F_{t,Rd}$ of an austenitic and duplex stainless steel bolt are referred to the threaded bolt part defined by the nominal tensile stress area $A_{s,nom}$. Herein, a differentiation of the bolt failure types and resulting bolt resistances can be carried out, which, however, leads to the same intended interaction equation of (Eq. 6.5-2):

- If failure of a partially or fully threaded austenitic or duplex stainless steel bolt with threaded bolt part in the shear plane (or if the bolt threads cannot certainly be excluded in the shear plane) is occurring in the threaded part under combined tension and shear loading, then no further differentiation is needed. In this case, the design of the tension and shear resistances $F_{t,Rd}$ and $F_{v,Rd}$, according to FprEN 1993-1-4, refer to the bolt threads as nominal tensile stress area $A_{s,nom}$.
- However, if failure of a partially threaded austenitic or duplex stainless steel bolt with the threaded part in the shear plane is occurring in the unthreaded bolt part (which may take place for austenitic stainless steel bolts with low shear load components like under a loading angle of 15°, see Chapter 6.4), then the higher shear resistance $F_{v,Rd}$ of the unthreaded bolt part is neglected in the interaction design. Consequently, on the safe side, the design of the tension and shear resistances $F_{t,Rd}$ and $F_{v,Rd}$ are again both referred to the nominal tensile stress area $A_{s,nom}$.

The proposed interaction equation of (Eq. 6.5-2) by Stranghöner/Abraham for the "threaded bolt part in the shear plane" is graphically presented in Figure 6.4-4 in red colour and lies

obviously between the quadratic approach of DIN 18800-1 and the statistically not verified approach of Renner/Lange (defined by an exponent of 1.5) for carbon steel bolts.

6.6 Reliability analysis of the interaction resistance of stainless steel bolts

6.6.1 General

The validity of the proposed interaction equations by Stranghöner/Abraham (see Chapter 6.5, (Eq. 6.5-1) and (Eq. 6.5-2)) for austenitic and duplex stainless steel bolting assemblies has already been checked and confirmed in [282] over all bolts by a statistical evaluation according to EN 1990, Annex D against the partial safety factor of γ_{M2} = 1.25 for connections. Partially undercutting of the proposed interaction equations (see red interaction curves in Figure 6.4-2 for the unthreaded and Figure 6.4-4 for the threaded bolt part in the shear plane), particularly for austenitic and duplex bolts in PC 10.9 and PC 12.9 were identified in [282] as uncritical. A comparison between the proposed interaction equations by Stranghöner/Abraham, the current bilinear interaction regulation of EN 1993-1-4 (based on EN 1993-1-8 for carbon steel bolts), the quadratic interaction according to DIN 18800-1 based on Knobloch/Schmidt and the approaches by Renner/Lange and Može (which were exclusivity developed for carbon steel bolts and not statistically verified) was conducted. Herein, for all interaction approaches, the already increased tension resistance $F_{t,Rd}$ (with k_2 = 1.0) and the proposed higher shear coefficients α for the shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolting assemblies were implemented in the statistical evaluation in order to guarantee direct comparability. Finally, it could be shown in [282] that the proposed interaction approach by Stranghöner/Abraham allows a safe, reliable and more economical design of the interaction resistance of austenitic and duplex stainless steel bolting assemblies and fulfilling the safety requirements of the Eurocode. The proposed interaction equations were already implemented in FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022.

In the frame of this thesis, a summary of the reliability analysis is outlined and complemented by an in-depth analysis of the distributions of the resulting partial safety factors γ_M* across all steel grades, property classes and loading angles to improve the reliability of the proposed design approach for the interaction resistance of stainless steel bolting assemblies. The input parameters and definition of the reformulated theoretical r_t and nominal r_n resistance functions and the interaction conditions (I-III) of the reliability analysis are summarised. As a supplement to [282], the resulting partial safety factors γ_M* of the current bilinear approach according to EN 1993-1-4 and the German national annex DIN EN 1993-1-4/NA without any increased tension resistance $F_{t,Rd}$ (with k_2 = 0.9) or increased shear coefficients α are presented. However, the trilinear North American interaction approaches like AISC 360, AISC 370-21, AISC Design Guide 27 (2nd Edition) as well as SEI/ASCE 8-22 (see Chapter 3.5) are not implemented in the extended reliability analysis because of the clear overestimation of the combined load bearing capacity of stainless steel bolting assemblies under high shear loads in particular under 67.5° loading angle, see Figure 6.4-2 and Figure 6.4-4. Furthermore, all North American interaction approaches are based on a different and not directly transferable design format of the allowable stress design (ASD) and load and resistance factor design (LRFD), which modify the pure bolt tension resistance to consider the effects of shear stresses.

Finally, in order to describe the load bearing behaviour of austenitic and duplex stainless steel bolts and bolting assemblies accurately, a conclusive comparison of the bolt interaction resistance is given and complemented by an evaluation of selected approaches by the modified assessment criteria.

6.6.2 Input parameters and definition of resistance functions of the reliability analysis

6.6.2.1 General

The input parameters and definition of resistance functions for the interaction resistance of stainless steel bolts with the unthreaded bolt part or the threaded bolt part in the shear plane are outlined in the following. The normal distribution of the geometrical basic variables (as the measured gross cross-sectional area A_{meas} of the unthreaded bolt part and the measured tensile stress area $A_{s,meas}$ of the threaded bolt part), as well as the normal distribution of the material-specific basic variable (the experimental tensile strength of a bolt $f_{ub,exp}$), was already confirmed, see Chapters 4.7.54.7.5 and 5.8.2.

In the frame of the reliability analysis, the theoretical resistance functions r_t and the nominal resistance functions r_n of the various selected interaction design rules must consider the design approaches for the tension and shear components. Herein, following the methodology of the Background Report BI-88-087 from 1988 [355, 411] and the Background Documentation to prEN 1993-1-8 from 2004 [412], the theoretical resistance functions r_t and nominal resistance functions r_n of each evaluated interaction concept are reformulated. More precisely, in addition to the interaction conditions of bolts subjected to combined tension and shear loading ($r_{t/n,1}$; $r_{t,1}$ and $r_{n,1}$), pure shear conditions ($r_{t/n,2}$; $r_{t,2}$ and $r_{n,2}$) and pure tension conditions ($r_{t/n,3}$; $r_{t,3}$ and $r_{n,3}$) for the theoretical r_t and nominal r_n resistance, functions were added to consider all limiting cases and possible bolt failure types in the statistical evaluation, see [282]. Consequently, the restriction of a maximum tensile loading of $F_{t,Ed}/F_{t,Rd} \leq 1.0$ is included to avoid exceeding the bolt minimum ultimate load F_{mf} in all cases, if required in the interaction design approach.

Analogues to the statistical evaluation of the tension resistance $F_{t,Rd}$ (Chapter 4.7) and shear resistance $F_{v,Rd}$ (Chapter 5.8) of stainless steel bolts, the scattering of the tensile strength (f_{ub}) is considered by a coefficient of variation (COV) of 3 %. The scattering of the gross cross-sectional area (A) and tensile stress area (A_s) is considered each by a coefficient of variation (COV) of 1 %.

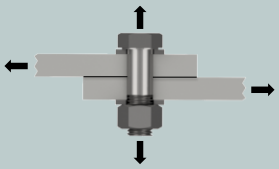
6.6.2.2 Input parameters and definition of resistance functions for the unthreaded bolt part in the shear plane

The reformulated theoretical resistance functions $r_t = \min(r_{t,1}; r_{t,2}; r_{t,3})$ and nominal resistance functions $r_n = \min(r_{n,1}; r_{n,2}; r_{n,3})$ for the interaction resistance of selected European and German interaction equations, as well as interaction approaches from Renner/Lange ((Eq. 3.5-17) and (Eq. 3.5-18)) and Može ((Eq. 3.5-21) and (Eq. 3.5-22) with unthreaded bolt part in the shear plane are summarised in Table 6.6-1. Furthermore, the derivations and reformulations of the theoretical and nominal resistance functions for each investigated interaction equation are summarised in Appendix G. Furthermore, to allow direct comparability, the terminology of Eurocode 3 is used as far as possible.

The theoretical r_t and nominal r_n resistance functions of the interaction resistance of stainless steel bolts are considering basic variables $\underline{X}$ based on the experimental or nominal tensile strength f_{ub} as the material basic variable and the measured or nominal gross cross-sectional area A or the measured or nominal tensile stress area A_s as the geometrical basic variables of every individual bolt. The shear coefficients α are part of the theoretical and nominal resistance functions, not a basic variable. Furthermore, the ratio between the gross cross-sectional area of the unthreaded gross cross-sectional area A and the tensile stress area A_s of a bolt is for the most bolt dimensions in steel construction (M12 to M36) about $A/A_s \approx 1.28$. Thus, the formulation of the gross cross-sectional area of the unthreaded bolt part was considered with $A = 1.25 \cdot A_s$ and $F_{t,A} = 1.25 \cdot F_{t,As}$ on the safe side.

Due to a large number of tests (n = 456 ≥ 100), again, the simplified formula in (Eq. E.12) for obtaining the design value r_d with a fractile factor of $k_{d,n} = 3.04$ was applied for the determination of the partial safety factor γ_M* over all interaction tests and all defined interaction subsets with unthreaded bolt part in the shear plane regardless of their property class and steel grade.

Table 6.6-1: Summary of the theoretical r_t and nominal r_n resistance functions for selected interaction approaches for austenitic and duplex stainless steel bolting assemblies with unthreaded bolt part in the shear plane



Theoretical resistance functions r_t with
$A = A_{meas}$; $A_s = A_{s,meas}$; $f_{ub} = f_{ub,exp}$; $F_{mf} = f_{ub,exp} \cdot A_{s,meas}$; $F_{m,min} = f_{ub,exp} \cdot A_{s,meas}$
$r_t = \min(r_{t,1}; r_{t,2}; r_{t,3})$
Nominal resistance functions r_n with
$A = A_{nom}$; $A_s = A_{s,nom}$; $f_{ub} = f_{ub,nom}$; $F_{mf} = f_{ub,nom} \cdot A_{s,nom}$; $F_{m,min} = f_{ub,exp} \cdot A_{s,meas}$
$r_n = \min(r_{n,1}; r_{n,2}; r_{n,3})$

Interaction equation	$r_{t/n,1}$ (interaction condition)	$r_{t/n,2}$ (shear condition)	$r_{t/n,3}$ (tension condition)	Eq.
Stranghöner/ Abraham for FprEN 1993-1-4 + abZ/aBG Z-30.3-6	$r_{t/n,1} = \frac{f_{ub}}{\sqrt[1.7]{\left(\frac{\sin(\varphi)}{\alpha \cdot A}\right)^{1.7} + \left(\frac{\cos(\varphi)}{1.25 \cdot k_2 \cdot A_s}\right)^{1.7}}}$	$r_{t/n,2} = \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min \begin{cases} \frac{1.25 \cdot k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-1)
EN 1993-1-4 (bilinear)	$r_{t/n,1} = \frac{f_{ub}}{\frac{\sin(\varphi)}{\alpha \cdot A} + \frac{\cos(\varphi)}{1.4 \cdot k_2 \cdot A_s}}$	$r_{t/n,2} = \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min \begin{cases} \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-2)
German national annex of EN 1993-1-4 (bilinear)	$r_{t/n,1} = \frac{f_{ub}}{\frac{\sin(\varphi)}{\alpha \cdot A_s} + \frac{\cos(\varphi)}{1.4 \cdot k_2 \cdot A_s}}$	$r_{t/n,2} = \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min \begin{cases} \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-3)
DIN 18800-1 (quadratic) for carbon steel bolts	$r_{t/n,1} = \frac{f_{ub}}{\sqrt{\left(\frac{\sin(\varphi)}{\alpha \cdot A}\right)^{2} + \left(\frac{1.25 \cdot \cos(\varphi)}{A_s}\right)^{2}}}$	$r_{t/n,2} = \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min \begin{cases} \frac{f_{ub} \cdot A_s}{1.25 \cdot \cos(\varphi)} \\ F_{m,min} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-4)
Approach of Renner/Lange for carbon steel bolts	$r_{t/n,1} = \frac{f_{ub}}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha \cdot A}\right)^{1.5} + \left(\frac{\cos(\varphi)}{1.25 \cdot k_2 \cdot A_s}\right)^{1.5}}}$	$r_{t/n,2} = \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min \begin{cases} \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{m,min} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-5)
Approach of Može for carbon steel bolts	$r_{t/n,1} = \frac{f_{ub}}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha \cdot A}\right)^{1.5} + \left(\frac{0.9 \cdot \cos(\varphi)}{k_2 \cdot A_s}\right)^{1.5}}}$	$r_{t/n,2} = \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min \begin{cases} \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{m,min} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-6)

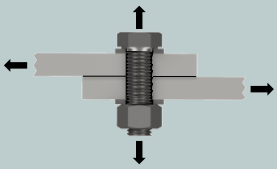
6.6.2.3 Input parameters and definition of resistance functions for the threaded bolt part in the shear plane

Table 6.6-2 summarises the reformulated theoretical resistance functions $r_t = \min(r_{t,1}; r_{t,2}; r_{t,3})$ and nominal resistance functions $r_n = \min(r_{n,1}; r_{n,2}; r_{n,3})$ for the bolt interaction resistance of selected European and German interaction equations as well as interaction approaches from Renner/Lange and Može considering the threaded part in the shear plane. The terminology of Eurocode 3 is used, as far as possible, and the derivations and reformulations of the theoretical and nominal resistance functions for each interaction equation with threaded bolt part in the shear plane are summarised in Appendix G.

Herein, the basic variables $\underline{X}$ based on the experimental or nominal tensile strength f_{ub} as the material basic variable and the measured or nominal tensile stress area A_s as the geometrical basic variables of every individual bolt are considered for the theoretical r_t and nominal r_n resistance functions of the interaction resistance of stainless steel bolts and bolting assemblies. Consequently, the shear coefficients α are part of the theoretical and nominal resistance functions, not a basic variable. The simplified formula in (Eq. E.12) for obtaining the design value r_d with a fractile factor of $k_{d,n} = 3.04$ was applied for the determination of the partial

safety factor γ_M* regardless of their property class and steel grade due to the large number of tests (n = 392 ≥ 100).

Table 6.6-2: Summary of the theoretical r_t and nominal r_n resistance functions for selected interaction approaches for austenitic and duplex stainless steel bolting assemblies with threaded bolt part in the shear plane



Theoretical resistance functions r_t with
$A_s = A_{s,meas}$; $f_{ub} = f_{ub,exp}$; $F_{mf} = f_{ub,exp} \cdot A_{s,meas}$; $F_{m,min} = f_{ub,exp} \cdot A_{s,meas}$
$r_t = \min(r_{t,1}; r_{t,2}; r_{t,3})$

Nominal resistance functions r_n with
$A_s = A_{s,nom}$; $f_{ub} = f_{ub,nom}$; $F_{mf} = f_{ub,nom} \cdot A_{s,nom}$; $F_{m,min} = f_{ub,exp} \cdot A_{s,meas}$
$r_n = \min(r_{n,1}; r_{n,2}; r_{n,3})$

Interaction equation	$r_{t/n,1}$ (interaction condition)	$r_{t/n,2}$ (shear condition)	$r_{t/n,3}$ (tension condition)	Eq.
Stranghöner/ Abraham for FprEN 1993-1-4 + abZ/aBG Z-30.3-6	$r_{t/n,1} = \frac{f_{ub}}{\sqrt[1.7]{\left(\frac{\sin(\varphi)}{\alpha}\right)^{1.7} + \left(\frac{\cos(\varphi)}{k_2}\right)^{1.7}}}$	$r_{t/n,2} = \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min\begin{cases} \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-7)
EN 1993-1-4 (bilinear)	$r_{t/n,1} = \frac{f_{ub} \cdot A_s}{\frac{\sin(\varphi)}{\alpha} + \frac{\cos(\varphi)}{1.4 \cdot k_2}}$	$r_{t/n,2} = \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min\begin{cases} \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-8)
German national annex of EN 1993-1-4 (bilinear)	$r_{t/n,1} = \frac{f_{ub} \cdot A_s}{\frac{\sin(\varphi)}{\alpha} + \frac{\cos(\varphi)}{1.4 \cdot k_2}}$	$r_{t/n,2} = \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min\begin{cases} \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-9)
DIN 18800-1 (quadratic) for carbon steel bolts	$r_{t/n,1} = \frac{f_{ub} \cdot A_s}{\sqrt{\left(\frac{\sin(\varphi)}{\alpha}\right)^2 + \left(\cos(\varphi) \cdot 1.25\right)^2}}$	$r_{t/n,2} = \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min\begin{cases} \frac{f_{ub} \cdot A_s}{1.25 \cdot \cos(\varphi)} \\ F_{m,min} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-10)
Approach of Renner/Lange for carbon steel bolts	$r_{t/n,1} = \frac{f_{ub} \cdot A_s}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha}\right)^{1.5} + \left(\frac{\cos(\varphi)}{k_2}\right)^{1.5}}}$	$r_{t/n,2} = \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min\begin{cases} \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{m,min} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-11)
Approach of Može for carbon steel bolts	$r_{t/n,1} = \frac{f_{ub} \cdot A_s}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha}\right)^{1.5} + \left(\frac{0.9 \cdot \cos(\varphi)}{k_2}\right)^{1.5}}}$	$r_{t/n,2} = \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$	$r_{t/n,3} = \min\begin{cases} \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{m,min} = f_{ub} \cdot A_s \end{cases}$	(Eq. 6.6-12)

6.6.3 Results of the reliability analysis for the unthreaded bolt part in the shear plane based on single-shear interaction testing

A comprehensive summary of the resulting partial safety factors γ_M* of the extended reliability analysis for the single-shear interaction resistance of austenitic and duplex stainless steel bolting assemblies with unthreaded bolt part in the shear plane is presented in Table 6.6-3. The resulting partial safety factors γ_M* across all austenitic or duplex bolting assemblies are evaluated, as well as the partial safety factors γ_M* for each property class, by defining subsets in the frame of the reliability analysis. For the sake of comparability, the statistical evaluations are considering both the resulting partial safety factors γ_M* only based on the given normative specifications without any increased tension and shear resistance (with k_2 = 0.9 and the shear coefficients α defined by the standard) as well as the resulting partial safety factors γ_M* of the various interaction equations by considering an increased tension and shear resistance (with k_2 = 1.0 and the proposed higher shear coefficients α for FprEN 1993-1-4). In total, 456 single-shear interaction tests are considered in the statistical evaluation according to EN 1990, Annex D. Furthermore, comparisons of the experimental and theoretical values (r_e/r_t) as well as experimental and nominal values (r_e/r_n) for the single-shear interaction resistance of austenitic and duplex stainless steel bolting assemblies with unthreaded bolt part in the shear plane, are provided in Figure 6.6-1 and Figure 6.6-2. The main parameters of the statistical evaluations are provided to allow direct comparisons of the mean value correction factor b and the scattering parameters V_δ (informative) and Q for the simplified design resistance value r_d.

Table 6.6-3: Summary of the reliability analysis of the single-shear interaction resistance for austenitic and duplex bolting assemblies for the unthreaded part in the shear plane with maximum COV (f_{ub}) = 3 % and maximum COV (A; A_s) = 1 %

Interaction equation	Property class		Austenitic					Duplex				
			PC 50	PC 70	PC 80	PC 8.8	PC 10.9	PC 70	PC 80	PC 100	PC 10.9	PC 12.9
	k_2	α	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]
Stranghöner/Abraham for FprEN 1993-1-4 + abZ/aBG Z-30.3-6	1.00	α_{prop} 1)	0.89	1.12	1.23	1.24	1.14	1.10	1.10	1.16	1.12	1.22
			1.22					1.19				
			γ_M* = 1.21 with b = 0.9515, V_δ = 0.0740, Q = 0.0803									
EN 1993-1-4 (bilinear)	0.90	$\alpha_{EC3-1-4}$ 2)	0.75	0.90	0.98	- 2)	- 2)	0.91	0.90	- 2)	- 2)	- 2)
			0.94					0.91				
			γ_M* = 0.94 with b = 1.2516, V_δ = 0.0814, Q = 0.0871									
	1.00	α_{prop} 1)	0.82	1.01	1.11	1.04	0.99	1.02	1.01	1.04	0.99	1.08
			1.07					1.04				
			γ_M* = 1.06 with b = 1.0737, V_δ = 0.0703, Q = 0.0770									
German national annex DIN EN 1993-1-4/NA (bilinear)	0.90	$\alpha_{EC3-1-4/NA}$ 3)	0.75	0.93	1.05	- 3)	- 3)	0.89	0.86	- 3)	- 3)	- 3)
			0.97					0.87				
			γ_M* = 1.01 with b = 1.3963, V_δ = 0.1421, Q = 0.1448									
	1.00	α_{prop} 1)	0.83	0.96	1.03	0.97	0.92	1.01	0.97	1.00	0.94	1.05
			1.00					0.99				
			γ_M* = 1.00 with b = 1.2248, V_δ = 0.0938, Q = 0.0987									
DIN 18800-1 (quadratic) for carbon steel bolts	- 4)	α_{prop} 1)	1.01	1.19	1.35	1.38	1.32	1.21	1.17	1.18	1.15	1.26
			1.28					1.21				
			γ_M* = 1.26 with b = 1.0904, V_δ = 0.1333, Q = 0.1363									
Approach of Renner/Lange for carbon steel bolts	0.90	$\alpha_{EC3-1-4}$ 2)	0.78	0.96	1.05	- 2)	- 2)	0.96	0.95	- 2)	- 2)	- 2)
			1.01					0.96				
			γ_M* = 1.07 with b = 1.1090, V_δ = 0.0850, Q = 0.0905									
	1.00	α_{prop} 1)	0.93	1.10	1.21	1.22	1.09	1.13	1.07	1.11	1.07	1.15
			1.19					1.14				
			γ_M* = 1.18 with b = 0.9711, V_δ = 0.0624, Q = 0.0696									
Approach of Može for carbon steel bolts	0.90	$\alpha_{EC3-1-4}$ 2)	0.92	0.90	1.01	- 2)	- 2)	0.87	0.89	- 2)	- 2)	- 2)
			0.95					0.88				
			γ_M* = 0.95 with b = 1.1593, V_δ = 0.0589, Q = 0.0668									
	1.00	α_{prop} 1)	0.86	1.03	1.17	1.16	1.03	1.05	1.02	1.05	1.02	1.10
			1.12					1.08				
			γ_M* = 1.11 with b = 1.0050, V_δ = 0.0604, Q = 0.0681									
Number of tests for each property class			12	178	90	40	20	20	24	20	32	20
Number of tests for each steel grade			340					116				
Number of total tests			**456**									

1) Proposed shear coefficients α for stainless steel bolts according to Table 5.7-1. | 2) Normative shear coefficients α as provided in EN 1993-1-4 | 3) Normative shear coefficients α as provided in DIN EN 1993-1-4/NA based on A_s. | 4) Reduction factor k_2 not used.

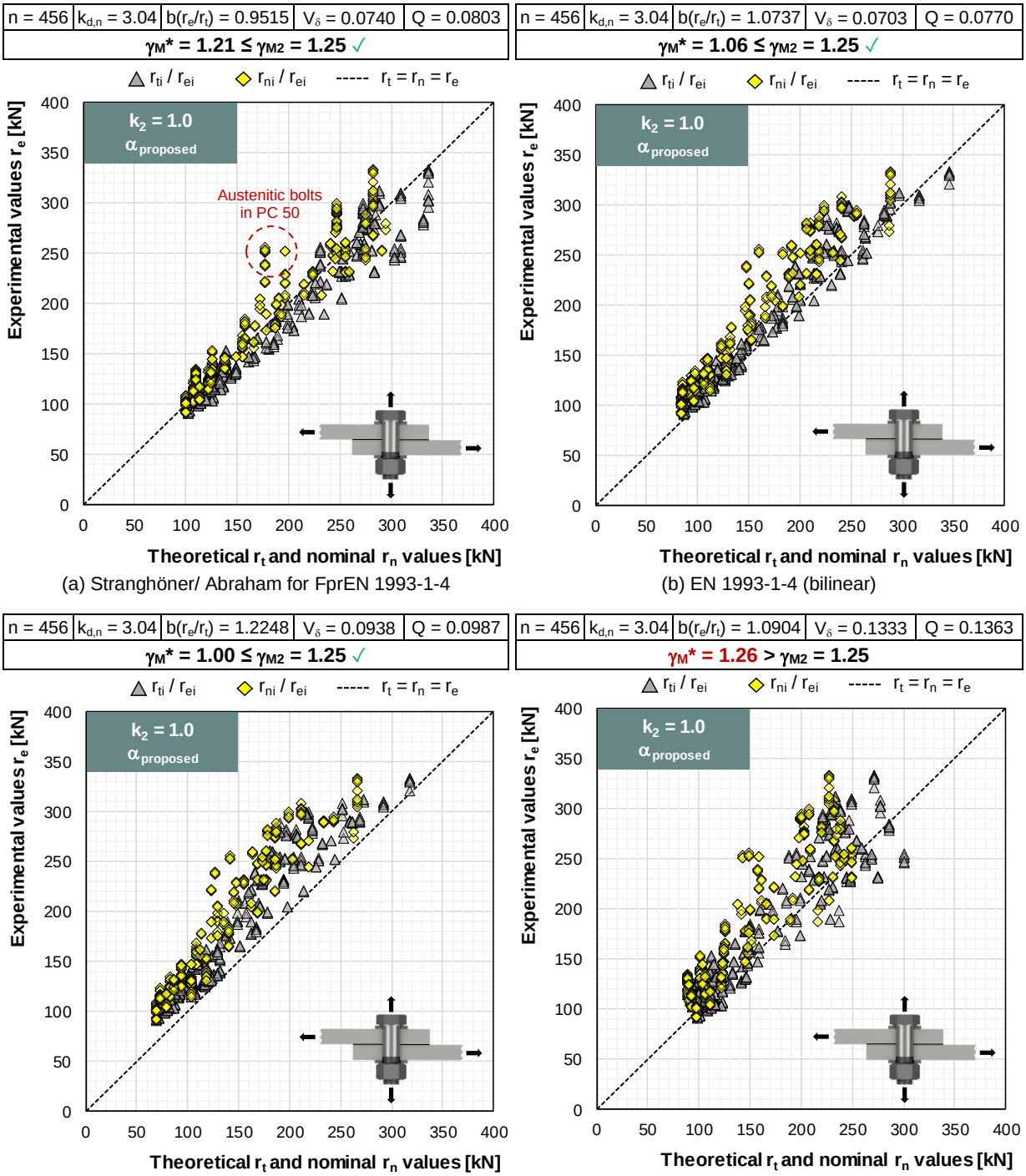
It can be shown in Table 6.6-3 that for all interaction approaches, except for the withdrawn German approach according to DIN 18800-1, all resulting partial safety factors γ_M* in all property classes and across all austenitic or duplex bolting assemblies are below γ_{M2} = 1.25 for connections on the safe side. For the proposed interaction equations for FprEN 1993-1-4 and abZ Z-30.3-6:2022, the property class subsets are showing partial safety factors between γ_M* = 0.89 (PC 50) and γ_M* = 1.24 (PC 8.8) for austenitic and between γ_M* = 1.10 (PC 70 and 80) and γ_M* = 1.16 (PC 100) for duplex stainless steel bolting assemblies.

Over all austenitic and bolting assemblies in all bolt property classes, the reliability analysis results in a partial safety factor of $\gamma_M^* = 1.21 \leq \gamma_{M2} = 1.25$ (with $b(r_e/r_t) = 0.9515$, $V_\delta = 0.0740$, $Q = 0.0803$). Since the mean value correction factor b for the interaction resistance of stainless steel bolts of FprEN 1993-1-4 is about $b(r_e/r_t) = 0.9515$, generally, the r_e/r_t values slightly shift below the angle bisector. However, the r_e/r_n values mainly lie on the angle bisector, even with some data points of austenitic bolts in PC 50 located far on the safe side, see Figure 6.6-1 (a). The scattering of the experimental/theoretical values (r_e/r_t) as well as experimental/nominal values (r_e/r_n) data points is comparable to the interaction rule of the current EN 1993-1-4, see Figure 6.6-1 (b).

The current bilinear interaction according to EN 1993-1-4 leads to partial safety factors γ_M^* between $\gamma_M^* = 0.75$ (PC 50) and $\gamma_M^* = 0.98$ (PC 80) for austenitic and between $\gamma_M^* = 0.90$ (PC 80) and $\gamma_M^* = 0.91$ (PC 70) for duplex stainless steel bolting assemblies, if the bolt tension and shear resistance are not increased. Across all austenitic and duplex bolting assemblies, the reliability analysis results to $\gamma_M^* = 0.94 \leq \gamma_{M2} = 1.25$ (with $b(r_e/r_t) = 1.2516$, $V\delta = 0.0814$, $Q = 0.0871$), if the tension and shear resistance are not increased. Under consideration of $k_2 = 1.0$ and the proposed higher shear coefficients α for FprEN 1993-1-4, the resulting partial safety factor γ_M^* for the bilinear interaction approach of EN 1993-1-4 is in the amount of $\gamma_M^* = 1.06 \leq \gamma_{M2} = 1.25$ (with $b(r_e/r_t) = 1.0737$, $V_\delta = 0.0703$, $Q = 0.0770$). The conservative bilinear interaction approach is particularly evident in the case of high shear components under loading angles of 30°, 45° and 67.5° and is not capable to accurately representing the actual load bearing behaviour of austenitic and duplex stainless steel bolting assemblies. Due to a mean value correction factor $b > 1$, the r_e/r_t values slightly shift above the angle bisector on the safe but non-economical side. Furthermore, nearly all r_e/r_n values mainly lie above the angle bisector, see Figure 6.6-1 (c).

As expected, the interaction approach of the German national annex DIN EN 1993-1-4/NA (which is always based on the tensile stress area A_s even when the bolt shank is in the shear plane) is most conservative with $\gamma_M^* = 1.00 \leq \gamma_{M2} = 1.25$ (with $b(r_e/r_t) = 1.2248$, $V_\delta = 0.0938$, $Q = 0.0987$) even by increased tension resistance of $k_2 = 1.0$ and the proposed higher shear coefficients α for FprEN 1993-1-4. Compared to the interaction approaches of FprEN 1993-1-4 and EN 1993-1-4, the scattering is increased, and all experimental and theoretical values (r_e/r_t), as well as experimental and nominal values (r_e/r_n) data points are above the angle bisector on the non-economical safe side.

On the contrary, the quadratic interaction equation according to the German DIN 18800-1 (which was valid exclusively for carbon steel bolts) leads to partial safety factors between $\gamma_M^* = 1.01$ (PC 50) and $\gamma_M^* = 1.38$ (PC 8.8) for austenitic and between $\gamma_M^* = 1.15$ (PC 10.9) and $\gamma_M^* = 1.26 > \gamma_{M2} = 1.25$ (PC 12.9) for duplex stainless steel bolting assemblies. Over all investigated austenitic and duplex bolting assemblies, the reliability analysis results to $\gamma_M^* = 1.26 > \gamma_{M2} = 1.25$ (with $b(r_e/r_t) = 1.0904$, $V_\delta = 0.1333$, $Q = 0.1363$), if an increased bolt tension and shear resistance by α_{prop} are considered. Therefore, in addition to the interaction test evaluations conducted in Chapter 6.4, it can be statistically verified that the quadratic interaction (with increased shear coefficients α) overestimates the combined load bearing capacity of stainless steel bolts with unthreaded bolt part in the shear plane. The scattering of the experimental and theoretical values (r_e/r_t) as well as experimental and nominal values (r_e/r_n) data points is the largest compared to the other interaction approaches placed around the angle bisector with deviations to both the safe ($b(r_e/r_t) > 1$) and unsafe ($b(r_e/r_t) < 1$) side, see Figure 6.6-1 (d).



(a) Stranghöner/ Abraham for FprEN 1993-1-4

(b) EN 1993-1-4 (bilinear)

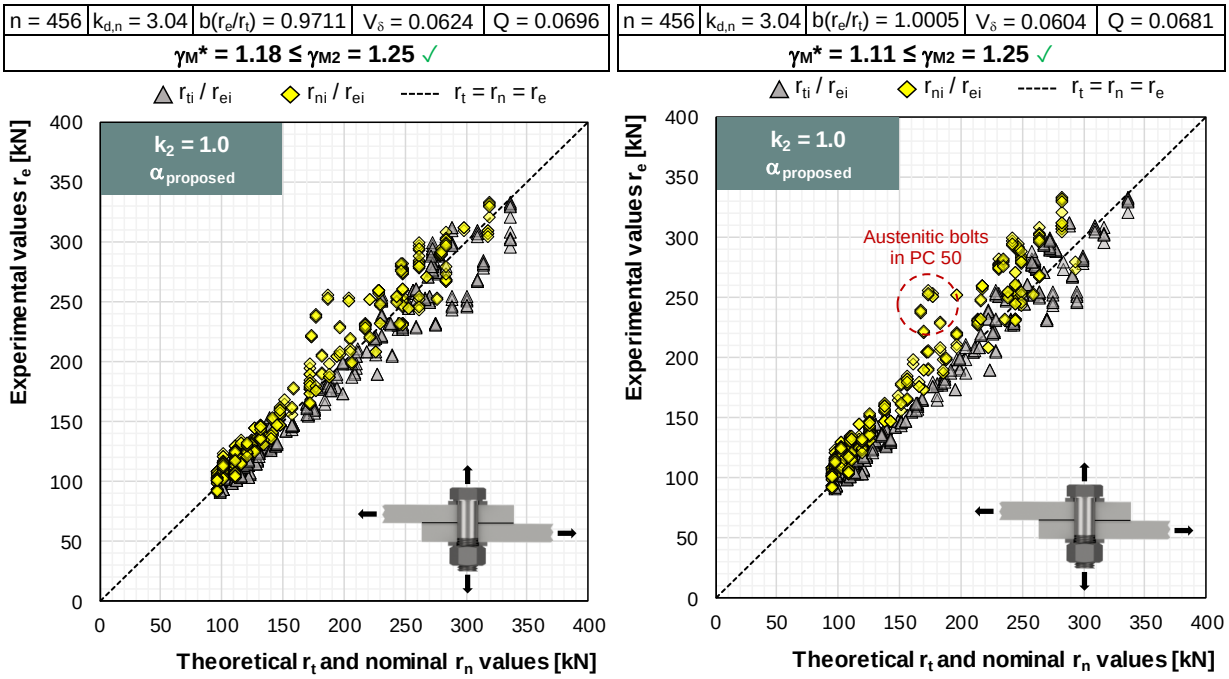
(c) German national annex DIN EN 1993-1-4/NA (bilinear)

(d) DIN 18800-1 (quadratic) for carbon steel bolts

Figure 6.6-1: Comparison of the experimental r_e and theoretical r_t/nominal r_n interaction resistances for austenitic and duplex stainless steel bolting assemblies including literature data for the unthreaded part in the shear plane according to FprEN 1993-1-4, EN 1993-1-4, DIN EN 1993-1-4/NA and DIN 18800-1

The interaction approaches by Renner/Lange and Može, exclusively developed for carbon steel bolts and adapted here for stainless steel bolting assemblies, lead to partial safety factors of γ_M^* = 1.18 (Renner/Lange; with $b(r_e/r_t)$ = 0.9711, V_δ = 0.0624, Q = 0.0696) and γ_M^* = 1.11 (Može; with $b(r_e/r_t)$ = 1.0050, V_δ = 0.0604, Q = 0.0681) over all austenitic and duplex stainless steel bolting assemblies, if the bolt tension and shear resistance is increased by k_2 = 1.0 and the proposed higher shear coefficients α for FprEN 1993-1-4. While the interaction approach of Renner/Lange generally shows a good agreement with the test data (see Chapter 6.4) but still underestimates the combined load bearing capacity of austenitic/duplex bolting assemblies under loading angles of 30° and 45°, on the contrary, the approach of Može can

be identified as too conservative and not suitable to describe the bolt interaction behaviour accurately. Compared to the above interaction approaches, the scattering is lower for Renner/Lange and Može. All experimental and theoretical values (r_e/r_t), as well as experimental and nominal values (r_e/r_n) data points indicate a comparable distribution around the angle bisector; see Figure 6.6-2 (a, b). Again, the data points for partially threaded austenitic stainless steel bolting assemblies in PC 50 are located far on the safe side.



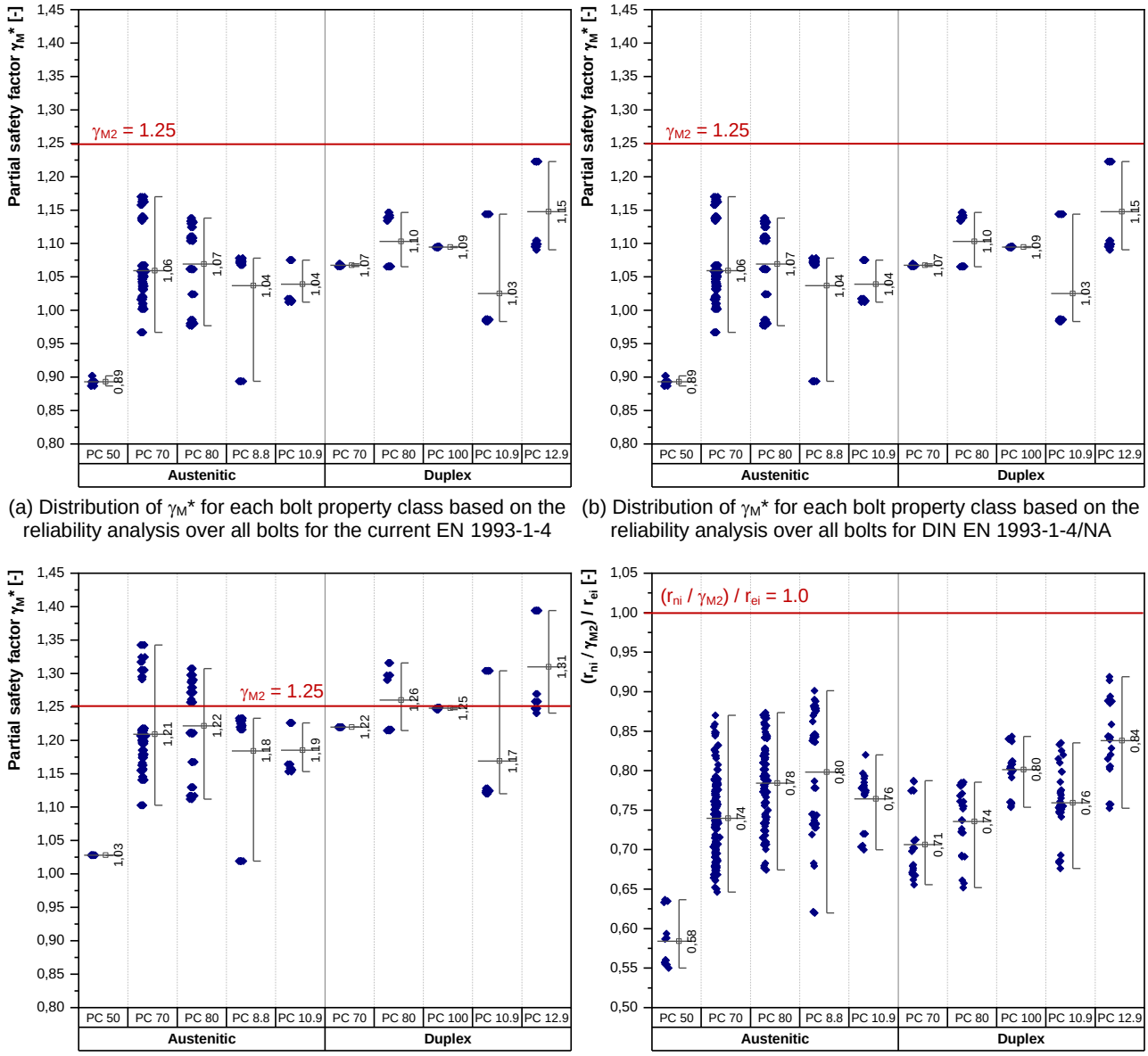
(a) Approach of Renner/Lange for carbon steel bolts (b) Approach of Može for carbon steel bolts

Figure 6.6-2: Comparison of the experimental r_e and theoretical r_t/nominal r_n shear resistances for austenitic and duplex stainless steel bolts and bolting assemblies including literature data for the unthreaded part in the shear plane for Renner/Lange and Može

To visualise the distribution of the resulting individual partial safety factors $\gamma_{M,i}$* for EN 1993-1-4 (a), DIN EN 1993-1-4/NA (b) and FprEN 1993-1-4 (c) across all austenitic and duplex bolting assemblies across all investigated bolt property classes, the individual data points $\gamma_{M,i}$* of each tested bolting assembly including literature data are summarised graphically in Figure 6.6-3. Plots of the range and resulting mean partial safety factors γ_M* based on the reliability analysis over all bolts are informatively included. All resulting individual partial safety factors $\gamma_{M,i}$* of the interaction resistance of austenitic and duplex bolting assemblies for the current EN 1993-1-4 (see Figure 6.6-3 (a)) and the German national annex DIN EN 1993-1-4/NA (see Figure 6.6-3 (b)) are clearly below γ_{M2} = 1.25 and therefore confirming the conservatism of these currently valid European and German interaction design rules. However, the proposed approach for FprEN 1993-1-4 shows partially $\gamma_{M,i}$* values exceeding γ_{M2} = 1.25 for connections, while the mean partial safety factors γ_M* for all austenitic and duplex bolt property classes (with exception for duplex bolts in PC 12.9 which are not fulfilling the requirements of $R_{m,nom}$ = 1200 N/mm²) are below γ_{M2} = 1.25, as presented in Figure 6.6-3 (c).

To assess the suitability and quality of the interaction design approaches of EN 1993-1-4, DIN EN 1993-1-4/NA and the proposed interaction approach by Stranghöner/Abraham for FprEN 1993-1-4, and to verify if partially exceeding γ_{M2} may be critical, again the modified assessment criteria (see Chapter 4.7.4) are applied. Herein, a plausibility check (criterion III) proves that all nominal design values (r_{ni}/γ_{M2}) for FprEN 1993-1-4 are below the experimental resistances r_{ei} and therefore sufficient safety reserves are guaranteed, see Figure 6.6-3 (d).

A summary of the assessment is presented in Table 6.6-4. Finally, it can be confirmed that all criteria are fulfilled for EN 1993-1-4, DIN EN 1993-1-4/NA and the proposed and more economical approach for FprEN 1993-1-4 regarding the interaction resistance of austenitic and duplex bolting assemblies with unthreaded part in the shear plane.



(a) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for the current EN 1993-1-4

(b) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for DIN EN 1993-1-4/NA

(c) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for FprEN 1993-1-4

(d) Distribution of the ratio of the individual nominal design r_{ni}/γ_{M2} and experimental r_{ei} results for FprEN 1993-1-4

Figure 6.6-3: Distribution of the partial safety factors γ_M* of austenitic and duplex bolting assemblies for each property class for the single-shear interaction resistance with k_2 = 1.0 and α_{prop} for the unthreaded bolt part in the shear plane

Table 6.6-4: Evaluation of the reliability analysis for the interaction resistance of stainless steel bolting assemblies for EN 1993-1-4, DIN EN 1993-1-4/NA and FprEN 1993-1-4 acc. to the modified safety assessment criteria

Evaluation criteria (Chapter 4.7.4)		EN 1993-1-4 with k_2 = 1.0 and α_{prop}	DIN EN 1993-1-4/NA with k_2 = 1.0 and α_{prop}	FprEN 1993-1-4 with k_2 = 1.0 and α_{prop}
I	Maximum error ≤ 1.15 · γ_{M2}	1.22 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.15 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.39[1)] ≤ 1.15 · γ_{M2} = 1.44 ✓
II	Maximum number of unsafe results ≤ 20 %	0 % ≤ 20 % ✓	0 % ≤ 20 % ✓	18.86 % ≤ 20 % ✓
III	Plausibility check	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓

[1)] Maximum individual partial safety factor of max γ_M* = 1.39 for duplex bolts in PC 12.9 from literature date which are not fulfilling the normative requirements according to EN ISO 3506-1. Consequently, if this duplex bolt series in PC 12.9 from literature is neglected, then the maximum individual partial safety factor is reduced to max γ_M* = 1.33.

Furthermore, an analysis of the resulting individual partial safety factors $\gamma_{M,i}$ over all steel grades, property classes and loading angles for the tension/shear interaction resistance by Stranghöner/Abraham with $k_2 = 1.0$ and the proposed higher shear coefficients α for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022 is provided in Figure 6.6-4.

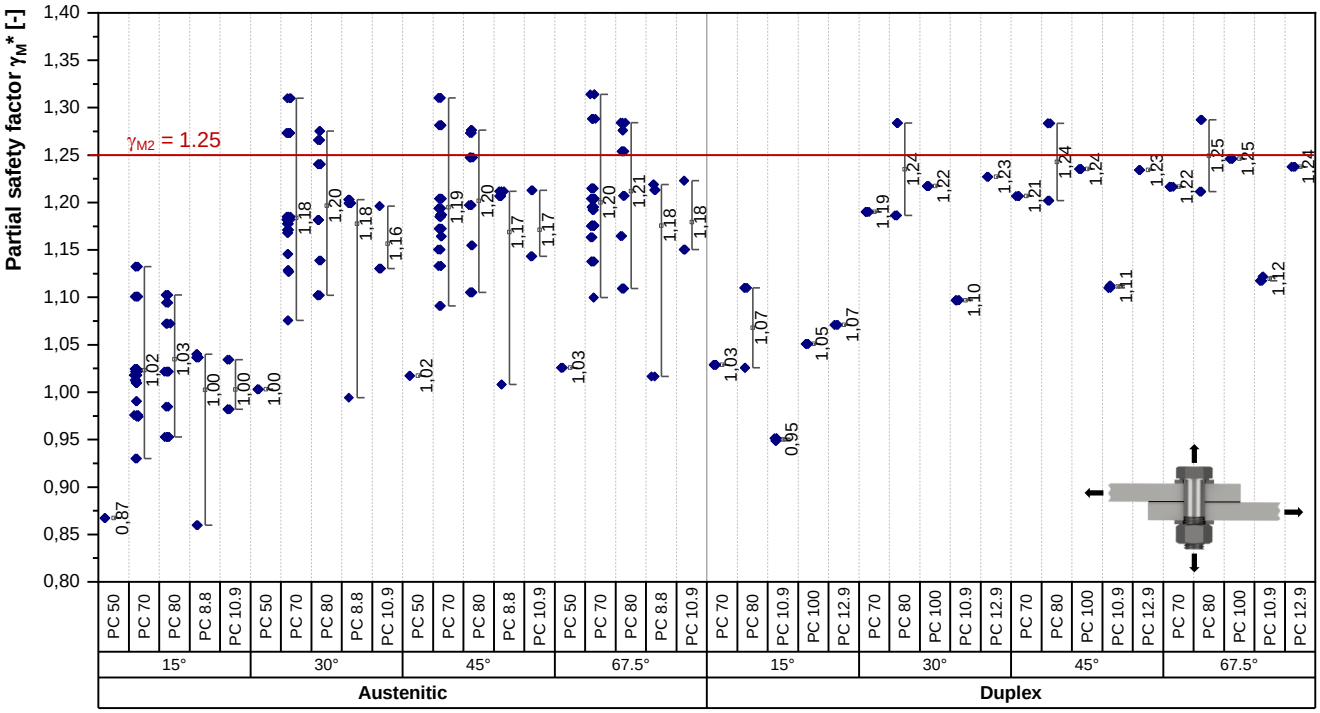


Figure 6.6-4: Analysis of the distribution of the partial safety factors γ_M* of austenitic and duplex stainless steel bolting assemblies for the single-shear interaction resistance according to FprEN 1993-1-4 with unthreaded part in the shear plane

Finally, a loading angle of 15° is identified as uncritical for all austenitic and duplex bolting assemblies across all property classes. However, for loading angles of 15°, 30° and 67.5°, the higher shear load and consequently the effect of higher proposed shear coefficients α are visible and lead to individual partial safety factors $\gamma_{M,i}$ partially exceeding $\gamma_{M2} = 1.25$ in PC 70 and PC 80 for austenitic bolts and PC 80 for duplex bolts. However, the number of unsafe results is 12.61 % less 20 % according to the modified assessment criteria (criterion II). Additionally, the evaluation criterion of the maximum error (criterion I) and the plausibility check (criterion III) are also fulfilled in all cases.

6.6.4 Results of the reliability analysis for the threaded bolt part in the shear plane based on single-shear interaction testing

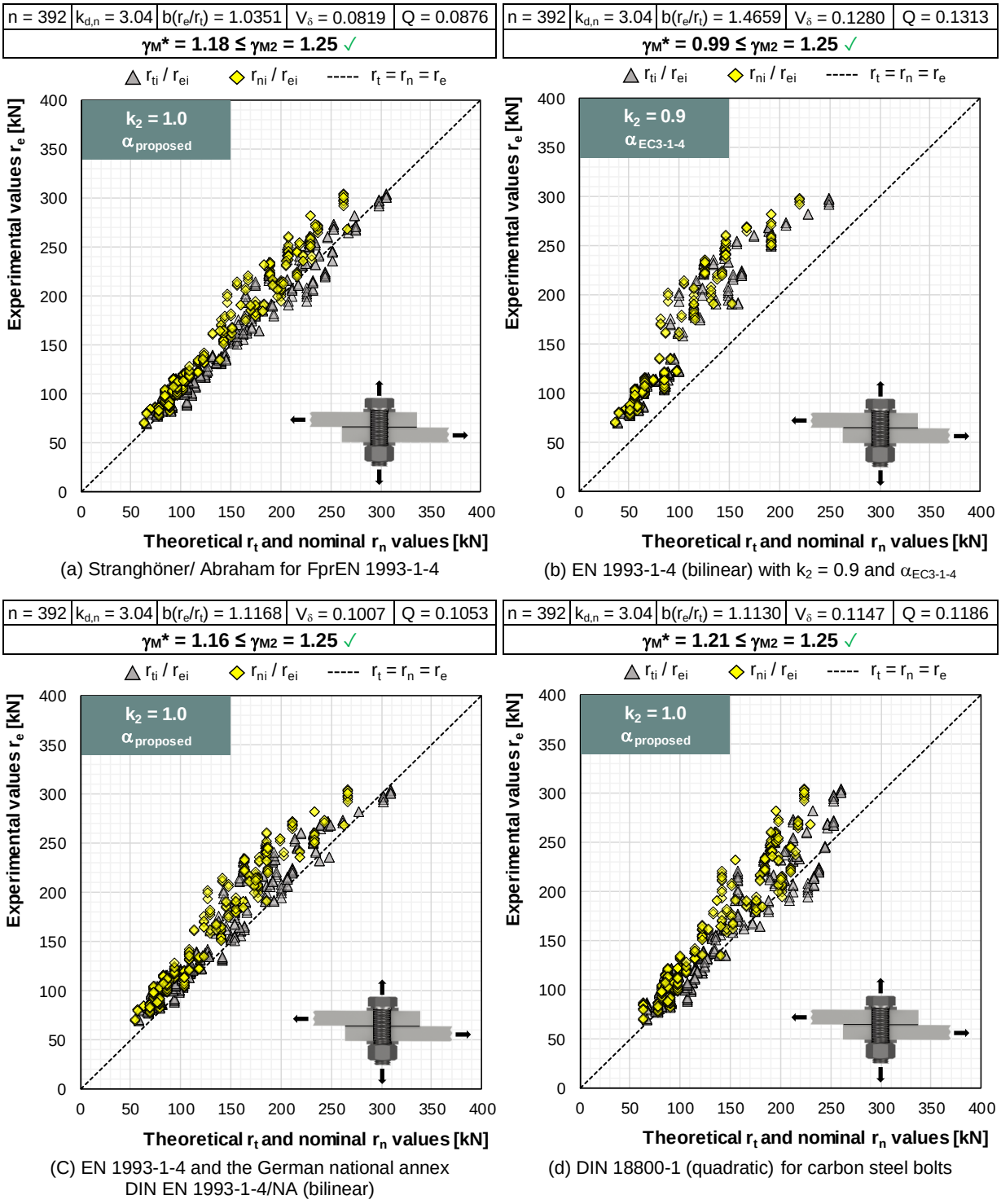
A comprehensive summary of the resulting partial safety factors γ_M* of the extended reliability analysis for the single-shear interaction resistance of austenitic and duplex bolting assemblies with threaded bolt part in the shear plane is presented in Table 6.6-5. Analogues to the statistical evaluation of the unthreaded bolt part in the shear plane, the partial safety factors γ_M* over all austenitic or duplex bolting assemblies as well as the partial safety factors γ_M* for each property class individually by subsets are evaluated. In total, 392 single-shear interaction tests are considered in the statistical evaluation according to EN 1990, Annex D.

Table 6.6-5: Summary of the reliability analysis of the single-shear interaction resistance for austenitic and duplex stainless steel bolting assemblies for the threaded bolt part in the shear plane with maximum COV (f_{ub}) = 3 % and maximum COV (A; A_s) = 1 %

Interaction equation	Property class		Austenitic					Duplex				
			PC 50	PC 70	PC 80	PC 8.8	PC 10.9	PC 70	PC 80	PC 100	PC 10.9	PC 12.9
	k_2	α	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]
Stranghöner/Abraham for FprEN 1993-1-4 + abZ/aBG Z-30.3-6	1.00	α_{prop} 1)	0.93	1.08	1.19	1.02	1.05	1.09	- 4)	- 4)	1.03	1.08
			1.21					1.08				
			γ_M* = 1.18 with b = 1.0351, V_δ = 0.0819, Q = 0.0876									
EN 1993-1-4 (bilinear)	0.90	$\alpha_{EC3-1-4}$ 2)	0.85	0.94	0.96	- 2)	- 2)	0.87	- 4)	- 2)	- 2)	- 2)
			1.00					0.87				
			γ_M* = 0.99 with b = 1.4659, V_δ = 0.1280, Q = 0.1313									
	1.00	α_{prop} 1)	0.99	1.11	1.15	1.00	1.02	1.05	- 4)	- 4)	1.04	1.13
			1.18					1.06				
			γ_M* = 1.16 with b = 1.168, V_δ = 0.1007, Q = 0.1053									
German national annex DIN EN 1993-1-4/NA (bilinear) 5)	0.90	$\alpha_{EC3-1-4/NA}$ 3)	0.90	1.07	1.24	- 3)	- 3)	0.87	- 4)	- 3)	- 3)	- 3)
			1.15					0.87				
			γ_M* = 1.16 with b = 1.3011, V_δ = 0.1416, Q = 0.1443									
	1.00	α_{prop} 1)	0.99	1.11	1.15	1.00	1.02	1.05	- 4)	- 4)	1.04	1.13
			1.18					1.06				
			γ_M* = 1.16 5) with b = 1.168, V_δ = 0.1007, Q = 0.1053									
DIN 18800-1 (quadratic) for carbon steel bolts	- 4)	α_{prop} 1)	0.98	1.10	1.28	1.11	1.12	1.20	- 4)	- 4)	1.06	1.11
			1.23					1.12				
			γ_M* = 1.21 with b = 1.1130, V_δ = 0.1147, Q = 0.1186									
Approach of Renner/Lange for carbon steel bolts	0.90	$\alpha_{EC3-1-4}$ 2)	0.77	0.87	0.91	- 2)	- 2)	0.80	- 4)	- 2)	- 2)	- 2)
			0.95					0.80				
			γ_M* = 0.93 with b = 1.4036, V_δ = 0.0952, Q = 0.1000									
	1.00	α_{prop} 1)	0.91	1.06	1.16	1.00	1.03	1.06	- 4)	- 4)	1.00	1.05
			1.17					1.04				
			γ_M* = 1.15 with b = 1.0802, V_δ = 0.0863, Q = 0.0917									
Approach of Može for carbon steel bolts	0.90	$\alpha_{EC3-1-4}$ 2)	0.87	0.96	0.99	- 2)	- 2)	0.90	- 4)	- 2)	- 2)	- 2)
			1.04					0.90				
			γ_M* = 1.02 with b = 1.3333, V_δ = 0.1086, Q = 0.1127									
	1.00	α_{prop} 1)	0.96	1.11	1.19	1.02	1.06	1.07	- 4)	- 4)	1.07	1.14
			1.22					1.09				
			γ_M* = 1.20 with b = 1.0239, V_δ = 0.0824, Q = 0.0881									
Number of tests for each property class			24	140	60	48	28	24	- 4)	- 4)	60	8
Number of tests for each steel grade			300					92				
Number of total tests			**392**									

1) Proposed shear coefficients α for stainless steel bolts according to Table 5.7-1. | 2) Normative shear coefficients α as provided in EN 1993-1-4 | 3) Normative shear coefficients α as provided in DIN EN 1993-1-4/NA based on A_s. | 4) Reduction factor k_2 not used.

The experimental and theoretical values (r_e/r_t), as well as experimental and nominal values (r_e/r_n) for the single-shear interaction resistance of austenitic and duplex stainless steel bolting assemblies with threaded bolt part in the shear plane, are given in Figure 6.6-5 (for FprEN 1993-1-4, EN 1993-1-4, DIN EN 1993-1-4/NA and DIN 18800-1) and Figure 6.6-6 (for the interaction approaches of Renner/Lange and Može).



(a) Stranghöner/ Abraham for FprEN 1993-1-4

(b) EN 1993-1-4 (bilinear) with k_2 = 0.9 and $\alpha_{EC3-1-4}$

(C) EN 1993-1-4 and the German national annex DIN EN 1993-1-4/NA (bilinear)

(d) DIN 18800-1 (quadratic) for carbon steel bolts

Figure 6.6-5: Comparison of the experimental r_e and theoretical r_t/nominal r_n interaction resistances for austenitic and duplex stainless steel bolting assemblies including literature data for the threaded part in the shear plane according to FprEN 1993-1-4, EN 1993-1-4, DIN EN 1993-1-4/NA and DIN 18800-1

It can be shown in Table 6.6-5 that for all interaction approaches, except for austenitic bolts in PC 80 for the withdrawn German approach according to DIN 18800-1, all partial safety factors γ_M* in all property classes and over all austenitic or duplex bolting assemblies are below γ_{M2} = 1.25 on the safe side. The proposed interaction equations by Stranghöner/Abraham for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022 result in partial safety factors between γ_M* = 0.93 (PC 50) and γ_M* = 1.19 (PC 80) for austenitic and between γ_M* = 1.03 (PC 10.9) and γ_M* = 1.09 (PC 70) for duplex stainless steel bolting assemblies.

The reliability analysis over all austenitic and duplex bolting assemblies in all bolt property classes results in a partial safety factor of $\gamma_M^* = 1.18 \leq \gamma_{M2} = 1.25$ (with $b(r_e/r_t) = 1.0351$, $V_\delta = 0.0819$, $Q = 0.0876$). The experimental and theoretical values (r_e/r_t) lie mainly on the angle bisector with $b(r_e/r_t) = 1.0351$, while the r_e/r_n data points lie on and slightly above the angle bisector. The scattering parameters $Q = 0.0917$ and $V_\delta = 0.0863$ of the interaction equation for FprEN 1993-1-4 are the lowest compared to the other presented interaction approaches, see Figure 6.6-5 (a).

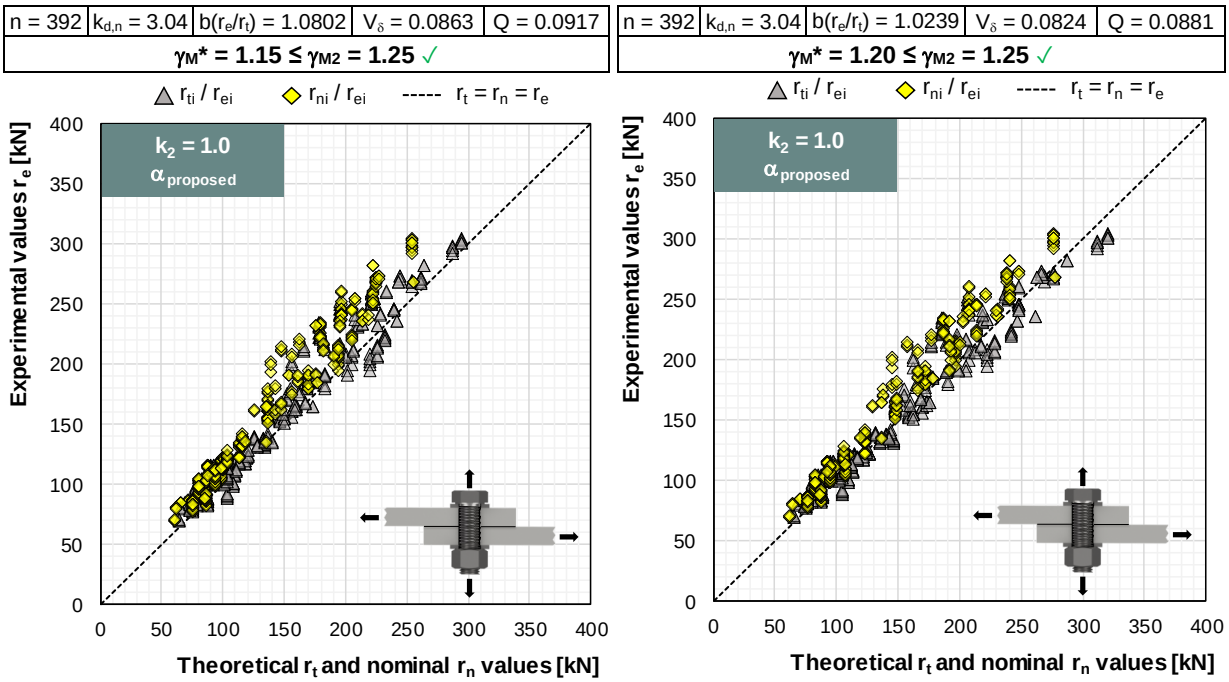
The bilinear interaction according to EN 1993-1-4 leads to partial safety factors γ_M^* between $\gamma_M^* = 0.85$ (PC 50) and $\gamma_M^* = 0.96$ (PC 80) for austenitic and $\gamma_M^* = 0.87$ (PC 70) for duplex bolting assemblies, if the statistical evaluation is based on $k_2 = 0.9$ and the shear coefficients given by EN 1993-1-4. Herein, the reliability analysis results to $\gamma_M^* = 0.99 \leq \gamma_{M2} = 1.25$ (with $b(r_e/r_t) = 1.4659$, $V\delta = 0.1280$, $Q = 0.1313$) over all austenitic and duplex stainless steel bolting assemblies significantly on the safe but non-economical side ($b(r_e/r_t) > 1$), see Figure 6.6-5 (b). Under consideration of an increased tension resistance and the proposed shear coefficients α for FprEN 1993-1-4, the resulting partial safety factors γ_M^* values for the bilinear interaction approach according to EN 1993-1-4 and DIN EN 1993-1-4/NA (which are now identical) is in the amount of $\gamma_M^* = 1.16 \leq \gamma_{M2} = 1.25$ (with $b(r_e/r_t) = 1.1168$, $V_\delta = 0.1007$, $Q = 0.1053$). The r_e/r_t data points lie on, slightly above and below the angle bisector, while all r_e/r_n data points lie on or slightly above the angle bisector, see Figure 6.6-5 (c).

However, the quadratic interaction equation according to the withdrawn German DIN 18800-1 leads to partial safety factors between $\gamma_M^* = 0.98$ (PC 50) and $\gamma_M^* = 1.28 > \gamma_{M2} = 1.25$ (PC 80) for austenitic and between $\gamma_M^* = 1.06$ (PC 10.9) and $\gamma_M^* = 1.20$ (PC 70) for duplex stainless steel bolting assemblies. Over all interaction tests of austenitic and duplex bolting assemblies, the statistical evaluation according to EN 1990, Annex D results to $\gamma_M^* = 1.21 < \gamma_{M2} = 1.25$ (with $b(r_e/r_t) = 1.1130$, $V_\delta = 0.1147$, $Q = 0.1186$), if an increased bolt tension and shear resistance by α_{prop} are considered. Herein, the scattering parameters $Q = 0.1147$ and $V_\delta = 0.1186$ of the quadratic interaction equation are the highest compared to the other presented interaction approaches, see Figure 6.6-5 (d).

Furthermore, the interaction approaches by Renner/Lange and Može, here adapted for austenitic and duplex bolting assemblies, result to partial safety factors γ_M^* of $\gamma_M^* = 1.15$ (Renner/Lange; with $b(r_e/r_t) = 1.0802$, $V_\delta = 0.0863$, $Q = 0.0917$) and $\gamma_M^* = 1.20$ (Može; with $b(r_e/r_t) = 1.0239$, $V_\delta = 0.0824$, $Q = 0.0881$) over all austenitic and duplex stainless steel bolting assemblies, if the bolt tension/shear resistance are increased by $k_2 = 1.0$ and the proposed higher shear coefficients for FprEN 1993-1-4. The scattering of the experimental and theoretical values (r_e/r_t) as well as the experimental and nominal values (r_e/r_n) are comparable and only slightly higher compared to the proposed FprEN 1993-1-4 approach, see Figure 6.6-6 (b).

Finally, based on the statistical evaluation of the interaction resistance of stainless steel bolting assemblies with threaded bolt part in the shear plane, it can be concluded that the current bilinear approach according to EN 1993-1-4 is significantly on the safe but non-economical side, while the German national annex DIN EN 1993-1-4/NA generally lead to higher interaction resistances due to increased shear coefficients, but is still too conservative. Based on the reliability analyses, the interaction approaches by Stranghöner/Abraham or Može (both with increased tension resistance with $k_2 = 1.0$ and proposed shear coefficients for FprEN 1993-1-4) seem to be most suitable to describe the interaction resistance of austenitic and duplex stainless steel bolting assemblies.

However, for “Ease of Use”, the interaction equation by Stranghöner/Abraham is proposed in order to provide a uniform and integral design concept for the interaction resistance of stainless steel bolting assemblies with unthreaded or threaded bolt part in the shear plane.

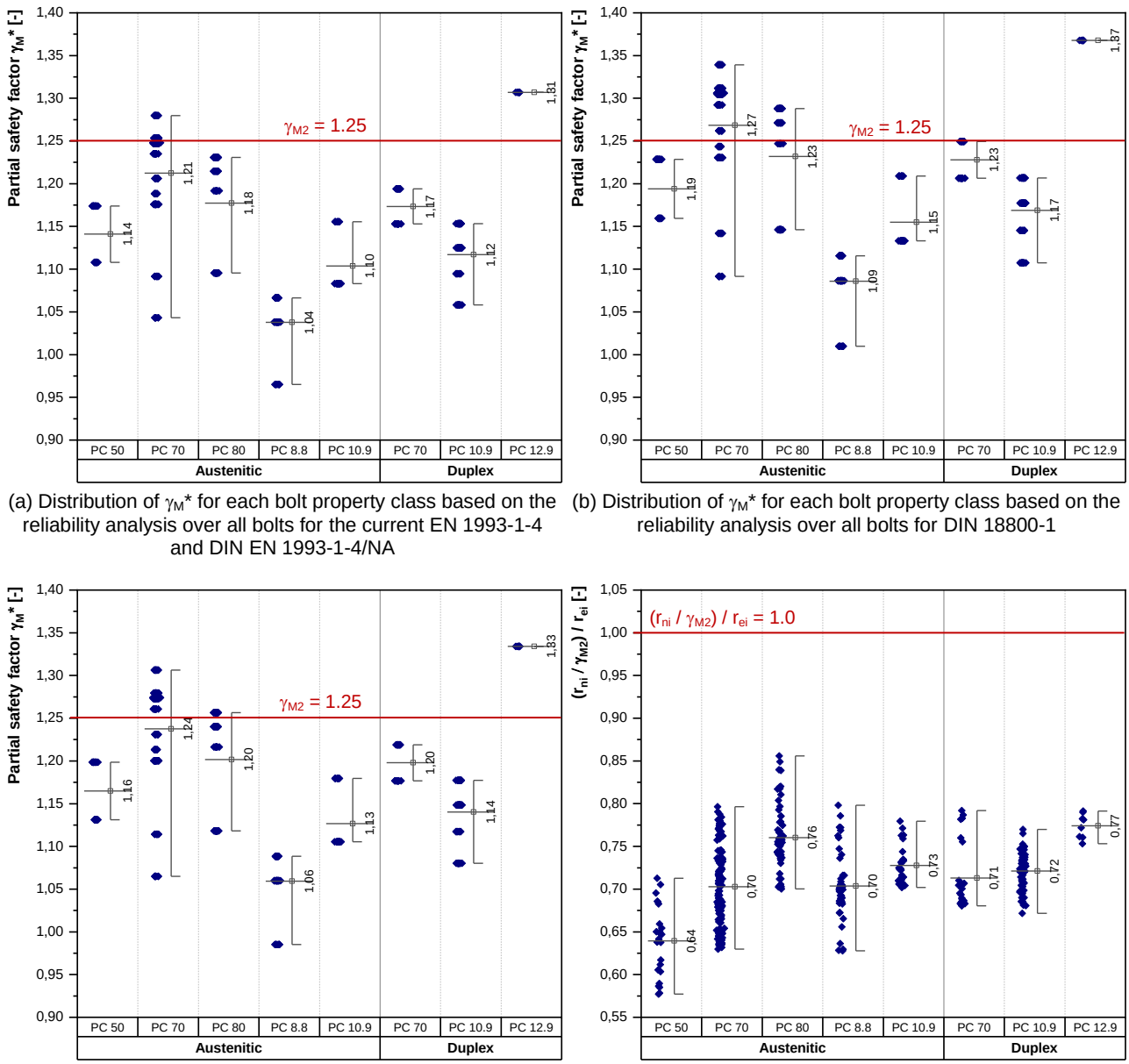


(a) Approach of Renner/Lange for carbon steel bolts (b) Approach of Može for carbon steel bolts

Figure 6.6-6: Comparison of the experimental r_e and theoretical r_t/nominal r_n shear resistances for austenitic and duplex stainless steel bolts and bolting assemblies including literature data for the threaded part in the shear plane for Renner/Lange and Može

In order to graphically represent the distribution of the resulting individual partial safety factors $\gamma_{M,i}$* for EN 1993-1-4 and DIN EN 1993-1-4/NA (a), DIN 1800-1 (b) and FprEN 1993-1-4 (c) over all austenitic and duplex bolting assemblies across all investigated bolt property classes, the individual data points $\gamma_{M,i}$* of each tested bolting assembly including literature data are summarised in Figure 6.6-7. Analogues to the statistical evaluation of the unthreaded bolt part, again plots of the range and resulting mean partial safety factors γ_M* based on the reliability analysis over all bolts are informatively included (which are again not identical with those partial safety factors γ_M* from the property class subsets given in Table 6.6-5).

It can be shown that for the reliability analysis over all fully threaded bolting assemblies for EN 1993-1-4 and DIN EN 1993-1-4/NA (see Figure 6.6-7 (a)) with k_2 = 1.0 and α_{prop}, partially exceeding the individual partial safety factors $\gamma_{M,i}$* of γ_{M2} = 1.25 occurs for austenitic bolting assemblies in PC 70, while duplex bolting assemblies in PC 12.9 with $\gamma_{M,,D12.9,mean}$* = 1.31 cleary exceed γ_{M2} = 1.25. However, the statistical evaluation according to EN 1990, Annex D for the subset of duplex PC 12.9 bolting assemblies shows that safety requirements of the Eurocode are fulfilled with γ_M* = 1.13, cf. Table 6.6-5. Herein, the high individual partial safety factors of $\gamma_{M,D12.9,mean}$* = 1.31 result from the large dataset’s scattering over all austenitic and duplex bolting assemblies considering all bolt property classes and depict the worst-case scenario. For the quadratic interaction approach according to DIN 18800-1 (see Figure 6.6-7 (b)) and the proposed interaction by Stranghöner/Abraham (see Figure 6.6-7 (c)), partially exceeding of the individual partial safety factors $\gamma_{M,i}$* of γ_{M2} = 1.25 occur for austenitic bolting assemblies in PC 70 and PC 80. The same overshooting effect can be observed for duplex bolting assemblies in PC 12.9. However, the mean partial safety factors γ_M* for all austenitic/duplex property classes (except for duplex bolts in PC 12.9) are below γ_{M2} = 1.25.



(a) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for the current EN 1993-1-4 and DIN EN 1993-1-4/NA

(b) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for DIN 18800-1

(c) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for FprEN 1993-1-4

(d) Distribution of the ratio of the individual nominal design r_{ni}/γ_{M2} and experimental r_{ei} results for FprEN 1993-1-4

Figure 6.6-7: Distribution of the partial safety factors γ_M* of austenitic and duplex bolting assemblies for each property class for the single-shear interaction resistance with k_2 = 1.0 and α_{prop} for threaded bolt part in the shear plane

The modified assessment criteria (see Chapter 4.7.4) are applied for the interaction equation of FprEN 1993-1-4 to check whether partially exceeding the resulting individual partial safety factors $\gamma_{M,i}$* against γ_{M2} = 1.25 for connections has to be identified as critical for the reliability of the bolted connection. As a result of a plausibility check (criterion III), it can be shown that all nominal design values (r_{ni}/γ_{M2}) for FprEN 1993-1-4 are below the experimental resistances r_{ei} and that always sufficient safety reserves are guaranteed. A summary of the assessment for all evaluated criteria is presented in Table 6.6-6. It can be confirmed that all criteria are fulfilled for EN 1993-1-4, DIN EN 1993-1-4/NA and the proposed and more economical approach for FprEN 1993-1-4 regarding the interaction resistance of stainless steel bolting assemblies with threaded bolt part in the shear plane.

Table 6.6-6: Evaluation of the reliability analysis for the interaction resistance of stainless steel bolting assemblies for EN 1993-1-4, DIN EN 1993-1-4/NA and FprEN 1993-1-4 acc. to the modified safety assesment criteria

Evaluation criteria (Chapter 4.7.4)		EN 1993-1-4 and DIN EN 1993-1-4/NA with k_2 = 0.9 and $\alpha_{EC3-1-4}$	EN 1993-1-4 and DIN EN 1993-1-4/NA with k_2 = 1.0 and α_{prop}	FprEN 1993-1-4 with k_2 = 1.0 and α_{prop}
I	Maximum error ≤ 1.15 · γ_{M2}	1.06 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.31 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.33 ≤ 1.15 · γ_{M2} = 1.44 ✓
II	Maximum number of unsafe results ≤ 20 %	0 % ≤ 20 % ✓	10.20 % ≤ 20 % ✓	17.81 % ≤ 20 % ✓
III	Plausibility check	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓

Analogues to the interaction resistance of stainless steel bolting assemblies with unthreaded bolt part in the shear plane, also an analysis of the resulting individual partial safety factors $\gamma_{M,i}$ across all steel grades, property classes and loading angles for the interaction resistance by Stranghöner/Abraham for FprEN 1993-1-4 is carried out and presented in Figure 6.6-8. Herein, a new reliability analysis is conducted for each loading angle (leading to four subsets) with k_2 = 1.0 and the proposed shear coefficients α for FprEN 1993-1-4.

As a result, loading angles of 45° and 67.5° are identified as critical for austenitic stainless steel bolting assemblies in PC 70, which partially exceeds the partial safety factor of γ_{M2} = 1.25 for connections. However, the number of unsafe individual results $\gamma_{M,i}$* is less than 20 % according to the modified safety assessment criteria (criterion II). Additionally, the evaluation criteria regarding the maximum error (criterion I) and the plausibility check (criterion III) are fulfilled for the reliability analysis over all bolts, steel grades, PC and loading angles.

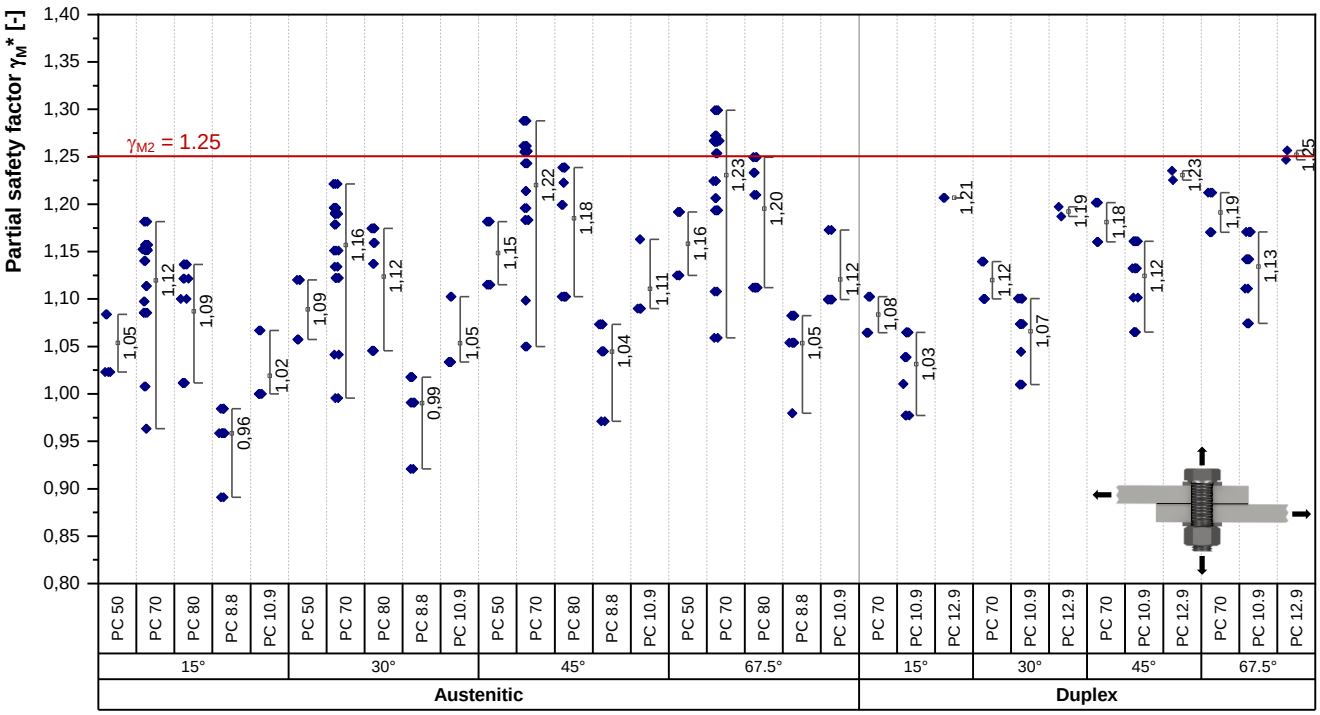


Figure 6.6-8: Analysis of the distribution of the partial safety factors γ_M* of austenitic and duplex stainless steel bolting assemblies for the single-shear interaction resistance according to FprEN 1993-1-4 with threaded bolt part in the shear plane

6.7 Summary and conclusions

A comprehensive overview of the experimental investigations and statistical evaluations according to EN 1990, Annex D, regarding the interaction resistance of austenitic and duplex stainless steel bolting assemblies, is presented in Chapter 6. These systematic investigations were embedded in the German research project FOSTA P 1386 / IGF-No. 20651 N and further

research activities conducted at UDE-IML. Furthermore, the suitability of different international interaction design approaches in order to describe the interaction resistance of austenitic and duplex stainless steel bolting assemblies was checked and complemented by an extended reliability analysis according to EN 1990, Annex D including the proposed more economical design approaches for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022 by Stranghöner/Abraham regarding the bolt interaction resistance of austenitic and duplex stainless steel bolting assemblies. Herein, the distribution of the resulting partial safety factors γ_M* across various bolt property classes, loading angles and different interaction design approaches was investigated. In total, 456 interaction tests with unthreaded bolt part and 392 interaction tests with threaded bolt part in the shear plane on austenitic and duplex stainless steel bolting assemblies were considered and complemented by numerical FEM investigations.

Herein, all resulting individual partial safety factors $\gamma_{M,i}$* of the interaction resistance of austenitic and duplex bolting assemblies with unthreaded or threaded bolt part in the shear plane for the interaction approaches of the current EN 1993-1-4 and the German national annex DIN EN 1993-1-4/NA are clearly below γ_{M2} = 1.25 confirming the conservatism of these interaction design rules. On the contrary, an in-depth analysis of the resulting individual partial safety factors $\gamma_{M,i}$ over all steel grades, property classes and loading angles for the more economical tension/shear interaction resistance by Stranghöner/Abraham for FprEN 1993-1-4 and abZ/aBG Z-30.3-6 is fulfilling the safety requirements of the Eurocode. The statistical evaluations over all austenitic and duplex stainless steel bolting assemblies show a resulting partial safety factor of γ_M* = 1.21 ≤ γ_{M2} = 1.25 for the unthreaded and γ_M* = 1.18 ≤ γ_{M2} = 1.25 for the threaded bolt part in the shear plane.

The proposed new interaction equations by Stranghöner/Abraham already consider the increased tension resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolts with the proposed k_2-factor of k_2 =1.0 (with the exception of countersunk bolts, which are not part of the investigations) and the increased shear resistance $F_{v,Rd}$ with the proposed higher and more economical shear coefficients α for FprEN 1993-1-4. Finally, a coherent and self-contained tension, shear and interaction design concept is available for the engineer.

7 New proposed harmonised design rules for carbon steel bolting assemblies

7.1 General

As a supplement to the experimental investigations and reliability analyses of the proposed design approaches for the tension, shear and interaction resistance of austenitic and duplex stainless steel bolts, it was questioned whether the design rules for carbon steel bolted connections according to EN 1993-1-8 [72] and EN 1993-1-8:2024 [82] do not also need a fundamental revision to allow a more suitable and finally, more economical design. Furthermore, in the meantime, various new experimental studies into carbon steel bolts under tension, shear and interaction have become available but have yet to be implemented in a statistical re-evaluation. Even though new design approaches of the shear and interaction resistance of carbon steel bolts were developed by various authors, particularly in the frame of the currently ongoing revision process of EN 1993-1-8, all these proposed new regulations were not statistically verified according to EN 1990, Annex D [79] regarding the resulting partial safety factors γ_M* to prove them against the partial safety factor γ_{M2} = 1.25 for connections.

Therefore, a renewed review of the safety concept of the Eurocode for carbon steel bolting assemblies is indicated. It has to be investigated if possibly more suitable and economical design rules for non-preloaded carbon steel bolted connections can be realised and, if possible, harmonised with the proposed design rules of stainless steel bolted connections for FprEN 1993-1-4 [80] ("Ease of Use"). To contribute, own experimental investigations considering tensile, single-/double-shear and interaction tests on different types of carbon steel bolts and bolting assemblies were carried out within the frame of this thesis. A majority of these experimental investigations, supplemented by test data available in the literature, have already been statistically evaluated, and finally new and statistically verified design rules harmonised with FprEN 1993-1-4 have been proposed [413, 414].

All investigations are supplemented by double-shear tests on carbon steel bolting assemblies and an extended literature review. In addition to [413, 414], an in-depth statistical evaluation according to EN 1990, Annex D of the resulting partial safety factors γ_M* is conducted and complemented by a safety assessment of the proposed tension, shear and interaction design rules for bolted connections made of carbon steel. Furthermore, the differences in the reliability analysis from the 1st generation of EN 1993-1-8 to the present are clarified.

7.2 Experimental investigations: Test programmes and test procedures

For the sake of extending the existing experimental studies on carbon steel bolts, systematic experimental investigations into the tension, shear and combined tension and shear resistance of carbon steel bolts and bolting assemblies were conducted at UDE-IML. In total, 31 tensile tests, 31 single-shear tests, 57 additional double-shear tests and 121 single-shear interaction tests under loading angles of 15°, 30°, 45° and 67.5° were conducted. As described in [413], and in [414], different bolt types were considered for testing either the unthreaded part (gross cross-sectional area A) or the threaded part (tensile stress area A_s) of the bolt in the shear plane. Therefore, fully threaded hexagon head bolts according to EN ISO 4017 [121] were applied for the threaded bolt part in the shear plane, while in case that the shear plane passes through the unthreaded portion, partially threaded hexagon head bolts according to EN ISO 4014 [119] as well as high-strength structural bolting assemblies according to EN 14399-3 [117] (System HR) and EN 14399-4 [118] (System HV) were investigated. In the

tests, EN ISO 4014/4017 structural carbon steel bolts were matched with EN ISO 4032 [394] nuts. Washers were not applied. Additionally, four different bolt manufacturers and traders (C1-C4) in PC 8.8 and 10.9 were considered.

The detailed test matrixes of the tensile, single-shear, double-shear and interaction tests are given in Table B.15 to Table B.18 of Appendix B

The same test procedures and test rigs were applied to ensure direct comparability between the load bearing behaviour of bolts made of stainless and carbon steel. The tensile tests were conducted on the whole bolt according to EN ISO 3506-1 [73], Clause 9.2 and 9.3, following the specifications presented in Chapter 4.4.2. Tensile tests were performed on M16 carbon steel bolts using displacement control at a consistent testing speed of 0.08 mm/s until bolt failure occured. Throughout the entire test, the bolt elongation was continuously measured using a high-precision video extensometer, specifically the Mercury VEX-50®. For the single-/ double-shear tests, the test procedures outlined in Figure 5.4-4 and Figure 5.4-5 were applied. Analogues to the investigations into the shear load bearing behaviour of austenitic and duplex stainless steel bolts, double-shear tests on structural carbon steel bolts tested with or without nuts were performed to determine the load bearing effect of the nut. In this way, the resulting shear resistance of carbon steel bolts and bolting assemblies and possible supporting effects of the nuts can be compared directly and contrasted with those of stainless steel bolts. In addition, the test procedures for all interaction tests are summarised in Figure 6.3-3.

7.3 Experimental investigations: Comparison between carbon and stainless steel bolts

7.3.1 General

An overview of the experimental results of the tensile, single-shear and single-shear interaction tests on carbon steel bolts are presented in [414]. Additionally, all test results on carbon steel bolts are presented in Appendix C. In the following, only the main findings regarding the different load bearing behaviour of partially and fully threaded bolts between austenitic/duplex stainless steel and carbon steel are briefly outlined.

7.3.2 Comparison between the tension resistance of carbon and stainless steel bolts

Since the pronounced overstrength and outstanding ductility of austenitic and duplex stainless steel bolts were already outlined in the previous chapters as important characteristics of stainless steel, it can be stated that the tensile overstrength and ductility of the investigated partially and fully threaded carbon steel bolts are less pronounced compared to stainless steel bolts.

Finally, four main conclusions can be drawn from the studies presented in [414]:

- While the tensile overstrength ratio between the experimental mean maximum load $F_{mf,exp,mean}$ and the minimum ultimate tensile load $F_{mf,nom}$ of the tested partially threaded austenitic stainless steel bolts is between 1.04 and 1.35 (the majority of the 21 tested austenitic bolt series failed in the unthreaded part of the bolt) and for duplex stainless steel bolts between 1.06 and 1.22, the tensile overstrength ratio of partially threaded carbon steel bolts is evidently reduced between 1.05 and 1.12. It is striking that the elongation at fracture $A_{exp,mean}$ of carbon steel bolts is significantly lower (0.20d to 0.38d) compared to austenitic (0.40d to 2.07d) and duplex (0.40d to 0.70d) stainless steel bolts. As intended, bolt failure of carbon steel bolts always occurred in the threaded bolt part due to the smaller cross-sectional area.

- The tensile overstrength ratios $F_{mf,exp,mean}$ / $F_{mf,nom}$ of fully threaded austenitic bolts are between 1.01 and 1.23 and for duplex stainless steel bolts between 1.09 and 1.20. On the contrary, the tensile overstrength ratios of the investigated fully threaded carbon steel bolts are between 1.09 and 1.12. The ratio of the elongation at fracture $A_{exp,mean}$ / A_{nom} of carbon steel bolts is between 0.50d and 0.59d and therefore again significantly lower compared to austenitic (1.25d to 3.48d) and duplex (2.05d to 2.75d) stainless steel bolts.
- Based on the test results, it could be shown that fully threaded carbon steel bolts according to EN ISO 4017 are generally characterised by higher bolt elongation and therefore higher ductility compared to partially threaded bolts due to the unrestrained deformation capacity of the threaded part. However, the ductility of carbon steel bolts is significantly reduced in contrast to austenitic and duplex stainless steel bolts, which should be considered in the design and execution of bolted connections and joints.
- As expected, bolt failure of carbon steel bolts always occurred in the free-loaded threaded part for all tested series subjected to quasi-static tension loading due to the intended construction principle of the bolts.

7.3.3 Comparison between the single-shear resistance of carbon and stainless steel bolts

As already pointed out in Chapter 2.5, Thomala [169] and Wiegand et al. [176] confirmed an approximately linear relationship between the shear coefficient α and the tensile strength of carbon steel bolts. Furthermore, Knobloch [173] stated that linking the shear coefficient with the bolt property class is primarily not an expression of a correlation between shear and tensile strength but a dependence on the ductility and plastic deformation capacity of the bolt material. Knobloch [173] concluded that higher bolt property classes directly correlate to reduced ductility and plastic deformation capacity (and thus reduced shear coefficients α).

In Chapter 5, the correlations between the experimental tensile and shear strength could be confirmed in correlation analyses for partially and fully threaded austenitic and duplex stainless steel bolts. Analogues to this, also decreasing experimental shear coefficients α and bolt ductility with increasing tensile strengths could be observed for structural carbon steel bolts based on own experimental investigations at UDE-IML and an extensive literature review, see [414]. Interestingly, despite the significantly higher plastic deformation capacity of bolts made of (particularly) austenitic or duplex steel, the resulting experimental mean shear coefficients α are generally of a similar order of magnitude or even smaller as summarised in Table 7.3-1. Therefore, a direct comparison of the shear coefficients between carbon steel and stainless steel bolts is not possible, as in addition to the plastic deformation capacity, also cold working, strain hardening including martensitic material transformation must also be taken into account, which results in complex relationships of the pure material shear capacity.

Nevertheless, regarding the design of the shear resistance $F_{v,Rd}$ of bolts in PC 8.8 and 10.9, it can be simplified that the resulting ultimate shear coefficients α of carbon and stainless steels bolts are nearly comparable within a deviation range of ± 0.07.

Table 7.3-1: Comparison of the resulting experimental mean shear coefficients α of partially and fully threaded bolts made of stainless steel and carbon steel based on [164] and [414]

Unthreaded bolt part in the shear plane: Partially threaded bolts acc. to EN ISO 4014[1], EN 14399-3[2] and EN 14399-4[3]					
Carbon steel bolts		**Austenitic stainless steel bolts** (including deviation from carbon steel bolts in brackets)		**Duplex stainless steel bolts** (including deviation from carbon steel bolts in brackets)	
Property class	Mean shear coefficient [-]	Property class	Mean shear coefficient [-]	Property class	Mean shear coefficient [-]
PC 8.8[1]	0.65	PC 80[1]	0.61 (-0.04)	PC 80[1]	0.68 (+0.03)
		PC 8.8[1]	0.58 (-0.07)	PC 8.8[1]	-
PC 10.9[2][3]	0.61	PC 100[1]	-	PC 100[1]	0.57 (-0.04)
		PC 10.9[1]	0.54 (-0.07)	PC 10.9[1]	0.57 (-0.04)
Threaded bolt part in the shear plane: Fully threaded bolts acc. to EN ISO 4017					
Carbon steel bolts		**Austenitic stainless steel bolts** (including deviation from carbon steel bolts in brackets)		**Duplex stainless steel bolts** (including deviation from carbon steel bolts in brackets)	
Property class	Mean shear coefficient [-]	Property class	Mean shear coefficient [-]	Property class	Mean shear coefficient [-]
PC 8.8	0.62	PC 80	0.69 (+0.07)	PC 80	-
		PC 8.8	0.63 (+0.01)	PC 8.8	-
PC 10.9	0.61	PC 100	-	PC 100	-
		PC 10.9	0.60 (-0.01)	PC 10.9	0.63 (+0.02)

[1] All tests were conducted with EN ISO 4014 partially threaded bolts. | [2] All tests were conducted with EN 14399-3 HR bolting assemblies. | [3] All tests were conducted with EN 14399-4 HV bolting assemblies.

7.3.4 Comparison between the single- and double-shear resistance of carbon and stainless steel bolts

Analogues to the experimental investigations into the load bearing behaviour of austenitic and duplex stainless steel bolts subjected to pure single-shear or pure double-shear loading, also additional tests on the single- and double-shear resistance of carbon steel bolts were conducted in the frame of this thesis. However, the influence of the different hole clearance on the bolt shear resistance $F_{v,Rd}$ was not investigated, as this had already been sufficiently demonstrated in the aforementioned studies on stainless steel bolts and bolting assemblies. Furthermore, the impact of the hole clearance on stainless steel bolts could also be confirmed on carbon steel bolts in preliminary studies.

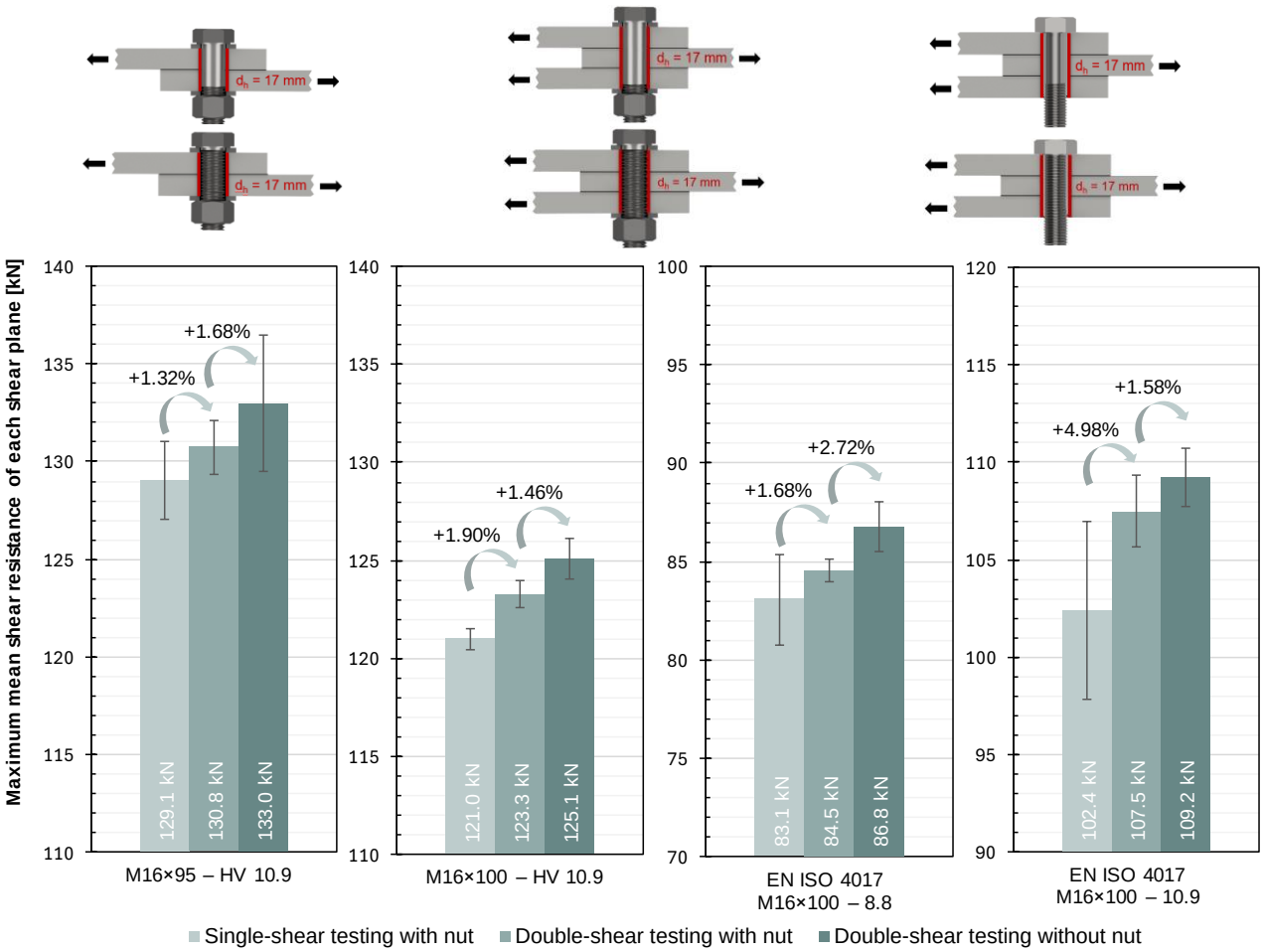
The main findings of the experimental investigations between the single- and double-shear resistance of carbon steel bolts can be summarised as follows:

- If the bolt hole clearance was kept constant with Δd= 1 mm, the lowest shear resistance of carbon steel bolts in PC 8.8 and 10.9 with unthreaded or threaded parts in the shear plane was always achieved by single-shear testing. Therefore, single-shear testing could also be verified for carbon steel bolts on the safe side.
- Analogues to the double-shear tests on austenitic and duplex bolts, it can be stated that the double-shear tests follow the lowest shear resistance of carbon steel bolts by single-shear testing performed both with nut. If a double-shear test on carbon steel bolts is carried out without a nut, the highest shear resistances between +1.46 % and +2.72 % are achieved across all tested series caused by the most pronounced skewing of the bolts and the resulting enlargement of the cross-section in the shear plane, see also Chapter 5.5.2.
- In the case of carbon steel bolts with unthreaded parts in the shear plane, testing without a nut leads to significant scattering of the test results. However, this observation could not be confirmed for carbon steel bolts with threaded parts in the shear planes since the thread

support is inhomogeneous and not comparable in each test. Therefore, no generally valid conclusions can be drawn here.

- In principle, all observed experimental results are to be understood more as a trend since the differences in the single-shear and double-shear resistances of carbon steel bolts are in the range of the scattering. The differences between the mean values of single-shear and double-shear testing with nut are between +1.32 % and +4.98 % and can be neglected in the design of bolted shear connections. However, the trends observed in the frame of the experimental studies could be shown across all tested bolt series.

A graphical representation of the double-shear test results on carbon steel bolts is presented in Figure 7.3-1.



(a) Mean single-shear vs. double-shear test results with both shear planes in the unthreaded bolt part

(b) Mean single-shear vs. double-shear test results with both shear planes in the threaded bolt part

Figure 7.3-1: Comparison between the single-shear test results and double-shear test results on carbon steel bolts and bolting assemblies in PC 8.8 and 10.9 with unthreaded or threaded bolt parts in the shear plane

7.3.5 Comparison between the interaction resistance of carbon and stainless steel bolts

It could be shown in [361, 414] that the proposed Stranghöner/Abraham bolt interaction equations for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022 [81], which were primarily developed for austenitic and duplex bolts, see (Eq. 6.5-1) for “unthreaded bolt part in the shear plane” and (Eq. 6.5-2) for “threaded bolt part in the shear plane”, are also capable to describe the interaction resistance of carbon steel bolts. The new interaction approach leads to a statistically verified and more economical design approach compared to the EN 1993-1-8 [72].

In the case that the unthreaded bolt part is located in the shear plane, a direct comparison shows that the data points for carbon steel bolts tend to be lower than those of stainless steel bolts close to the Renner/Lange approach, see (Eq. 3.5-17), and therefore, have lower load-bearing capacities under combined tensile and shear loading. In the case of high tensile ratios like 0° and 15°, the difference failure between carbon and stainless steel bolts becomes most evident: While austenitic stainless steel bolts fail predominantly in the unthreaded bolt part, and the higher shank load-bearing capacity can be activated here, carbon steel bolts always fail in the threaded bolt part under high tensile loading. Even under higher shear ratios, it is visible that the interaction resistance of carbon steel bolts in PC 4.6, 8.8 and 10.9 is generally lower than those of stainless steel bolts. On the contrary, no clear difference can be detected graphically for the interaction resistance of carbon and stainless steel bolts with threaded bolt parts in the shear plane. The scattering of the test data for carbon and stainless steel bolts across the different property classes is comparable, so it can be concluded that a consistent interaction approach is expedient.

7.4 New proposed harmonised design rules for the tension resistance of carbon steel bolts

7.4.1 General

In the following, the implemented studies for the statistical evaluation of the tension resistance of carbon steel bolts $F_{t,Rd}$ are outlined and complemented by a discussion of the normative revision process from the 1st and 2nd Eurocode generation to the proposed design rules in the frame of this thesis. Furthermore, an extended reliability analysis for the bolt tension resistance of carbon steel bolts according to EN 1990, Annex D is carried out.

7.4.2 Implemented studies and discussion of the normative revision process

An overview of considered experimental studies into the tension resistance $F_{t,Rd}$ of partially and fully threaded carbon steel bolts for the pre-Eurocode draft standard ENV 1993-1-1 from 1992 [415], the revision of Eurocode EN 1993-1-8 of 2005 [416] for connections and the proposed new design rules is presented in Table 7.4-1. In total, 347 tests into the tension resistance of carbon steel bolts were considered in the Background documentation/TNO-report to Eurocode 3 from 1988 [355, 411]. Unfortunately, no clear assignment to the experimental investigations is possible, as only the universities and institutes involved are named, but not the specific publications. Nevertheless, a classification could be proposed in Table 7.4-1 that most likely covers the relevant studies in the background document from 1988. On the contrary, 344 tensile tests are implemented in the background documentation to prEN 1993-1-8 for the revision of 2005 with clear assignment of the relevant studies (but lacking precise definition of which experiments were used in the subsets). In the framework of this thesis, the conducted statistical evaluation according to EN 1990, Annex D is based on a significantly extended database of 717 tests into the bolt tension resistance, more than twice as in the previous studies. Various experimental studies between 1971 and 2020 from the literature were used and supplemented by own experimental investigations at UDE-IML in this thesis. A detailed list of the studies and their specifications, like bolt types and standards, bolt dimensions and property classes for structural carbon steel bolts, has already been provided in Chapter 2.5.

Table 7.4-1: Overview of considered experimental studies investigations into the tension resistance of carbon steel bolts for prior revisions of EN 1993-1-8 and the proposed new design rules

Tension resistance of carbon steel bolts, $F_{t,Rd}$				
Revision process	**Bolt type and shear planes**	**Considered studies**	**Number of tests**	**Total test numbers**
Proposed design rules for carbon steel bolts in the frame of the thesis	Partially and fully threaded bolts	Bilderbeek, 1971 [222]	27	717
		Hassler, 1973 [223]	5	
		Shakir-Khalil and Ho, 1979 [225]	14	
		Scheer, 1980 [226]	145	
		Scheer, 1983 [228]	95	
		Knobloch/Schmidt, 1987-90 [171] to [173]	55	
		Petersen, 1989 [229]	5	
		Valtinat and Dangelmaier, 1990 [230]	31	
		Friede and Lange, 2010 [233]	13	
		Renner and Lange, 2012-19 [178] to [183]	26	
		Dörre et al., 2019 [175]	240	
		Li et al., 2020 [236, 237]	24	
		Song et al., 2020 [5]	6	
		UDE-IML, 2023	31	
Background documentation to prEN 1993-1-8 for the revision of 2005 [412]	Partially and fully threaded bolts	Scheer, 1980 [226]	145	344
		Scheer, 1983 [228]	60[1)]	
		Bijaard[2)], 1987 [417]	88	
		Knobloch/Schmidt, 1987 [171]	51[3)]	
Background documentation/TNO-report to Eurocode 3 from 1988 [355, 411]	Partially and fully threaded bolts	Presumed: Bilderbeek, 1971 [222]	-[4)]	347
		Presumed: Scheer, 1980 [226]	-[4)]	
		Presumed: Scheer, 1983 [228]	-[4)]	
		Presumed: Bijaard[2)], 1987 [417]	-[4)]	
		Presumed: Knobloch/Schmidt, 1987 [171]	-[4)]	

[1)] Only 60 of 95 tensile tests were considered in the Background documentation to prEN 1993-1-8 for the revision of 2005. The reasons for the reduced number of tests could not be clarified due to incomplete documentation. | [2)] Tensile tests on carbon steel bolts in PC 8.8 by Bijaard (report BI-84-76/63.4.3410) from TNO Institute Delft, Netherlands, could not be made available for detailed evaluation of the testing procedure and test results. | [3)] Only 51 of 55 tests from Knobloch/Schmidt were considered. The reasons for the reduced number of tests could not be clarified due to incomplete documentation. | [4)] Experimental studies are only presumed based on the given information in the background documentation/TNO-report to Eurocode 3 from 1988. Thus, the number of tests cannot be clearly assigned.

In the course of the introduction of the Eurocodes, the reduction factor $k_2 = 0.9$ was established for carbon steel bolts because in the statistical evaluation of the Background report/TNO-report to Eurocode 3 as “common unified rules for steel structures” conducted by Snijder et al. in 1988 [355, 411], the resulting partial safety factors γ_M* for carbon steel bolts exceeded the partial safety factor for connections of by 10 % in all defined subsets and over all 347 bolts. Therefore, the implemented reduction factor $k_2 = 0.9$ served to compensate for uncertainties and inaccuracies in the design concept of the tension resistance $F_{t,Rd}$ for carbon steel bolts leading to a partial safety factors over all bolts to $\gamma_M^* = 1.201 < \gamma_{M2} = 1.25$, which is still striking high. In the following revision process of EN 1993-1-8 from 2005, a reliability analysis (with a slightly modified statistical procedure compared to the current EN 1990, Annex D procedure) was conducted by Sedlacek and Schneider from the Institute of Steel Construction of the RWTH University of Aachen, Germany, in order to prove the resulting partial safety factor γ_M* against the safety element of $\gamma_{M2} = 1.25$, see [412]. However, the suitability of the design from 1988 regarding the required reduction down to 90 % for the tension resistance $F_{t,Rd}$ of carbon steel bolts was not critically re-evaluated in the reliability analysis.

The main results of both statistical evaluations are presented in Figure 7.4-1.

Background documentation/TNO-report to Eurocode 3 from 1988 [355, 411]
with $F_{t,Rd} = k_2 \cdot f_{ub} \cdot A_s / \gamma_{M2}$ or $F_{t,Rd} = k_2 \cdot f_{ub} \cdot A_s / \gamma_{M2}$

Table I.1.2: Statistical evaluation, eqn. (I.1.1), $F_t = f_{ub} A_s$.

(sub) sample	no. of tests	k_s	k_d	$\bar{b}$	V_δ	R_k	R_d	γ_M	ΔK	γ_M^*
11.0	347	1.64	3.04	0.988	0.100	0.786	0.645	1.218	1.095	1.334
11.1	141	1.64	3.04	1.058	0.103	0.783	0.641	1.222	1.026	1.254
11.2	12	1.64	3.04	0.907	0.042	0.830	0.711	1.167	1.130	1.318
11.3	120	1.64	3.04	0.947	0.060	0.821	0.698	1.177	1.093	1.286
11.4	74	1.64	3.04	0.933	0.046	0.830	0.712	1.166	1.097	1.279

The ΔK factors are about 10% greater than unity while γ_M^* factors are too great. Therefore it was decided to modify the strength function into:

$$F_{ts} = 0.9\, f_{ub} A_s \qquad \text{..... (I.1.2)}$$

(sub) sample	no. of tests	k_s	k_d	$\bar{b}$	V_δ	R_k	R_d	γ_M	ΔK	γ_M^*
12.0	347	1.64	3.04	1.098	0.100	0.786	0.645	1.218	0.986	1.201
12.1	141	1.64	3.04	1.176	0.103	0.783	0.641	1.222	0.924	1.129
12.2	12	1.64	3.04	1.008	0.042	0.830	0.711	1.167	1.017	1.186
12.3	120	1.64	3.04	1.052	0.060	0.821	0.698	1.177	0.984	1.157
12.4	74	1.64	3.04	1.037	0.046	0.830	0.712	1.166	0.987	1.151

Background documentation to prEN 1993-1-8 from 2004 [412] with $F_{t,Rd} = k_2 \cdot f_{ub} \cdot A_s / \gamma_{M2}$

(a) Tensile strength f_{ub} was not measured (that means the theoretical resistance function r_t is based on $f_{ub,nom}$)

	Standard approach	Tangent approach
Number of tests	344	
Mean value $\bar{b}$	1,109	
Coefficient of Variation V_δ	0,108	
γ_M^*	**1,169**	

(b) Tensile strength f_{ub} was measured (that means the theoretical resistance function r_t is based on $f_{ub,exp}$)

	Standard approach	Tangent approach
Number of tests	344	8
Mean value $\bar{b}$	1,153	1,290
Coefficient of Variation V_δ	0,0747	0,0947
γ_M^*	**1,033**	**0,969**

Figure 7.4-1: Main findings of the statistical evaluations from 1988 (above) and 2004 (below) regarding the tension resistance of carbon steel bolts according to [355, 411, 412]

Interestingly, the Eurocode 3 draft from 1984 ("Common Unified Rules for Steel Structures", Report EUR 8849) [354] proposed a reduction of the bolt tension resistance $F_{t,Rd}$ down to 80 % without any partial safety factor, while the "reformatted" Eurocode 3 draft from 1984 includes the partial safety factor $\gamma_{M2} = 1.25$ without further reduction. This shows that the first design approaches for carbon steel bolts in the pre-Eurocode did not reduce the tension resistance. In the revision process of EN 1993-1-8 from 2005, the reduction factor $k_2 = 0.9$ for the bolt tension resistance $F_{t,Rd}$ was maintained in the design, and the statistical evaluation confirms that even by neglecting overstrength (by replacing $f_{ub,exp}$ with $f_{ub,nom}$ in the theoretical resistance function r_t), the Eurocode safety requirements are fulfilled with $\gamma_M^* = 1.169 \leq \gamma_{M2} = 1.25$ for connections. In case the tensile overstrength of the carbon steel bolts is considered (as an integral part of the statistical evaluation and to mirror scatter appropriately), the partial safety factor γ_M^* over all bolts results in $\gamma_M^* = 1.033$, underlining the conservatism of this approach.

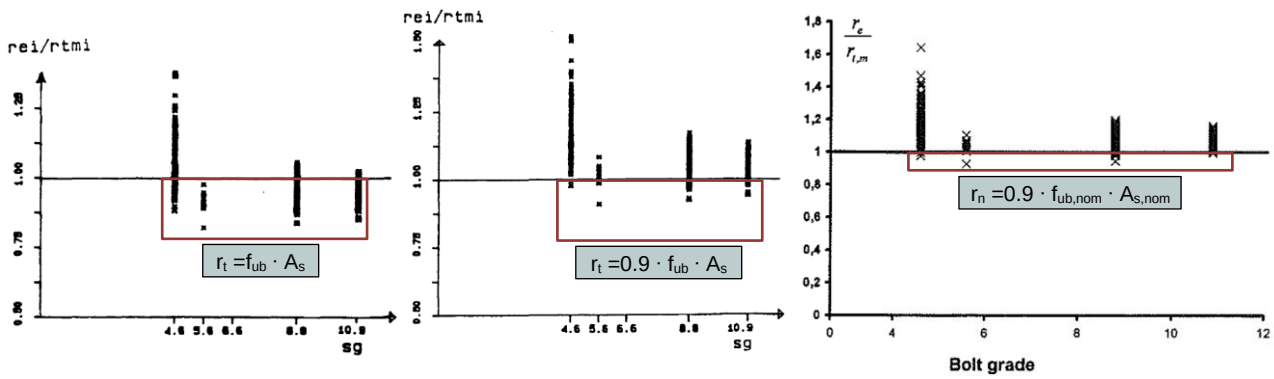
The question arises why the design regulation for the tension resistance of carbon steel bolts was not statistically re-evaluated by neglecting the reduction factor $k_2 = 0.9$ in order to allow a more economical design and to harmonise the design with the regulations of EN ISO 898-1 regarding the minimum ultimate tensile load $F_{m,min}$ and other international standards, as outlined in Chapter 3.3. Even after introducing the reduction factor of $k_2 = 0.9$, the strikingly

high partial safety factors γ_M* from the Background documentation/TNO-report from 1988 must be critically questioned. Herein, the statistical evaluation from 1988 follows the methodology of the TNO-report BI-87-112 "Procedure for the determination of design resistance from tests" from 1987 [418], which was later incorporated into EN 1990 in an adapted form. A closer look at the statistical procedure compared to EN 1990 shows only minor deviations in the estimation of the mean value correction factor b (Step 3), the estimation of the coefficient of variation of the errors V_δ (Step 4) and γ_M* as the product of a factor ΔK and the partial safety factor γ_M (as the ratio of the characteristic resistance r_k and the design resistance r_d). Factor ΔK from the TNO-report BI-87-112 was not implemented in EN 1990 in the further course. However, in comparative reliability analyses, it could be shown that methodical deviations are negligible for the resulting partial safety factors γ_M*. Consequently, the reason for the significantly higher partial safety factors γ_M* must be found in the test data and the assumptions for the geometrical and material-specific basic variables.

The scatter of the tensile strength $f_{ub,exp}$ was estimated in the past *"from preknowledge at $V_{X,fub}$ = 7 %",* which can be stated as too high based on the own experimental investigations and extended literature review on carbon steel bolts. However, as it is not retraceable in the TNO-report [355, 411] from which studies the subsets 11.0 and 12.0 were generated, a reconstruction of the statistical evaluation is impossible. Nevertheless, it can be shown in r_{ei}/r_{ti} sensitivity diagrams of the background documentation from 1988 that for the bolt tension resistance $F_{t,Rd}$ without reduction factor, most of the test data points for PC 5.6, 8.8 and 10.9 lie on the unsafe side with $r_{ei}/r_{ti} < 1$, as presented in Figure 7.4-2 (left). Here, it must be concluded that the carbon steel bolts in the statistical evaluation from 1988 did not mainly fulfil the normative requirements of the minimum ultimate tensile load $F_{m,min}$ as $f_{ub,nom} \cdot A_{s,nom}$.

For example, Knobloch/Schmidt [171–173] applied in their studies also unthreaded rods made of different steel grades to simulate bolt material in various property classes (St 37-2 for PC 4.6, St 52-3 for PC 5.6, C45 for PC 8.8 and 42CrMo4 for PC 10.9). Furthermore, the tested threaded rods in PC 5.6 and 10.9 did not fulfil the minimum ultimate tensile load and bolt elongation at fracture. Mainly r_{ei}/r_{ti} ratios higher than 1 over all bolts result in the background documentations from 1988 and 2004 if the reduction factor of $k_2 = 0.9$ is implemented in the r_t function; see Figure 7.4-2 (middle and right). Furthermore, the high scatter of the coefficient of variation of the errors of $V_\delta = 0.1$ over all bolts (specified as subset 11.0) is striking in the background documentation from 1988, see Figure 7.4-1. If $V_\delta = 0.1$ is adopted in the reliability analysis for the bolt tension resistance over all bolts based on own experimental investigations and extended literature review in the frame of this thesis (as an outlook to Chapter 7.4), the resulting partial safety factors γ_M* increase significantly from γ_M* = 0.99 to γ_M* = 1.18 if $V_\delta = 0.1$ is applied (instead of $V_\delta = 0.0074$), or even from γ_M* = 1.14 to γ_M* = 1.29 > γ_{M2} = 1.25 if the tensile overstrength of the bolts is neglected. Consequently, introducing the reduction factor of $k_2 = 0.9$ would be imperative here. Unfortunately, due to the lack of documentation, the reason for the high coefficient of variation of the errors V_δ cannot be identified. The substitution of experimental values r_{ei} by nominal values r_{ni}, e.g. for the tensile strength f_{ub}, can be a possible explanation, which would also explain the striking high partial safety factors from the 1988 revision.

It can therefore be concluded that the combination of the high coefficient of variation of the tensile strength $V_{X,fub}$ with the high scatter of the test data basis (indicated by $V_\delta = 0.1$) plus the implementation of test data that do not fulfil the requirements of EN ISO 898-1:1979 [419] regarding the minimum ultimate tensile load $F_{m,min}$ (or which is based on nominal instead of experimental basic variables) leads to disproportionately high partial safety factors, which must be seen critically and are disproved by own statistical evaluations.



(a) Background documentation/TNO-report to EC-3 from 1988 [355, 411] (n = 347, subset 11.0)

(b) Background documentation/TNO-report to EC-3 from 1988 [355, 411] (n = 347, subset 12.0)

(c) Background documentation to prEN 1993-1-8 from 2004 [412] (n = 344, subset 11.10)

Figure 7.4-2: Comparison of the sensitivity diagrams for all evaluated bolt property classes based on the background documentations to Eurocode 3 from 1988 and prEN 1993-1-8 from 2004

7.4.3 Extended reliability analysis for the bolt tension resistance

The required definitions of the theoretical r_t and nominal r_n resistance functions regarding the statistical evaluation of the tension resistance of carbon steel bolts are identical to those for stainless steel bolts, as already outlined in Chapter 4.7.5.2. Furthermore, the scatter V_{Xi} of the material-specific and geometrical basic variables $\underline{X}$ was estimated *"from preknowledge"* to COV (f_{ub}) = 7.0 %, COV (A) = 0.5 % and COV (A_s) = 1.0 % in the Background documentation/ TNO-report to Eurocode 3 from 1988. From today's perspective and considering the improved bolt manufacturer's quality assessment, the coefficient of variation of the tensile strength COV (f_{ub}) seems unreasonable and far too conservative.

Therefore, all basic variables were rechecked by own and more recent experimental studies in [414, 413]. It was found that the maximum coefficient of variation of the tensile strength for carbon steel bolts can be observed for Scheer (1983) [228] with max. COV(f_{ub}) = 3.6 %. Consequently, for the statistical evaluation according to EN 1990, Annex D, a constant maximum scatter of COV(f_{ub}) = 4.0 % was assumed for all bolts on the safe side. Additionally, the resulting coefficients of variation of the measured cross-sectional area A_{meas} and tensile stress area $A_{s,meas}$ of partially and fully threaded carbon steel bolts were re-evaluated based on own experimental investigations and those from Knobloch/Schmidt [171]. It could be concluded that the maximum coefficient of variation of the measured cross-sectional areas is max. COV (A; A_s) = 0.7 %, see [414, 413]. Finally, a constant value of COV (A; A_s) = 1.0 % was assumed for the statistical evaluation. This aligns with the geometrical COV considered for the reliability analyses for austenitic and duplex stainless steel bolts.

Finally, the results of the reliability analysis for the tension resistance of carbon steel bolts in PC 4.6, 5.6, 8.8, 10.9 and 12.9 including literature data are summarised in Table 7.4-2. Herein, the reduction factor k_2 according to EN 1993-1-8 is stepwise increased from k_2 = 0.9 to k_2 = 1.0 (as the proposed approach for carbon steel bolts and harmonised with FprEN 1993-1-4), k_2 = 1.1 and k_2 =1.2 in order to evaluate the resulting partial safety factors γ_M* against the partial safety factor γ_{M2} = 1.25 for connections. In the frame of this thesis, an increased dataset of 717 tensile tests from own experimental investigations and literature became available for statistical evaluation. For this large number of available tensile tests (n ≥ 100), the simplified formula for obtaining the design value r_d given in (Eq. E.12) was applied with a fractile factor of $k_{d,n}$ = 3.04 for an infinite number of tests.

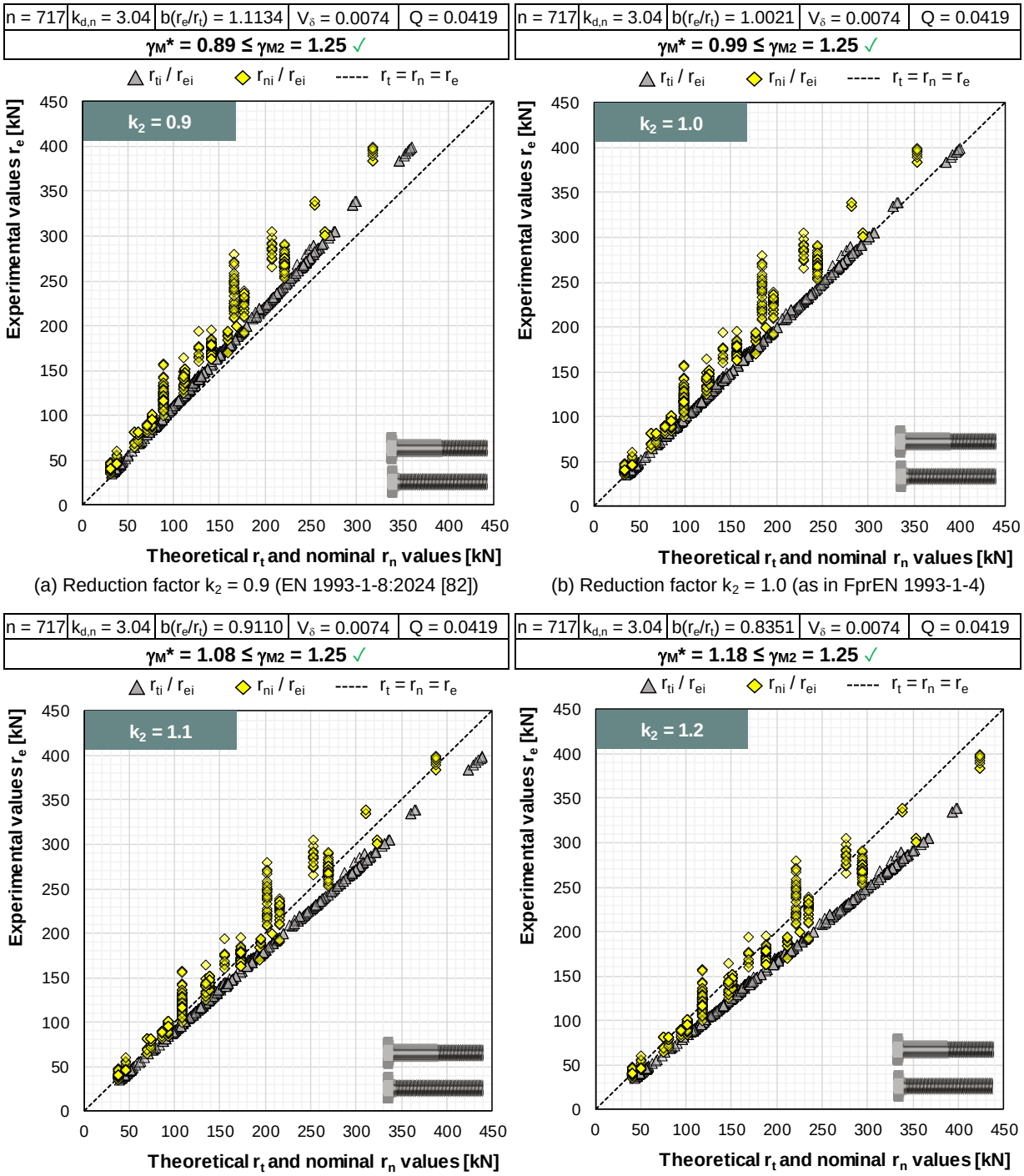
Table 7.4-2: Summary of the extended reliability analysis for the tension resistance of carbon steel bolts with maximum COV (f_{ub}) = 4 % and maximum COV (A_s) = 1 %

PC	Number of tests	k_2 = 0.9			k_2 = 1.0			k_2 = 1.1			k_2 = 1.2		
		γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]	γ_M* [-]
PC 4.6	198	0.83	0.86	**0.89**	0.93	0.96	**0.99**	1.02	1.05	**1.08**	1.11	1.15	**1.18**
PC 5.6	126	0.90			1.00			1.10			1.20		
PC 8.8	107	0.88	0.91		0.98	1.01		1.07	1.11		1.17	1.21	
PC 10.9	274	0.92			1.02			1.12			1.23		
PC 12.9	12	0.97			1.08			1.18			1.29		

In order to improve comparability, the resulting partial safety factors γ_M* of Table 7.4-2 are separately evaluated in subsets for each bolt property class and finally over all bolts for an in-depth analysis of the distribution of the γ_M* values. The determined partial safety factors γ_M* are in all subsets and over all bolts even for k_2 = 1.2 below γ_{M2} = 1.25 on the safe side except for carbon steel bolts in PC 12.9 with k_2 = 1.2 leading to γ_M* = 1.29 > γ_{M2} = 1.25. However, bolts in PC 12.9 are currently not approved according to EN 1993-1-8 due to the lower ductility and the risk of hydrogen embrittlement but were also considered in the context of these investigations. Furthermore, an extended comparison of the experimental and theoretical values (r_e/r_t) as well as experimental and nominal values (r_e/r_n) for carbon steel bolts with k_2 = 0.9 / 1.0 / 1.1 / 1.2 is provided in Figure 7.4-3.

It can be shown that the mean value correction factor for a reduction factor of k_2 = 1.0 is about b(r_e/r_t) = 1.0021 showing nearly a perfect agreement between the data points of the theoretical r_{ti} and experimental r_{ei} tension resistance of each tested carbon steel bolt lying on the angle bisector with negligible scattering. For k_2 = 0.9, the r_{ti} / r_{ei} data points lie above the angle bisector with b(r_e/r_t) = 1.1134 on the safe but noneconomical side. On the contrary, the r_{ti} / r_{ei} data points shift below the angle bisector with b(r_e/r_t) = 0.9110 for k_2 = 1.1 and even b(r_e/r_t) = 0.83515 for k_2 = 1.2. Nevertheless, the resulting partial safety factors γ_M* over all bolts are still below γ_{M2} = 1.25 for connections.

Analogues to austenitic and duplex stainless steel bolts, it can be concluded that the resistance function with k_2 = 1.0 seems to be most suitable to describe the tension resistance of carbon steel bolts and still includes sufficient safety reserves against bolt overstressing or failure due to prying effects, eccentricity, bending of the bolt and/or imperfections. Herein, an entirely harmonisation of the bolt tension resistance $F_{t,Rd}$ between carbon steel bolts and stainless steel bolts according to FprEN 1993-1-4 as well as between the product standards EN ISO 898-1 and EN ISO 3506-1 regarding the minimum ultimate tensile loads can be achieved. Furthermore, the proposed tension design approach with k_2 = 1.0 is in alignment with international major standards like North American ANSI/AISC 370, AISC Design Guide 27 and SEI/ASCE 8 and Australian/New Zealand AS/NZS 4673 and other standards.



(a) Reduction factor k_2 = 0.9 (EN 1993-1-8:2024 [82])

(b) Reduction factor k_2 = 1.0 (as in FprEN 1993-1-4)

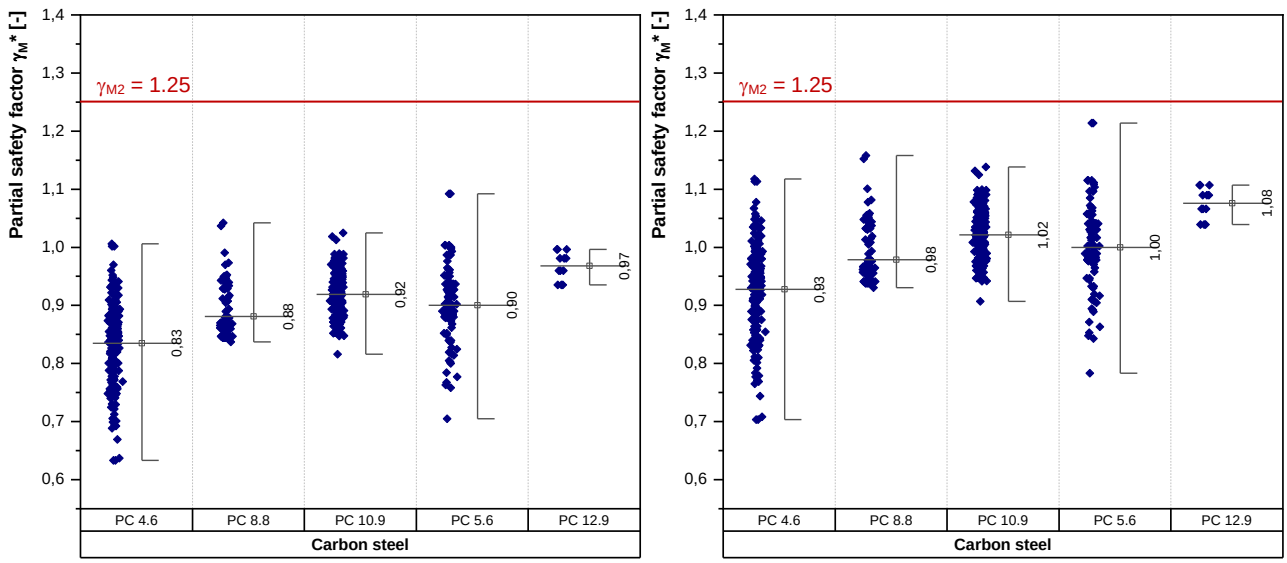
(c) Reduction factor k_2 = 1.1

(d) Reduction factor k_2 = 1.2

Figure 7.4-3: Comparison of the experimental r_e and theoretical r_t/nominal r_n tension resistances for carbon steel bolts based on tensile tests according to EN ISO 898-1 and literature data

In order to present the distribution of the resulting individual partial safety factors $\gamma_{M,i}$* over all carbon steel across all investigated bolt property classes for k_2 = 0.9 and k_2 = 1.0, the individual data points of each tested bolt and from literature data are summarised graphically in Figure 7.4-4 including plots of the range and resulting partial safety factor mean values γ_M*. In both cases it can be shown that all individual partial safety factors $\gamma_{M,i}$* are clearly below γ_{M2} = 1.25 in all investigated property classes 4.6, 5.6, 8.8, 10.9 and 12.9. Since the individual partial safety factors $\gamma_{M,i}$* are not exceeding γ_{M2} = 1.25, a further evaluation is not imperative. A statistical evaluation of the tension resistance of carbon steel bolts $F_{t,Rd}$ without consideration of tensile overstrength was also carried out informatively and still leads to partial safety factors

of γ_M* = 1.14 (n = 717, $k_{d,n}$ = 3.04, b(r_e/r_t) = 1.1353, V_δ = 0.0723, Q = 0.0831) below γ_{M2} = 1.25 on the safe side.



(a) Distribution of γ_M* for each bolt property class with k_2 = 0.9 based on the reliability analysis over all bolts

(b) Distribution of γ_M* for each bolt property class with k_2 = 1.0 based on the reliability analysis over all bolts

Figure 7.4-4: Distribution of the partial safety factors γ_M* of carbon steel bolts for each property class with k_2 = 0.9 and k_2 = 1.0 based on the tensile tests according to EN ISO 898-1 and literature data

7.5 New proposed harmonised design rules for the shear resistance of carbon steel bolts

7.5.1 General

Analogues to the statistical investigations into the tension resistance $F_{t,Rd}$ of carbon steel bolts, in the following the implemented studies for the statistical evaluation of the shear resistance of carbon steel bolts $F_{v,Rd}$ are outlined and supplemented by a brief discussion of the normative revision process. Finally, an extended reliability analysis according to EN 1990, Annex D for the bolt shear resistance of carbon steel bolts with unthreaded and threaded bolt part in the shear plane is carried out based on additional double-shear tests at UDE-IML and an extended literature review in the frame of this thesis.

7.5.2 Implemented studies and discussion of the normative revision process

A comprehensive overview of considered experimental studies into the shear resistance $F_{v,Rd}$ of carbon steel bolts with unthreaded and threaded bolt part in the shear plane for the pre-Eurocode draft standard ENV 1993-1-1 from 1992 [415], the revision of EN 1993-1-8 from 2005 [416] and the proposed new design rules is presented in Table 7.5-1. In total, 283 single- and double-shear tests on carbon steel bolts with unthreaded or threaded part in the shear plane were considered in the Background documentation/TNO-report to Eurocode 3 from 1988. Analogues to the tension resistance, again no clear assignment to the experimental investigations is possible, as only the universities and institutes involved are named, but not the specific publications. Nevertheless, a classification could be proposed in Table 7.5-1 that most likely covers the relevant studies in the background document from 1988. In contrast, 278 shear tests are implemented in the background documentation to prEN 1993-1-8 for the revision of 2005 with clear assignment of the relevant studies (but again lacking precise definition of which experiments were used in the subsets and for which reason a slight reduction of the database was conducted).

However, in this thesis, the conducted statistical evaluation according to EN 1990, Annex D is based on a significantly extended database of in total 723 tests into the bolt shear resistance, more than double as in the previous studies. The extended statistical validation is based on various experimental studies between 1971 and 2020, which were not considered in a statistical re-evaluation up to now and supplemented by own experimental investigations at UDE-IML for this thesis. A detailed list of studies and their specifications, like bolt types and standards, bolt dimensions and property classes for structural carbon steel bolts, has already been provided in Chapter 2.5.

Table 7.5-1: Overview of considered experimental studies investigations into the shear resistance of carbon steel bolts for prior revisions of EN 1993-1-8 and the proposed new design rules

Shear resistance of carbon steel bolts, $F_{v,Rd}$				
Revision process	**Bolt type and shear planes**	**Considered studies**	**Number of tests**	**Total test numbers**
Proposed design rules for carbon steel bolts in the frame of the thesis	Partially threaded bolts with unthreaded part in the shear plane	Bilderbeek, 1971 [222]	24	363
		Hassler, 1973 [223]	5	
		Shakir-Khalil and Ho, 1979 [225]	7	
		Knobloch/Schmidt, 1987-90 [171] to [173]	55	
		Friede and Lange, 2010 [233]	13	
		Renner and Lange, 2012-19 [178] to [183]	25	
		Dörre et al., 2019 [175]	177	
		Li et al., 2020 [236, 237]	21	
		Song et al., 2020 [5]	3	
		UDE-IML, 2023 [414] + supplement. tests	33	
	Fully threaded bolts with threaded part in the shear plane	Bilderbeek, 1971 [222]	19	360
		Shakir-Khalil and Ho, 1979 [225]	4	
		Knobloch/Schmidt, 1987-90 [171] to [173]	40	
		Valtinat and Dangelmaier, 1990 [230]	120	
		Renner and Lange, 2012-19 [178] to [183]	23	
		Dörre et al., 2019 [175]	115	
		Li et al., 2020 [236, 237]	6	
		Song et al., 2020 [5]	3	
		UDE-IML, 2023 [414] + supplement. tests	30	
Background documentation to prEN 1993-1-8 for the revision of 2005 [412]	Partially and threaded bolts with unthreaded or threaded part in the shear plane	Bilderbeek, 1971 [222]	46	278[1)]
		Rhodes and Harvey,1974 [224]	36	
		Shakir-Khalil & Ho, 1979 [225]	7	
		Scheer, 1980 [226]	86	
		Knobloch/Schmidt, 1987 [171]	95	
Background documentation/TNO-report to Eurocode 3 from 1988 [355, 411]	Partially and threaded bolts with unthreaded or threaded part in the shear plane	Presumed: Bilderbeek, 1971 [222]	-[2)]	283
		Presumed: Rhodes and Harvey,1974 [224]	-[2)]	
		Presumed: Shakir-Khalil & Ho, 1979 [225]	-[2)]	
		Presumed: Scheer, 1980 [226]	-[2)]	
		Presumed: Knobloch/Schmidt, 1987 [171]	-[2)]	

[1)] Eight shear tests with unthreaded bolt part in the shear plane were conducted by /24/ of the background documentation to prEN 1993-1-8 for the revision of 2005. However, the reference /24/ is not listened in the literature overview. It is presumed that the tests were conducted by Valtinat from the Technical University of Hamburg. | [2)] Experimental studies are only presumed based on the given information in the background documentation/TNO-report to Eurocode 3 from 1988. Thus, the number of tests cannot be clearly assigned.

The investigations of Scheer [226, 228] from 1980/1983 as well as the experimental studies of Petersen [229] from 1989 are not considered in the statistical re-evaluation since the testing specifications do mainly focus on unsupported or supported bolted shear connections.

During the normative process from the background documentation/TNO-report to Eurocode 3 from 1988 up to the revised draft version EN 1993-1-8:2024, the design rules regarding the shear resistance $F_{v,Rd}$ of carbon steel bolts has been maintained: The shear coefficient α for all property classes of carbon steel bolts with unthreaded bolt part in the shear plane is defined

as α = 0.6, while the shear coefficient for bolts with threaded bolt part in the shear plane must be distinguished into α = 0.6 for PC 4.6, 5.6 and 8.8, and α = 0.5 for PC 4.8, 5.8, 6.8 and 10.9. Primary, higher shear coefficients of α = 0.7 for both the unthreaded and threaded bolt part were intended in the background documentation/TNO-report but had to be reduced to fulfil the requirements of $\gamma_M^* \leq \gamma_{M2}$ = 1.25. Analogues to the bolt tension resistance, also the design shear resistance $F_{v,Rd}$ of carbon steel bolts was not critically re-evaluated during the last revision processes of EN 1993-1-8.

7.5.3 Extended reliability analysis for the bolt shear resistance for the unthreaded bolt part in the shear plane

All definitions of the theoretical r_t and nominal r_n resistance functions regarding the statistical evaluation of the shear resistance of carbon steel bolts with unthreaded bolt part in the shear plane are identical to those for austenitic and duplex stainless steel bolts, as already outlined in Chapter 5.8.2.2. Analogues to the tension resistance of carbon steel bolts, again constant maximum scatters of COV(f_{ub}) = 4.0 % and COV (A; A_s) = 1.0 % are assumed for all bolts on the safe side (cf. Chapter 7.4.3).

In the following, three reliability analyses according to EN 1990, Annex D are carried out based on an extended test database of 363 tests (instead of 314 tests considered in [414]): In the first instance, the resulting partial safety factors γ_M^* are presented if the shear coefficients of EN 1993-1-8 are considered in the statistical evaluation. Secondly, the resulting partial safety factors γ_M^* are summarised for the case that the shear coefficients are increased for all PC to α = 0.7, as primary proposed by the background documentation/TNO-report from 1988. And thirdly, the more economical shear coefficients of α = 0.7 for PC 4.6 and 5.6 as well as α = 0.65 for PC 8.8, 10.9 (and PC 12.9 informative) are implemented in the reliability analyses, as proposed in [414, 413], and the resulting partial safety factors are discussed. The main results of the statistical evaluations including mean value correction factors b, the coefficients of variation of errors V_δ and scattering parameters Q are summarised in Table 7.5-2.

It can be shown that the resulting partial safety factors γ_M^* for all investigated approaches and for all defined subsets of each property class are below the partial safety factor γ_{M2} = 1.25 for connections. The highest partial safety factors γ_M^* for all approaches can be observed for PC 4.6 (e.g. γ_M^* = 1.21 for the proposed approach and the initial approach from the TNO-report) and PC 10.9 (e.g. γ_M^* = 1.14 for the proposed approach and γ_M^* = 1.23 for the initial approach from the TNO-report). However, if the partial safety factors γ_M^* for all available test data of carbon steel bolts with unthreaded bolt part in the shear plane are determined over all property class, the initial approach from the TNO-report with unified shear coefficients of α = 0.70 results to γ_M^* = 1.31 on the unsafe side exceeding γ_{M2} = 1.25 (even if PC 12.9 is removed from the database).

Nevertheless, the resulting partial safety factors γ_M^* over all property classes for the design rule of EN 1993-1-8 and the proposed approach are below γ_{M2} = 1.25 on the safe side. The extent to which these approaches withstand an extended safety assessment (e.g. with regard to exceeding individual partial safety factors $\gamma_{M^*,i}$ above γ_{M2} = 1.25) will be discussed later.

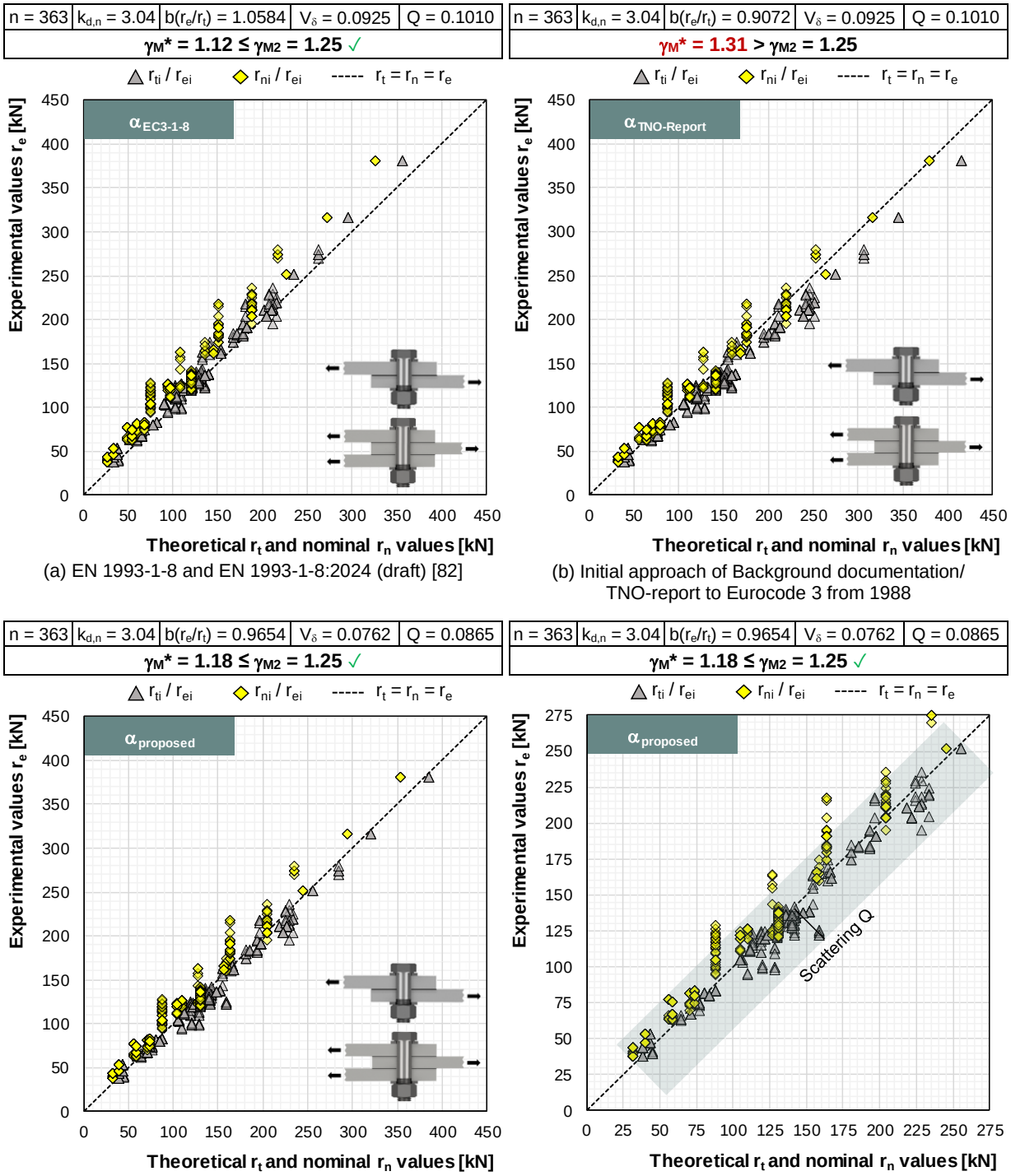
Table 7.5-2: Summary of the extended reliability analysis for the shear resistance of carbon steel bolts with unthreaded bolt part in the shear plane considering maximum COV (f_{ub}) = 4 % and maximum COV (A) = 1 %

Design approach	PC	Number of tests n	α [-]	b (r_e/r_t) [-]	V_δ [-]	Q [-]	γ_M^* [-]	γ_M^* [-]
EN 1993-1-8	**PC 4.6**	87	0.60	1.0914	0.1088	0.1159	1.03	**1.12**
	PC 5.6	55		1.1872	0.0807	0.0904	1.00	
	PC 8.8	75		0.9876	0.0398	0.0572	1.03	
	PC 10.9	134		1.0286	0.0392	0.0568	1.06	
	PC 12.9[1)]	12		1.0720	0.0109	0.0426	1.00	
Initial approach of Background documentation/ TNO-report from 1988 [355, 411]	**PC 4.6**	87	0.70	0.9355	0.1088	0.1159	1.21	**1.31**
	PC 5.6	55		1.0176	0.0807	0.0904	1.17	
	PC 8.8	75		0.9170	0.0398	0.0572	1.11	
	PC 10.9	134		0.8816	0.0392	0.0568	1.23	
	PC 12.9[1)]	12		0.9189	0.0109	0.0426	1.17	
Proposed	**PC 4.6**	87	0.70	0.9355	0.1088	0.1159	1.21	**1.18**
	PC 5.6	55		1.0176	0.0807	0.0904	1.17	
	PC 8.8	75	0.65	0.9876	0.0398	0.0572	1.03	
	PC 10.9	134		0.9495	0.0392	0.0568	1.14	
	PC 12.9[1)]	12		0.9896	0.0109	0.0426	1.08	

[1)] PC 12.9 is excluded in EN 1993-1-8 for the application in steel structures. Nevertheless, PC 12.9 was considered in the statistical evaluations according to EN 1990, Annex D with the given shear coefficients α.

Additionally, comparisons of the experimental and theoretical values (r_e/r_t) aligned with experimental and nominal values (r_e/r_n) for the shear resistance $F_{v,Rd}$ of carbon steel bolts with unthreaded part in the shear plane for EN 1993-1-8, the initial approach of the background documentation/TNO-report from 1988 and the proposed approach in the frame of this thesis (see also in [414, 413]) are provided in Figure 7.5-1. Herein, the most relevant parameters of the statistical evaluations according to EN 1990, Annex D are given to allow comparisons of the mean value correction factor b and the scattering parameters V_δ (informative) and Q for the simplified design resistance value r_d. Furthermore, an illustration of the scattering of the experimental r_e and theoretical r_t shear resistances in the relevant range for the proposed approach is presented in Figure 7.5-1 (d).

The mean value correction factor b for the shear resistance of carbon steel bolts with unthreaded part in the shear plane of the EN 1993-1-8 approach is about b(r_e/r_t) = 1.0584 with a scattering of Q = 0.1010 and V_δ = 0.0925. The r_e/r_t values are mainly on or above or only partially below the angle bisector. However, all r_e/r_n values lie above the angle bisector on the safe but also non-economical side. If the (more economical) initial approach of the background documentation/TNO-report is applied, all r_e/r_t values shift below the angle bisector on the unsafe side, while the r_e/r_n values lie above or on the angle bisector. The mean value correction factor b of the initial approach of the TNO-report results to b(r_e/r_t) = 0.9072. The proposed approach in the frame of this thesis for carbon steel bolts shows r_e/r_t values mainly on or partially below the angle bisector with b(r_e/r_t) = 0.9654 and reduced scattering of Q = 0.0865 and V_δ = 0.0762, see the scattering band in Figure 7.5-1 (d). Therefore, it can be concluded that based on a comparison of the experimental r_e and theoretical r_t/nominal r_n shear resistances for carbon steel bolts and bolting assemblies the proposed approach with higher shear coefficients α compared to EN 1993-1-8 allows a more economical design of the shear resistance $F_{v,Rd}$ of carbon steel bolts with unthreaded part in the shear plane.



(a) EN 1993-1-8 and EN 1993-1-8:2024 (draft) [82]

(b) Initial approach of Background documentation/ TNO-report to Eurocode 3 from 1988

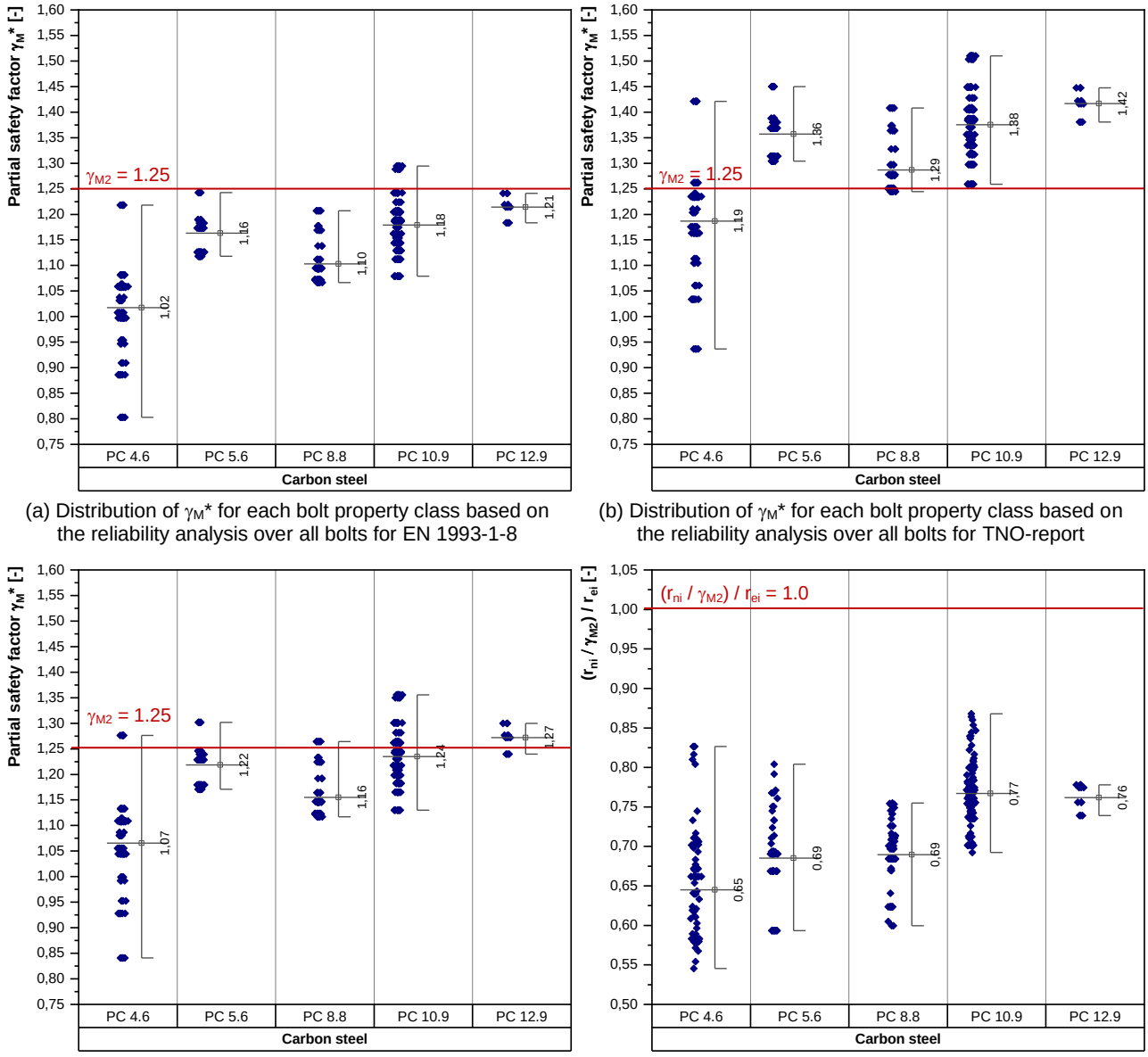
(c) Proposed approach for the shear resistance of carbon steel bolts with unthreaded bolt part in the shear plane

(d) Illustration of the scattering of the experimental r_e and theoretical r_t shear resistances for the proposed approach in the relevant range

Figure 7.5-1: Comparison of the experimental r_e and theoretical r_t/nominal r_n shear resistances for carbon steel bolts and bolting assemblies including literature data for the unthreaded part in the shear plane

In order to present the distribution of the resulting individual partial safety factors $\gamma_{M,i}$* over all bolts and bolting assemblies across all investigated bolt property classes for the design rule of EN 1993-1-8, the initial approach of the background documentation/TNO-report from 1988 and the proposed approach in the frame of this thesis, all individual data points of each tested bolt and from literature are summarised graphically in Figure 7.5-2 including plots of the range and resulting partial safety factor mean values γ_M*.

Plots of the range and resulting partial safety factor mean values γ_M* based on the reliability analysis over all bolts are informatively included (which can not be compared with the partial safety factors γ_M* from the subsets given in Table 7.5-2).



(a) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for EN 1993-1-8

(b) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for TNO-report

(c) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for the proposed approach

(d) Distribution of the ratio of the individual nominal design r_{ni}/γ_{M2} and experimental r_{ei} results for the proposed approach

Figure 7.5-2: Distribution of the partial safety factors γ_M* of carbon steel bolts regarding the shear resistance $F_{v,Rd}$ with unthreaded bolt part in the shear plane for each property class

It can be seen that all individual partial safety factors $\gamma_{M,i}$* of the current EN 1993-1-8 design approach with exception of PC 10.9 are below γ_{M2} = 1.25. However, the $\gamma_{M,i}$* values of the initial TNO-report approach are clearly exceeding γ_{M2} = 1.25 in all property classes, if the reliability analysis is conducted over all bolts (which leads generally to higher partial safety factors due to the increased impact of scattering). The proposed approach in the frame of this thesis shows partially exceeding of individual partial safety factors $\gamma_{M,i}$* in all property classes but seems to be a good compromise between both approaches mentioned above, which still allows a more economic design by utilizing higher shear resistances for all property classes.

Nevertheless, in order to assess the quality of the design approaches (EN 1993-1-8, TNO-report and the proposed approach) regarding the shear resistance $F_{v,Rd}$ of carbon steel bolts with unthreaded part in the shear plane, and to check if partially individual exceeding of

γ_{M2} = 1.25 may be critical, the modified assessment criteria introduced in Chapter 4.7.4 are again applied. The results of the evaluation are presented in Table 7.5-3. It could be verified in a plausibility check (as criterion III in Figure 7.5-2 (d)) that all nominal design values (r_{ni}/γ_{M2}) for all approaches are clearly below r_{ei}. Therefore, always sufficient safety reserves are guaranteed. However, criterion I and II both failed for the initial approach of the TNO-report with increased shear coefficients of α = 0.70 over all property class. As a conclusion, the initial approach of the TNO-report must be rejected, while the current EN 1993-1-8 approach is too conservative. On the contrary, the proposed approach in the frame of this thesis for a future revision of EN 1993-1-8 is fulfilling all criteria and allows a more economical but safe and reliable design of the shear resistance of carbon steel bolts with unthreaded bolt part in the shear plane.

Table 7.5-3: Evaluation of the reliability analysis for the shear resistance of carbon steel bolts with unthreaded bolt part in the shear plane according to the modified the evaluation criteria

Evaluation criteria (Chapter 4.7.4)		EN 1993-1-8	Initial approach of the TNO-report	Proposed
I	Maximum error ≤ 1.15 · γ_{M2}	1.29 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.51 ≤ 1.15 · γ_{M2} = 1.44 ↯	1.36 ≤ 1.15 · γ_{M2} = 1.44 ✓
II	Maximum number of unsafe results ≤ 20 %	3.6 % ≤ 20 % ✓	71.4 % ≤ 20 % ↯	19.3 % ≤ 20 % ✓
III	Plausibility check	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓

7.5.4 Extended reliability analysis for the bolt shear resistance for the threaded bolt part in the shear plane

Analogues to carbon steel bolts with unthreaded bolt portion in the shear plane, again all definitions of the theoretical r_t and nominal r_n resistance functions of austenitic and duplex stainless steel bolting assemblies are adopted, see Chapter 5.8.2.2. Maximum scatters of the material-specific and geometrical basic variable are considered based on preliminary statistical analyses with COV(f_{ub}) = 4.0 % and COV (A_s) = 1.0 % for all bolts on the safe side.

Again, three reliability analyses according to EN 1990, Annex D are carried out based on an extended test database of 360 tests (instead of 211 tests considered in [414]) regarding the approaches of EN 1993-1-8, the initial approach of the background documentation/TNO-report from 1988 with increased shear coefficients for all PC to α = 0.7, and thirdly, the more economical shear coefficients of α = 0.7 for PC 4.6 and 5.6 as well as α = 0.65 for PC 8.8, 10.9 (and PC 12.9 informative) as proposed in [414, 413]. The main results of the statistical evaluations including mean value correction factors b, the coefficients of variation of errors V_δ and scattering parameters Q are summarised in Table 7.5-4 complemented by discussions of the resulting partial safety factors γ_M* in order to allow a more economical but also safe and reliable design which consistently fulfils the safety requirements of the Eurocode.

Analogues to carbon steel bolts with unthreaded part in the shear plane, it can be shown that also for carbon steel bolts with threaded part in the shear plane the resulting partial safety factors γ_M* for all defined subsets of each property class are below or equal γ_{M2} = 1.25 for connections. The highest partial safety factors γ_M* for all approaches can be observed for PC 10.9 (e.g. γ_M* = 1.16 for the proposed approach and γ_M* = 1.25 for the initial approach from the TNO-report) and PC 12.9 (e.g. γ_M* = 1.14 for the proposed approach and γ_M* = 1.23 for the initial approach from the TNO-report). However, if again the partial safety factors γ_M* for all available test data of carbon steel bolts with threaded bolt part in the shear plane are determined over all property class, the initial approach from the TNO-report with unified shear coefficients of α = 0.70 results to γ_M* = 1.34 on the unsafe side exceeding γ_{M2} = 1.25 (even if PC 12.9 is not considered in the database). On the contrary, the resulting partial safety factors

γ_M* over all bolts and property classes for EN 1993-1-8 and the proposed approach are below γ_{M2} = 1.25 on the safe side. The extent to which these design approaches withstand an extended safety assessment will be discussed later.

Table 7.5-4: Summary of the extended reliability analysis for the shear resistance of carbon steel bolts with threaded bolt part in the shear plane considering maximum COV (f_{ub}) = 4 % and maximum COV (A) = 1 %

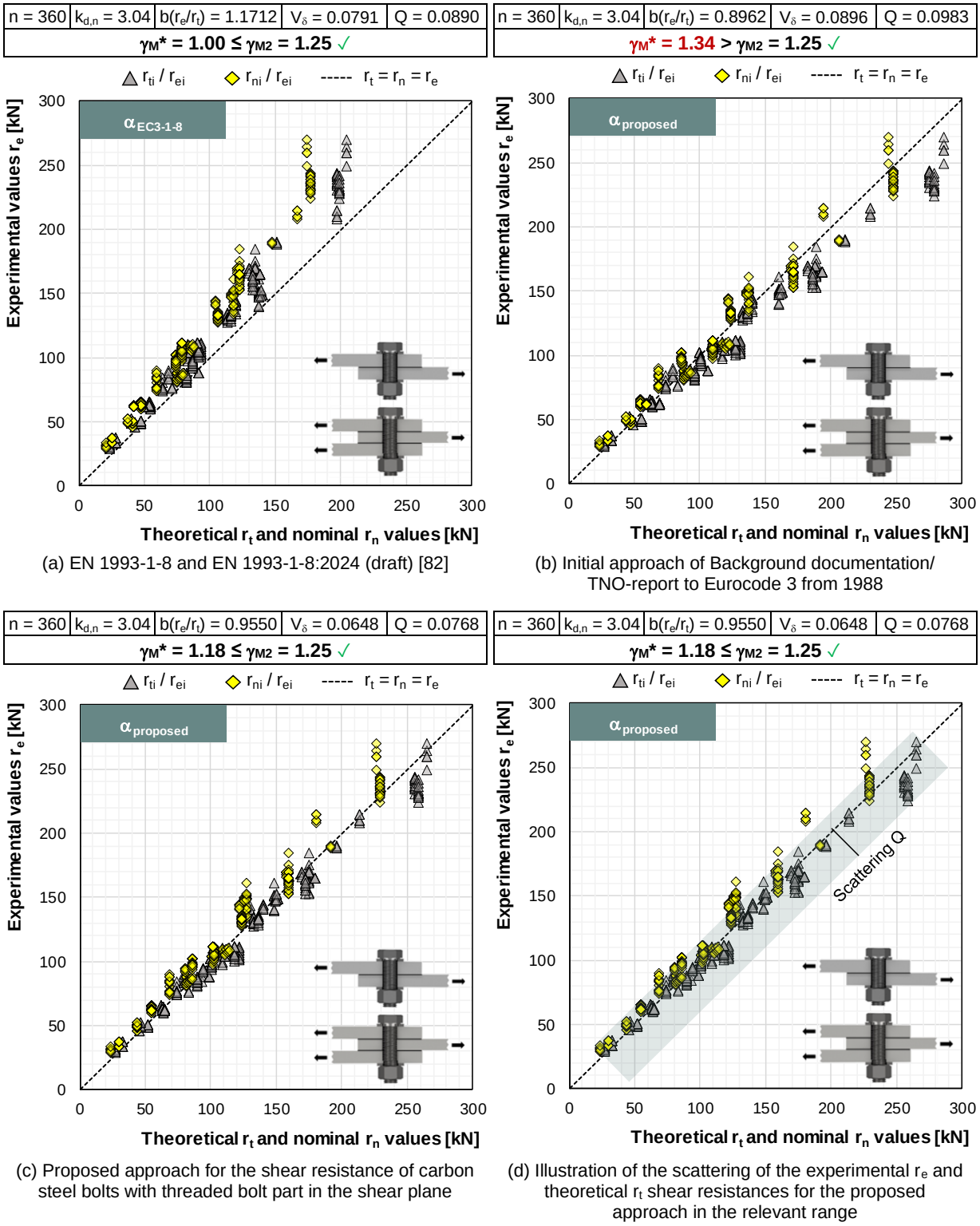
Design approach	PC	Number of tests n	α [-]	b (r_e/r_t) [-]	V_δ [-]	Q [-]	γ_M* [-]	γ_M* [-]
EN 1993-1-8	**PC 4.6**	28	0.60	1.2065	0.0813	0.0910	0.97	**1.00**
	PC 5.6	100		1.1640	0.0490	0.0640	0.93	
	PC 8.8	87		1.0657	0.0470	0.0624	0.99	
	PC 10.9	142	0.50	1.2140	0.0470	0.0624	0.89	
	PC 12.9[1)]	3		1.2612	0.0053	0.0415	0.88	
Initial approach of Background documentation/ TNO-report from 1988 [355, 411]	**PC 4.6**	28	0.70	1.0342	0.0813	0.0910	1.13	**1.34**
	PC 5.6	100		0.9977	0.0490	0.0640	1.08	
	PC 8.8	87		0.9135	0.0470	0.0624	1.16	
	PC 10.9	142		0.8671	0.0470	0.0622	1.25	
	PC 12.9[1)]	3		0.9009	0.0053	0.0415	1.23	
Proposed	**PC 4.6**	28	0.70	1.0342	0.0813	0.0910	1.13	**1.18**
	PC 5.6	100		0.9977	0.0490	0.0640	1.08	
	PC 8.8	87	0.65	0.9838	0.0470	0.0624	1.07	
	PC 10.9	142		0.9338	0.0467	0.0623	1.16	
	PC 12.9[1)]	3		0.9702	0.0053	0.0415	1.14	

[1)] PC 12.9 is excluded in EN 1993-1-8 for the application in steel structures. Nevertheless, PC 12.9 was considered in the statistical evaluations according to EN 1990, Annex D with the given shear coefficients α.

In order to allow a deeper analysis of the different approaches, graphical comparisons of the experimental and theoretical values (r_e/r_t) aligned with experimental and nominal values (r_e/r_n) for the shear resistance $F_{v,Rd}$ of carbon steel bolts with threaded part in the shear plane for EN 1993-1-8, the initial approach of the background documentation/TNO-report from 1988 and the proposed approach in the frame of this thesis (see also in [413, 414]) are provided in Figure 7.5-3. Furthermore, a detailed illustration of the scattering of the experimental r_e and theoretical r_t shear resistances in the relevant range for the proposed approach is presented in Figure 7.5-3 (d).

It can be shown that the mean value correction factor b for the shear resistance of carbon steel bolts with threaded part in the shear plane of EN 1993-1-8 is about b(r_e/r_t) = 1.1712 with a scattering of Q = 0.0890 and V_δ = 0.0791. The r_e/r_t and r_e/r_n values lie mainly above and only partially on the angle bisector on the safe but also non-economical side with γ_M* = 1.00 significantly smaller than γ_{M2} = 1.25. If the initial approach of the TNO-report is applied with higher and unified shear coefficients of α = 0.7, mainly all r_e/r_t values shift easily identifiable below the angle bisector on the unsafe side, while the r_e/r_n values are widely distributed around the angle bisector. The mean value correction factor b of the initial approach of the TNO-report results to b(r_e/r_t) = 0.8962 with a scattering of Q = 0.0983 and V_δ = 0.0896. In the frame of this thesis, the proposed approach for carbon steel bolts with threaded bolt part in the shear plane shows r_e/r_t values mainly on or partially below the angle bisector with b(r_e/r_t) = 0.9550 and complemented by reduced scattering of Q = 0.0768 and V_δ = 0.00648, see Figure 7.5-1 (d).

Finally, it can be concluded that the proposed approach with higher shear coefficients α compared to EN 1993-1-8 allows a more economical design of the shear resistance $F_{v,Rd}$ of carbon steel bolts with threaded part in the shear plane.



(a) EN 1993-1-8 and EN 1993-1-8:2024 (draft) [82]

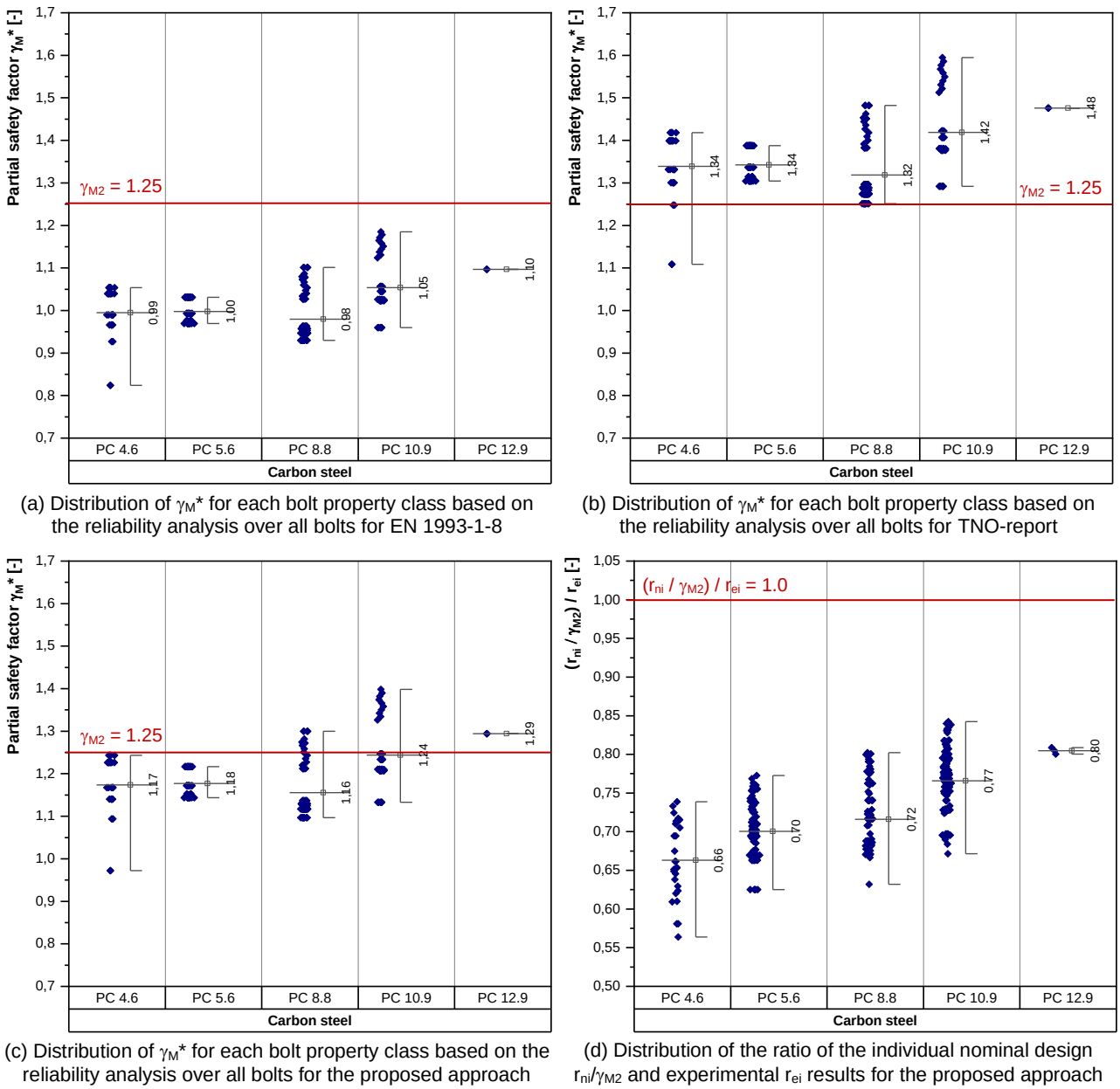
(b) Initial approach of Background documentation/ TNO-report to Eurocode 3 from 1988

(c) Proposed approach for the shear resistance of carbon steel bolts with threaded bolt part in the shear plane

(d) Illustration of the scattering of the experimental r_e and theoretical r_t shear resistances for the proposed approach in the relevant range

Figure 7.5-3: Comparison of the experimental r_e and theoretical r_t/nominal r_n shear resistances for carbon steel bolts and bolting assemblies including literature data for the threaded part in the shear plane

The distribution of the resulting individual partial safety factors $\gamma_{M,i}$* over all bolts and bolting assemblies across all investigated bolt property classes for the design of EN 1993-1-8, the initial approach of the background documentation/TNO-report from 1988 and the proposed approach is presented in Figure 7.5-4. All individual data points of each tested bolt and from literature are summarised graphically including plots of the range and resulting partial safety factor mean values γ_M*. It must be noted that the plots of the range and resulting partial safety factor mean values γ_M* are based on the reliability analysis over all bolts and are only informatively included (which are not comparable with those given in Table 7.5-4).



(a) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for EN 1993-1-8

(b) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for TNO-report

(c) Distribution of γ_M* for each bolt property class based on the reliability analysis over all bolts for the proposed approach

(d) Distribution of the ratio of the individual nominal design r_{ni}/γ_{M2} and experimental r_{ei} results for the proposed approach

Figure 7.5-4: Distribution of the partial safety factors γ_M* of carbon steel bolts regarding the shear resistance $F_{v,Rd}$ with threaded bolt part in the shear plane for each property class

It can be seen in Figure 7.5-4 (a) that all individual partial safety factors $\gamma_{M,i}$* of the EN 1993-1-8 design approach are clearly below γ_{M2} = 1.25, which again reflects the conservatism of the Eurocode approach. On the contrary, the $\gamma_{M,i}$* values of the initial TNO-report approach are clearly exceeding γ_{M2} = 1.25 in all property classes, if the reliability analysis is conducted over all bolts. The proposed approach shows partially exceeding of individual partial safety factors $\gamma_{M,i}$* in PC 8.8 and 10.9 but seems to be a good compromise between both approaches mentioned above, which allows a more economic design by utilizing higher shear resistances for all property classes. All individual partial safety factors $\gamma_{M,i}$* of PC 12.9 are exceeding γ_{M2} = 1.25. However, it should be remembered that the application of bolts in PC 12.9 is not provided in steel construction according to EN 1993-1-8.

Furthermore, the quality of the design approaches (EN 1993-1-8, TNO-report and the proposed approach) regarding the shear resistance $F_{v,Rd}$ of carbon steel bolts with threaded part in the shear plane is again assessed. The results of the evaluation are summarised in Table 7.5-5. Analogues to the assessment of carbon steel bolts with unthreaded bolt part in the shear plane, criterion I and II both failed for the initial approach of the TNO-report with

increased shear coefficients of α = 0.70 over all property class. Therefore, the initial approach of the TNO-report must be rejected, while the current EN 1993-1-8 approach is too conservative as already outlined before. As a conclusion, it can be stated that the proposed approach is fulfilling all criteria and allows a more economical but safe and reliable design of the shear resistance of carbon steel bolts with threaded bolt part in the shear plane.

Table 7.5-5: Evaluation of the reliability analysis for the shear resistance of carbon steel bolts with threaded bolt part in the shear plane according to the modified safety assessment criteria

Evaluation criteria (Chapter 4.7.4)		EN 1993-1-8	Initial approach of the TNO-report	Proposed
I	Maximum error ≤ 1.15 · γ_{M2}	1.18 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.59 ≤ 1.15 · γ_{M2} = 1.44 ↯	1.40 ≤ 1.15 · γ_{M2} = 1.44 ✓
II	Maximum number of unsafe results ≤ 20 %	0 % ≤ 20 % ✓	98.9 % ≤ 20 % ↯	7.2 % ≤ 20 % ✓
III	Plausibility check	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓

7.6 New proposed harmonised design rules for the interaction resistance of carbon steel bolts

7.6.1 General

For the sake of harmonisation of the interaction design rules between stainless steel bolts and carbon steel bolts, it could be shown in [413, 414] that the Stranghöner/Abraham interaction approach for FprEN 1993-1-4, which was basically developed for austenitic and duplex stainless steel, is also capable to describe the interaction resistance of carbon steel bolts appropriately. Concerning a more comprehensive analysis, the test database from literature is extended to 485 interaction tests with unthreaded or threaded bolt part in the shear plane compared to 354 interaction tests from the reliability analysis conducted [414]. However, in the frame of this thesis, no further single-shear interaction tests are performed. Instead, the focus is here on an in-depth examination of the results of the statistical evaluation according to EN 1990, Annex D particularly regarding the safety assessment of the Eurocode across all bolt property classes and for each tested angle, which has not been carried out so far. Previously, based on [414], only statements regarding the suitability and resulting partial safety factors γ_M* of different interaction design approaches over all bolts were possible.

7.6.2 Implemented studies and discussion of the normative revision process

Analogues to the tension and shear resistance of carbon steel bolts, again a comprehensive overview of the considered experimental studies into the interaction resistance of carbon steel bolts with unthreaded and threaded bolt part in the shear plane for the pre-Eurocode draft standard ENV 1993-1-1 from 1992 [415], the revision of Eurocode EN 1993-1-8 of 2005 [416] for connections and the proposed new design rules is presented in Table 7.6-1. In total, 283 single-shear interaction tests on carbon steel bolts with unthreaded or threaded part in the shear plane were considered in the Background documentation/TNO-report to Eurocode 3 from 1988 and the revision of 2005. Unfortunately, the (negligible) discrepancy of one interaction test from Bilderbeek [222] between the TNO-report and the revision of 2005 cannot be identified due to incomplete documentation. For statistical re-evaluation of the interaction design approach, the database was significantly extended up to 327 interaction tests on carbon steel bolts with unthreaded bolt part in the shear plane and 152 interaction tests with threaded bolt part in the shear plane. Thus, in total 480 interaction tests are available for statistical re-evaluation. The studies by Li et al. [236, 237] and Song et al. [5] dealing on the interaction load bearing behaviour of carbon steel bolts in PC 8.8, 10.9 and 12.9 were added. However, the experimental studies from Knobloch/Schmidt into the interaction behaviour of carbon steel

bolts are not considered in the statistical evaluation according to EN 1990, Annex D due to the following reasons (see also Chapter 2.5.3): Instead of structural bolts, Knobloch and Schmidt used unthreaded rods (d = 20 mm) for the unthreaded part in the shear plane and threaded rods (M16 and M24) for the threaded part in the shear plane. Furthermore, the unthreaded rods were made of different steel grades to simulate bolt material in various property classes like St 37-2 (≈ PC 4.6), St 52-3 (≈ PC 5.6), C45 (≈ PC 8.8) and 42CrMo4 (≈ PC 10.9). The threaded rods in PC 5.6 and 10.9 were tested but not fulfilling the normative requirements regarding the minimum tensile strength and elongation at fracture. Therefore, it was decided not to implement the data in the reliability analysis (analogues to the TNO-report and revision of 2005 both also not considering the studies of Knobloch/Schmidt).

Table 7.6-1: Overview of considered experimental studies investigations into the interaction resistance of carbon steel bolts for prior revisions of EN 1993-1-8 and the proposed new design rules

Interaction resistance of carbon steel bolts				
Revision process	**Bolt type and shear planes**	**Considered studies**	**Number of tests**	**Total test numbers**
Proposed design rules for carbon steel bolts in the frame of the thesis	Partially threaded bolts with unthreaded part in the shear plane	Bilderbeek, 1971 [222]	61	327
		Hassler, 1973 [223]	15	
		Shakir-Khalil and Ho, 1979 [225]	30	
		Renner and Lange, 2012-19 [178] to [183]	48	
		Li et al., 2020 [236, 237]	84	
		Song et al., 2020 [5]	8	
		UDE-IML, 2023 [414]	81	
	Fully threaded bolts with threaded part in the shear plane	Bilderbeek, 1971 [222]	35	153
		Shakir-Khalil and Ho, 1979 [225]	10	
		Renner and Lange, 2012-19 [178] to [183]	36	
		Li et al., 2020 [236, 237]	24	
		Song et al., 2020 [5]	8	
		UDE-IML, 2023 [414]	40	
Background documentation to prEN 1993-1-8 for the revision of 2005 [412]	Partially and threaded bolts with unthreaded or threaded part in the shear plane	Bilderbeek, 1971 [222]	102	141
		Shakir-Khalil & Ho, 1979 [225]	39	
Background documentation/TNO-report to Eurocode 3 from 1988 [355, 411]	Partially and threaded bolts with unthreaded or threaded part in the shear plane	Presumed: Bilderbeek, 1971 [222]	103[1)]	142
		Presumed: Shakir-Khalil & Ho, 1979 [225]	39[1)]	

[1)] Experimental studies are only presumed based on the given information in the background documentation/TNO-report to Eurocode 3 from 1988. Thus, the number of tests cannot be clearly assigned. Additionally, the discrepancy of one interaction test from Bilderbeek between the TNO-report and the revision of 2005 cannot be identified due to incomplete documentation.

7.6.3 Extended reliability analysis for the bolt interaction resistance for the unthreaded bolt part in the shear plane

Since the changes resulting from the statistical re-evaluation based on an extended dataset are small and the main results of the reliability analysis conducted in [414, 413] are still valid. Therefore, in the following only the proposed design approach for the interaction resistance of carbon steel bolts (harmonised with the approach for FprEN 1993-1-4 for stainless steel bolts) in contrast to the current bilinear approach of EN 1993-1-8 is discussed in greater depth. The quadratic interaction approach, which is still widely used in international standardisation (see Chapter 3.5) and was implemented in the withdrawn German DIN 18800-1 in the pre-Eurocode era, was already rejected in [413, 414] as too unsafe under the premise that both the bolt tension resistance $F_{t,Rd}$ with k_2 = 1.0 and the shear coefficients α are increased for the sake of an overall more economic design of bolted connections. It could be revealed in [413, 414] that the quadratic interaction approach generally overestimates the load bearing capacity

of carbon steel bolts subjected to tension and shear loading resulting in high partial safety factors γ_M* across all bolt property classes.

Regarding the extended reliability analysis for the bolt interaction resistance for the unthreaded part in the shear plane, the definitions of the theoretical r_t and nominal r_n resistance functions are identical to those for austenitic and duplex stainless steel bolts, as already outlined in Chapter 6.6.2.2. Analogues to the pure tension and shear resistance of carbon steel bolts, again maximum scatters of COV(f_{ub}) = 4.0 % and COV (A; A_s) = 1.0 % are assumed for all bolts on the safe side (cf. Chapter 7.4.3). Due to a large number of tests (n = 327 ≥ 100), again, the simplified formula in (Eq. E.12) for obtaining the design value r_d with a fractile factor of $k_{d,n}$ = 3.04 was applied for the determination of the partial safety factor γ_M* over all interaction tests and all defined interaction subsets with unthreaded bolt part in the shear plane. The main results of the statistical evaluations of the current EN 1993-1-8 design rule and the proposed approach including mean value correction factors b, the coefficients of variation of errors V_δ and scattering parameters Q are presented comparatively in Table 7.6-2.

Table 7.6-2: Summary of the extended reliability analysis for the interaction resistance of carbon steel bolts with unthreaded part in the shear plane considering maximum COV (f_{ub}) = 4 % and maximum COV (A) = 1 %

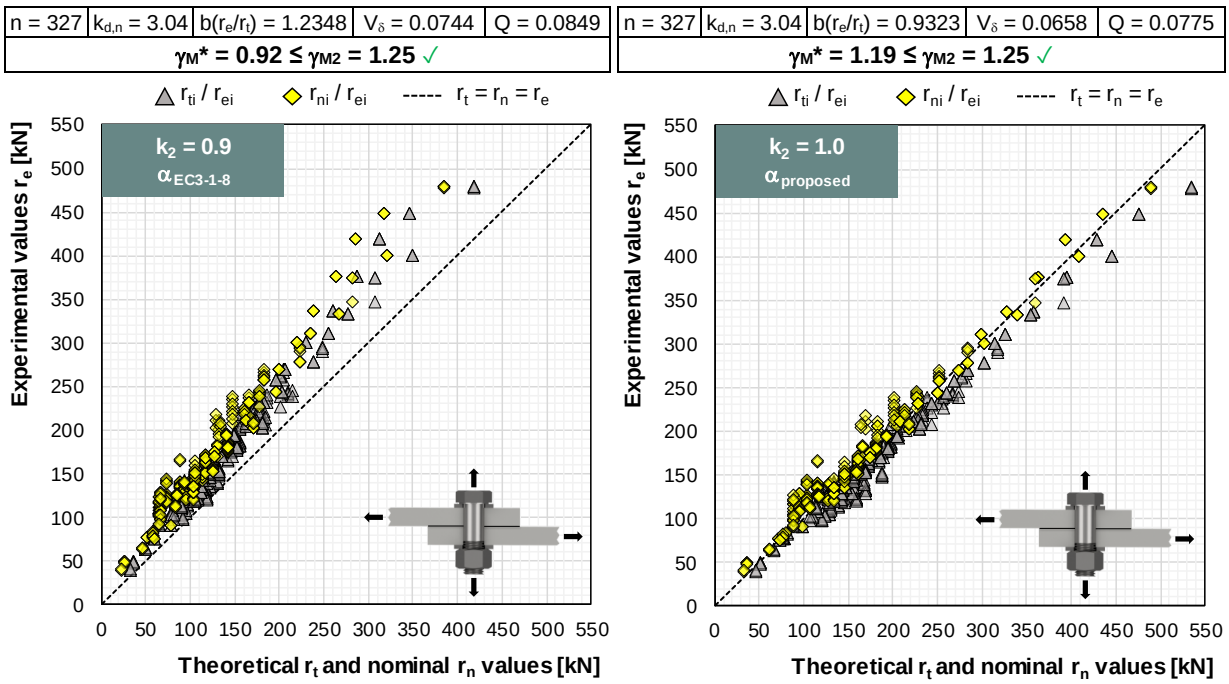
Design approach	PC	Number of tests n	k_2 [-]	α [-]	b (r_e/r_t) [-]	V_δ [-]	Q [-]	γ_M* [-]	γ_M* [-]
EN 1993-1-8	**PC 4.6**	87	0.90	0.60	1.1844	0.0941	0.1024	0.86	**0.92**
	PC 5.6[1)]	-			-	-	-	-	
	PC 8.8	57			1.2533	0.0672	0.0787	0.90	
	PC 10.9	135			1.2425	0.0597	0.0724	0.94	
	PC 12.9[1)]	48			1.2336	0.0606	0.0732	0.96	
Proposed	**PC 4.6**	87	1.00	0.70	0.8642	0.0835	0.0929	1.14	**1.19**
	PC 5.6[1)]	-			-	-	-	-	
	PC 8.8	57		0.65	0.9511	0.0485	0.0636	1.13	
	PC 10.9	135			0.9419	0.0374	0.0556	1.18	
	PC 12.9[1)]	48			0.9362	0.0284	0.0501	1.17	

[1)] No test data of bolts in PC 5.6 was available for statistical evaluation which fulfill the mechanical requirements according to EN ISO 898-1. | [2)] PC 12.9 is excluded in EN 1993-1-8 for the application in steel structures. Nevertheless, PC 12.9 was considered in the statistical evaluations according to EN 1990, Annex D with the given shear coefficients α.

It can be proven that the resulting partial safety factors γ_M* for both investigated approaches over all bolts and for all defined subsets of each property class are below the normative partial safety factor γ_{M2} = 1.25 for connections. The highest partial safety factors γ_M* can be observed for the proposed approach with γ_M* = 1.19 over all bolts and γ_M* = 1.18 for PC 10.9. On the contrary, the conservativsm of the EN 1993-1-8 design rule regarding the interaction resistance with unthreaded bolt part in the shear plane is striking with low partial safety factors between γ_M* = 0.86 for PC 4.6 and γ_M* = 0.94 for PC 10.9. It is worth remembering that the application of carbon steel bolts in PC 12.9 (γ_M* = 0.96) is not permitted in steel structures according to EN 1993-1-8, and the extent to which both design approaches withstand an extended safety assessment will be discussed later.

In Figure 7.4-3, the experimental and theoretical values (r_e/r_t) as well as experimental and nominal values (r_e/r_n) for the interaction resistance of carbon steel bolts with unthreaded part in the shear plane are comparatively presented for EN 1993-1-8 and the proposed design approach. The mean value correction factor b for the interaction resistance of carbon steel bolts with unthreaded part in the shear plane of the current bilinear EN 1993-1-8 approach is about b(r_e/r_t) = 1.2348 with a scattering of Q = 0.0849 and V_δ = 0.0744.

All r_e/r_t and r_e/r_n values lie partially on or mainly clearly above the angle bisector on the safe but also clearly non-economical side leading to a partial safety factor of $\gamma_M^* = 0.96 \leq \gamma_{M2} = 1.25$ over all bolts. On the contrary, the reliability analysis for the proposed approach for carbon steel bolts with unthreaded part in the shear plane yields to mean value correction factor b of $b(r_e/r_t) = 0.9323$ with a scattering of $Q = 0.0775$ and $V_\delta = 0.0658$. The r_e/r_n values are positioned on or scattered around the angle bisector, while the r_e/r_t values lie on or below the angle bisector. Therefore, it can be shown by the experimental and nominal values (r_e/r_n) that the proposed approach is more suitable compared to the EN 1993-1-8 design rule in order to describe the interaction behaviour of carbon steel bolts with unthreaded bolt part in the shear plane more precisely and economically.



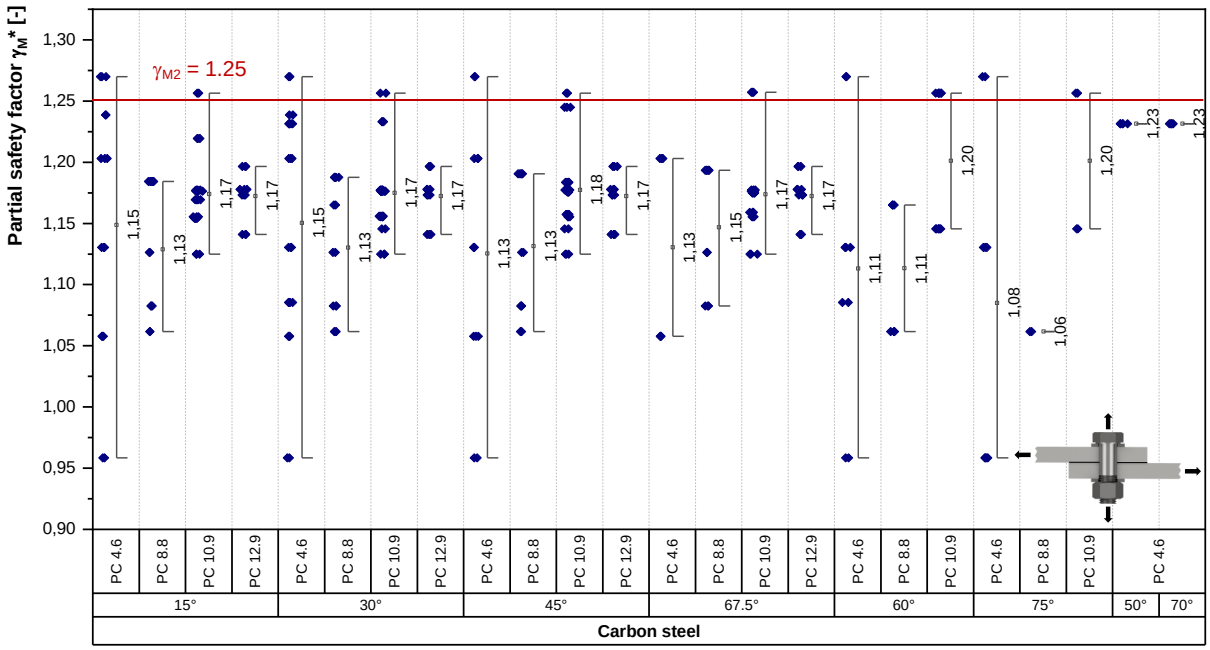
(a) EN 1993-1-8 and EN 1993-1-8:2024 (draft) [82]

(b) Proposed approach

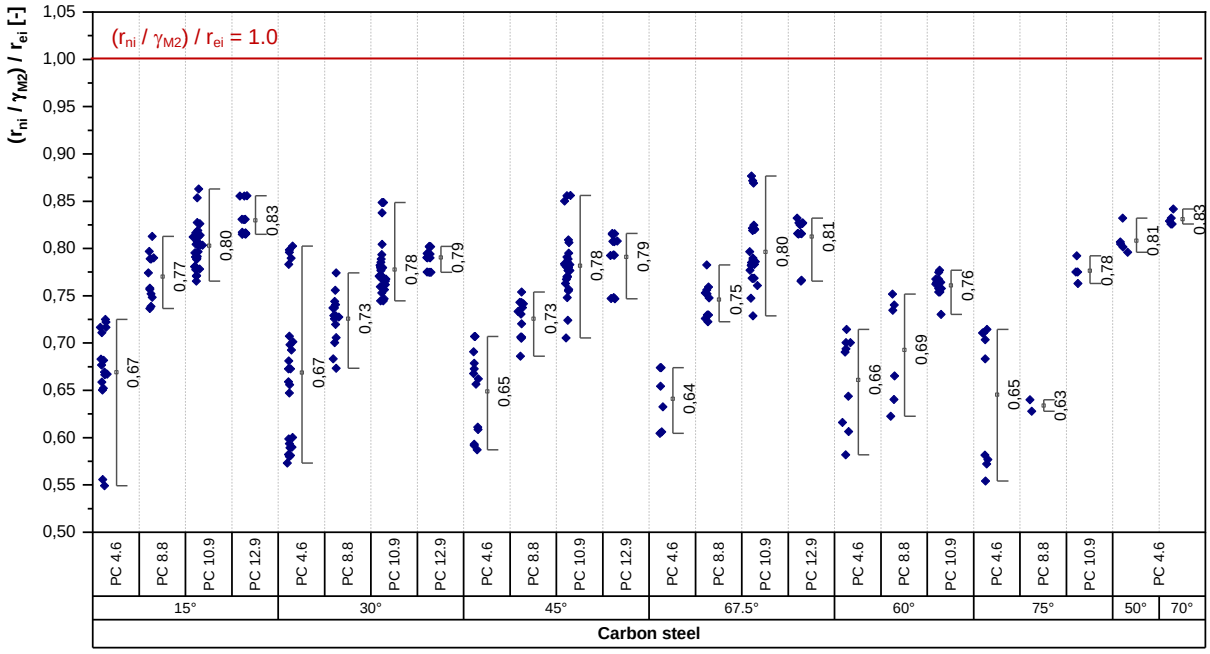
Figure 7.6-1: Comparison of the experimental r_e and theoretical r_t/nominal r_n interaction resistances for carbon steel bolts and bolting assemblies including literature data for the unthreaded part in the shear plane

Analogues to the statistical evaluations into the tension and shear resistance of carbon steel bolts, also the distribution of the resulting individual partial safety factors $\gamma_{M,i}^*$ of subsets based on own single-shear interaction tests and literature review for each investigated property class and each tested loading angle for the proposed approach is presented in Figure 7.6-2 (a). Obviously, all individual partial safety factors $\gamma_{M,i}^*$ of the proposed more economical approach are below $\gamma_{M2} = 1.25$ with exception of PC 4.6 and 10.9. This partial exceeding of $\gamma_{M2} = 1.25$ occurs at all tested angles and is therefore consistent. Furthermore, the distribution of the ratio of all individual nominal design r_{ni}/γ_{M2} and experimental r_{ei} results for the proposed approach over all property classes and loading angles are always less 1 on the safe side, see Figure 7.6-2 (b). Thus, sufficient safety reserves are guaranteed.

So as to assess the quality of the proposed approach for the interaction resistance of carbon steel bolts with unthreaded part in the shear plane, and to check if partially individual exceeding of $\gamma_{M2} = 1.25$ in PC 4.6 and 10.9 may be critical, again the modified safety assessment criteria introduced in Chapter 4.7.4 are applied. The results of the evaluation are presented in Table 7.6-3. It could be verified that for PC 4.6, 8.8 and 10.9 all defined evaluation criteria are fulfilled and that sufficient safety reserves are guaranteed for a more economical but safe and reliable interaction design.



(a) Distribution of γ_M* for each bolt property class and loading angle for the proposed approach



(b) Distribution of the ratio of the individual nominal design r_{ni}/γ_{M2} and experimental r_{ei} results for the proposed approach

Figure 7.6-2: Analysis of the distribution of the partial safety factors γ_M* of carbon steel bolting assemblies for bolt property class and loading angle for the interaction resistance with unthreaded bolt part in the shear plane

Table 7.6-3: Evaluation of the reliability analysis for the interaction resistance of carbon steel bolts with unthreaded bolt part in the shear plane according to the modified safety assessment criteria

Evaluation criteria (Chapter 4.7.4)		PC 4.6	PC 8.8	PC 10.9
I	Maximum error ≤ 1.15 · γ_{M2}	1.27 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.19 ≤ 1.15 · γ_{M2} = 1.44 ✓	1.26 ≤ 1.15 · γ_{M2} = 1.44 ✓
II	Maximum number of unsafe results ≤ 20 %	12.6 % ≤ 20 % ✓	0 % ≤ 20 % ✓	12.6 % ≤ 20 % ✓
III	Plausibility check	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓	All (r_{ni}/γ_{M2}) / r_{ei} ≤ 1.0 ✓

7.6.4 Extended reliability analysis for the bolt interaction resistance for the threaded bolt part in the shear plane

Regarding the extended reliability analysis for the interaction resistance of carbon steel bolts with threaded portion bolt in the shear plane, the definitions of the theoretical r_t and nominal r_n resistance functions are identical to those for austenitic and duplex stainless steel bolts, as already outlined in Chapter 6.6.2.3. To ensure consistency and comparability, again maximum scatters of COV(f_{ub}) = 4.0 % and COV (A; A_s) = 1.0 % are assumed for all bolts on the safe side with a fractile factor of $k_{d,n}$ = 3.04. The main results of the statistical evaluations of the current EN 1993-1-8 design rule and the proposed approach including mean value correction factors b, the coefficients of variation of errors V_δ and scattering parameters Q are summarised in Table 7.6-4.

Table 7.6-4: Summary of the extended reliability analysis for the interaction resistance of carbon steel bolts with threaded part in the shear plane considering maximum COV (f_{ub}) = 4 % and maximum COV (A) = 1 %

Design approach	PC	Number of tests n	k_2 [-]	α [-]	b (r_e/r_t) [-]	V_δ [-]	Q [-]	γ_M^* [-]	γ_M^* [-]
EN 1993-1-8	**PC 4.6**	41	0.90	0.60	1.2647	0.1107	0.1177	0.98	**0.98**
	PC 5.6[1)]	-			-	-	-	-	
	PC 8.8	56			1.1960	0.0645	0.0764	0.96	
	PC 10.9	44		0.50	1.2774	0.0630	0.0752	0.91	
	PC 12.9[1)]	12			1.2609	0.0592	0.0720	0.97	
Proposed	**PC 4.6**	41	1.00	0.70	1.1098	0.1055	0.1129	1.10	**1.13**
	PC 5.6[1)]	-			-	-	-	-	
	PC 8.8	56		0.65	1.0917	0.0662	0.0778	1.06	
	PC 10.9	44			1.0537	0.0508	0.0654	1.07	
	PC 12.9[1)]	12			1.0401	0.0418	0.0587	1.12	

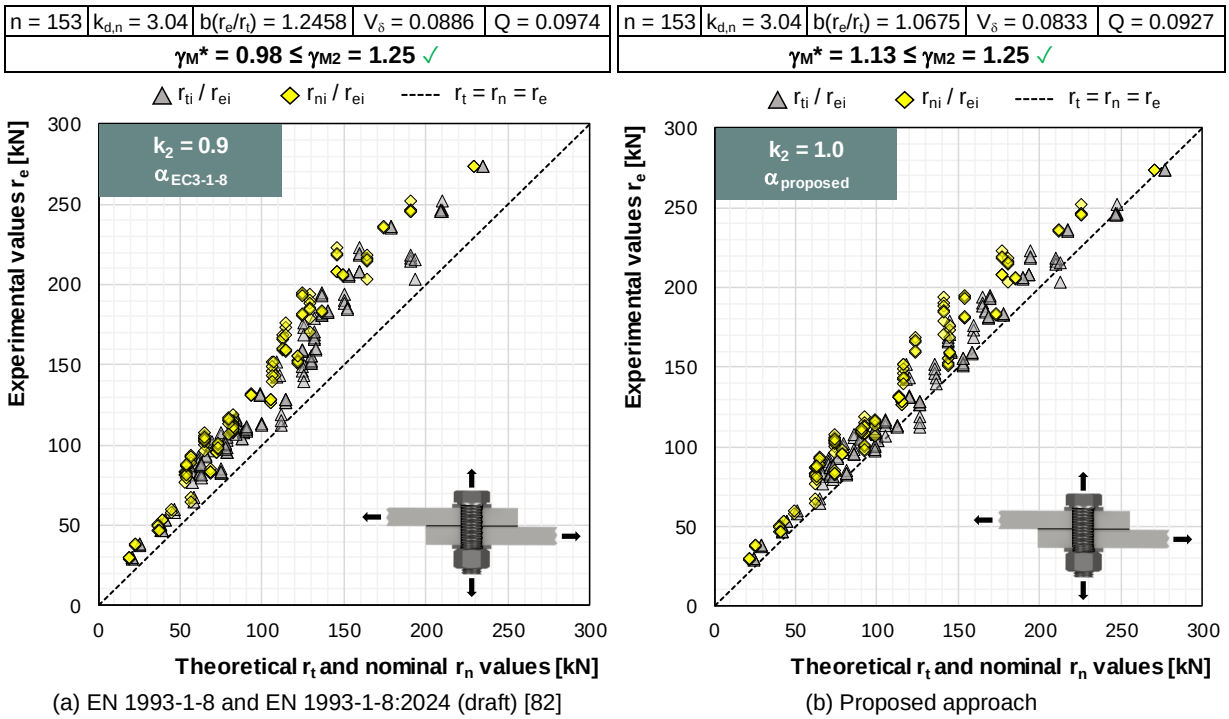
[1)] No test data of bolts in PC 5.6 was available for statistical evaluation which fulfill the mechanical requirements according to EN ISO 898-1. | [2)] PC 12.9 is excluded in EN 1993-1-8 for the application in steel structures. Nevertheless, PC 12.9 was considered in the statistical evaluations according to EN 1990, Annex D with the given shear coefficients α.

Analogues to the unthreaded bolt part in the shear plane, it can be shown in Table 7.6-4 that the resulting partial safety factors γ_M* for both investigated approaches over all bolts and for all defined subsets of each bolt property class are below γ_{M2} = 1.25 for connections. The highest partial safety factors γ_M* can be observed for the proposed approach with γ_M* = 1.13 over all bolts and γ_M* = 1.18 for PC 12.9, which is not permitted in steel structures according to EN 1993-1-8. Again the conservatism of the current EN 1993-1-8 bilinear design regarding the interaction resistance with threaded bolt part in the shear plane is striking with low partial safety factors between γ_M* = 0.91 for PC 10.9 and γ_M* = 0.98 for PC 4.6 (in contrast to the unthreaded bolt part, which identified PC 4.6 as the lowest partial safety factor, see Table 7.6-2).

In order to allow a deeper analysis of both design approaches, again graphical comparisons of the experimental and theoretical values (r_e/r_t) aligned with experimental and nominal values (r_e/r_n) for the interaction resistance of carbon steel bolts with threaded part in the shear plane for EN 1993-1-8 and the proposed harmonised approach are provided in Figure 7.6-3. The mean value correction factor b for the interaction resistance of carbon steel bolts with threaded part in the shear plane of the bilinear EN 1993-1-8 approach is about b(r_e/r_t) = 1.2458 with a scattering of Q = 0.0974 and V_δ = 0.0886. All r_e/r_t and r_e/r_n values lie clearly above the angle bisector on the safe non-economical side leading to γ_M* = 0.98 ≤ γ_{M2} = 1.25 over all bolts.

The reliability analysis for the proposed approach for carbon steel bolts with threaded part in the shear plane leads to a mean value correction factor b of b(r_e/r_t) = 1.0675 > 1 with scattering of Q = 0.0775 and V_δ = 0.0658. The r_e/r_n values are positioned on or above the angle bisector

on the safe side, while the r_e/r_t values are scattered around the angle bisector. Therefore, it can firstly be shown by the experimental and nominal values (r_e/r_n) that the proposed harmonised approach is also for the threaded part in the shear plane more suitable compared to the EN 1993-1-8 design rule to describe the interaction behaviour of carbon steel bolts more precisely and economically. Secondly, the own conducted experimental investigations at UDE-IML and the extended reliability analyses both reveal that carbon steel bolts with threaded part in the shear plane exhibit a superior, more elliptical or even quadratic combined load bearing behaviour under tension and shear loading in contrast to bolts with unthreaded part in the shear plane, which also confirms the investigations of Renner and Lange ([178] to [183]). As shown in Chapter 6.4 and examined by Renner and Lange, a compression ring forms in the bolt threads in the shear plane, which has a stabilising effect and counteracts a reduction in cross-section due to shear and transverse contraction due to tension. As a result, for an even more economical design, carbon steel bolts with threaded bolt part(s) in the shear plane include the potential to increase the interaction resistance with $\gamma_M^* = 1.13 \leq \gamma_{M2} = 1.25$ over all bolts by further increasing the shear coefficients α. However, a further increase of the shear coefficients α is not conducted for the threaded part for harmonisation and “Ease of Use”.



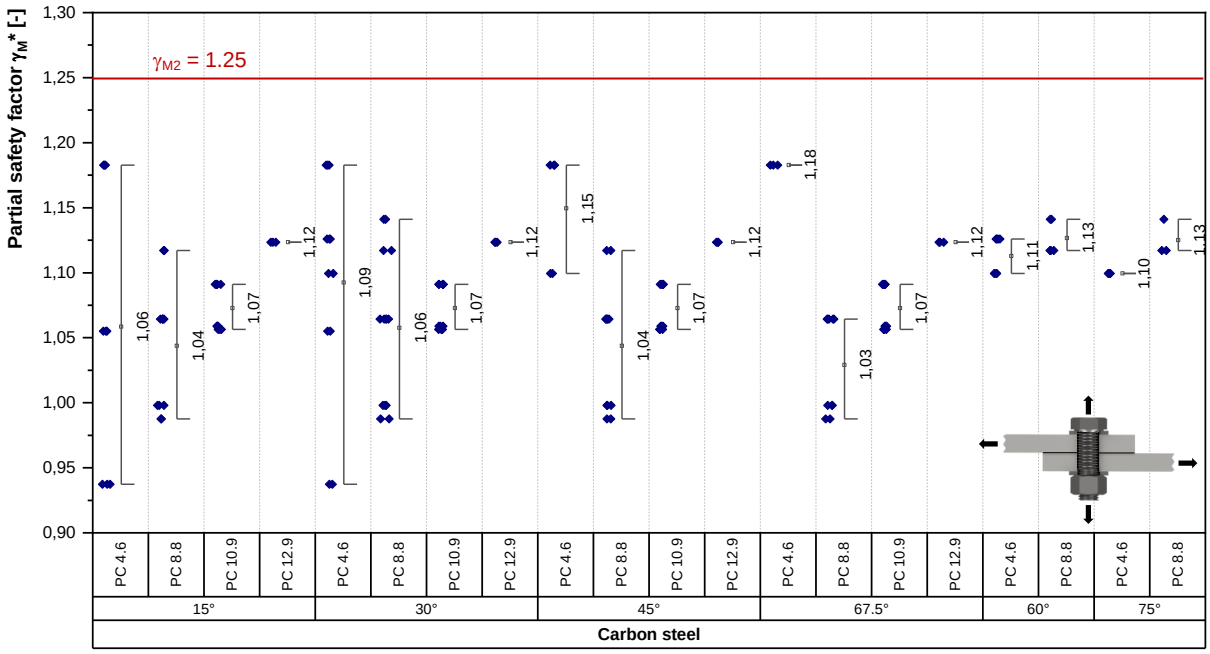
(a) EN 1993-1-8 and EN 1993-1-8:2024 (draft) [82] (b) Proposed approach

Figure 7.6-3: Comparison of the experimental r_e and theoretical r_t/nominal r_n interaction resistances for carbon steel bolts and bolting assemblies including literature data for the threaded part in the shear plane

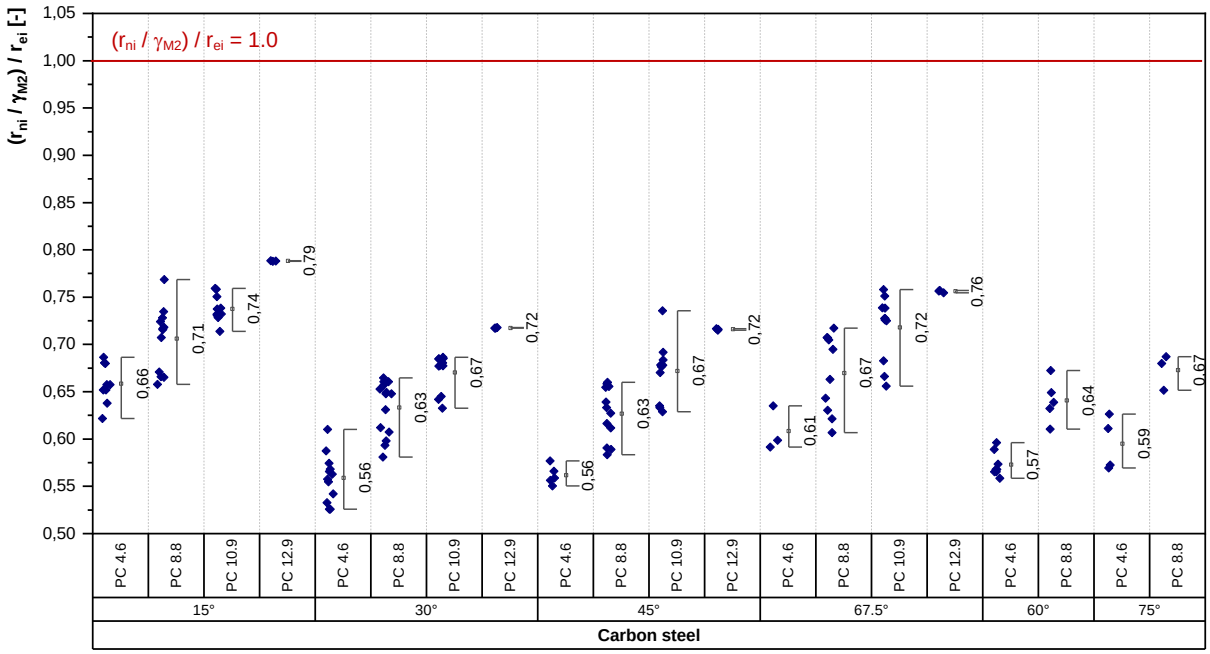
The distribution of the resulting individual partial safety factors $\gamma_{M,i}^*$ over all bolting assemblies across all investigated PC and loading angles for EN 1993-1-8 and the proposed approach is presented in Figure 7.6-4 (a). All individual data points of each tested bolt and from literature are summarised graphically including plots of the range and resulting partial safety factor mean values γ_M^*. It can be seen that all individual partial safety factors $\gamma_{M,i}^*$ of the proposed approach are below $\gamma_{M2} = 1.25$ without exception. Furthermore, the distribution of the ratio of all individual nominal design r_{ni}/γ_{M2} and experimental r_{ei} results for the proposed approach over all property classes and loading angles are always less than 1 and guarantee sufficient safety reserves, see Figure 7.6-4 (b).

Since no individual partial safety factors exceeding of $\gamma_{M2} = 1.25$ occurred, a detailed safety assessment is redundant.

Therefore, the proposed interaction approach for carbon steel bolts with threaded part in the shear plane can be concluded as safe and reliable for all cases. However, it must be remembered that PC 5.6 was neither tested nor evaluated as it was not possible to collect sufficient data.



(a) Distribution of γ_M* for each bolt property class and loading angle for the proposed approach



(b) Distribution of the ratio of the individual nominal design r_{ni}/γ_{M2} and experimental r_{ei} results for the proposed approach

Figure 7.6-4: In-depth analysis of the distribution of the partial safety factors γ_M* of carbon steel bolting assemblies for bolt property class and loading angle for the interaction resistance with threaded bolt part in the shear plane

7.7 Summary and conclusions

As a supplement to the experimental investigations and statistical evaluations according to EN 1990, Annex D of the new and more economically proposed design approaches for the tension, shear and interaction resistance of austenitic and duplex stainless steel bolts presented in Chapters 4 to 6, the question had arisen whether the design rules for carbon steel bolted connections according to EN 1993-1-8 and EN 1993-1-8:2024 (draft) [82] also offer the

possibility for a more suitable and economical design. Therefore, the objective is to harmonise the design rules for bolts made of austenitic/duplex and carbon steel and to validate these approaches in reliability analyses according to EN 1990, Annex D and further safety assessments.

Therefore, a renewed review of the safety concept of the Eurocode for carbon steel bolting assemblies was carried out. The reliability analyses were based on new experimental studies into carbon steel bolts under tension, shear and interaction. These have become available in the meantime but have yet to be implemented in a statistical re-evaluation. Furthermore, own experimental investigations considering tensile, single-/double-shear and interaction tests on different types of carbon steel bolts were carried out at UDE-IML within the frame of this thesis, leading to an extended database of 1920 tests including literature data. Compared to previous research at UDE-IML, the reliability analyses are not only extended but also significantly deepened in order to be able to evaluate the distribution of the individual partial safety factors $\gamma_{M,i}$* more comprehensively, for example, by taking into account the loading angle and the assessment of partially individual exceeding of γ_{M2}.

Finally, the more economical and statistically verified design approaches for the tension, shear and interaction resistance of carbon steel bolts were reconfirmed and harmonised with the new design rules for stainless steel bolts according to FprEN 1993-1-4 and fulfilling the safety concept of the Eurocode.

As outlined in [361], the statistically validated proposed design approaches and modifications include:

- the design tension resistance $F_{t,Rd}$ of partially and fully threaded carbon steel bolts can be increased by modifying the reduction factor k_2 according to EN 1993-1-8 to $k_2 = 1.0$ following the normative requirements of a minimum ultimate tensile load $F_{m,min}$ according to EN ISO 898-1,
- new shear coefficients α have been proposed for the design shear resistance $F_{v,Rd}$ of carbon steel bolts, which allow a statistically validated and more economical design. The proposed shear coefficients ($\alpha_{proposed} = 0.70$ for PC 4.6 and 5.6, and $\alpha_{proposed} = 0.65$ for PC 8.8 and 10.9) are independent of the position of the shear plane, and
- the Stranghöner/Abraham interaction approach, which was developed for austenitic and duplex stainless steel bolts for FprEN 1993-1-4, is also suitable to describe the interaction resistance of carbon steel bolts with unthreaded or threaded bolt part(s) in the shear plane and lead to a statistically verified and more economical design compared to the current bilinear EN 1993-1-8 approach. The proposed interaction equations already consider the increased bolt tension resistance $F_{t,Rd}$ with $k_2 = 1.0$ and the increased shear resistance $F_{v,Rd}$ with the proposed higher and more economical shear coefficients $\alpha_{proposed}$.

8 Amendments for standardisation

8.1 General

Comprehensive experimental investigations and statistical evaluations according to EN 1990, Annex D [79] were conducted in the framework of FOSTA P 1386 / IGF-No. 20651 N titled "Load bearing capacity of bolted connections loaded in shear and tension made of stainless steel M12 to M36" [78] and further research activities at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen, Germany. These investigations were supplemented in the frame of this thesis by additional experimental studies in order to consider various aspects (particularly the load bearing behaviour of bolts in single-shear and double-shear bolted connections) and to significantly increase the data basis to analyse the resulting partial safety factors in extended reliability analyses. The proposed new design rules for the ongoing revision of EN 1993-1-4 [67], FprEN 1993-1-4 [80], and the German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022 [81] could be further validated concerning their suitability to determine the tension resistance $F_{t,Rd}$, the shear resistance $F_{v,Rd}$ and the interaction resistance of stainless and carbon steel bolts, fulfilling the safety requirements of the Eurocode. The proposed new and more economical design rules for stainless and carbon steel bolts and the related amendments for standardisation are outlined in the following.

Furthermore, in the framework of this thesis and [413, 414], various single-/double-shear and single-shear interaction tests on structural stainless and carbon steel bolts were conducted. Due to the current lack of European standardisation for these types of tests, new annexes are proposed as amendments for future revisions of EN ISO 898-1 [76] and EN ISO 3506-1 [73], which allow the determination of mechanical properties of carbon and stainless steel bolts in terms of simplified test procedures for the shear resistance (as single-shear test procedure) and interaction resistance (which can also be used for single-shear testing and for tensile tests on bolting assemblies fulfilling the requirements of EN 15048-2 [365]).

8.2 Amendments for the harmonised design of stainless steel bolts

The proposed new design rules for the ongoing revision of EN 1993-1-4 [67] outlined in the Chapters 4, 5 and 6 were already implemented in the final draft version FprEN 1993-1-4 [80] in Clause 10.2 (3) to (5) for the shear resistance $F_{v,Rd}$, tension resistance $F_{t,Rd}$ and interaction resistance of bolts made of stainless steel. The relevant parts for FprEN 1993-1-4 are:

Implemented to FprEN 1993-1-4, Clause 10.2 (3)

(3) The shear resistance of a bolt, $F_{v,Rd}$ should be calculated from Formula (10.2):

$$F_{v,Rd} = \frac{\alpha f_{ub} A}{\gamma_{M2}} \tag{10.2}$$

where

A is the gross cross-section area of the bolt (if the shear plane passes through the unthreaded portion of the bolt), or the tensile stress area of the bolt (if the shear plane passes through the threaded portion of the bolt);

f_{ub} is the ultimate tensile strength of the bolt, see Table 5.5.

α is given in Table 10.3 and applies whether the shear plane passes through the unthreaded or the threaded portions of the bolt.

Table 10.3 —Values of α

Property Class	Austenitic	Duplex
50	0,8	-
70	0,7	0,8
80	0,7	0,7
100	0,6	0,6

Implemented to FprEN 1993-1-4, Clause 10.2 (4)

(4) The tension resistance of a bolt, $F_{\mathrm{t,Rd}}$ should be calculated from Formula (10.3):

$$F_{t,\mathrm{Rd}} = \frac{k_2 f_{\mathrm{ub}} A_s}{\gamma_{\mathrm{M2}}} \tag{10.3}$$

where

k_2 = 0.63 for countersunk bolt, otherwise k_2 = 1.0;

A_s is the tensile stress area of the bolt.

Implemented to FprEN 1993-1-4, Clause 10.2 (5)

(5) Bolts which are subjected to combined shear and tension should satisfy the criterion (10.4) or (10.5):

If the threads are not excluded from the shear plane:

$$\left(\frac{F_{\mathrm{v,Ed}}}{F_{\mathrm{v,Rd}}}\right)^{1.7} + \left(\frac{F_{\mathrm{t,Ed}}}{F_{\mathrm{t,Rd}}}\right)^{1.7} \leq 1{,}0 \qquad \text{but} \quad \frac{F_{\mathrm{t,Ed}}}{F_{\mathrm{t,Rd}}} \leq 1{,}0 \tag{10.4}$$

If the threads are excluded from the shear plane:

$$\left(\frac{F_{\mathrm{v,Ed}}}{F_{\mathrm{v,Rd}}}\right)^{1.7} + \left(\frac{F_{\mathrm{t,Ed}}}{1{,}25 F_{\mathrm{t,Rd}}}\right)^{1.7} \leq 1{,}0 \qquad \text{but} \quad \frac{F_{\mathrm{t,Ed}}}{F_{\mathrm{t,Rd}}} \leq 1{,}0 \tag{10.5}$$

The amendments to abZ/aBG Z-30.3-6:2022, Clause 3.3 are identical to those of FprEN 1993-1-4, as the author has only translated the pre-normative text into German without any changes in the content. Afterwards, the German Institute for Building Technology (DIBt), Berlin, adopted the editorial format to meet the approval requirements. For this reason, the amendments for abZ/aBG Z-30.3-6:2022 are not presented further.

8.3 Amendments for the harmonised design of carbon steel bolts

The proposed new design rules for the shear $F_{v,Rd}$, tension $F_{t,Rd}$ and interaction resistance of bolts made of carbon steel were outlined in Chapter 7 and presented as an amendment to draft EN 1993-1-8:2024, Table 5.9 [82]. For each design case, the current status according to EN 1993-1-8:2024 is presented as well as which passages of the pre-normative text could be replaced for a more economical design that at the same time fully complies with the safety requirements of the Eurocode. The proposed approach for the shear resistance $F_{v,Rd}$ per shear plane of a carbon steel bolt utilises higher shear coefficients α_v for the bolt property classes (PC) 4.6, 5.6, 8.8 and 10.9. It is simplified by the fact that the design process needs to consider no distinction between the unthreaded or threaded bolt part in the shear plane anymore ("Ease of Use"). Since in the framework of this thesis and [413, 414] no carbon steel bolts of PC 4.8, 5.8 and 6.8 were considered in the experimental studies and the statistical evaluations, it is recommended to maintain for these PC with $\alpha_v = 0.6$ as provided in EN1993-1-8:2024. However, it is worth mentioning that in Germany, according to NDP to Clause 5.1.1(3) of

DIN EN 1993-1-8/NA [284] components with external threads (like bolts, studs and threaded rods) in PC 4.8, 5.8 and 6.8 are not permitted for application in steel structures.

Amendment to EN 1993-1-8:2024 [82], Table 5.9, Shear resistance $F_{v,Rd}$ of bolts

Table 5.9 – Design resistance for individual fasteners in normal round holes subjected to shear and/or tension

Failure mode	Bolts	Rivets
Shear resistance, per shear plane[a]	If the threads are not excluded from the shear plane (A_s is the tensile stress area of the bolt): $F_{v,Rd} = \frac{\alpha_v \ f_{ub} \ A_s}{\gamma_{M2}}$ — for property classes 4.6, 5.6 and 8.8: $\alpha_v = 0{,}6$ — for property classes 4.8, 5.8, 6.8 and 10.9: $\alpha_v = 0{,}5$ If the threads are excluded from the shear plane (A is the gross cross-section of the bolt): $F_{v,Rd} = \frac{0{,}6 \ f_{ub} \ A}{\gamma_{M2}}$ **To be improved by:** If the threads are not excluded from the shear plane (A_s is the tensile stress area of the bolt): $F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$ — for property class 4.6 and 5.6: $\alpha_v = 0.70$ — for property class 8.8 and 10.9: $\alpha_v = 0.65$ — for property class 4.8, 5.8 and 6.8: $\alpha_v = 0.50$ If the threads are excluded from the shear plane (A is the gross cross-section of the bolt): $F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A}{\gamma_{M2}}$ — for property class 4.6 and 5.6: $\alpha_v = 0.70$ — for property class 8.8 and 10.9: $\alpha_v = 0.65$ — for property class 4.8, 5.8 and 6.8: $\alpha_v = 0.50$	$F_{v,Rd} = \frac{0{,}6 \ f_{ur} \ A_0}{\gamma_{M2}}$ (A_0 is the area of the rivet hole)

The proposed increase of the tension resistance $F_{t,Rd}$ of carbon steel bolts serves to harmonise between the design rules of EN 1993-1-8 and EN 1993-1-8:2024 to the requirements of EN ISO 898-1 regarding the minimum ultimate tensile load $F_{m,min}$ (defined as $R_{m,min} \cdot A_{s,nom}$). Furthermore, harmonisation between the determination of the tension resistance $F_{t,Rd}$ of stainless steel bolts (according to FprEN 1993-1-4) and carbon steel bolts is intended.

Amendment to EN 1993-1-8:2024 [82], Table 5.9, Tension resistance $F_{t,Rd}$ of bolts

Table 5.9 – Design resistance for individual fasteners in normal round holes subjected to shear and/or tension

Failure mode	Bolts	Rivets
Tension resistance[b]	$F_{t,Rd} = \frac{0{,}9 \ f_{ub} A_s}{\gamma_{M2}}$ **To be improved by:** $F_{t,Rd} = \frac{f_{ub} \cdot A_s}{\gamma_{M2}}$	$F_{t,Rd} = \frac{0{,}6 \ f_{ur} \ A_0}{\gamma_{M2}}$ $F_{t,Rd}$ should be multiplied by 0,7 for countersunk rivets.

Furthermore, the interaction resistance of carbon steel bolts under combined tension and shear is harmonised with the new and more economical approach by Stranghöner/Abraham

developed for FprEN 1993-1-4 for stainless steel bolts but is also suitable to describe the load bearing interaction behaviour of carbon steel bolts accurately.

Amendment to EN 1993-1-8:2024 [82], Table 5.9, Interaction resistance of bolts

Table 5.9 – Design resistance for individual fasteners in normal round holes subjected to shear and/or tension

Failure mode	Bolts	Rivets
Combined shear and tension[f]	$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)+\left(\frac{F_{t,Ed}}{1{,}4\,F_{t,Rd}}\right)\leq 1$ but $\frac{F_{t,Ed}}{F_{t,Rd}}\leq 1$ **To be improved by:** If the threads are not excluded from the shear plane: $\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^{1,7}+\left(\frac{F_{t,Ed}}{F_{t,Rd}}\right)^{1,7}\leq 1{,}0$ but $\frac{F_{t,Ed}}{F_{t,Rd}}\leq 1{,}0$ If the threads are excluded from the shear plane: $\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^{1,7}+\left(\frac{F_{t,Ed}}{1{,}25\cdot F_{t,Rd}}\right)^{1,7}\leq 1{,}0$ but $\frac{F_{t,Ed}}{F_{t,Rd}}\leq 1{,}0$	

8.4 Draft for a new single-shear test procedure for fasteners of EN ISO 898-1

8.4.1 General

Based on the findings from the experimental investigations and numerical studies conducted in Chapter 5, a draft for a new single-shear test procedure for fasteners is developed and formulated as an informative annex to EN ISO 898-1 to complete the determination of the mechanical parameters of fasteners made of carbon and alloy steel regarding the ultimate shear load F_{sb} and resulting shear stresses τ_{sb}. The single-shear test procedure for fasteners is strongly based on the tensile tests according to EN ISO 898-1 and only modified at specific points. The purpose is to carry out the single-shear tests as simply and quickly as possible with sufficient accuracy of the test results. Therefore, a new normative text for Annex D of EN ISO 898-1 is proposed. As the test specification is also intended as a new Annex B of EN ISO 3506-1 for stainless steel bolts, references to EN ISO 3506-1 are marked in grey in the proposed text for EN ISO 898-1.

8.4.2 Proposed single-shear test procedure for fasteners of Annex D of EN ISO 898-1

Annex D
(informative)

Single-shear test procedure for fasteners

D.1 General

The test procedure targets determining the ultimate shear load $F_{st,max}$, the maximum shear stresses $\tau_{st,A}$ or $\tau_{st,As}$, and, if the customer requires, the shear displacement δ_{st} of fasteners. The test procedure is intended to ensure reproducible single-shear test results of fasteners while being as simple and practical as possible test execution.

D.2 Scope

This single-shear test procedure applies to full-size fasteners with full or reduced loadability according to the specifications given in EN ISO 898-1, Clause 9.1.2 *or EN ISO 3506-1, Clause 9.1.1*.

D.3 Symbols and Definitions

The following symbols apply to the single-shear test procedure for fasteners:

F_{st} Shear load continuously measured in the single-shear test, in Newton,

$F_{st,max}$ Maximum load observed in the shear test defined as ultimate shear load, in Newton,

$\tau_{st,A}$ Resulting shear stress in the unthreaded part A of the fastener at $F_{st,max}$, in megapascal,

$\tau_{st,As}$ Resulting shear stress in the threaded part A_s of the fastener at $F_{st,max}$, in megapascal,

d_{hst} Hole diameter of the shear inserts for standard fasteners, in millimetre,

d_{hstf} Hole diameter of the shear inserts for fitting bolts, in millimetre,

A_{st} Measured cross-sectional area in the shear plane, in square millimetre,

d_{meas} Measured diameter of the unthreaded part of the fastener, in millimetre,

$d_{2,meas}$ Measured pitch diameter of external thread, in millimetre,

$d_{3,meas}$ Measured minor diameter of external thread, in millimetre,

δ_{st} Shear displacement measured in the single-shear test, in millimetre,

$\delta_{st,max}$ Resulting shear displacement at $F_{st,max}$, in millimetre.

D.4 Apparatus

The tensile test machine shall be in accordance with ISO 7500-1, Class 1 or better. Since the single-shear test procedure for fasteners is intended as a displacement-controlled tensile test procedure to avoid erroneously higher shear loads from the compressive testing procedure, a compression testing machine shall not be used.

D.5 Testing device

Generally, the testing device consists of a steel support structure and shear inserts. The testing device shall be sufficiently rigid to avoid even small deformation or gap formation that could influence the determination of the ultimate shear load $F_{st,max}$.

The steel support structure shall be as follows:

— massive and rigid support structure made of suitable high-strength steel material,

— designed for flat clamping jaws (recommended) or alternative types of connection to stud bolts or threaded rods, or as flat plate connections,

— hardness of 45 HRC minimum,

— precise fitting of the shear inserts by pressing or constructed as a fine pitch threaded connection,

— if the shear displacement δ_{st} should be measured during the test, reference points for optical measuring systems or fixations for LVDTs must be provided in the test apparatus, see Figure D.1.

The shear inserts shall be as follows:

— shear inserts made of high-strength steel material with sufficient steel material around the holes to avoid any bending or bearing failure,

— hardness of 60 HRC minimum,

— for tensile strengths of the fasteners greater than 1300 N/mm², reinforcements of the shear inserts and higher hardness should be considered to exclude any plastic deformation,

— depending on the length of the fasteners and the desired position of the shear plane in the unthreaded or threaded part, the thickness of the shear inserts must be adjusted,

— hole diameter for standard fasteners, d_{hst}, as defined in Table D.1 under consideration of ISO tolerance H8 for holes according to EN ISO 286-2,

— hole diameter for fitting bolts, d_{hstf}, defined as nominal thread diameter d ($d_{hstf,min}$) and ISO tolerance H8 for holes ($d_{hstf,max}$) according to EN ISO 286-2,

— no gap between the shear inserts in the shear plane should be visible after installation.

Table D.1 — Hole diameters for standard fasteners, d_{hst}

Nominal thread diameter, *d*	d_{hst} min.	d_{hst} max.	**Nominal thread diameter,** *d*	d_{hst} min.	d_{hst} max.
3	3,4	3,58	16	17	17,27
3,5	3,9	4,08	18	19	19,33
4	4,5	4,68	20	21	21,33
5	5,5	5,68	22	23	23,33
6	6,6	6,82	24	25	25,33
7	7,6	7,85	27	29	29,33
8	9	9,22	30	32	32,39
10	11	11,27	33	35	35,39
12	13	13,27	36	38	38,39
14	15	15,27	39	41	41,39

An example of testing device for single-shear tests on fasteners are shown in Figure D.1, which need to be adapted to the customer's requirements and the tensile testing machine used. The single-shear testing device need not to conform to the examples of Figure D.1 but must be sufficiently massive and rigid for the abovementioned reasons.

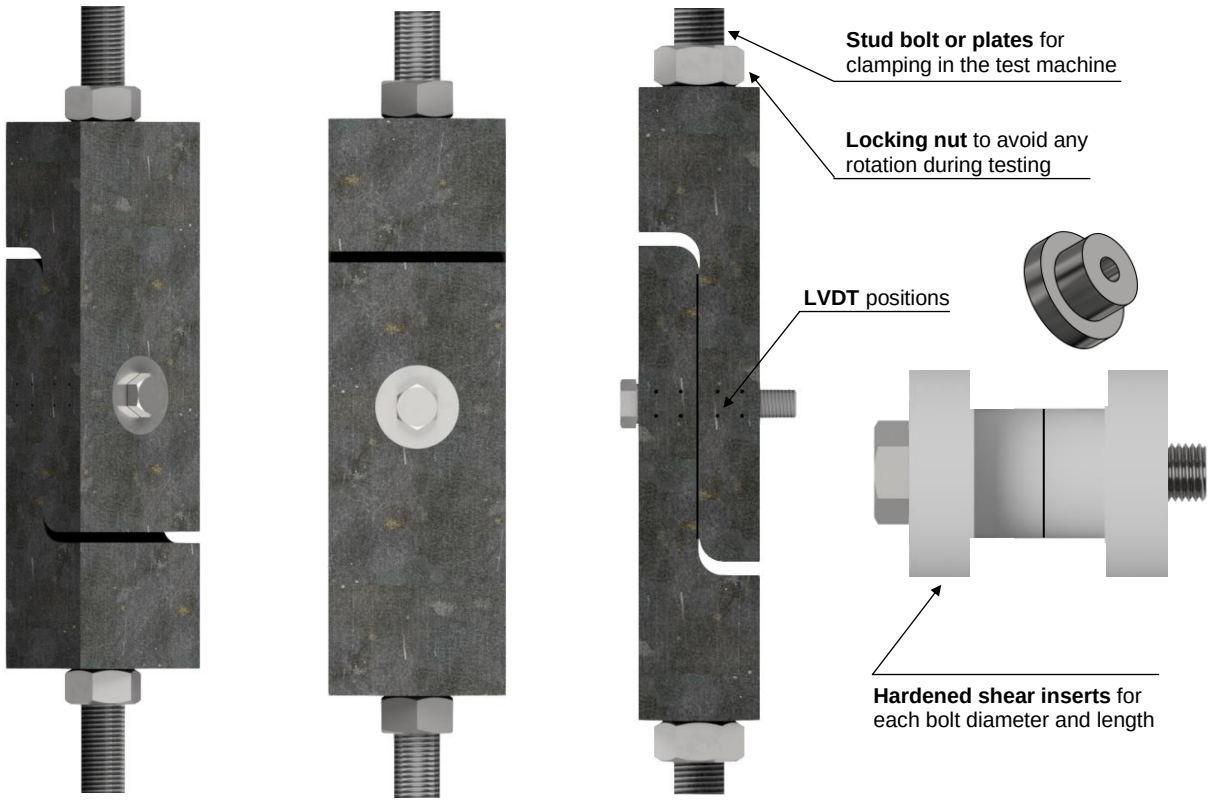


Figure D.1 — Examples of testing devices for single-shear on fasteners

Plastic deformation of the bearing of the shear inserts and gap formulation in the shear plane during pure shear testing and possible accumulation of fastener material has to be excluded in all cases.

The fasteners to be tested have to be mounted into the shear inserts, as shown in Figure D.1, without a nut or washer(s).

D.6 Test procedure

All fasteners with full or reduced loadability shall be tested as received.

Before single-shear testing, the cross-sectional area A_{st} (as the gross cross-sectional area of the unthreaded portion or as the tensile stress area of the threaded portion) of the fastener in the shear plane must be determined. Herein, all length measurements shall be made with an accuracy of 0,02 mm or better. In agreement with the client, nominal cross-sectional values can be used instead of the measured values under consideration of the product class or thread tolerance class, which must be noted in the test report accordingly.

If the shear displacement δ_{st} of fasteners should be measured, reference points for high-accuracy optical measuring systems or LVDTs have to be mounted.

The testing speed, as determined with a free-running cross-head, shall not exceed 10 mm/min. The single-shear test shall be continued until bolt fracture occurs. The shear load F_{st} and, if required, the shear displacement δ_{st}, have to be recorded continuously.

At least three single-shear test per batch of fasteners should be carried out. After each test, the parts of the broken fastener sample are removed from the testing device. Care must be taken so that no fragments remain between the faces of the shear inserts. Furthermore, the bearing of the shear inserts must be checked carefully for any visible plastic deformation and replaced if necessary.

D.7 Test results

The maximum load observed in the single-shear test $F_{st,max}$ is representing the ultimate shear load. The resulting shear stresses $\tau_{st,A}$ or $\tau_{st,As}$ shall be calculated as follows:

If the unthreaded part of the fastener is in the shear plane:

$$\tau_{st,A} = \frac{F_{st,max}}{A_{st}} = \frac{F_{st,max}}{\frac{\pi \cdot d_{meas}^{\ 2}}{4}} \tag{D.1}$$

where

d_{meas} is the measured diameter of the unthreaded part of the fastener.

If the threaded part of the fastener is in the shear plane:

$$\tau_{st,As} = \frac{F_{st,max}}{A_{st}} = \frac{F_{st,max}}{\frac{\pi}{4} \cdot \left(\frac{d_{2,meas} + d_{3,meas}}{2} \right)^2} \tag{D.2}$$

where

$d_{2,meas}$ is the measured pitch diameter of external thread, see ISO 724,

$d_{3,meas}$ is the measured minor diameter of external thread.

D.8 Test report

The following minimum information shall be included in the test documentation:

— identification of the laboratory,

— identification of the organisation ordering the test,

— date of reception of the fasteners,

— product specification and lot number of the fasteners tested,

— date of testing,

— number of fasteners tested,

— details of the test equipment including specifications of the shear inserts,

— testing conditions,

— test results,

— if required, documentation of the shear fracture and fracture surfaces,

— if required, shear load-shear displacement curves,

— conclusions.

8.5 Draft for a universal test procedure for fasteners of EN ISO 898-1

8.5.1 General

Based on the findings from the experimental investigations and numerical studies conducted in Chapter 6, a draft for a universal test procedure for fasteners is developed and formulated as an informative annex to EN ISO 898-1. The procedure is primarily intended to give guidance regarding the performance of interaction tests on fasteners but also enables to conduct tensile tests on bolting assemblies according to EN 15048-2 and single-shear tests on fasteners complying with the aforementioned proposed specifications for Annex D of EN ISO 898-1, see Chapter 8.4.2. As the test specification is intended as a new Annex C for EN ISO 3506-1 for stainless steel bolts, references to EN ISO 3506-1 are again marked in grey.

8.5.2 Proposed universal test procedure for fasteners of Annex E of EN ISO 898-1

Annex E

(informative)

Universal test procedure for fasteners
Tension, shear and interaction test procedure

E.1 General

The test procedure targets determining the ultimate interaction load $F_{it,max}$ of fasteners subjected to combined tension and shear, the resulting axial stresses $\sigma_{it,A}$ or $\sigma_{it,As}$ and shear stresses $\tau_{it,A}$ or $\tau_{it,As}$, and, if the customer requires, the displacement δ_{it} of fasteners during testing. The interaction test for fasteners is designed as single-shear testing procedure while being as simple and practical as possible test execution. Furthermore, this test procedure

allows to conduct pure tension tests fulfilling the requirements of EN 15048-2, Clause 6, and pure single-shear tests (following the specifications given in EN ISO 898-1, Annex D *or EN ISO 3506-1, Annex B*).

E.2 Scope

This interaction test procedure applies to full-size fasteners with full or reduced loadability according to the specifications given in EN ISO 898-1, Clause 9.1.2 *or EN ISO 3506-1, Clause 9.1.1*.

E.3 Symbols and Definitions

The following symbols apply to the interaction test procedure for fasteners:

F_{it} Combined tension and shear load measured in the interaction test, in Newton,

$F_{it,max}$ Maximum load observed in the test defined as ultimate interaction load and further distinguished into $F_{it,max,axial}$ and $F_{it,max,shear}$, in Newton,

$\sigma_{it,A}$ Resulting axial stress in the unthreaded part A of the fastener at $F_{it,max,}$ in megapascal,

$\sigma_{it,As}$ Resulting axial stress in the threaded part A_s of the fastener at $F_{it,max,}$ in megapascal,

$\tau_{it,A}$ Resulting shear stress in the unthreaded part A of the fastener at $F_{it,max,}$ in megapascal,

$\tau_{it,As}$ Resulting shear stress in the threaded part A_s of the fastener at $F_{it,max,}$ in megapascal,

β Loading angle related to the longitudinal axis of the fastener, in degree,

d_{hit} Hole diameter of the shear inserts for standard fasteners, in millimetre,

d_{hitf} Hole diameter of the shear inserts for fitting bolts, in millimetre,

A_{it} Measured cross-sectional area in the shear plane, in square millimetre,

d_{meas} Measured diameter of the unthreaded part of the fastener, in millimetre,

$d_{2,meas}$ Measured pitch diameter of external thread, in millimetre,

$d_{3,meas}$ Measured minor diameter of external thread, in millimetre,

δ_{it} Combined displacement measured in the interaction test, in millimetre,

$\delta_{it,axial}$ Calculated axial displacement measured in the interaction test, in millimetre,

$\delta_{it,transv}$ Calculated shear displacement measured in the interaction test, in millimetre,

$\delta_{it,max}$ Resulting combined displacement at $F_{it,max}$, in millimetre.

E.4 Apparatus

The tensile test machine shall be in accordance with ISO 7500-1, Class 1 or better.

E.5 Testing device

The testing device is derived from the North American NASM 1312-2:2023 [E.1] standard test method and the single-shear interaction test rig by Steeve and Wingate [E.2] and is adopted to the testing requirements of EN ISO 898-1 *or EN ISO 3506-1.* The testing device allows to test loading angles of 0°, 15°, 30°, 45°, 60°, 75° and 90° in order to realise different ratios of combined tension and shear on the fastener.

Generally, the testing device consists of a two massive steel support structures, shear inserts (equal to EN ISO 898-1, Annex D *or EN ISO 3506-1, Annex B*) and two holders to be clamped in the tensile testing machine. The testing device shall be sufficiently rigid.

The steel support structures shall be as follows:

— massive and rigid support structures made of suitable high-strength steel material,

— hardness of 45 HRC minimum,

— precise fitting of the shear inserts by pressing or constructed as a fine pitch threaded connection,

— if the combined tension and shear displacement δ_{it} should be measured during the test, reference points for optical measuring systems or fixations for LVDTs must be provided in the test apparatus, see Figure E.1,

— both steel support structures should be secured against sudden rotation during assembly and testing, particularly in the case of fastener failure.

The shear inserts shall be as follows:

— shear inserts made of high-strength steel material with sufficient steel material around the holes to avoid any bending or bearing failure,

— hardness of 60 HRC minimum,

— for tensile strengths of the fasteners greater than 1300 N/mm², reinforcements of the shear inserts and higher hardness should be considered to exclude any plastic deformation,

— depending on the length of the fasteners and the desired position of the shear plane in the unthreaded or threaded part, the thickness of the shear inserts must be adjusted,

— hole diameter for standard fasteners, d_{hst}, as defined in Table E.1 under consideration of ISO tolerance H8 for holes according to EN ISO 286-2,

— hole diameter for fitting bolts, d_{hstf}, defined as nominal thread diameter d ($d_{hstf,min}$) and ISO tolerance H8 for holes ($d_{hstf,max}$) according to EN ISO 286-2,

— no gap between the shear inserts in the shear plane should be visible after installation.

Table E.1 — Hole diameters for standard fasteners, d_{hst}

Nominal thread diameter, *d*	***d_{hst}***		**Nominal thread diameter, *d***	***d_{hst}***	
	min.	max.		min.	max.
3	3,4	3,58	16	17	17,27
3,5	3,9	4,08	18	19	19,33
4	4,5	4,68	20	21	21,33
5	5,5	5,68	22	23	23,33
6	6,6	6,82	24	25	25,33
7	7,6	7,85	27	29	29,33
8	9	9,22	30	32	32,39
10	11	11,27	33	35	35,39
12	13	13,27	36	38	38,39
14	15	15,27	39	41	41,39

An exemplary testing device is proposed in Figure E.1, which need to be adapted to the customer's requirements and the tensile testing machine used. The interaction testing device need not to conform to the examples of Figure E.1 but must be sufficiently massive and rigid for the abovementioned reasons.

Plastic deformation of the bearing of the shear inserts and gap formulation in the shear plane during pure shear testing and possible accumulation of fastener material has to be excluded in all cases.

The fasteners to be tested have to be mounted into the shear inserts with a nut, as shown in Figure E.1 but without washer(s).

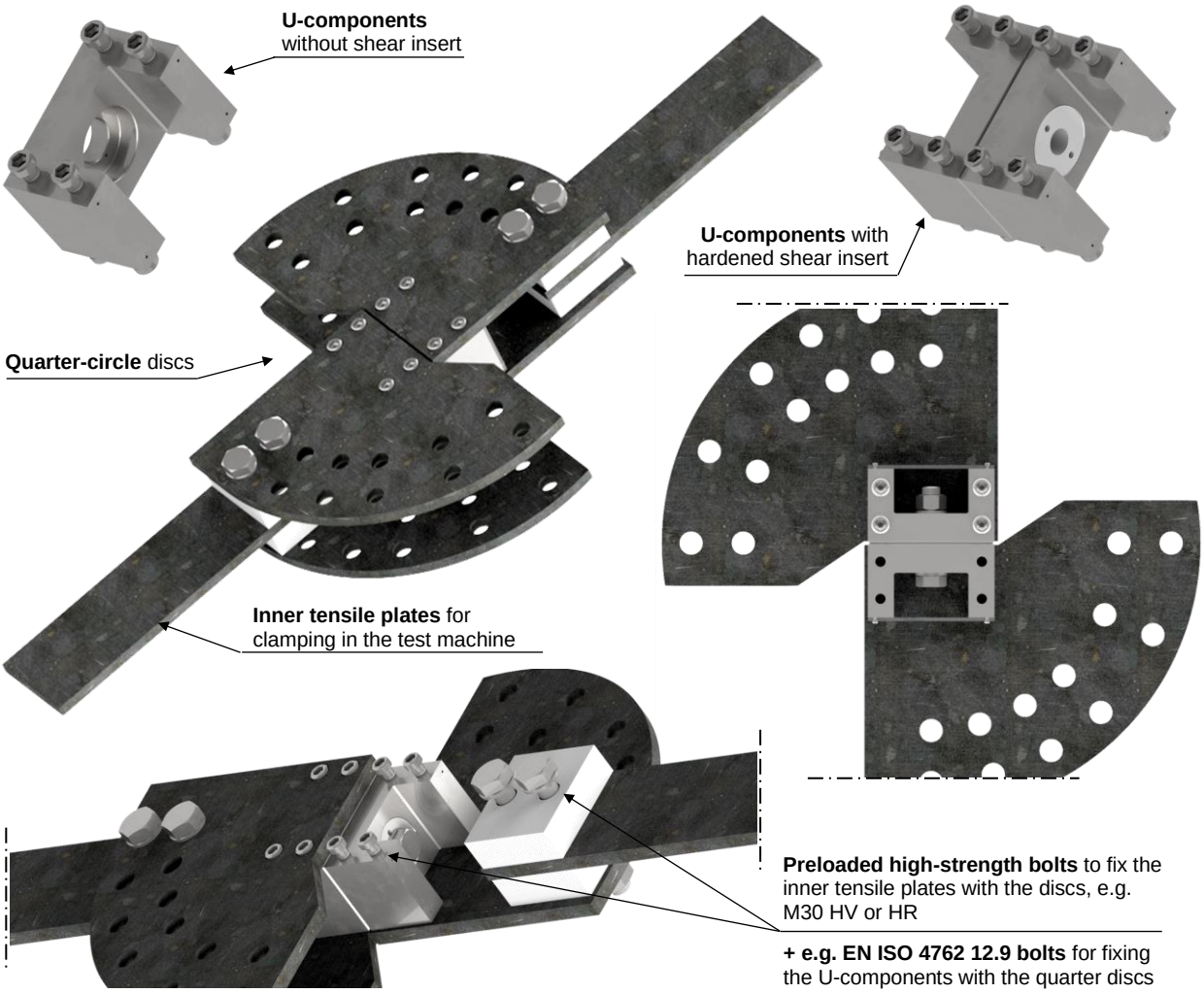


Figure E.1 — Example of testing device for interaction tests on fasteners

E.6 Test procedure

All fasteners with full or reduced loadability shall be tested as received.

Before tension, shear or interaction testing, the cross-sectional area A_{it} (as the gross cross-sectional area of the unthreaded portion or as the tensile stress area of the threaded portion) of the fastener in the shear plane must be determined. Herein, all length measurements shall be made with an accuracy of 0,02 mm or better. In agreement with the client, nominal cross-sectional values can be used instead of the measured values under consideration of the product class or thread tolerance class, which must be noted in the test report accordingly.

If the combined tension and shear displacement δ_{it} should be measured during the test, reference points for high-accuracy optical measuring systems or LVDTs have to be mounted.

The testing speed, as determined with a free-running cross-head, shall not exceed 10 mm/min. The tests shall be continued until bolt fracture occurs. The combined tension and shear load F_{it} and, if required, the combined displacement δ_{it}, have to be recorded continuously.

At least three single-shear test per batch of fasteners should be carried out. After each test, the parts of the broken fastener sample are removed from the testing device. Care must be taken so that no fragments remain in shear inserts and bearing. Furthermore, the bearing of the shear inserts must be checked for visible plastic deformation and replaced if necessary.

E.7 Test results

The maximum load observed in the interaction test $F_{it,max}$ represents a combination of tension and shear load depending on the tested loading angle β, which can simply be distinguished into the corresponding tension component, see Eq. (E.1), and shear component, see Eq. (E.2).

$$F_{it,max,axial} = F_{it,max} \cdot \cos(\beta) \tag{E.1}$$

$$F_{it,max,shear} = F_{it,max} \cdot \sin(\beta) \tag{E.2}$$

The resulting axial stresses $\sigma_{it,A}$ or $\sigma_{it,As}$ shall be calculated as follows:

If the unthreaded part of the fastener is in the shear plane:

$$\tau_{st,A} = \frac{F_{st,max}}{A_{st}} = \frac{F_{st,max}}{\frac{\pi \cdot d_{meas}^{\ 2}}{4}} \tag{E.3}$$

where

d_{meas} is the measured diameter of the unthreaded part of the fastener.

If the threaded part of the fastener is in the shear plane:

$$\sigma_{it,As} = \frac{F_{it,max,axial}}{A_{it}} = \frac{F_{it,max} \cdot \cos(\beta)}{\frac{\pi}{4} \cdot \left(\frac{d_{2,meas} + d_{3,meas}}{2}\right)^2} \tag{E.4}$$

where

$d_{2,meas}$ is the measured pitch diameter of external thread, see ISO 724,

$d_{3,meas}$ is the measured minor diameter of external thread.

The resulting shear stresses $\tau_{it,A}$ or $\tau_{it,As}$ shall be calculated as follows:

If the unthreaded part of the fastener is in the shear plane:

$$\tau_{it,A} = \frac{F_{it,max,shear}}{A_{it}} = \frac{F_{it,max} \cdot \sin(\beta)}{\frac{\pi \cdot d_{meas}^{\ 2}}{4}} \tag{E.5}$$

where

d_{meas} is the measured diameter of the unthreaded part of the fastener.

If the threaded part of the fastener is in the shear plane:

$$\tau_{it,As} = \frac{F_{it,max,shear}}{A_{it}} = \frac{F_{it,max} \cdot \sin(\beta)}{\frac{\pi}{4} \cdot \left(\frac{d_{2,meas} + d_{3,meas}}{2}\right)^2} \tag{E.6}$$

where

$d_{2,meas}$ is the measured pitch diameter of external thread, see ISO 724,

$d_{3,meas}$ is the measured minor diameter of external thread.

If required, the resulting axial and transversal displacements $\delta_{it,axial}$ or $\delta_{it,transv}$ can be calculated at any point as follows:

$$\delta_{it,axial} = \delta_{it} \cdot \cos(\beta \tag{E.7}$$

$$\delta_{it,transv} = \delta_{it} \cdot \sin(\beta) \tag{E.8}$$

E.8 Test report

The following minimum information shall be included in the test documentation:

— identification of the laboratory,

— identification of the organisation ordering the test,

— date of reception of the fasteners,

— product specification and lot number of the fasteners tested,

— date of testing,

— number of fasteners tested,

— details of the test equipment including specifications of the shear inserts,

— testing conditions,

— tested loading angle,

— test results,

— if required, documentation of the fracture surfaces,

— if required, requirements of EN 15048-2, Clause 6.4 regarding $F_{bi,max} \geq F_{ub}$,

— if required, interaction diagrams and/or tension-shear component load curves,

— conclusions.

8.6 Summary and conclusions

Amendments for standardisation for FprEN 1993-1-4 and the German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022 (for bolts made of stainless steel) and EN 1993-1-8:2024 [82] (for bolts made of carbon steel) regarding the tension resistance $F_{t,Rd}$, the shear resistance $F_{v,Rd}$ and the interaction resistance were outlined. The amendments are based on [78] and further research activities at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen, Germany. Finally, new and more economical design approaches for non-preloaded stainless and carbon steel bolts could be proposed, which are statistically verified against the partial safety factor $\gamma_{M2} = 1.25$ for connections and fulfilling the safety requirements of the Eurocode.

Furthermore, new test procedures for fasteners are proposed:

Firstly, based on the experimental and numerical findings, a draft text for a single-shear test procedure for fasteners was proposed as informative Annex D of EN ISO 3506-1 and Annex C of EN ISO 3506-1. This simplified single-shear test procedure aims to determine the ultimate shear load $F_{st,max}$, the resulting shear stresses $\tau_{st,A}$ or $\tau_{st,As}$, and (if required) the shear displacement δ_{st} of fasteners. Secondly, a draft text for a universal test procedure for fasteners was developed. The procedure is primarily intended to give guidance regarding the performance of interaction tests on fasteners but also enables the conduct of tensile tests on bolting assemblies according to EN 15048-2 and single-shear tests on fasteners complying with the proposed specifications for Annex D of EN ISO 898-1.

Both annexes proposed for future revisions of EN ISO 898-1 and EN ISO 3506-1 allow a comprehensive characterisation by testing the shear strength and interaction behaviour of

carbon steel and stainless steel bolts, which are not covered in the European standardisation until now.

9 Overall summary, conclusions and outlook

9.1 Overall summary

In steel structures, bolted connections made of austenitic and austenitic-ferritic (duplex) stainless steel according to the design standard EN 1993-1-4 [67] are predominantly executed as non-preloaded category A bearing type connections, category D tension connections or as category A+D bolted connections subjected to combined tension and shear loading according to the current European design regulations primarily developed for carbon steel bolts and specified in EN 1993-1-8 [72] for connections. However, the load bearing behaviour of stainless steel bolts is significantly affected by their specific material properties, such as nonlinearity and the transformation of austenitic to forming induced martensitic material in the tensile cross-section originating from the thread rolling process with a larger hardness and higher strength in the border of the cross-section of the threads, which must be considered already in the design process of these bolted connections for a safe and reliable structural application over the whole service life. Herein, uncritical adoption of existing design regulations for carbon steel bolts to stainless steel bolted connections are not expedient. Hence, it was imperative to close this normative gap in comprehensive investigations.

Experimental and numerical investigations and reliability analyses into the load bearing behaviour of austenitic and duplex stainless steel bolts and bolting assemblies under tension, single-shear and combined tension and shear have been systematically carried out within the German research project FOSTA P 1386 / IGF-No. 20651 N [78] and further studies at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen, Germany. Finally, new and more economical design rules for the tension resistance $F_{t,Rd}$, shear resistance $F_{v,Rd}$ and interaction resistance of austenitic and duplex bolts could be proposed and verified by statistical evaluations according to EN 1990, Annex D [79] against the partial safety factor γ_{M2} = 1.25 for connections. These new proposed design rules were successfully implemented in the revision of EN 1993-1-4, FprEN 1993-1-4 [80], and the German national technical approval/General construction technique permit abZ/aBGZ-30.3-6:2022 [81].

In this thesis, firstly, the background of the new proposed design rules for austenitic and duplex stainless steel bolts was discussed in the frame of different international design concepts, and secondly, extended by supplementary investigations into the tension and single-/double-shear resistance of bolts and bolting assemblies. Further statistical evaluations complemented these supplementary studies including analyses of the resulting partial safety factors γ_M* regarding the Eurocode safety assessment. For this purpose, new assessment criteria were developed.

Furthermore, the maintained design regulations for carbon steel bolted connections according to EN 1993-1-8 and EN 1993-1-8:2024 were statistically re-evaluated according to EN 1990, Annex D under consideration of various new experimental studies from literature on carbon steel bolts under tension, shear and interaction, which have become available in the meantime but were not statistically verified. Therefore, in the frame of this thesis, own experimental investigations on carbon steel bolts on the tension, single-/double-shear and interaction resistance and an extensive literature review were conducted and implemented in the renewed reliability analyses to prove the suitability of various design approaches for the tension $F_{t,Rd}$, shear $F_{v,Rd}$ and interaction resistance of carbon steel bolting assemblies. As a result, new and more economical design rules for carbon steel bolts were proposed and harmonised with the new design rules for stainless steel bolts proposed for FprEN 1993-1-4 and the normative requirements of EN ISO 898-1 [76] regarding the minimum ultimate tensile load $F_{m,min}$.

Finally, due to the lack of European standardisation for these types of tests, new annexes are proposed as amendments for future revisions of EN ISO 898-1 and EN ISO 3506-1 [73], which allow the determination of mechanical properties of carbon and stainless steel bolts in terms of simplified test procedures for the shear resistance (as single-shear test procedure) and single-shear interaction resistance (which can also be used for single-shear testing and for tensile tests on bolting assemblies fulfilling the requirements of EN 15048-2 [365]).

9.2 Conclusions

In the following, the main conclusions of the investigations into the tension, single-/double-shear and interaction resistance of stainless and carbon steel bolts are presented:

Comparison of selected international design rules

Selected international design rules for non-preloaded bolted connections made of carbon and stainless steel from Europe, Germany, the UK, the USA, Canada, Australia, New Zealand, Japan, South Africa, India, China and Russia were introduced and compared with respect to the resulting characteristic and design bolt resistance in tension, shear and interaction. It could be outlined in a global comparison that the design regulations for stainless steel bolts are essentially based on the regulations of bolted connections made of carbon steel: the basic design concept is intentionally maintained in most cases and only slightly modified generally on the conservative side. It was shown that there are considerable differences in the tension, shear and interaction resistance of carbon and stainless steel bolts: Firstly, only Eurocode 3 (EN 1993-1-8 and EN 1993-1-4) limits the tension resistance $F_{t,Rd}$ of carbon or stainless steel bolts to 90 %, justified by the fact that prying effects must be implicitly considered in the design and that the statistical evaluation at the time of the introduction of the Eurocode made a reduction in the design necessary to fulfil the safety requirements of the Eurocode. However, partial safety factors γ_M* exceeding γ_{M2} = 1.25 for connections are mainly based on nominal tensile strengths implemented in the reliability analyses, as the experimental tensile strengths of the bolts were mainly unknown. This was a purely methodological problem that needed to be re-verified by a new reliability analysis based on the measured tensile strength of the bolts and significantly expanded test database. Secondly, the widely differing shear coefficients α in an international comparison for the design of the shear resistance $F_{v,Rd}$ of carbon and stainless steel bolts are striking and there was an urgent need for clarification. Thirdly, the conservatism of the bilinear interaction equation according to EN 1993-1-8, especially for the case "unthreaded bolt part in the shear plane", is striking compared to other international interaction equations. The quadratic bolt interaction or trilinear bolt approach as a simplified expression can be found in many design standards worldwide, allowing a significantly higher utilisation of the interaction resistance compared to the conservative bilinear Eurocode design regulation.

New harmonised design rules for stainless steel bolts

Tension resistance of a bolt, $F_{t,Rd}$

It could be shown that austenitic and duplex stainless steel bolts are characterised by outstanding high ductility and high tensile strengths compared to structural carbon steel bolts. The resulting overstrength ratios between the experimental mean maximum load $F_{mf,exp,mean}$ and the minimum ultimate tensile load $F_{mf,nom}$ of the tested partially threaded austenitic bolts are due to the varying degrees of transformation of austenitic to forming induced martensitic material in the threaded bolt part between 1.07 and 1.35 and between 1.06 and 1.23 for duplex bolts. Fully threaded austenitic bolts according to EN ISO 4017 [121] show overstrength ratios between 1.01 and 1.23 and are less pronounced, while duplex bolts exhibit overstrength ratios

between 1.09 and 1.20 comparable to the partially threaded bolts. Due to the significant overstrength, it was proposed to increase the tension resistance $F_{t,Rd}$ of stainless steel bolts with $k_2 = 1.0$ instead of $k_2 = 0.9$. Herein, possible prying effects are implicitly taken into consideration.

The supplementary experimental investigations covered tensile tests on austenitic and duplex stainless steel bolting assemblies according to EN 15048-2 and tensile coupon test specimens machined from M16 stainless steel bolts according to EN ISO 6892-1 [366] to investigate the strength distribution. Due to the transformation of austenitic to forming induced martensitic material in the tensile cross-section originating from the thread rolling process in the border of the cross-section of the threads, finally a nonhomogeneous distribution of the tensile and yield strength in the unthreaded and threaded parts of austenitic and even duplex stainless steel bolts could be confirmed. The main failure mode of austenitic bolts occurred in the unthreaded part due to high overstrength in the bolt threads, while all duplex bolts and only a few austenitic bolt series failed in the threaded bolt part. It can be concluded that tensile tests on bolts according to EN ISO 3506-1 and tensile tests on bolting assemblies according to EN 15048-2 lead to the same tension resistances and that the load bearing differences from the testing procedures and the nut are negligible (as expected).

A reliability analysis according to EN 1990, Annex D was conducted based on an extended database of 375 tensile tests including literature data in order to prove the resulting partial safety factors γ_M* of the proposed design approach for the tension resistance of stainless steel bolts with $k_2 = 1.0$ against the partial safety factor $\gamma_{M2} = 1.25$ for connections. It could be shown that in all subsets the resulting individual partial safety factors $\gamma_{M,i}$* are clearly below $\gamma_{M2} = 1.25$ on the safe side in all investigated property classes and over all stainless steel bolts and bolting assemblies. Furthermore, a harmonisation of the tension resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolts between EN 1993-1-4 and EN ISO 3506-1 ($F_{m,min}$) and other major international design standards is accomplished.

Shear resistance of a bolt, $F_{v,Rd}$

It could be confirmed in supplementary experimental investigations into the shear resistance of austenitic and duplex stainless steel bolts and bolting assemblies that depending on the bolt's specific alignment in the hole clearance and considering the extraordinarily high deformation capacity of austenitic/duplex stainless steel, the maximum bolt shear resistance achieved in tests can vary measurably. However, single-shear testing of M16 bolts with a hole diameter of $d_h = 17$ mm leads to lower bolt shear resistances for each shear plane on the safe side compared to double-shear testing under the same clearance. The application of hardened shear adapters without nominal bolt hole clearance of $d_{h,nom} = 16$ mm in ISO tolerance field H8 leads to measurably lower shear resistances, which lie with except for one tested bolt series within the range of scattering and are negligible. Skewing and possible misalignments of the bolt during shear testing could be confirmed in numerical FEM investigations, leading to an increased cross-sectional area and higher shear resistance of bolts. It was shown in the that the local material properties and multiaxial stress state in the shear plane are decisive for the shear (and interaction) resistance of bolts.

For the unthreaded or threaded bolt part in the shear plane, a direct positive correlation between the tensile strength and shear strength exists ($r = 0.89$ for the unthreaded part and $r = 0.94$ for the threaded part) accompanied by indirect strong correlations of the bolt property class and steel grade. However, the indirect correlations stemming from bolt diameter and bolt hole clearance are relatively weaker concerning their impact on the relationship between tensile strength and shear strength. Based on the pathway analysis, the relationship between

tensile strength and shear strength can also be determined by *Indirect Path 2* as “tensile strength to property class” combined with “property class to shear strength”.

Finally, it could be confirmed in an extended reliability analysis according to EN 1990, Annex D that the proposed approach for FprEN 1993-1-4 regarding the shear resistance $F_{v,Rd}$ of austenitic and duplex stainless steel bolts with new and more economic shear coefficients α fulfils the safety requirements of the Eurocode with γ_M* = 1.18 for the unthreaded bolt part and γ_M* = 1.15 for the threaded bolt part in the shear plane based. The extended reliability analysis for statistical re-verification is based on a significantly expanded database and complemented by modified assesment criteria.

Interaction resistance of a bolt

The suitability of different international interaction design approaches to describe the combined tension and shear resistance of austenitic and duplex stainless steel bolting assemblies was evaluated. It was complemented by a reliability analysis according to EN 1990, Annex D including the proposed more economical design approaches for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022 by Stranghöner/Abraham for the interaction resistance of austenitic and duplex stainless steel bolting assemblies. Herein, the distribution of the resulting partial safety factors γ_M* across all bolt property classes, loading angles and different interaction design approaches was investigated. In total, 456 interaction tests with unthreaded bolt part and 392 interaction tests with threaded bolt part in the shear plane on austenitic and duplex stainless steel bolting assemblies were considered.

It can be concluded that for the interaction approaches of the current EN 1993-1-4 and the German national annex DIN EN 1993-1-4/NA [71] all resulting individual partial safety factors $\gamma_{M,i}$* of the interaction resistance of austenitic and duplex bolting assemblies with unthreaded or threaded bolt part in the shear plane are clearly below γ_{M2} = 1.25 confirming the conservatism of these approaches. On the contrary, an in-depth analysis of the resulting individual partial safety factors γ_M* over all steel grades, property classes and loading angles for the more economical interaction resistance by Stranghöner/Abraham for FprEN 1993-1-4 is fulfilling the safety requirements of the Eurocode. The statistical evaluations over all austenitic and duplex bolts show a resulting partial safety factor of γ_M* = 1.21 ≤ γ_{M2} = 1.25 for the unthreaded and γ_M* = 1.18 ≤ γ_{M2} = 1.25 for the threaded bolt part in the shear plane. Loading angles of 30° and 45° were identified as critical for austenitic stainless steel bolting assemblies in PC 70, which are partially exceeding the partial safety factor of γ_{M2} = 1.25 for connections. However, the number of unsafe individual results $\gamma_{M,i}$* is less 20 % and therefore uncritical, while the mean values of the PC subsets are always below γ_{M2} = 1.25. The proposed new interaction equations by Stranghöner/Abraham already consider the increased tension resistance $F_{t,Rd}$ of austenitic and duplex stainless steel bolting assemblies with the proposed k_2-factor of k_2 = 1.0 and the increased shear resistance $F_{v,Rd}$ for FprEN 1993-1-4.

New harmonised design rules for carbon steel bolts

Tension resistance of a bolt, $F_{t,Rd}$

Based on an extended reliability analysis on partially and fully threaded carbon steel bolts in PC 4.6, 5.6, 8.8, 10.9 and 12.9 with 717 tensile tests from own experimental investigations and literature review, finally also the design tension resistance $F_{t,Rd}$ of carbon steel bolts can be increased by k_2 = 1.0. The extended statistical evaluation according to EN 1990, Annex D of the proposed tension resistance $F_{t,Rd}$ results to γ_M* = 0.99 ≤ γ_{M2} = 1.25 for all partially and fully threaded carbon steel bolts.

Analogues to austenitic and duplex stainless steel bolts, it can be concluded that the resistance function with k_2 = 1.0 seems to be most suitable to describe the tension resistance of carbon steel bolts and still includes sufficient safety reserves against bolt overstressing or failure due to prying effects, eccentricity, bending of the bolt and/or imperfections. Therefore, an entirely harmonisation of the tension resistance $F_{t,Rd}$ between carbon steel and stainless steel bolts according to FprEN 1993-1-4 as well as between the product standards EN ISO 898-1 and EN ISO 3506-1 regarding the minimum ultimate tensile loads can be achieved. Furthermore, the proposed bolt tension design approach with k_2 = 1.0 is in alignment with other international design codes and standards like North American ANSI/AISC 360 [293], SEI/ASCE 8 [298], CSA S16 [295], SANS 10162-1 [313] and other standards.

Shear resistance of a bolt, $F_{v,Rd}$

In view of a more economical but safe and reliable design of carbon steel bolts with unthreaded or threaded bolt part(s) in the shear plane, finally new and higher shear coefficients α have been proposed for the design shear resistance $F_{v,Rd}$ of bolts. The proposed shear coefficients ($\alpha_{proposed}$ = 0.70 for PC 4.6 and 5.6, and $\alpha_{proposed}$ = 0.65 for PC 8.8 and 10.9) are independent of the position of the shear plane ("Ease of Use") and based on an extended reliability analyses of 723 shear tests. The extended reliability analyses according to EN 1990, Annex D for the proposed bolt shear resistance $F_{v,Rd}$ results both to γ_M* = 1.18 ≤ γ_{M2} = 1.25 for the unthreaded and threaded bolt part in the shear plane.

Regarding the different load bearing behaviour of carbon steel bolts tested subjected to single-shear or double-shear, the main findings of the experimental investigations and the resulting shear resistances of carbon steel bolts can be summarised as follows:

- Single-shear testing could also be verified for carbon steel bolts on the safe side. Double-shear testing of carbon steel bolts results to higher shear resistance for each shear plane.
- In the case of carbon steel bolts with unthreaded parts in the shear plane, testing without a nut leads to significant scattering of the test results. However, this observation could not be confirmed for carbon steel bolts with threaded part in the shear planes. Therefore, no generally valid conclusions can be drawn here.
- In principle, all observed experimental results are to be understood more as a trend since the differences in the single-shear and double-shear resistances of carbon steel bolts are in the range of the scattering. Therefore, definitive statements are impossible or should only be evaluated with caution. The differences between the mean values of single-shear and double-shear testing with nut are between +1.32 % and +4.98 % and can therefore be neglected in the design of bolted shear connections.

Interaction resistance

The Stranghöner/Abraham interaction approach, which was primarily developed for austenitic and duplex stainless steel bolts for FprEN 1993-1-4 and is in the meantime also implemented in the renewed German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022, is also suitable to describe the interaction resistance of carbon steel bolts with unthreaded or threaded bolt part(s) in the shear plane. The approach leads to a statistically verified and more economical design compared to the current bilinear EN 1993-1-8 design rule. The extended statistical evaluation according to EN 1990, Annex D of the proposed bolt interaction results to γ_M* = 1.19 ≤ γ_{M2} = 1.25 for the unthreaded bolt part and γ_M* = 1.13 ≤ γ_{M2} = 1.25 for the threaded bolt part in the shear plane. It must be mentioned that the proposed interaction equations already consider the increased bolt tension resistance $F_{t,Rd}$ with k_2 = 1.0 and the increased shear resistance $F_{v,Rd}$ with the proposed higher and more economical shear coefficients $\alpha_{proposed}$ to offer a consistent, fully integrated design concept.

Furthermore, regarding the general interaction failure mechanism of carbon steel bolts, it can be proven that carbon steel bolts with threaded part in the shear plane exhibit a superior, more elliptical or even quadratic combined load bearing behaviour under tension and shear loading in contrast to carbon steel bolts with unthreaded part in the shear plane. The reason for this is that a compression ring forms in the bolt threads in the shear plane, which has a stabilising effect and counteracts a reduction in cross-section due to shear and transverse contraction due to tension. Consequently, for an even more economical design, carbon steel bolts with threaded bolt part(s) in the shear plane still include the potential to increase the interaction resistance with $\gamma_M^* = 1.13 \leq \gamma_{M2} = 1.25$ over all bolts.

Drafts for new single-shear and interaction test procedures for fasteners

Due to the current lack of European standardisation for these types of tests, new annexes were proposed as amendments for future revisions of EN ISO 898-1 and EN ISO 3506-1, which allow the determination of mechanical properties of carbon and stainless steel bolts in terms of simplified test procedures for the shear resistance and resulting shear stresses (as single-shear test procedure) and the interaction resistance (which can also be used for single-shear testing and for tensile tests on bolting assemblies fulfilling the requirements of EN 15048-2). The purpose of both annexes is to carry out the shear and interaction tests as simply and quickly as possible with sufficient accuracy of the test results and finally to close the European normative gap regarding the mechanical characterisation of fastener.

9.3 Outlook

Normative implementation

The presented investigations targeted different experimental and statistical aspects of non-preloaded stainless and carbon steel bolted connections subjected to tension, shear and combined tension and shear loading in order to propose new, more suitable and economical design rules, which are statistically verified in reliability analyses according to EN 1990, Annex D fulfilling the safety requirements of the Eurocode. These new proposed regulations for the design of bolts made of austenitic and duplex stainless steel were successfully implemented in FprEN 1993-1-4 and the German national technical approval/General construction technique permit abZ/aBG Z-30.3-6:2022. Furthermore, a discussion is desirable for the new proposed and harmonised design rules for carbon steel bolts, which may lead to normative amendments in the following revision process of EN 1993-1-8 to allow utilising more economical and, at the same time, safe and reliable designs according to the Eurocode safety requirements. Aligning with the new proposed design rules for stainless steel bolts of FprEN 1993-1-4 is expedient in offering the structural engineer a uniform design concept. This not only promotes and increases the acceptance of bolted connections made of stainless steel as an alternative to conventional fastening technology but also leads to an alignment of international design rules for engineers, who increasingly operate worldwide.

Extending the database of bolted tension/shear connections

Despite the large number of tests presented in [78] and this thesis, it should be noted that the number of tested stainless or carbon steel bolts in some property classes remains small (e.g. austenitic/duplex bolts in PC 50 with unthreaded part in the shear plane, austenitic/duplex bolts in PC 100 with threaded bolt part in the shear plane and interaction tests of carbon steel bolts in PC 5.6 are missing entirely). An extended test database with different bolt manufacturers is desirable to accurately implement the occurring scattering of the material-specific and geometrical basic variables in the statistical evaluation. Additionally, the tension, shear and

interaction resistance of countersunk bolts were not investigated in the frame of the German research project FOSTA P 1386 / IGF-No. 20651 N [78] and this thesis. Here, it remains to be clarified to what extent the reduction of the load bearing capacities is justified and to what extent the existing design concepts should be adapted in future normative revisions. Furthermore, bolts made of carbon and stainless steel from the North American region, for instance, hexagon head bolts, countersunk and hex cap bolts following the regulations of ASTM F3125/F3125M-23 [420] or ASTM F593-22 [329], could also be considered in future studies on the bolt tension, shear and interaction resistance. These studies could be extended to applications with low and elevated temperatures and fire design, leading to a European/ North American harmonised design concept.

Future research topics on bolted tension and shear connections

Regarding the design of bolted connections made of carbon or stainless steel, it should be noted that sustainable use of resources in the construction industry must also be aimed at, in addition to an economical and safe design. This contributes to bringing global energy-related carbon dioxide emissions to net zero by 2050 and participating in a climate-neutral society, as stated by the European Union, which aligns with the EU's commitment to global climate action under the Paris Agreement. In order to contribute to this thesis's objectives and to allow a more economical, safe, and resource-saving design, it is proposed that the load bearing capacity of long joints as bolted lap connections be fundamentally investigated in future studies. Regarding inhomogeneous load distribution, additional specifications exist for long joints, such as bolted lap connections, for example, in EN 1993-1-8, Clause 3.8 for carbon steel bolts. The reduction of the shear resistance of a bolt is also considered in other standards, e.g. in the Australian Standard AS 4100 by the reduction factor k_r. The thesis findings could be extended to include the unequal load distribution, the load-bearing capacity of a group of bolts and practical examples of design and construction explicitly covering carbon steel and stainless steel bolts and plates.

These investigations could be supplemented by numerical FEM analyses, artificial intelligence and machine learning in order to gain a deeper understanding of the main factors influencing the load-bearing capacity of bolted lap connections and to develop an improved design concept that meets the safety requirements of the Eurocode. Furthermore, the influence of low and elevated temperatures, fire impact and imperfections during the execution on site on the load bearing capacity of bolted lap connections should be quantified.

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[363] **Abraham, C.; Stranghöner, N.,** DASt-Forschungskolloquium, Einblicke in das Tragverhalten von zugbeanspruchten Scher-/Lochleibungsverbindungen aus nichtrostendem Stahl, Duisburg-Essen.

[364] **Abraham, C.; Stranghöner, N.,** New Harmonised Design Rules for Stainless and Carbon Steel Bolts Subjected to Tension, Shear and Combined Tension and Shear Loading, In: Proceedings of the Thirty-Third International Ocean and Polar Engineering Conference, ISOPE-2023 Ottawa, Canada.

[414] **Stranghöner, N.; Abraham, C.; Ehrhardt, L.,** New design approaches for tension, shear and interaction resistance of carbon steel bolts, Journal of Constructional Steel Research, 2024, 212, pp. 108260, DOI: https://doi.org/10.1016/j.jcsr.2023.108260.

Supervised bachelor and master theses

As part of the teaching activities at the Institute for Metal and Lightweight Structures at the University of Duisburg-Essen, the author supervised the following theses on the subject of this dissertation:

Malesevic, M., Einblicke in das Tragverhalten von zugbeanspruchten Scher-/Lochleibungsverbindungen aus Kohlenstoffstahl und nichtrostendem Stahl, Bachelor thesis, University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Essen, Germany, 2019.

Ehrhardt, L., Experimentelle Untersuchungen zum Tragverhalten von zugbeanspruchten Scher-/Lochleibungsverbindungen aus nichtrostendem Stahl, Bachelor thesis, University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Essen, Germany, 2020.

Khoury, T., Numerische Simulation und Parameterstudien des Tragverhaltens von zugbeanspruchten Scher-/Lochleibungsverbindungen aus nichtrostendem Stahl, Master thesis, University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Essen, Germany, 2020.

Soudan, H., Modellierung von nichtrostenden Stählen unter Berücksichtigung kinematischer Verfestigung und Viskoplastizität in ANSYS Workbench und ABAQUS, Master thesis, University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Essen, Germany, 2021.

Ehrhardt, L., Statistische Überprüfung von Widerstandsmodellen zugbeanspruchter Scher-/ Lochleibungsverbindungen aus nichtrostendem Stahl und Kohlenstoffstahl, Master thesis, University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Essen, Germany, 2021.

Hegde, N., Numerische Simulation und Parameterstudien zum Scher- und Zugtragverhalten von Schrauben aus nichtrostendem Stahl, Master thesis, University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Essen, Germany, 2021.

Ammana, L. R., Numerical simulation and parametric studies into the load bearing behaviour of stainless steel bolting assemblies, Master thesis, University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Essen, Germany, 2022.

Berger, M. S., Experimentelle und numerische Untersuchungen zum einschnittigen und zweischnittigen Tragverhalten von Schrauben aus Kohlenstoffstahl und nichtrostendem Stahl, Bachelor thesis, University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Essen, Germany, 2023.

Appendix A: Detailed literature review on carbon and stainless steel bolts

A.1 Literature review on the tension, shear and combined tension and shear load bearing behaviour of carbon steel bolts

A.1.1 Carbon steel bolts subjected to pure tension or shear loading

Already in 1964, Wallart and Fischer [220] from the Fritz Engineering Laboratory of the Lehigh University in Bethlehem, Pennsylvania, USA, investigated fundamentally the shear behaviour and shear strength of high-strength A354 BC, A354 BD and A440 bolts made of A440 and constructional alloy steel in double-shear tests. The experimental investigations include a tension and compression test rig in order to investigate differences in the testing procedure, the effect of lubrication on the shear load-deformation behaviour as well as the impact of changing positions of the shear planes in the unthreaded and/or threaded part of a bolt. The studies were accompanied by sawed sections of the double-shear tests with A325 and A490 bolts at different loading stages and allow a better understanding of the shear behaviour and shear strength of these type of bolted connections. Further studies regarding the shear behaviour of bolts with shear plane in the threaded part were conducted in 1974 by Rhodes and Harvey [224] from the University of Strathclyde Glasgow in 1974.

In Germany, Scheer from the Technical University of Braunschweig investigated the load bearing behaviour of one-bolt connections systematically and focussed in his research reports No. 6061 from 1980 [226] and No. 6064 from 1983 [228] on the one-bolt vs two-bolt bearing resistance but also on the tension (240 tests) and shear resistance (86 tests) of carbon steel bolts. The tension and shear tests include M12, M20 and M27 bolts in varying lengths and property classes 4.6, 5.6 and 10.9.

As already discussed in Chapter 2.4.5, the studies from Thomala [169] in 1984 and Wiegand et al. [176] confirmed an approximately linear relationship between the shear coefficient α and the tensile strength for carbon and austenitic stainless steel bolts almost independently of the chemical composition of the bolt material itself. Due to this behaviour, the shear strength and herewith the shear coefficient α decrease with increasing tensile strength. As the experimental investigations were conducted on unnotched bars, the test data will not be used in this this.

Hereafter, Petersen [229] from the Bundeswehr University Munich conducted in 1989 double-shear bearing tests with St 37 and St 52 steel plates and M16 10.9 HV bolting assemblies according to EN 14399-4. Petersen observed in some cases shear failure of the bolts with shear plane in the unthreaded part which allowed to determine the ratio between the shear and tensile strength of high-strength bolts in PC 10.9. Regarding the shear behaviour of high-strength bolts with threaded part in the shear plane, Valtinat and Dangelmaier [230] from the Technical University of Hamburg conducted 61 tensile tests on machined bolts and 120 double-shear tests for M16, M20 and M24 bolting assemblies in PC 5.6 (as reference) and PC 10.9 in 1990. As a continuation of these studies, Valtinat [421] also focused 1997 on the low-cycle fatigue behaviour of bolted shear connections with threaded part in the shear plane.

As part of the normative process of the revision of DIN 18800-1:1988-03 [379] and the draft of Eurocode 3 [380], new design regulations on the shear resistance of carbon steel bolts were developed based on all studies carried out up to 1991. However, the revised regulations of DIN 18800-1 from March 1981 resulted in significantly higher shear resistances $F_{v,Rd}$ due to the partial safety factor of $\gamma_M = 1.1$ compared to the partial safety factor of $\gamma_{M2} = 1.25$ of the Eurocode 3 approach. For this reason, all available test results and the methodology were statistically re-checked in a meta-analysis by Valinat et al. [381].

In order to gain a deeper insight of the resulting tension resistance of structural carbon steel bolts, Steurer [232] from ETH Zürich was investigating 1996 in his PhD thesis the tension load bearing and deformation behaviour of carbon steel bolts. Steurer focused, inter alia, on the correlation between bolt shape, tensile strength and deformation capacity of different partially threaded and fully threaded bolt types, the impact of subzero temperatures on the bolting assembly and the nut in different configurations and with varying free-threaded lengths.

Friede and Lange [233] from the Technical University of Darmstadt, Germany, investigated systematically the influence of the bolt preload on the resistance of category A bearing type connections in 2010. They conducted single-shear tests on M16 bolts in PC 10.9 considering three different preloading levels ($F_{v,1}$ snug-tightened with M_A = 35 Nm, $F_{v,2}$ with M_A = 250 Nm into the elastic range and $F_{v,3}$ tightened by the combined method according to DIN 18800-7 [422] into the plastic range). It could be concluded that preloading has only minor effect on the shear resistance in the ultimate limit state explained by Friede and Lange by the fact that the bolt plasticises in the failure state, which results in a reduction of the bolt preload. In further studies, Friede et al. [234] focussed on the load bearing behaviour of bolted shear connections with beginning of the threaded bolt part in the shear plane. The investigations shown that “the full shear resistance is not yet achieved when the shear plane coincides with the end of the unthreaded cross-section. Only when the unthreaded bolt part projects beyond the shear plane by approximately 0.1 ·d the full shear resistance of the unthreaded part section can be assumed”. In the meantime, this design recommendation was implemented in EN 1993-1-8:2024 [82].

Dörre et al. [175] (2019) from the Fraunhofer Institute for Large Structures in Production Engineering IGP in Rostock, Germany, carried out over 1000 tests covering tensile, single-shear and double-shear tests on carbon steel bolts from M8 to M20 with PC 4.6, 5.6, 8.8 and 10.9. However, it must be specified that the tensile tests are not carried out directly on whole bolts but on machined bolt specimens according to EN ISO 898-1, Clause 9.7. However, it must be critically assessed that the double-shear tests in their studies are not double-shear tests on one fastener subjected to two shear planes. Instead, bolts were inserted on both sides of the test rig and simultaneously subjected to single-shear during the test. Furthermore, all shear tests were done under compression testing, which also must be considered critical due to higher resulting load-bearing capacities. In the experimental investigations of Dörre et al., different types of partially and fully threaded bolts were considered including the loading cases with shear plane in the unthreaded and/or threaded part of a bolt. Since only bolts M12 and larger may be used in steel construction, consequently the results for bolt dimensions M8 and M10 are not considered in the following investigations. Based on statistical evaluations and 5 %-quantiles under consideration of the Gaussian law of error propagation and second-order Taylor approximation to describe the correlation between tensile and shear strength appropriately, which is deviating from the procedure of EN 1990, Annex D, finally Dörre et al. proposed new shear coefficients α for the untreaded and threaded part in the shear plane:

- PC 4.6: α = 0.70 for the unthreaded part of a bolt in the shear plane,
- PC 5.6: α = 0.65 for the unthreaded and α = 0.70 for the threaded part of a bolt,
- PC 8.8: α = 0.65 for the unthreaded and α = 0.55 for the threaded part of a bolt,
- PC 10.9: α = 0.60 for the unthreaded and α = 0.55 for the threaded part of a bolt.

Furthermore, Dörre et al. emphasize that all proposed shear coefficients α have to be reduced by 0.05, if the shear connection is designed as a single-shear connection, which was identified in their experimental investigations as the more critical case. This is particularly relevant, because in the other presented studies, either no distinction was made between single-shear

and double/multi-shear connections, or double-shear connections were identified as the more critical part (cf. Renner/Lange [178–183]). Moreover, the existing testing standards for the determination of the shear resistance of bolts are mainly based on double-shear test rigs, see Chapter 5.4.2. Dörre et al. also emphasize the importance of the shear plane itself: Even a minor gap between the shear plates during testing might accumulate bolt material in the shear plane which can lead to erroneously higher shear resistance of bolts.

A.1.2 Carbon steel bolts subjected to combined tension and shear loading

First tension, single-shear and interaction tests on carbon steel A325 (low and high hardness) and A354 BD bolting assemblies were conducted by Chesson et al. [221], [264] in Illinois, USA, in 1964 and 1965. Based on a test rig with two massive metal discs with interchangeable U-shaped metal blocks in between for the tested bolting assembly (see Figure A.1 (a)), in total 115 pure tension, single-shear and interaction tests under 11.25°, 22.5°, 33.75°, 45° and 67.5° loading angle were performed. In addition, the bolting assemblies were always preloaded (assuming the bolt preload has no impact on the shear and interaction behaviour) and both shear planes in the unthreaded and threaded part of a bolt were considered. Furthermore, Chesson et al. conducted tests under consideration of different material of the U-shaped blocks and with varying bolt lengths (3, 4 and 6 inches). In Europe, by using a comparable test rig like Chesson et al. with minor modifications, Bilderbeek [222] from the Technical University of Delft, Netherlands, conducted in 1971 in total 175 tension, single-shear and interaction tests under 15°, 30°, 60° and 75° loading angle on M12 and M20 bolting assemblies in various property classes, see Figure A.1 (b). Following the studies from Chesson et al., the experimental investigations were accompanied by testing of different material of the U-shaped blocks and investigating the impact of preloading on the resulting resistances in some tests.

Shakir-Khalil and Ho [225] from the University of Manchester, UK, carried out in 1979 an experimental study of 51 “black” bolting assemblies (that means just a plain finish or no finish of the bolt and nut components) under tension, single-shear and interaction under loading angles of 15°, 30°, 45°, 60° and 75°. At this time, the British Standard BS 449 [423] regarding “The use of structural steel in building” (59th Edition from 1968, withdrawn) gave the engineers no guidance concerning the ultimate or design load of a black bolt, when it is subjected to combined tension and shear. Therefore, the experimental findings from Shakir-Khalil and Ho were implemented in Amendment AMD I787 [424] in July 1975. In contrast to Chesson et al. and Bilderbeek, the test rig was based on a T-stubs construction principle instead of the interchangeable U-shaped metal blocks. The two massive metal discs were centrally located and modified to quarter discs and allow testing of two bolting assemblies simultaneously under loading angles of 0° (as pure tension), 15°, 30°, 45°, 60°, 75° and 90° (as pure single-shear). The test rig is presented in see Figure A.1 (c). As a supplement to the studies of Shakir-Khalil and Ho , Godley and Needham [227] have investigated in 1982 the tension resistance and double-shear resistance of HSFG bolts (High Strength Friction Grip) of PC 8.8 in order to evaluate the regulations of the withdrawn BS 449. Their studies also focus on the impact of the property class of the nut in the bolting assembly.

In Germany, first experimental investigations into the load bearing behaviour of bolts under combined tension and shear were 1973 conducted by Hassler [223] from the Institute for Steel and Timber Construction of the University of Stuttgart. For the sake of simplification, Hassler used for his tests unthreaded rods to simulate the shear plane in the unthreaded part of a bolt. However, the fixed ends of the rods were threaded and therefore it was possible to determine the tension resistance of both the threaded and unthreaded part of the rods. In contrast to the interaction tests of Chesson et al. and Bilderbeek, the loading angles were split into different vectorial tension and shear components and the rods were tested in a two-step procedure: First, the predefined tension component (as ratio of the maximum tension resistance) was

applied on the unthreaded rod by the testing machine. Secondly, the shear load was applied by a double-shear test rig until failure occurs to determine the maximum shear load and shear component. To prevent the rod from being pulled out of the test plane and therefore to avoid bending and eccentricity, single-shear testing was not possible.

In 1987, Knobloch and Schmidt [171] from the former Department of Steel Construction at the University of Essen, now the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen (UDE-IML), Germany, carried out experimental investigations into the pure shear and combined tension and shear behaviour of carbon steel bolts in steel construction. Their studies were embedded in the normative procedure of the development of the revised DIN 18800-1 and the preparations for Eurocode 3 for steel construction. The test rig follows the approach of Hassler by firstly applying a predefined tension component (as ratio of the maximum tension resistance) and secondly applying double-shear loading until bolt failure occurs, see Figure A.1 (d). Consequently, Knobloch and Schmidt used unthreaded rods (d = 20 mm) for simulating bolts with unthreaded part in the shear plane and threaded rods (M16 and M24) for the threaded part in the shear plane. However, it must be mentioned that the unthreaded rods were made of different steel grades to simulate bolt material in various property classes: St 37-2 (≈ PC 4.6), St 52-3 (≈ PC 5.6), C45 (≈ PC 8.8) and 42CrMo4 (≈ PC 10.9). Furthermore, the threaded rods were in PC 5.6 and 10.9 but not fulfilling the normative requirements regarding the minimum tensile strength and elongation at fracture. Nevertheless, Knobloch and Schmidt implemented the threaded rods in their studies and stated that they mechanical properties are “sufficient enough to simulate bolts in steel structures in particular regarding the still high and sufficient elongation at fracture”. Knobloch and Schmidt recommended a quadratic interaction approach for standardisation.

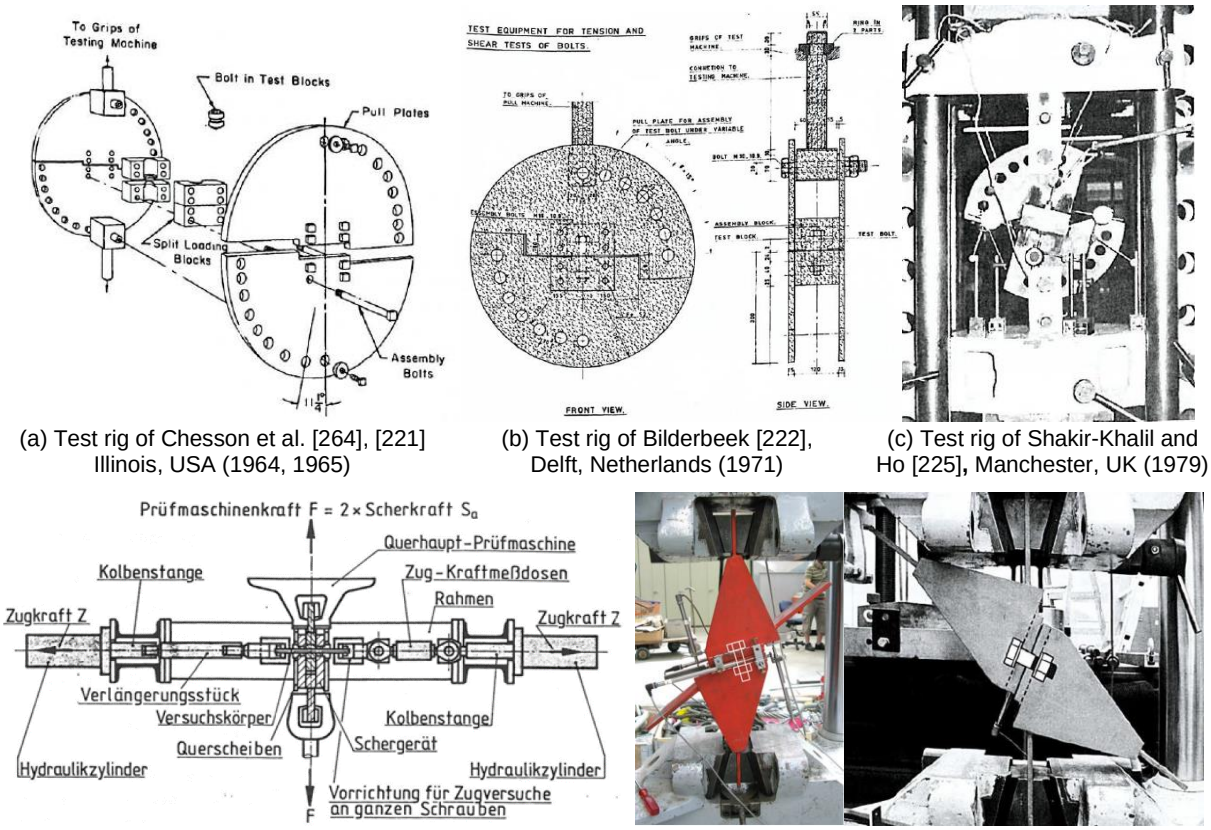
Furthermore, between 2012 to 2019, Renner and Lange [178–183, 235] from the Technical University of Darmstadt, Germany, investigated the load bearing behaviour of carbon steel bolts subjected to tension, shear and combined tension and shear. Their intention was to conduct fundamental research and to provide a more extensive basis of reliable test data in order to be able to assess the load bearing behaviour of carbon steel bolts and the related normative regulations of DIN 18800 and EN 1993-1-8 with greater certainty. Thus, their experimental investigations include tensile tests on bolting assemblies as well as tensile tests on machined tensile test coupons, single-shear and double-shear tests on bolting assemblies as well as single-shear interaction tests with unthreaded and/or threaded part of a bolt in the shear plane, see Figure A.1 (e). The studies of Renner and Lange include 158 tests and were complemented by numerical FEM analyses but lacking entirely a statistical evaluation of the proposed interaction approach, which has to be conducted to check if the proposed approach is suitable to fulfil the Eurocode safety requirements. Furthermore, no statements were made about the resulting shear coefficients α compared to the current EN 1993-1-8 regulations for carbon steel bolts.

Focussing of the tension, shear and combined tension and shear load bearing behaviour of partially and fully threaded high-strength carbon steel bolts in PC 10.9 and 12.9, Li et al. [236, 237] from the University of Sydney, Australia, published the results of their experimental and numerical results in 2020. The experimental programme was completed by tensile coupon tests and hardness measurements (only for bolts in PC 12.9). Additionally, snug-tightened and preloaded bolts in PC 12.9 were considered in the studies as well as the load bearing behaviour of countersunk bolts. The results were compared with EN 1993-1-8, AISC 360 and AS 4100 and finally a quadratic interaction approach was proposed following AS 4100 but with modified shear coefficients. Li et al. stated that the tension and shear resistance as well as the deformation capacity of countersunk bolts is comparable to plain head bolts. Therefore, a reduction of the tension resistance to k_2 = 0.63 in EN 1993-1-8 might not be necessary. As a

numerical supplement to the studies of Li et al., Xin et al. [425] focussed on the numerical FEM simulation of ductile fracture and fracture locus under combined loading of carbon steel high-strength bolts in PC 10.9 using the “mesoscale critical equivalent plastic strain” (MCEPS) in order to develop models which are accurate to describe the interaction behaviour of bolts.

Song et al. [5] (2020) from the aforementioned research group of the University of Sydney, Australia, focused in their investigations mainly on the experimental behaviour and fracture prediction of austenitic and duplex stainless steel bolts but also conducted tension, single-shear and interaction tests on partially and fully threaded carbon steel bolts in PC 8.8 as reference tests. Unfortunately, double-shear tests on carbon steel bolts were not conducted which would allow a direct comparison of the shear resistances of both testing configurations.

Furthermore, additional studies from the North American region regarding the tension, shear and combined tension and shear load bearing behaviour of bolts and bolting assemblies according to ASTM standards can be found by Kulak and Fisher [426] (1967), Allan [261] (1967, focusing on the effect of oversize and slotted holes on the behaviour of bolted connections), Allan and Fisher [339] (1968), Kulak et al. [343] (1987), Kulak [427] (2005), Moore et al. [347] (2008), Taylor et al. [349] (2008), Tide et al. [428] (2010), Swanson et al. [348] (2020) and Tide [346] (2022). However, for comparability, these test results are not implemented for the further statistical evaluations according to EN 1990, Annex D, as they explicitly refer to bolts and bolting assemblies according to the North American standardisation.



(a) Test rig of Chesson et al. [264], [221] Illinois, USA (1964, 1965)

(b) Test rig of Bilderbeek [222], Delft, Netherlands (1971)

(c) Test rig of Shakir-Khalil and Ho [225], Manchester, UK (1979)

(d) Test rig of Knobloch and Schmidt [171] Essen, Germany (1987)

(e) Test rigs of Renner/Lange for different loading angles Darmstadt, Germany (2012 to 2019)

Figure A.1: Selected test rigs for testing of carbon steel bolting assemblies subjected to combined tension and shear loading; © according to the references

A.2 Literature review on the tension, shear and combined tension and shear load bearing behaviour of stainless steel bolts

A.2.1 Stainless steel bolts subjected to pure tension or shear loading

Already in 1974, Errera et al. [265] from the Cornell University in Ithaca, USA, carried out research activities regarding bolted and welded stainless steel connections. The experimental investigations include bearing tests with Type 301 austenitic stainless steel sheets as single-shear and double-shear bolted connection. However, quenched and tempered medium carbon steel bolts were used and the load bearing behaviour of the bolts was not considered.

Thomala [169] (1984) and Wiegand et al. [176] (2007) confirmed also an approximately linear relationship between the shear coefficient α and the tensile strength for A2 and A4 austenitic stainless steel bolt material independently of the chemical composition of the bolt material itself. Due to this behaviour, the shear strength and herewith the shear coefficient α decrease with increasing tensile strength. Thomala refers to the plastic deformation capacity as a link between ultimate shear and tensile strength. However, as the experimental investigations were conducted on unnotched bars, the test data will not be used for the following investigations. However, Dünkel [289] (2001) points out that the test results of Thomala [169] were used to roughly estimate the shear coefficients of austenitic stainless steel bolts in PC 50, 70 and 80 for the German national annex DIN EN 1993-1-4/NA. Furthermore, according to Dünkel [184, 276] for austenitic stainless steel bolts always the smaller tensile stress area A_s should be used for the calculation of the shear resistance, since the ultimate strength of these bolts is set in such a way that they fail after exceeding the minimum ultimate tensile load in the weakest area, which can be either in the unthreaded or threaded part of the bolt due to the locally different strain hardening and forming induced martensitic material. For further information regarding the design of the shear resistance of DIN EN 1993-1-4/NA, see Chapter 3.4. In addition, studies on the shear-tensile strength ratio of duplex stainless steel bolts were not available and were only conservatively estimated. Nevertheless, Dünkel refers in [290] to the publication of Dose and Pitter [429] from 1996 which are stating that the shear coefficient of austenitic stainless steel bolts can be defined uniformly to $\alpha = 0.7$, while for ferritic and martensitic stainless steels as well as carbon bolts a shear-tensile strength ratio of $1 / \sqrt{3} \approx 0.577$ in accordance with the shape modification hypothesis by von Mises results. However, this contradicts the previous experimental results (e.g. Thomala [169] in 1984 and Wiegand et al. [176], Knobloch [173]) which could prove a direct correlation between the shear and tensile strength of carbon and austenitic bolts.

In the framework of the European Coal and Steel Community (ECSC) project 7210-SA/327 “Development of the use of stainless steel in construction” [269] and by participation of industry partners and European R&D from UK, Finland, Sweden, France and Germany, the European design rules for stainless steel structures of “pre-standard” ENV 1993-1-4 [430] were proven in experimental investigations to ensure the safety and reliability of these structures. Finally, more economic guidance for the design of structural stainless steel could be developed and published in the 2nd Edition of the Design Manual for Structural Stainless Steel (DMSSS) [431]. ENV 1993-1-4 was published four years after the 1st Edition of the DMSSS [267] and was strongly based on the Design Manual, which mainly adopts conservatively design rules from carbon steel and modified them if necessary. In the frame of the ECSC project, experimental investigations into bolted connections made of stainless steel were carried out by Bouchair and Muzeau [268] (1999), The Steel Construction Institute [269] (2000), Ryan [270] (2000) and Bouchaïr et al. [271] (2001).

Ryan [270] focused in the final report of Work Package 4.2 on bolted connections made of stainless steel. In the research project, bearing tests on bolted cover plate connections were conducted as well as tension and double-shear tests on individual bolts.

In all cases, partially threaded A4-80 austenitic stainless steel bolts M12, M16 and M16 according to EN ISO 3506-1 were examined. Based on the experimental investigations, Ryan concluded that "the design requirements of the Eurocode 3 can be adopted without modification. There is no reason to believe that this should not be valid for other standard stainless steel bolts also." The tension tests on austenitic stainless steel bolts show good agreement with $f_{ub,nom} \cdot A_{s,nom}$ as well as $f_{ub,exp} \cdot A_{s,nom}$ significantly above the standard requirements considering the reduction factor of $k_2 = 0.9$. Furthermore, Ryan states that the shear-tensile strength ratio is clearly above $\alpha = 0.6$ as the recommend value for the shear coefficient for stainless steel bolts in Eurocode and therefore on the safe side. Analogues to Wallart and Fischer [220] for carbon steel bolts, Ryan confirmed that the ultimate shear strengths also of austenitic stainless steel bolts tested in tension configuration are about ≈ 5 % lower than those tested in compression loading.

In 2014, the researchers Cai and Young [274] from the University of Hong Kong, China, investigated the behaviour of cold-formed austenitic and lean duplex stainless steel bolted connections M8, M10 and M12 with single-shear and double-shear bearing tests The researchers focussed on the bearing and net section resistance of stainless steel plates but also observed bolt shear failure in their tests. Furthermore, Cai and Young carried out single-shear tests on individual fully threaded austenitic stainless steel M6, M8, M10 A4-80 bolts. Unfortunately, the application of these small bolt diameters is not allowed in steel construction. Additionally, the experimental tensile strength of the M12 A4-80 austenitic stainless steel bolts was not determined. Therefore, the results could not be used for the following investigations.

As a supplement to the studies from Tide [428] on the shear resistances of North American ASTM A325 and A490 high-strength carbon steel bolts in long bolted connections, recently in 2022, Zhao et al. [275] conducted experimental and numerical studies on the reduction coefficient of the shear resistance of long austenitic stainless steel bolted connections. They concluded that in a length range of $15d_0$ *to* $64d_0$ the reduction coefficient decreases linearly with the increase of connection length correlated with a more uneven stress distribution of the long-bolted connections. However, only groups of M8 bolts were used in the shear tests with different connection lengths, which are excluded in steel construction.

A.2.2 Stainless steel bolts subjected to combined tension and shear loading

Studies regarding the load bearing behaviour of stainless steel bolted connections under combined tension and shear are very limited and briefly described in the following:

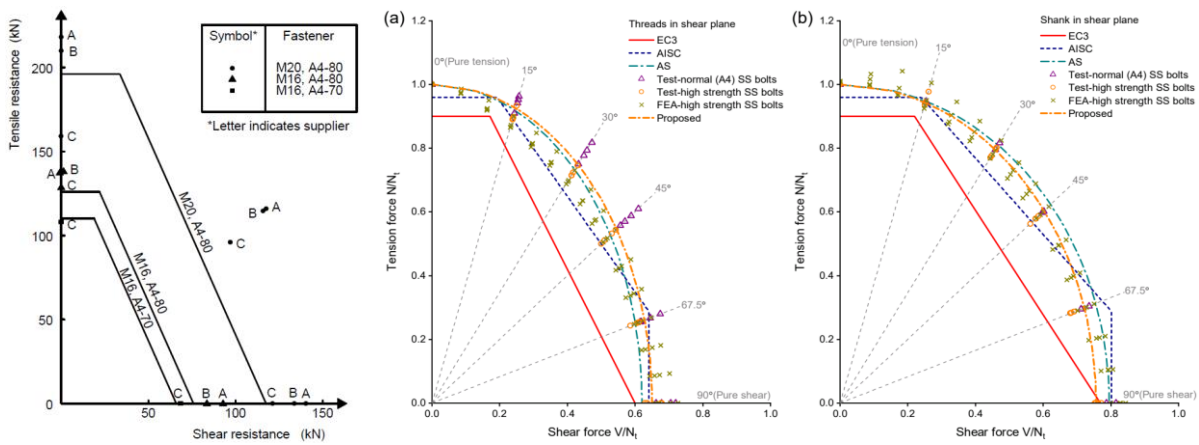
In order to generate experimental data for the 1st Edition of the Design Manual for Structural Stainless Steel [267], a limited test programme was conducted by the Steel Construction Institute (SCI) in 1990 covering fully threaded austenitic A4-70 (M16) and A4-80 (M16, M20) stainless steel bolts subjected to tension, double-shear and combined tension and shear (only M20 A4-80). In total, 87 tests were conducted and evaluated against the design rules from EN 1993-1-8 for carbon steel bolts. It could be shown that all test results clearly exceed the nominal tension, shear and interaction resistance of stainless steel bolts (with exception of one series with experimental tension resistance slightly lower than the minimum ultimate tensile load F_{mf} according to EN ISO 3506-1). In particular, the conservatism of the bilinear interaction approach according to EN 1993-1-4 and EN 1993-1-8 becomes obvious, see Figure A.2 (a).

In 2012, Steeve and Wingate [273] from the National Aeronautics and Space Administration (NASA) working at the George C. Marshall Space Flight Center in Huntsville, Alabama, USA, investigated the strengths of aerospace threaded fastener under combined tension and shear loading. The test rig was based on the test method of MIL-STD-1312-2 [409] from 1984 (superseded by NASM 1312 Method 2) with small modifications and allows single-shear testing of loading angles of 0°, 15°, 30°, 45°, 60°, 75° and 90°. The interaction test rig,

nowadays regulated in the current NASM 1312-2 testing standard [408], is similar to the test rigs of Chesson et al. [221] (by adapting the testing principle) and Shakir-Khalil and Ho [225] (by simplifying the test rig to quarter discs). Further information of the interaction testing procedure can be found in Chapter 6. Surprisingly, the test rig and testing procedure of MIL-STD-1312-2 or the current NASM 1312-2 was not adopted in the other studies. Bolting assemblies were tested as well as bolts threaded in an adapter insert with the unthreaded and threaded bolted part in the shear plane. The tested bolts were 3/8-inch bolts (≈ M10) of type NAS1956C14 with stainless steel alloy type 660. Alloy 660 is a precipitation hardening austenitic stainless steel known for its high minimum yield strength of 724 N/mm² and tensile strength of 1241 N/mm² even at high temperatures up to 700 °C. Steeve and Wingate carried out tests without and with initial preload, which does not affect the ultimate resistance of the bolts *"when the joint separates before the bolt ruptures under pure tension loading"*. Modified failure criteria (see Chapter 2.5.3) were developed and pointing out the role of the separation of the connection during testing "which allowed bending to develop within the fastener under the simultaneously applied shear load".

The publications of Song et al. from 2020 are dealing with the experimental behaviour and fracture prediction of austenitic (1.4432) stainless steel A4-70 and A4-80 bolts [5] as well as austenitic (1.4432) and duplex (1.4462) stainless steel bolts in PC 8.8, 10.9 and 12.9 [6], which are deviating from the regulations of EN ISO 3506-1 but fulfilling the requirements of EN 15048-1. The failure mode, strength and ductility of these M20 partially threaded stainless steel bolts according to EN ISO 4014 and fully threaded bolts according to EN ISO 4017 stainless steel bolts under different combinations of tension and shear were evaluated based on experimental and numerical investigations. Furthermore, double-shear tests on M20 A4-70 and A4-80 bolts were carried out to compare the resulting shear resistance per shear plane with those achieved in single-shear tests. All tests were conducted under tension loading.

Finally, Song et al. proposed slightly modified new design rules: $0.59 \cdot f_{ub,nom} \cdot A_{nom}$ instead of $0.62 \cdot f_{ub,nom} \cdot A_{nom}$ if the shear plane passed through the unthreaded part and $0.65 \cdot f_{ub} \cdot A_s$ instead of $0.62 \cdot f_{ub} \cdot A_s$ if the shear plane passed through the threaded part of a bolt. The quadratic interaction approach of AS 4100 has been retained, see Figure A.2 (b). Song et al. show that the bilinear interaction according to EN 1993-1-4, which was adopted from EN 1993-1-8 for carbon steel bolts, is clearly on the safe side for the threaded and unthreaded part of a bolt in the shear plane.



(a) Test results according to [266] for fully threaded austenitic bolts

(b) Test results according to Song et al. [5, 6] for fully threaded (middle) and partially threaded (right) austenitic and duplex bolts

Figure A.2: Results of Technical report 21 [266] (a) and Song et al. [5, 6] (b) of the tension, shear and interaction tests on stainless steel bolts

Appendix B: Experimental programme and test matrixes

B.1 Tensile tests on stainless steel bolts according to EN ISO 3506-1

In the framework of the German research project P 1386 / IGF-No. 20651 N [78] and already published in [282], 120 tensile tests on the whole bolt with EN ISO 4014 and EN ISO 4762 bolts as well as 90 tensile tests with EN ISO 4017 bolts in bolt dimensions M16×100/110 and M24×130 were conducted.

The tensile tests were performed in accordance with EN ISO 3506-1, Clause 9.1 on the whole bolt in order to determine the mechanical properties of the bolts as the resulting tensile strength $R_{mf,exp}$ (= $f_{ub,exp}$), yield strength $R_{pf,exp}$ (= $f_{yb,exp}$) and elongation at fracture A. The 120 tensile tests with partially threaded EN ISO 4014 and EN ISO 4762 bolts cover austenitic (PC 50, 70, 80, 8.8 and 10.9), duplex (PC 70, 80, 100 and 12.9) and super duplex (only PC 10.9) stainless steel bolts, while the 90 tensile tests with fully threaded EN ISO 4017 bolts contain austenitic (PC 50, 70, 80, 8.8 and 10.9), lean duplex (PC 10.9), duplex (PC 70 and 10.9) as well as super duplex (PC 10.9) stainless steel. Each configuration includes at least three test specimens from different anonymised bolt manufacturers or traders (abbreviated as C1 to C6) with either rolled or cut bolt threads (cf. Chapter 4.3.2) to represent the current European market as realistic as possible.

The test matrixes of the tested austenitic/duplex bolts are given in Table B.1 and Table B.2.

Table B.1: Test matrix of tensile tests according to EN ISO 3506-1 on partially threaded stainless steel bolts according to P 1386 / IGF-No. 20651 N

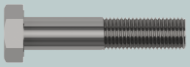
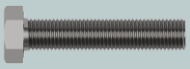
Partially threaded EN ISO 4014 and EN ISO 4762 bolts														
	**M16×100/110** (Number of tensile tests)							**M24×130** (Number of tensile tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	-	43	18	-	3	3	-	3	10	10	-	5	-	-
Lean Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duplex	-	-	3	5	-	-	3[1)]	-	5	3	-	-	-	-
Super Duplex	-	-	-	-	-	3+3[1]	-	-	-	-	-	-	-	-
Number of tests	-	43	21	5	3	9	3	3	15	13	-	5	-	-
Total tests	**120 tensile tests** on the whole bolt according to EN ISO 3506-1, Clause 9.1													
[1)] Partially threaded hexagon socket head cap bolts according to EN ISO 4762.														

Table B.2: Test matrix of tensile tests according to EN ISO 3506-1 on fully threaded stainless steel bolts according to P 1386 / IGF-No. 20651

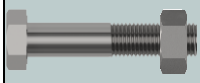
Fully threaded EN ISO 4017 bolts														
	**M16×100** (Number of tensile tests)							**M24×130/140** (Number of tensile tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	3	23	10	-	5	5	-	3	10	5	-	5	-	-
Lean Duplex	-		-	-	-	5	-	-	-	-	-	-	-	-
Duplex	-	3	-	-	-	5	-	-	3	-	-	-	-	-
Super Duplex	-	-	-	-	-	5	-	-	-	-	-	-	-	-
Number of tests	3	26	10	-	5	20	-	3	13	5	-	5	-	-
Total tests	**90 tensile tests** on the whole bolt according to EN ISO 3506-1, Clause 9.1													

B.2 Tensile tests on stainless steel bolting assemblies according to EN 15048-2

In order to extend the database for a more detailed statistical evaluation and to get knowledge about the difference between the tension resistance of bolts tested formerly according to EN ISO 3506-1, Clause 9.1 on the whole bolt and the resulting tension resistance of the bolting assembly (as bolt and nut excluding washer), further tensile tests according to EN 15048-2, Clause 6 were carried out. In this way, not the pure mechanical properties of the stainless steel bolts were tested, but the maximum achieved tension resistance of the bolting assemblies, which include the mechanical properties of the bolt and the nut and their mutual load bearing behaviour. Therefore, in addition to the tensile tests on bolts according to EN ISO 3506-1, in total 58 tensile tests with partially threaded austenitic (PC 70, 80, 8.8 and 10.9), duplex (PC 80 and 100) as well as super duplex bolting assemblies (only PC 10.9) were performed. Furthermore, in total 56 fully threaded austenitic (PC 50, 70, 80, 8.8 and 10.9), lean duplex (PC 10.9), duplex (PC 70 and 10.9) as well as super duplex bolting assemblies (PC 10.9) M16×100 or M16×110 were tested. M24 bolting assemblies were not tested. Analogues to the tensile tests according to EN ISO 3506-1, each bolt configuration includes at least three test specimens from different anonymised bolt manufacturers or traders.

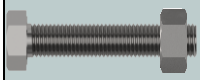
The detailed test matrixes of the tested austenitic and duplex stainless steel bolting assemblies are provided in Table B.3 and Table B.4.

Table B.3: Test matrix of tensile tests according to EN 15048-2 on partially threaded stainless steel bolting assemblies

Partially threaded EN ISO 4014, EN ISO 4762 bolts and EN ISO 4032 nuts														
	**M16×100/110** (Number of tensile tests)							**M24×130** (Number of tensile tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	-	25	10	-	3	3	-	-	-	-	-	-	-	-
Lean Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duplex	-	-	3	5	-	-	3	-	-	-	-	-	-	-
Super Duplex	-	-	-	-	-	3+3[1)]	-	-	-	-	-	-	-	-
Number of tests	-	25	13	5	3	9	3	-	-	-	-	-	-	-
Total tests	**58 tensile tests** on bolting assemblies according to EN 15048-2, Clause 6													

[1)] Partially threaded hexagon socket head cap bolts according to EN ISO 4762.

Table B.4: Test matrix of tensile tests according to EN 15048-2 on fully threaded stainless steel bolting assemblies

Fully threaded EN ISO 4017 bolts and EN ISO 4032 nuts														
	**M16×100** (Number of tensile tests)							**M24×120/130** (Number of tensile tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	3	15	10	-	5	5	-	-	-	-	-	-	-	-
Lean Duplex	-	-	-	-	-	5	-	-	-	-	-	-	-	-
Duplex	-	3	-	-	-	5	-	-	-	-	-	-	-	-
Super Duplex	-	-	-	-	-	5	-	-	-	-	-	-	-	-
Number of tests	3	18	10	-	5	20	-	-	-	-	-	-	-	-
Total tests	**56 tensile tests** on bolting assemblies according to EN 15048-2, Clause 6													

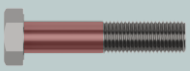
B.3 Tensile tests on machined bolts and the separated threaded bolt part to determine the tensile strength of the unthreaded and threaded parts

As already mentioned, predominantly austenitic stainless steel bolts fail in the unthreaded, shanked bolt part due to the transformation of austenitic to forming induced martensitic material of the threaded part during the thread rolling process, if finally the tension resistance of the threaded part is greater than the tension resistance of the unthreaded part, cf. Chapter 2.4.7 and 2.4.8. Consequently, a direct determination of the tensile strength of the unthreaded part $f_{ub,shank,i}$ based on the measured individual bolt geometry of the gross cross-sectional area $A_{meas,I}$ as well as the mean shank tensile strength $f_{ub,shank,mean}$ of the tested series are possible whenever bolt failure occurs in the unthreaded part. The exact tensile strength $f_{ub,threads}$ of the threaded bolt part is unknown but it can be concluded that it is equal or even greater than R_{mf} determined in a tensile test according to EN ISO 3506-1. In order to get knowledge about the exact tensile strength of the threaded bolt part $f_{ub,threads}$, additionally tensile tests exclusively on the threaded part sawn and separated from the stainless steel bolts are conducted.

However, if the bolt failure occurs in the threaded part as the intended failure mechanism of carbon steel and duplex stainless steel bolts (but also may occurring in some cases of austenitic bolts), a direct determination of the tensile strength of the unthreaded bolt part $f_{ub,shank}$ is not possible. The determined tensile strength in a tensile test according to EN ISO 3506-1 is nearly the exact tensile strength of the threaded part. To be precisely, EN ISO 3506-1 always determines the tensile strength with the nominal tensile stress area $A_{s,nom}$ without considering the thread tolerance class which would lead to a smaller tensile stress area. Therefore, the tensile strength of the threaded part $f_{ub,threads}$ is on the safe side. However, additional tests on modified test specimens must be conducted in order to determine the unknown tensile strength of the unthreaded part $f_{ub,shank,i}$ and the mean shank tensile strength $f_{ub,shank,mean}$ of the tested series. Herein, a simplification of $f_{ub,threads} \approx f_{ub,shank}$ is not possible particularly for austenitic bolts. In P 1386 / IGF-No. 20651 N, tensile tests on machined M16 and M24 bolts were conducted to determine the tensile strength of the unthreaded bolt part $f_{ub,exp,shank}$.

The detailed test matrix of the configurations of austenitic and duplex stainless steel bolts which have to be examined in additional tests with machined bolts in order to determine the tensile strength of the unthreaded part $f_{ub,shank}$ are provided in Table B.5. In total, 33 tensile tests on bolts with machined bolt shank were conducted with at least three test specimens for each bolt series.

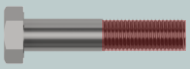
Table B.5: Test matrix of tensile tests on machined bolts to determine the tensile strength of the bolt shank according to P 1386 / IGF-No. 20651 N

Machined partially threaded EN ISO 4014 and EN ISO 4762 bolts with reduced shank diameter d_s														
	**M16×100/110** (Number of tensile tests)							**M24×130** (Number of tensile tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	3	3	3	-	-	3	-	-	-	-	-	-	-	-
Lean Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duplex	-	-	3	3	-	-	3	-	3	3	-	-	-	-
Super Duplex	-	-	-	-	-	3+3[1)]	-	-	-	-	-	-	-	-
Number of tests	3	3	6	3	-	9	3[1)]	-	3	3	-	-	-	-
Total tests	**33 tensile tests** on bolts with machined bolt shank													

[1)] Partially threaded hexagon socket head cap bolts according to EN ISO 4762.

Furthermore, the test matrix of the additionally tensile tests exclusively on the threaded bolt part to determine the tensile strength of the bolt threads $f_{ub,threads}$, which are separated from the stainless steel bolts, is presented in Table B.6. Only selected M16 bolt series are tested with at least three test specimens for each bolt series.

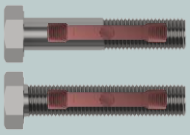
Table B.6: Test matrix of tensile tests on the separated threaded bolt part to determine the tensile strength of the bolt threads $f_{ub,threads}$

Separated threaded part of EN ISO 4014 and EN ISO 4762 bolts														
	**M16×100/110** (Number of tensile tests)							**M24×130** (Number of tensile tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	-	9	6	-	3	-	-	-	-	-	-	-	-	-
Lean Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Super Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Number of tests	-	9	6	-	3	-	-	-	-	-	-	-	-	-
Total tests	**18 tensile tests** on the separated threaded bolt part													

B.4 Tensile coupon test specimens machined from stainless steel bolts according to EN ISO 6892-1

In order to investigate the effect of strain hardening and forming induced martensitic material between the bolt core and the threaded part on the load bearing capacity of austenitic and duplex stainless steel bolts, tensile coupon test specimens B8×40 in accordance with DIN 50125 [371] of selected six bolt series were produced by the mechanical workshop of University of Duisburg-Essen. In total, 27 tensile tests on tensile coupon test specimens B8×40 according to EN ISO 6892-1 [366] were carried out with three tensile tests of each series, as presented in Table B.7.

Table B.7: Test matrix of tensile coupon test specimens machined from stainless steel bolts according to EN ISO 6892-1

Partially threaded EN ISO 4014 and fully threaded EN ISO 4017 bolts														
	**Partially threaded M16×100** (Number of tensile tests)							**Fully threaded M16×100** (Number of tensile tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	-	3	3	-	3	3	-	-	-	-	-	3	3	-
Lean Duplex	-	-		-	-	-	-	-	-	-	-	-	3	-
Duplex	-	-		-	-	-	-	-	-	-	-	-	3	-
Super Duplex	-	-		-	-	3	-	-	-	-	-	-	-	-
Number of tests	-	-		-	-	-	-	-	-	-	-	-	-	-
Total tests	**27 tensile tests** on tensile coupon test specimens B8×40													

B.5 Single-shear tests on stainless steel bolting assemblies

In the German research project P 1386 / IGF-No. 20651 N [78] and already published in [164], in total, 120 single-shear tests with unthreaded bolt part in the shear plane (partially threaded EN ISO 4014 or EN ISO 4762 bolts with EN ISO 4032 nuts) as well as 90 single-shear tests with threaded bolt part in the shear plane (fully threaded EN ISO 4017 bolts with EN ISO 4032 nuts) in bolt dimensions M16×100/110 and M24×130 were conducted.

The 120 single-shear tests with partially threaded EN ISO 4014 and EN ISO 4762 bolts cover austenitic (PC 50, 70, 80, 8.8 and 10.9), duplex (PC 70, 80, 100, 12.9) and super duplex (only PC 10.9) stainless steel bolts, while the 90 single-shear tests with fully threaded EN ISO 4017 bolts contain austenitic (PC 50, 70, 80, 8.8 and 10.9), lean duplex (PC 10.9), duplex (PC 70 and 10.9) as well as super duplex (PC 10.9) stainless steel. Analogues to the experimental investigations into the tension resistance of stainless steel bolts, each configuration includes at least three test specimens from different anonymised bolt manufacturers or traders (abbreviated as C1 to C6) with either rolled or cut threads to represent the current European market as realistic as possible.

The final test matrixes of the tested austenitic and duplex stainless steel bolting assemblies are presented in Table B.8 and Table B.9.

Table B.8: Test matrix of single-shear tests on partially threaded stainless steel bolting assemblies for the loading case "unthreaded bolt part in the shear plane" according to P 1386 / IGF-No. 20651 N

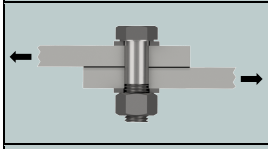
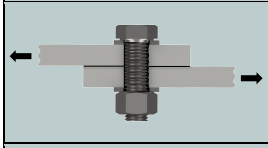
Unthreaded bolt part in the shear plane: Partially threaded EN ISO 4014 or EN ISO 4762 bolts with EN ISO 4032 nuts														
	**M16×100/110** (Number of single-shear tests)							**M24×130** (Number of single-shear tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	-	43	18	-	3	3	-	3	10	10	-	5	-	-
Lean Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duplex	-	-	3	5	-	-	3[1)]	-	5	3	-	-	-	-
Super Duplex	-	-	-	-	-	3+3[1]	-	-	-	-	-	-	-	-
Number of tests	-	43	21	5	3	9	3	3	15	13	-	5	-	-
Total tests	**120 single-shear tests** on a test rig specially developed for the project													
[1)] Partially threaded hexagon socket head cap bolts according to EN ISO 4762.														

Table B.9: Test matrix of single-shear tests on fully threaded stainless steel bolting assemblies for the loading case "threaded bolt part in the shear plane" according to P 1386 / IGF-No. 20651 N

Threaded bolt part in the shear plane: Fully threaded EN ISO 4017 bolts with EN ISO 4032 nuts														
	**M16×100** (Number of single-shear tests)							**M24×130/140** (Number of single-shear tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	3	23	10	-	5	5	-	3	10	5	-	5	-	-
Lean Duplex	-		-	-	-	5	-	-	-	-	-	-	-	-
Duplex	-	3	-	-	-	5	-	-	3	-	-	-	-	-
Super Duplex	-	-	-	-	-	5	-	-	-	-	-	-	-	-
Number of tests	3	26	10	-	5	20	-	3	13	5	-	5	-	-
Total tests	**90 single-shear tests** on a test rig specially developed for the project													

B.6 Double-shear tests on stainless steel bolts and bolting assemblies

A comprehensive experimental investigation into the double-shear resistance of M16×100 partially and fully threaded austenitic and duplex stainless steel bolts and bolting assemblies is defined in order to get deeper knowledge about the different load bearing characteristics of bolts subjected to single-shear or double-shear loading. Therefore, for both shear planes the loading cases "unthreaded bolt part in the shear planes" (a), "threaded bolt part in the shear planes" (b) and a combination of "unthreaded and threaded bolt part in the shear planes" (c) are covered in the experimental investigations.

Furthermore, double-shear tests on austenitic and duplex stainless steel bolts tested with or without EN ISO 4032 nuts are conducted to determine the load bearing effect of the nut. In this way, the resulting shear resistance of stainless steel bolts and bolting assemblies and possible supporting effects of the nuts can be compared directly. As a second parameter, the influence of the hole clearance in the M16 double-shear test rig has to be investigated. All single-shear tests in the German research project P 1386 / IGF-No. 20651 N are carried out with a nominal bolt hole diameter of $d_{h,nom}$ = 17 mm. The intention was to have a practicable installation situation for testing with as little hole clearance as possible to avoid possible misalignments of the bolt or bolting assemblies. To ensure direct comparability, special hardened adapters with a hole diameter of $d_{h,nom}$ = 17 mm were again applied for double-shear testing. Additionally, special hardened adapters with nominal bolt holes of $d_{h,nom}$ = 16 mm produced in ISO tolerance field H8 (+27 µm, -0 mm) according to EN ISO 286-1 [395] and EN ISO 286-2 [396] will be used to avoid any misalignments of the bolt or bolting assemblies during testing. Thus, the influence of possible inclination or misalignments of the bolts or bolting assemblies which are possibly increasing the shear area during the double-shear test will be taken into account and systematically investigated.

In total, 162 double-shear tests were conducted as a supplement to [164] in the frame of this thesis as presented in Table B.10 (a), Table B.11 (b) and Table B.12 (c).

Table B.10: Test matrix of double-shear tests on partially threaded stainless steel bolts and bolting assemblies for the loading case “unthreaded bolt part in the shear planes” (a)

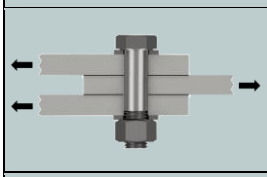
Unthreaded bolt part in the shear planes: Partially threaded EN ISO 4014 with/without EN ISO 4032 nuts														
	**M16×100 bolting assemblies** (Number of tests with nut and d_h = 17 mm / Number of tests with nut and d_h = 16 mm, H8)							**M16×100 bolts** (Number of tests without nut and d_h = 17 mm / Number of tests without nut and d_h = 16 mm, H8)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	-	5/3	5/3	-	-	-	-	-	5/3	5/3	-	-	-	-
Lean Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Super Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Number of tests	-	8	8	-	-	-	-	-	8	8	-	-	-	-
Total tests	**32 double-shear tests** on a test rig specially developed for the PhD thesis													
[1)] Partially threaded hexagon socket head cap bolts according to EN ISO 4762.														

Table B.11: Test matrix of double-shear tests on fully threaded stainless steel bolts and bolting assemblies for the loading case “threaded bolt part in the shear planes” (b)

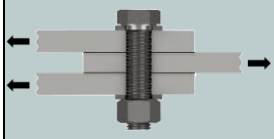
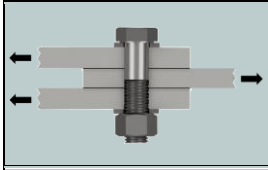
Threaded bolt part in the shear planes: Fully threaded EN ISO 4017 bolts with/without EN ISO 4032 nuts														
	**M16×100 bolting assemblies** (Number of tests with nut and d_h = 17 mm / Number of tests with nut and d_h = 16 mm, H8)							**M16×100 bolts** (Number of tests without nut and d_h = 17 mm / Number of tests without nut and d_h = 16 mm, H8						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	-	5/3	5/3	-	5/3	5/3	-	-	-	-	-	5/3	5/3	-
Lean Duplex	-	-	-	-	-	5/3	-	-	-	-	-	-	5/3	-
Duplex	-	-	-	-	-	5/3	-	-	-	-	-	-	5/3	-
Super Duplex	-	-	-	-	-	5/3	-	-	-	-	-	-	5/3	-
Number of tests	-	8	8	-	-	32	-	-	-	-	-	8	32	-
Total tests	**88 double-shear tests** on a test rig specially developed for the PhD thesis													

Table B.12: Test matrix of double-shear tests on partially threaded stainless steel bolts and bolting assemblies for the loading case “unthreaded and threaded bolt part in the shear planes” (c)

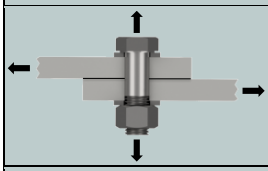
Unthreaded and threaded bolt part in the shear planes: Partially threaded EN ISO 4014 with/without EN ISO 4032 nuts														
	**M16×100 bolting assemblies** (Number of tests with nut and d_h = 17 mm / Number of tests with nut and d_h = 16 mm, H8)							**M16×100 bolts** (Number of tests without nut and d_h = 17 mm / Number of tests without nut and d_h = 16 mm, H8						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	-	-	5/3	-	5/3	5/3	-	-	-	-	-	-	3/3	-
Lean Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duplex	-	-	-	-	-	-	5/3	-	-	-	-	-	-	-
Super Duplex	-	-	-	-	-	5/3	-	-	-	-	-	-	3/3	-
Number of tests	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total tests	**42 double-shear tests** on a test rig specially developed for the PhD thesis													

B.7 Single-shear interaction tests on stainless steel bolting assemblies

As a supplement to the experimental investigations regarding the tension and shear resistance of austenitic and duplex stainless steel bolts and bolting assemblies already presented in Chapter 4 and Chapter 5, the interaction resistance of stainless steel bolting assemblies was systematically investigated in the framework of the German research project P 1386 / IGF-No. 20651 N [78]. In total, 408 single-shear interaction tests with unthreaded bolt part in the shear plane (partially threaded EN ISO 4014 or EN ISO 4762 bolts with EN ISO 4032 nuts) as well as 382 single-shear interaction tests with threaded bolt part in the shear plane (fully threaded EN ISO 4017 bolts with EN ISO 4032 nuts) in bolt dimensions M16×100/110 and M24×130 were conducted. Austenitic (PC 50, 70, 80, 8.8 and 10.9), lean duplex (PC 10.9), duplex (PC 70 and 10.9), as well as super duplex (PC 10.9) grades and property classes were considered. The main test results were already published in [78] and [164].

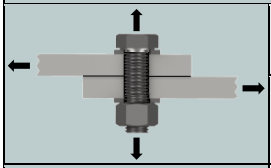
The final single-shear interaction test matrixes of the tested austenitic and duplex stainless steel bolting assemblies in various bolt property classes are presented in Table B.13 for the loading case “unthreaded bolt part in the shear plane” and Table B.14 for the loading case “threaded bolt part in the shear plane”. No further interaction tests on stainless steel bolts are conducted in the frame of this thesis.

Table B.13: Test matrix of single-shear interaction tests on partially threaded stainless steel bolting assemblies for the loading case “unthreaded bolt part in the shear plane” according to P 1386 / IGF-No. 20651 N

Unthreaded bolt part in the shear plane: Partially threaded EN ISO 4014 or EN ISO 4762 bolts with EN ISO 4032 nuts														
	**M16×100/110** (Number of single-shear interaction tests)							**M24×130** (Number of single-shear interaction tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	-	130	62	-	12	12	-	12	40	20	-	20	-	-
Lean Duplex	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Duplex	-	-	12	20	-	-	12[1)]	-	20	12	-	-	-	-
Super Duplex	-	-	-	-	-	12 + 12[1)]	-	-	-	-	-	-	-	-
Number of tests	-	130	74	20	12	36	12	12	60	32	-	20	-	-
Total tests	**408 single-shear interaction tests** on tests rig specially developed for the project													

[1)] Partially threaded hexagon socket head cap bolts according to EN ISO 4762.

Table B.14: Test matrix of single-shear interaction tests on fully threaded stainless steel bolting assemblies for the loading case “threaded bolt part in the shear plane” according to P 1386 / IGF-No. 20651 N

Threaded bolt part in the shear plane: Fully threaded EN ISO 4017 bolts with EN ISO 4032 nuts														
	**M16×100** (Number of single-shear interaction tests)							**M24×130/140** (Number of single-shear interaction tests)						
	PC 50	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**	**PC 50**	**PC 70**	**PC 80**	**PC 100**	**PC 8.8**	**PC 10.9**	**PC 12.9**
Austenitic	12	76	32	-	20	20	-	12	40	20	-	20	-	-
Lean Duplex		-	-	-	-	20	-	-	-	-	-	-	-	-
Duplex		12	-	-	-	20	-	-	12	-	-	-	-	-
Super Duplex		-	-	-	-	12	-	-	-	-	-	-	-	-
Number of tests	12	88	32	-	20	72	-	12	52	20	-	20	-	-
Total tests	**328 single-shear interaction tests** on tests rig specially developed for the project													

B.8 Tension, shear and interaction tests on carbon steel bolts and bolting assemblies

For the sake of extending the existing experimental studies on carbon steel bolts, systematic experimental investigations into the tension, shear and combined tension and shear resistance of carbon steel bolts and bolting assemblies were conducted at UDE-IML. In total, 31 tensile tests, 31 single-shear tests, 57 additional double-shear tests and 121 single-shear interaction tests under loading angles of 15°, 30°, 45° and 67.5° were conducted. As described in [413] and in [414], different bolt types were considered for testing either the unthreaded part (gross cross-sectional area A) or the threaded part (tensile stress area A_s) of the bolt in the shear plane. Therefore, fully threaded hexagon head bolts according to EN ISO 4017 were applied for the threaded bolt part in the shear plane, while in case that the shear plane passes through the unthreaded portion, partially threaded hexagon head bolts according to EN ISO 4014 as well as high-strength structural bolting assemblies according to EN 14399-3 (System HR) and EN 14399-4 (System HV) were investigated. In the tests, EN ISO 4014/4017 structural carbon steel bolts were matched with EN ISO 4032 nuts. Washers were not applied. Additionally, four different bolt manufacturers and traders (C1-C4) in PC 8.8 and 10.9 were considered.

The test matrixes of the tensile, single-shear, double-shear and interaction tests on carbon steel bolts and bolting assemblies are summarised in Table B.15 to Table B.18.

Table B.15: Test matrix of tensile tests according to EN ISO 898-1 on partially and fully threaded carbon steel bolts [414]

Tensile tests according to EN ISO 898-1 on carbon steel bolts							
Bolt types	**Partially threaded bolts**					**Fully threaded bolts**	
Bolt geometry	**M16×100**				**M16×95**	**M16×100**	
Bolt standard	**EN ISO 4014**		**EN 14399-3**	**EN 14399-4**		**EN ISO 4017**	
Property class	**PC 8.8**	**PC 10.9**	**PC 10.9**	**PC 10.9**	**PC 10.9**	**PC 8.8**	**PC 10.9**
Number of tests	5	5	5	3	3	5	5
Total tests	**31 tensile tests** on the whole bolt according to EN ISO 3506-1, Clause 9.2 and 9.3						

Table B.16: Test matrix of single-shear tests on partially and fully threaded carbon steel bolts [414]

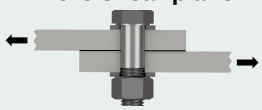
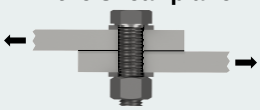
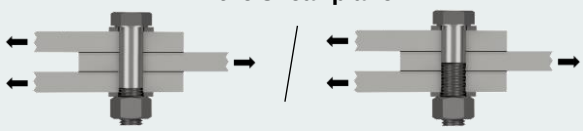
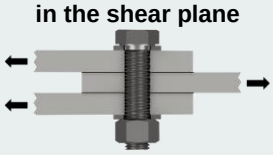
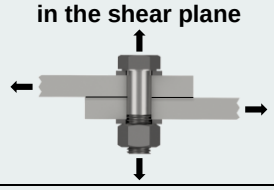
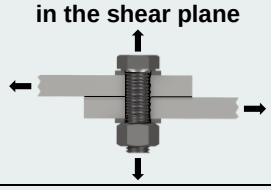
Single-shear tests on carbon steel bolts							
Shear plane	**Unthreaded bolt part in the shear plane** 					**Threaded bolt part in the shear plane** 	
Bolt geometry	**M16×100**				**M16×95**	**M16×100**	
Bolt standard	**EN ISO 4014**		**EN 14399-3**	**EN 14399-4**		**EN ISO 4017**	
Property class	**PC 8.8**	**PC 10.9**	**PC 10.9**	**PC 10.9**	**PC 10.9**	**PC 8.8**	**PC 10.9**
Number of tests	5	5	5	3	3	5	5
Total tests	**31 single-shear tests** on specially developed test rigs						

Table B.17: Test matrix of supplementary double-shear tests on partially and fully threaded carbon steel bolts

Double-shear tests on carbon steel bolts							
Shear planes	**Unthreaded bolt parts or unthreaded/threaded bolt parts in the shear plane** 					**Threaded bolt parts in the shear plane** 	
Bolt geometry	**M16×100**				**M16×95**	**M16×100**	
Bolt standard	**EN ISO 4014**		**EN 14399-3**	**EN 14399-4**		**EN ISO 4017**	
Property class	**PC 8.8**	**PC 10.9**	**PC 10.9**	**PC 10.9**	**PC 10.9**	**PC 8.8**	**PC 10.9**
Number of tests	-/5+5[1)]	-/5+5[1)]	-/5+5[1)]	3+3[1)]/-	3+3[1)]/-	5+5[1)]	5+5[1)]
Total tests	**62 additional double-shear tests** on a specially developed test rig						

[1)] Number of double-shear tests on a structural carbon steel bolt with nut + without nut.

Table B.18: Test matrix of single-shear interaction tests on partially and fully threaded carbon steel bolts [414]

Single-shear interaction tests on carbon steel bolts							
Shear plane	**Unthreaded bolt part in the shear plane** 					**Threaded bolt part in the shear plane** 	
Bolt geometry	**M16×100**				**M16×95**	**M16×100**	
Bolt standard	**EN ISO 4014**		**EN 14399-3**	**EN 14399-4**		**EN ISO 4017**	
Property class	**PC 8.8**	**PC 10.9**	**PC 10.9**	**PC 10.9**	**PC 10.9**	**PC 8.8**	**PC 10.9**
15° interaction	5	5	5	3	3	5	5
30° interaction	5	5	5	3	3	5	5
45° interaction	5	5	5	3	3	5	5
67.5° interaction	5	5	-	3	5	5	5
Total tests	**121 single-shear interaction tests** on specially developed test rigs						

Appendix C: Summary of test results from the literature

C.1 Summary of test results on carbon steel bolts from the literature

The test results on carbon steel bolts and bolting assemblies with unthreaded or threaded bolt part in the shear plane from the literature is summarised below. For further details and testing specifications, see Chapter 2.5.3 or the corresponding reference.

Table C.1: Test results from Bilderbeek (1971) [222]

Bilderbeek (1971)										
Specifications	**Tested series**									
Position of the shear plane	Threaded part				Unthreaded part					
Bolt geometry	M12	M20	M12	M20	M12	M20	M12	M20	M12	M20
Bolt property class	4.6	4.6	8.8	8.8	4.6	4.6	8.8	8.8	10.9	10.9
Maximum load F_{max} under 0° [kN]	39.0 39.5 36.3	118.0 107.0 116.0 115.0	71.0 69.5	215.0 192.0 193.0	47.5 48.3	158.0 158.0 157.0	75.5 72.5	239.0 233.0	84.0 85.0 84.5	270.0 272.0 266.0
Maximum load F_{max} under 15° [kN]	-	-	67.5 64.5	-	-	165.0 167.0	-	246.0 239.0	92.0 91.0	-
Maximum load F_{max} under 30° [kN]	38.0 38.5 38.5	106.0 108.5	58.5 60.0	171.0 179.0	49.4 50.0 50.2 48.5	145.0 140.0	77.5 78.5	230.0 208.0 222.0	92.0 93.0	263.0 262.0
Maximum load F_{max} under 45° [kN]	-	94.0 93.0	53.5 54.0	-	-	130.0 129.0	-	212.0 206.0	82.5 84.0	232.0 233.0
Maximum load F_{max} under 60° [kN]	29.5 30.3 29.8 29.8	87.0 83.5 82.5 87.0 86.5 82.5	50.5 50.0 47.5	152.0 143.0	40.0 41.8	119.0 124.0	65.5 64.5 66.0	212.0 218.0 204.0	80.0 80.0 79.0 83.0 78.0 79.5	225.0 221.0 222.0 225.0 222.0 219.0 220.0
Maximum load F_{max} under 70° [kN]	-	80.0 82.0 87.5 88.0	47.5 47.0	144.0	-	122.0 127.0 121.0 123.0	-	205.0 209.0	76.0 76.0	207.0 215.0
Maximum load F_{max} under 90° [kN]	32.5 32.5 29.0 31.0 30.0 33.5	86.0 84.0 90.0 84.0 88.0	46.0 49.5 48.5 46.0	144.0 134.0 136.0 141.0	41.5 40.8 39.5 40.0	124.0 127.0 122.0 129.0 126.0 125.0	64.0 66.5 62.5 63.5	218.0 216.0 218.0 204.0	83.5 82.5 75.0 75.0 77.0 77.0	230.0 228.0 216.0 219.0

Table C.2: Test results from Hassler (1973) [223]

Hassler (1973)	
Specifications	**Tested series**
Position of the shear plane	Unthreaded part
Bolt geometry	M24
Bolt property class	4.6
Maximum load F_{max} under 0° [kN]	175.3 176.6 176.2 178.0 176.6
Maximum load F_{max} under 30° [kN]	150.3 149.1 149.8 152.7 151.4
Maximum load F_{max} under 50° [kN]	135.0 134.1 133.6 133.2 129.2
Maximum load F_{max} under 70° [kN]	123.3 122.4 122.8 123.3 121.0
Maximum load F_{max} under 90° [kN]	122.6 125.1 124.1 126.0 122.6

Table C.3: Test results from Shakir-Khalil and Ho (1979) [225]

Shakir-Khalil and Ho (1979)					
Specifications	**Tested series**				
Position of the shear plane	Threaded part		Unthreaded part		
Bolt geometry	M20				
Bolt property class	4.6				
Maximum load F_{max} under 0° [kN]	133.7	118.8	133.0 131.0 137.0	120.0 119.0 118.0	125.5 118.5
Maximum load F_{max} under 15° [kN]	112.5 119.0 116.0	113.5 113.5 112.5	134.5 135.5 137.0	127.0 129.0 128.0	126.5 128.0
Maximum load F_{max} under 30° [kN]	104.5 104.0	103.5 105.5	120.0 123.5 123.5	122.0 119.0	117.5 118.5
Maximum load F_{max} under 45° [kN]	-	-	112.5 113.5 110.5	108.0 108.0	-
Maximum load F_{max} under 60° [kN]	-	-	103.0 104.5 103.0	101.0 104.0	-
Maximum load F_{max} under 75° [kN]	-	-	98.5 99.0 100.0	99.0 103.0	-
Maximum load F_{max} under 90° [kN]	85.0 88.5	77.0 76.5	99.0 101.5 100.0	105.0 103.0	94.5 96.0

Table C.4: Test results from Scheer (1980 + 1983) [226]**,** [228]

Scheer (1980 + 1983)									
Specifications	**Tested series**								
Position of the shear plane	Unthreaded or threaded part								
Bolt geometry	M12	M20	M27	M12	M20	M27	M12	M20	M27
Bolt property class	4.6			5.6			10.9		
Maximum load F_{max} under 0° [kN]	38.5	109.0	257.0	47.0	130.1	287.8	87.0	270.0	483.8
	38.5	107.1	249.2	47.0	125.9	292.8	89.0	271.0	504.0
	39.0	112.5	239.1	49.0	133.0	266.2	89.5	268.0	474.1
	38.5	111.0	251.1	52.0	130.1	286.0	90.0	271.0	515.9
	38.0	116.1	280.0	47.0	133.5	274.9	87.5	272.0	494.8
	39.0	113.9	221.2	46.8	149.0	284.1	97.5	255.0	482.9
	38.5	112.5	219.9	56.4	142.1	291.9	92.0	256.0	504.9
	39.0	112.0	222.2	47.6	149.0	298.8	95.5	266.1	499.9
	38.5	112.5	224.9	55.4	141.1	286.9	88.0	265.1	490.2
	37.5	110.0	221.2	61.0	164.9	305.2	97.0	253.1	480.1
	39.0	123.5	238.2			274.9	94.0	271.0	498.0
	40.5	122.0	242.8			291.0	97.0	271.0	515.9
	40.5	119.6	228.1			286.0	88.5	266.1	526.0
	37.0	118.6	224.9			275.9	91.0	268.0	507.2
	36.5	121.0	234.1			280.0	88.5	283.0	505.8
	39.5	129.6	272.2				101.0	292.0	549.9
	42.5	125.0	251.1				101.5	277.1	502.1
	40.0	125.9	268.1				99.5	283.0	530.1
	38.0	122.0	270.8				95.0	280.0	553.1
	39.0	125.0	259.8				95.5	283.0	507.2
	38.0	129.6	246.9				95.0		476.0
	38.5	118.1	252.9				94.0		533.8
	39.5	117.6	244.2				99.0		485.2
	43.0	128.6	247.9				91.0		509.9
	39.0	122.0	241.0				100.0		507.2
	35.5	121.0	207.9				97.5		526.0
	39.5	121.5	217.1				94.5		536.1
	39.0	122.5	214.8				91.5		540.2
	38.0	112.5	218.0				90.0		524.2
	40.5	118.1	210.2				89.5		521.9
	40.0	118.1					98.0		487.9
	40.5	108.5					94.0		505.8
	41.5	110.0					93.5		485.2
	41.0	113.9					94.5		483.8
	41.0	109.0					94.5		531.1
	44.5	115.4					92.0		
	45.5	105.1					91.0		
	40.5	111.5					94.5		
	46.0	99.5					90.5		
	46.5	106.1					89.5		
Maximum load F_{max} under 15° [kN]	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 30° [kN]	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 45° [kN]	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 67.5° [kN]	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 90° [kN]	Not considered in the statistical re-evaluation since the testing specifications do mainly focus on unsupported or supported bolted shear connections								

Table C.5: Test results from Knobloch/Schmidt (1987 + 1990) [171], [172] and Knobloch (1990) [173]

Knobloch/Schmidt (1987 + 1990) and Knobloch (1990)										
Specifications	**Tested series**									
Position of the shear plane	Unthreaded part									
Bolt geometry	M16				M20				M24	
Bolt property class	4.6	5.6	8.8	10.9	4.6	5.6	8.8	10.9	4.6	5.6
Maximum load F_{max} under 0° [kN]	70.0 65.0 70.0 65.0 69.0	82.0 90.0 87.3 82.2 84.0	145.0 149.0 144.5 143.0 143.5	170.0 170.0 176.0 175.5 170.0	134.0 137.0 127.5 133.0 134.0	135.0 130.0 130.0 133.0 130.0	220.0 220.0 220.0 215.0 210.0	290.0 269.5 280.0 285.5 290.0	167.0 165.0 168.5 160.0 195.0	185.0 170.0 185.0 185.0 170.0
Maximum load F_{max} under 15° [kN]	Test data available but not considered in the statistical re-evaluation									
Maximum load F_{max} under 30° [kN]										
Maximum load F_{max} under 45° [kN]										
Maximum load F_{max} under 67.5° [kN]										
Maximum load F_{max} under 90° [kN]	64.0 63.5 64.5 66.5 64.0	73.0 70.0 75.0 75.0 74.0	120.0 124.5 120.0 120.0 120.0	135.0 139.5 135.0 134.0 137.0	110.0 118.0 110.0 115.0 119.5	123.8 120.0 125.0 123.3 120.0	175.0 174.5 180.0 180.0 185.0	220.0 225.0 220.0 219.5 205.0	157.5 143.5 155.0 163.5 164.0	165.0 165.0 175.0 160.0 170.0
Specifications	**Tested series**									
Position of the shear plane	Unthreaded part		Threaded part							
Bolt geometry	M24		M16			M20		M24		
Bolt property class	8.8	10.9	4.6	8.8	10.9	8.8	10.9	5.6	8.8	10.9
Maximum load F_{max} under 0° [kN]	335.0 335.0 340.0 335.0 339.0	-	Determined by tensile tests on machined tensile test specimens, see [171], [172]							
Maximum load F_{max} under 15° [kN]	Test data available but not considered in the statistical re-evaluation									
Maximum load F_{max} under 30° [kN]										
Maximum load F_{max} under 45° [kN]										
Maximum load F_{max} under 67.5° [kN]										
Maximum load F_{max} under 90° [kN]	270.0 275.0 275.0 275.0 280.0	-	49.3 52.5 50.0 50.0 52.5	93.5 95.0 92.0 95.0 94.3	104.8 104.3 104.5 104.3 104.8	150.0 149.5 147.5 148.3 147.0	170.0 170.0 168.5 170.0 166.0	144.5 145.0 143.8 140.8 142.0	208.8 215.0 210.0 210.0 215.0	265.0 260.0 260.0 270.0 250.0

Table C.6: Test results from Valtinat and Dangelmaier (1990) [230]

Valtinat and Dangelmaier (1990)						
Specifications	**Tested series**					
Position of the shear plane	Threaded part					
Bolt geometry	M16	M20	M24	M16	M20	M24
Bolt property class	5.6			10.9		
Maximum load F_{max} under 0° [kN]	Determined by tensile tests on machined tensile test specimens, see [230]					
Maximum load F_{max} under 15° [kN]	-	-	-	-	-	-
Maximum load F_{max} under 30° [kN]	-	-	-	-	-	-
Maximum load F_{max} under 45° [kN]	-	-	-	-	-	-
Maximum load F_{max} under 67.5° [kN]	-	-	-	-	-	-
Maximum load F_{max} under 90° [kN]	62.9	99.0	131.4	103.7	160.2	231.2
	61.1	99.3	129.6	105.2	160.3	244.5
	59.9	98.7	127.9	109.0	158.2	234.5
	62.6	95.9	133.7	103.5	155.7	240.9
	65.4	98.0	130.3	112.0	153.2	236.4
	61.9	96.3	130.0	103.2	156.0	237.0
	60.6	97.4	134.9	106.7	164.7	242.4
	62.6	93.9	134.0	101.1	164.6	243.9
	63.0	97.8	130.9	108.6	159.2	239.3
	62.2	97.0	131.3	105.6	165.7	235.5
	62.5	95.8	130.8	102.7	164.7	237.1
	61.8	97.8	130.9	111.3	161.6	243.6
	61.9		128.6	108.2		224.5
	64.0		133.0	100.4		229.9
	61.9		130.3	103.9		242.3
	65.1		135.7	102.5		239.8
	62.0		136.4	106.4		231.5
	63.5		132.5	107.0		231.7
	62.5		135.6	107.1		233.5
	65.0		133.7	107.0		230.6
	62.6		133.9	104.1		228.5
	63.0		133.6	108.5		231.1
	63.0		133.3	106.1		229.6
	63.4		133.5	105.1		236.7

Table C.7: Test results from Friede and Lange (2010) [233]

Friede and Lange (2010)	
Specifications	**Tested series**
Position of the shear plane	Unthreaded part
Bolt geometry	M16
Bolt property class	10.9
Maximum load F_{max} under 0° [kN]	-
Maximum load F_{max} under 15° [kN]	-
Maximum load F_{max} under 30° [kN]	-
Maximum load F_{max} under 45° [kN]	-
Maximum load F_{max} under 67.5° [kN]	-
Maximum load F_{max} under 90° [kN]	138.4
	134.8
	138.4
	133.7
	137.1
	135.0
	136.7
	138.6
	140.4
	134.5
	136.5
	135.7
	135.7

Table C.8: Test results from Renner and Lange (2012 to 2019) [178]

Renner and Lange (2012 to 2019)							
Specifications	**Tested series**						
Position of the shear plane	Threaded part			Unthreaded part			
Bolt geometry	M20			M20			
Bolt property class	4.6	8.8	10.9	4.6		8.8	10.9
Maximum load F_{max} under 0° [kN]	107.4 106.0 104.2 106.3	230.5 226.9 228.6	264.4 270.7 272.3	144.1 142.7 141.8	124.4 124.9 124.6 127.0 127.1	232.4 229.3 229.7 234.5	275.3 278.4 273.4 270.1
Maximum load F_{max} under 15° [kN]	107.8 108.8 108.7	216.4 214.8 219.1	247.6 252.3 246.0	139.2 140.6 141.0	137.5 134.3 137.6	245.3 240.9 242.1	291.0 295.9 293.8
Maximum load F_{max} under 30° [kN]	100.1 96.4 102.4	194.5 190.4 188.9	223.2 218.9 220.0	126.7 126.1 128.4	143.0 138.8 140.9	235.7 239.2 228.2	266.2 257.7 269.6
Maximum load F_{max} under 45° [kN]	92.6 91.4 89.7	168.7 166.7 167.1	194.3 195.7 193.7	115.3 114.3 116.3	128.7 125.4 124.9	202.0 206.0 206.3	238.3 232.9 240.3
Maximum load F_{max} under 67.5° [kN]	82.2 83.2 77.5	152.5 146.8 148.9	173.6 176.3 169.4	105.3 105.3 108.5	117.4 117.1 112.2	182.1 183.0 183.9	218.3 213.8 222.2
Maximum load F_{max} under 90° [kN] as single-shear tests	84.6 77.3 81.3 76.7	151.9 161.3 150.8	176.0 184.7 169.3	112.8 113.6 109.8	120.2 119.4 123.1	194.8 195.2 195.3	229.4 195.2 236.0
Maximum load F_{max} under 90° [kN] as double-shear tests	149.7 148.6 153.8 151.5	280.7 279.8 282.5	343.9 327.4 324.9 307.7 305.9	200.4 200.6 196.4	233.5 227.4 231.2	366.3 368.0 364.7 368.0	429.3 436.4 426.8

Table C.9: Test results from Dörre et al. (2019) [175]

Dörre et al. (2019)									
Specifications	**Tested series (results only as mean values)**								
Position of the shear plane	Threaded part								
Bolt geometry	M12			M16			M20		
Bolt property class	5.6	8.8	10.9	5.6	8.8	10.9	4.6	8.8	10.9
Maximum load F_{max} under 0° [kN]	45.9	79.2	98.8	88.7	151.5	181.1	142.0	232.7	275.6
Maximum load F_{max} under 15° [kN]	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 30° [kN]	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 45° [kN]	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 67.5° [kN]	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 90° [kN] as single-shear tests	34.0	48.9	63.0	66.1	88.0	111.9	102.4	149.5	165.4
Maximum load F_{max} under 90° [kN] as double-shear tests	75.6	101.9	124.4	-	-	-	-	-	-

Specifications	**Tested series (results only as mean values)**									
Position of the shear plane	Unthreaded part									
Bolt geometry	M12					M16				
Bolt property class	4.6	5.6	8.8	10.9		4.6	5.6	8.8	10.9	
Maximum load F_{max} under 0° [kN]	41.1	46.4	81.3	100.9	96.4	81.2	89.8	147.8	18.9	176.9
Maximum load F_{max} under 15° [kN]	-	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 30° [kN]	-	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 45° [kN]	-	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 67.5° [kN]	-	-	-	-	-	-	-	-	-	-
Maximum load F_{max} under 90° [kN] as single-shear tests	38.3	47.4	67.1	83.9	80.0	77.2	81.5	122.2	138.7	137.4
Maximum load F_{max} under 90° [kN] as double-shear tests	87.4	106.8	151.4	-	-	-	-	-	-	-

Specifications	**Tested series (as mean values)**				
Position of the shear plane	Unthreaded part				
Bolt geometry	M20				
Bolt property class	4.6	5.6	8.8	10.9	
Maximum load F_{max} under 0° [kN]	117.0	141.5	236.3	272.2	266.3
Maximum load F_{max} under 15° [kN]	-	-	-	-	-
Maximum load F_{max} under 30° [kN]	-	-	-	-	-
Maximum load F_{max} under 45° [kN]	-	-	-	-	-
Maximum load F_{max} under 67.5° [kN]	-	-	-	-	-
Maximum load F_{max} under 90° [kN] as single-shear tests	104.8	126.9	190.9	211.8	204.1
Maximum load F_{max} under 90° [kN] as double-shear tests	-	-	-	-	-

Table C.10: Test results from Li et al. (2020) [236, 237]

Li et al. (2020)								
Specifications	**Tested series (results only as mean values)**							
Position of the shear plane	Threaded part		Unthreaded part					
Bolt geometry	M20		M16		M20		M24	
Bolt property class	10.9	12.9	10.9	12.9	10.9	12.9	10.9	12.9
Maximum load F_{max} under 0° [kN]	268.5	301.3	168.1	199.2 200.0	262.1	306.0	384.8	301.3
Maximum load F_{max} under 15° [kN]	246.1	274.2	180.2	203.2 209.2	278.2	333.3	401.8	274.2
Maximum load F_{max} under 30° [kN]	208.5	236.3	169.0	195.5 194.5	258.4	301.3	376.8	236.3
Maximum load F_{max} under 45° [kN]	181.5	206.0	151.1	176.1 171.1	232.5	270.0	337.2	206.0
Maximum load F_{max} under 67.5° [kN]	159.0	183.3	135.8	156.3 154.3	211.5	244.3	311.3	183.3
Maximum load F_{max} under 90° [kN]	169.9	190.0	136.2	166.0 162.0	210.7	252.0	316.8	190.0

Table C.11: Test results from Song et al. (2020) [5]

Song et al. (2020)		
Specifications	**Tested series**	
Position of the shear plane	Threaded part	Unthreaded part
Bolt geometry	M20	
Bolt property class	8.8	
Maximum load F_{max} under 0° [kN]	231.3 237.1 224.9	223.8 232.2 211.4
Maximum load F_{max} under 15° [kN]	216.4 203.7	239.4 227.4
Maximum load F_{max} under 30° [kN]	186.0 184.6	218.5 213.1
Maximum load F_{max} under 45° [kN]	159.7 160.9	196.2 193.0
Maximum load F_{max} under 67.5° [kN]	143.9 139.5	182.1 169.8
Maximum load F_{max} under 90° [kN]	152.2 148.2 152.9	183.1 183.2 184.5

C.2 Summary of test results on stainless steel bolts from the literature

The test results on stainless steel bolts and bolting assemblies with unthreaded or threaded bolt part in the shear plane from the literature is summarised below. For further details and testing specifications, see the corresponding chapters or references.

Table C.12: Test results from SCI, Technical report 21 (1990) [266] for the 1st Edition of DMSSS [267]

SCI, Technical report 21 (1990) for the 1st Edition of Design Manual for Structural Stainless Steel (DMSSS)						
Specifications	**Tested series (as mean values)**					
Position of the shear plane	Threaded part					
Bolt geometry	M16				M20	
Steel grade/Corrosion class	A4					
Bolt property class	70	80				
Maximum load F_{max} under 0° [kN]	108.0	134.6	137.9	128.1	213.8	209.6
Maximum load F_{max} under 15° [kN]	-	-	-	-	-	-
Maximum load F_{max} under 30° [kN]						
Maximum load F_{max} under 45° [kN]	-	-	-	-	165.5	163.3
Maximum load F_{max} under 67.5° [kN]	-	-	-	-	-	-
Maximum load F_{max} under 70° [kN]	-	-	-	-	-	-
Maximum load F_{max} under 90° [kN]	68.3	88.4	92.7	-	131.9	141.7

Table C.13: Test results from Bouchair and Muzeau (1999) [268], SCI (2000) [269], Ryan (2000) [270] and Bouchaïr et al. (2000) [271]

Bouchair and Muzeau (1999), SCI (2000), Ryan (2000) and Bouchaïr et al. (2000)			
Specifications	**Tested series**		
Position of the shear plane	Threaded part		
Bolt geometry	M12	M16	M20
Steel grade/Corrosion class	A4		
Bolt property class	80		
Maximum load F_{max} under 0° [kN]	71.5 71.8 70.8	147.6 143.5 147.2	211.1 202.7 208.8
Maximum load F_{max} under 15° [kN]	-	-	-
Maximum load F_{max} under 30° [kN]	-	-	-
Maximum load F_{max} under 45° [kN]	-	-	-
Maximum load F_{max} under 67.5° [kN]	-	-	-
Maximum load F_{max} under 90° [kN]	50.6 49.8 48.1	92.2 94.9 100.3	128.0 128.6 129.3

Table C.14: Test results from SCI (2007), Stainless Steel in Fire (SSIF) [272]

SCI (2007), Stainless Steel in Fire (SSIF)		
Specifications	**Tested series**	
Position of the shear plane	Unthreaded part	
Bolt geometry	M12	
Steel grade/Corrosion class	A2	A4
Bolt property class	70	80
Maximum load F_{max} under 0° [kN]	83.0	73.6 77.6
Maximum load F_{max} under 15° [kN]	-	-
Maximum load F_{max} under 30° [kN]	-	-
Maximum load F_{max} under 45° [kN]	-	-
Maximum load F_{max} under 67.5° [kN]	-	-
Maximum load F_{max} under 90° [kN]	58.7	53.0

Table C.15: Test results from Song et al. (2020) [5, 6]

Song et al. (2020)								
Specifications	**Tested series**							
Position of the shear plane	Threaded part							
Bolt geometry	M16	M20	M24	M20				
Steel grade/Corrosion class	A4						D6	
Bolt property class	70			80	8.8	10.9		12.9
Maximum load F_{max} under 0° [kN]	115.4 113.2 115.5	194.2 195.2 195.2	293.1 288.1 290.5	206.0 200.6 205.4	251.4 252.0 252.1	263.2 262.7	256.6 252.5 254.2	278.2 279.2 279.7
Maximum load F_{max} under 15° [kN]	114.6 114.0	192.2 192.1	283.1 283.5	192.7 191.7	232.8 232.6	242.6 241.7	236.9 236.1	269.6 269.4
Maximum load F_{max} under 30° [kN]	109.1 107.6	177.5 179.8	260.0 261.2	178.3 175.4	209.1 206.8	216.8 217.3	213.1 212.0	238.5 242.0
Maximum load F_{max} under 45° [kN]	98.7 99.2	161.9 162.3	234.0 234.5	159.1 162.4	180.5 183.2	185.2 186.7	190.9 192.1	215.6 213.3
Maximum load F_{max} under 67.5° [kN]	83.3 84.2	135.8 136.3	195.2 191.3	137.0 135.8	165.1 165.2	167.0 162.4	169.1 167.6	185.2 185.5
Maximum load F_{max} under 90° [kN]	83.9 82.8 80.9	143.8 131.1 137.3	205.3 185.5 186.7	138.3 135.1 140.9	160.2 156.2 164.5	163.1 164.3 169.2	175.3 174.4 168.4	191.7 187.5 187.8

Specifications	**Tested series**					
Position of the shear plane	Unthreaded part					
Bolt geometry	M20					
Steel grade/Corrosion class	A4				D6	
Bolt property class	70	80	8.8	10.9		12.9
Maximum load F_{max} under 0° [kN]	210.9 210.6 206.6	226.5 224.9 226.7	258.7 259.1 258.8	269.6 268.7 268.8	252.9 254.4 251.9	283.9 282.9 283.5
Maximum load F_{max} under 15° [kN]	204.9 205.3	220.9 221.9	253.0 252.4	272.2 272.3	245.4 245.5	273.9 280.2
Maximum load F_{max} under 30° [kN]	195.9 198.7	206.2 209.1	230.8 229.7	248.5 249.2	232.4 233.0	254.8 253.5
Maximum load F_{max} under 45° [kN]	177.5 179.1	191.8 190.5	206.2 205.3	219.4 220.9	211.3 208.6	231.1 232.6
Maximum load F_{max} under 67.5° [kN]	164.8 168.5	173.9 174.3	190.7 190.6	188.4 199.2	188.4 190.8	209.4 208.8
Maximum load F_{max} under 90° [kN]	169.6 169.6 173.1	177.8 180.6 178.4	196.2 195.8 195.0	205.2 205.2 205.8	195.8 195.6 194.4	212.7 212.6 214.9

Appendix D: Summary of tested stainless and carbon steel bolt series at UDE-IML

D.1 Summary of tested partially threaded stainless steel bolts with unthreaded bolt part in the shear plane at UDE-IML

D.1.1 General

Below, all experimental investigations conducted on partially threaded stainless steel bolts with unthreaded part in the shear plane are summarised.

Table D.1: Summary of tested partially threaded stainless steel bolts with unthreaded bolt part in the shear plane at UDE-IML

Partially threaded stainless steel bolts with unthreaded bolt part in the shear plane											
Steel type	**Property class acc. to EN ISO 3506-1**	**Corrosion class acc. to EN ISO 3506-1**	**Manufacturer or trader**	**Thread production type**	**Bolt type**	**Bolt geometry**	**Number of tensile tests**	**Number of single-shear tests**	**Number of double-shear tests**	**Number of interaction tests**	**Series designation**
Austenitic	**PC 50**	A4-50	C4	Cut	EN ISO 4014	M24×130	3	3	-	12	EN ISO 4014 – C4 – M24×130 – A4-50
	PC 70	A2-70	C2	Rolled	EN ISO 4014	M16×110	5	5	-	14	EN ISO 4014 – C2 – M16×110 – A2-70
			C1	Rolled	EN ISO 4014	M16×110	5	5	-	20	EN ISO 4014 – C1 – M16×110 – A2-70
				Rolled	EN ISO 4014	M16×100	5	5	-	20	EN ISO 4014 – C1 – M16×100 – A2-70
			C6	Rolled	EN ISO 4014	M16×100	5	5	-	12	EN ISO 4014 – C6 – M16×100 – A2-70
		A4-70	C2	Rolled	EN ISO 4014	M16×100	5	5	16	20	EN ISO 4014 – C2 – M16×100 – A4-70
			C1	Rolled	EN ISO 4014	M16×110	5	5	-	20	EN ISO 4014 – C1 – M16×110 – A4-70
			C4	Rolled	EN ISO 4014	M16×108	3	3	-	12	EN ISO 4014 – C4 – M16×108 – A4-70
			C2	Rolled	EN ISO 4014	M24×130	5	5	-	20	EN ISO 4014 – C2 – M24×130 – A4-70
			C1	Rolled	EN ISO 4014	M24×130	5	5	-	20	EN ISO 4014 – C1 – M24×130 – A4-70
			C6	Rolled	EN ISO 4014	M16×100	5	5	-	12	EN ISO 4014 – C6 – M16×100 – A4-70
		A5-70		Rolled	EN ISO 4014	M16×100	5	5	-	-	EN ISO 4014 – C6 – M16×100 – A5-70
	PC 80	A4-80	C2	Rolled	EN ISO 4014	M16×100	5	5	16	20	EN ISO 4014 – C2 – M16×100 – A4-80
				Rolled	EN ISO 4014	M16×110	5	5	-	18	EN ISO 4014 – C2 – M16×110 – A4-80
				Rolled	EN ISO 4014	M24×130	5	5	-	20	EN ISO 4014 – C2 – M24×130 – A4-80
			C6	Rolled	EN ISO 4014	M16×100	5	5	-	12	EN ISO 4014 – C6 – M16×100 – A4-80
				Rolled	EN ISO 4014	M24×130	5	5	-	-	EN ISO 4014 – C6 – M24×130 – A4-80
		A8-80	C4	Cut	EN ISO 4014	M16×100	3	3	-	12	EN ISO 4014 – C4 – M16×100 – A8-80
	PC 8.8	A4-8.8	C3	Rolled	EN ISO 4014	M16×100	3	3	-	12	EN ISO 4014 – C3 – M16×100 – A4-8.8
				Rolled	EN ISO 4014	M24×130	5	5	-	20	EN ISO 4014 – C3 – M24×130 – A4-8.8
	PC 10.9	A4-10.9		Rolled	EN ISO 4014	M16×100	3	3	-	12	EN ISO 4014 – C3 – M16×100 – A4-10.9
Duplex	**PC 70**	D6-70	C5	Rolled	EN ISO 4014	M24×130	5	5	-	20	EN ISO 4014 – C5 – M24×130 – D6-70
	PC 80	D6-80	C4	Cut	EN ISO 4014	M16×100	3	3	-	12	EN ISO 4014 – C4 – M16×100 – D6-80
				Cut	EN ISO 4014	M24×130	3	3	-	12	EN ISO 4014 – C4 – M24×130 – D6-80
	PC 100	D6–100	C5	Rolled	EN ISO 4014	M16×100	5	5	-	20	EN ISO 4014 – C5 – M16×100 – D6-100
	PC 10.9	D8-10.9	C3	Rolled	EN ISO 4014	M16×100	3	3	-	12	EN ISO 4014 – C3 – M16×100 – D8-10.9
				Rolled	EN ISO 4762	M16×100	3	3	-	12	EN ISO 4762 – C3 – M16×100 – D8-10.9
	PC 12.9	D8-12.9		Rolled	EN ISO 4762	M16×100	3	3	-	12	EN ISO 4762 – C3 – M16×100 – D6-12.9

D.1.2 EN ISO 4014 – C4 – M24×130 – A4-50 series

Table D.2: Specifications, geometrical parameters and tests results of EN ISO 4014 – C4 – M24×130 – A4-50

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 50	A4	EN ISO 4014	M24×130	C4	Cut

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
6	452.39 mm²	448.64 mm²	0.05 %	6	352.49 mm²	341.93 mm²	0.06 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	500						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	176.30						
Ultimate tensile load $F_{mf,exp}$ [kN]	239.05	236.83	237.58	-	-	237.82	0.47 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	678.18	671.88	674.01	-	-	674.69	0.47 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.356	1.343	1.348	-	-	1.349	0.47 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	210						
Nominal yield load $F_{pf,nom}$ [kN]	74.03						
Mean yield load $F_{pf,exp,mean}$ [kN]	174.14						1.70 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	494.03						1.70 %
Nominal elongation at fracture A_{nom} [x·d]	0.60						
Elongation at fracture A_{exp} [x·d]	0.82	0.81	0.85	-	-	0.83	2.75 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	176.30						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	615.00	629.42	620.13	-	-	621.52	1.18 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	217.68	222.01	222.34	-	-	220.67	1.18 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	254.02	251.88	251.65	-	-	252.52	0.52 %
Maximum load F_{max} under 30° [kN]	256.28	253.08	254.35	-	-	254.57	0.63 %
Maximum load F_{max} under 45° [kN]	237.52	240.24	239.75	-	-	239.17	0.61 %
Maximum load F_{max} under 67.5° [kN]	222.07	221.45	222.63	-	-	222.05	0.27 %

D.1.3 EN ISO 4014 – C2 – M16×110 – A2-70

Table D.3: Specifications, geometrical parameters and tests results of EN ISO 4014 – C2 – M16×110 – A2-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A2	EN ISO 4014	M16×110	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	196.50 mm²	0.21 %	10	156.67 mm²	151.91 mm²	0.68 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	132.20	130.80	131.10	132.85	131.64	131.72	0.63 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	843.81	834.88	836.79	847.96	840.24	840.74	0.63 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.205	1.192	1.195	1.211	1.200	1.201	0.63 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	90.33						1.30 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	576.57						1.30 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.95	1.90	1.88	1.86	1.90	1.90	1.71 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	133.97	133.22	132.97	132.77	134.01	133.39	0.43 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	855.11	850.32	848.73	847.45	855.37	851.40	0.43 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	672.77	665.65	667.18	676.08	669.92	670.32	0.63 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	106.18	106.36	105.37	105.38	105.63	105.79	0.43 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	134.88	135.74	134.54	-	-	135.05	0.46 %
Maximum load F_{max} under 30° [kN]	130.24	130.13	129.99	-	-	130.12	0.10 %
Maximum load F_{max} under 45° [kN]	124.15	121.73	121.16	-	-	122.35	1.30 %
Maximum load F_{max} under 67.5° [kN]	109.50	109.39	108.06	109.03	109.11	109.02	0.52 %

D.1.4 EN ISO 4014 – C1 – M16×110 – A2-70

Table D.4: Specifications, geometrical parameters and tests results of EN ISO 4014 – C1 – M16×110 – A2-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A2	EN ISO 4014	M16×110	C1	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	194.78 mm²	0.29 %	10	156.67 mm²	152.29 mm²	0.79 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	124.40	123.90	124.20	126.10	126.81	125.08	1.03 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	794.03	790.84	792.75	804.88	809.41	798.38	1.03 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.134	1.129	1.132	1.149	1.156	1.140	1.03 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	77.51						1.80 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	494.74						1.80 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	2.05	2.07	2.04	2.12	2.06	2.07	1.46 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	126.11	127.14	125.82	126.53	126.93	126.51	0.43 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	804.94	811.52	803.09	807.62	810.18	807.47	0.43 %
Failure location	Shank	Shank	Shank	Shank	Shank	Shank	Shank

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	638.67	636.10	637.64	647.40	651.04	642.17	1.03 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	625.50	622.60	622.99	-	-	623.70	0.25 %
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	395.10	392.25	383.88	-	-	390.41	1.49 %
Elongation at fracture $A_{exp,6892-1}$ [%]	36.56	34.26	36.31	-	-	35.71	3.53 %

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	98.29	99.35	97.67	99.81	100.22	99.07	1.07 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	128.30	130.37	127.77	128.15	127.02	128.32	0.97 %
Maximum load F_{max} under 30° [kN]	114.32	115.29	115.93	115.90	116.91	115.67	0.82 %
Maximum load F_{max} under 45° [kN]	116.81	115.06	113.90	117.85	113.27	115.38	1.67 %
Maximum load F_{max} under 67.5° [kN]	101.65	102.48	101.61	104.94	101.51	102.44	1.42 %

D.1.5 EN ISO 4014 – C1 – M16×100 – A2-70

Table D.5: Specifications, geometrical parameters and tests results of EN ISO 4014 – C1 – M16×100 – A2-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A2	EN ISO 4014	M16×100	C1	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	197.73 mm²	0.51 %	10	156.67 mm²	151.91 mm²	0.65 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	125.69	124.23	127.58	126.74	126.96	126.24	1.04 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	802.26	792.94	814.33	808.96	810.37	805.77	1.04 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.146	1.132	1.163	1.155	1.157	1.151	1.04 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	84.61						2.1 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	540.05						2.1 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.78	1.78	1.74	1.73	1.77	1.76	1.35 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	635.66	628.28	645.22	640.98	642.09	638.45	1.04 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	855.52	860.54	824.52	-	-	846.86	2.30 %
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	104.12	105.13	104.87	100.60	104.40	103.82	1.78 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	130.09	129.50	126.13	129.60	128.40	128.74	1.23 %
Maximum load F_{max} under 30° [kN]	122.56	119.15	124.23	124.08	124.68	122.94	1.84 %
Maximum load F_{max} under 45° [kN]	113.22	111.67	116.56	116.53	112.30	114.05	2.05 %
Maximum load F_{max} under 67.5° [kN]	104.12	105.13	104.87	100.60	104.40	103.82	1.78 %

D.1.6 EN ISO 4014 – C6 – M16×100 – A2-70

Table D.6: Specifications, geometrical parameters and tests results of EN ISO 4014 – C6 – M16×100 – A2-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A2	EN ISO 4014	M16×100	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	196.77 mm²	0.22 %	10	156.67 mm²	153.89 mm²	0.75 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	131.74	127.88	127.18	126.76	126.49	128.01	1.68 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	840.88	816.24	811.77	809.09	807.37	817.07	1.68 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.201	1.166	1.159	1.156	1.153	1.167	1.68 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	78.72						2.90 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	502.46						2.90 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.73	1.80	1.79	1.81	1.80	1.79	1.67 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	669.51	649.90	646.34	644.20	642.83	650.56	1. 68 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	104.70	104.24	104.53	104.77	104.10	104.47	0.28 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	131.28	132.70	132.73	-	-	132.24	0.63 %
Maximum load F_{max} under 30° [kN]	126.08	126.54	126.34	-	-	126.32	0.18 %
Maximum load F_{max} under 45° [kN]	114.80	116.58	114.75	-	-	115.37	0.90 %
Maximum load F_{max} under 67.5° [kN]	103.98	104.65	102.49	-	-	103.70	1.07 %

D.1.7 EN ISO 4014 – C2 – M16×100 – A4-70

Table D.7: Specifications, geometrical parameters and tests results of EN ISO 4014 – C2 – M16×100 – A4-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A2	EN ISO 4014	M16×100	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	195.69 mm²	0.22 %	10	156.67 mm²	153.09 mm²	0.51 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	126.67	125.23	124.13	126.15	128.42	126.12	1.28 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	808.51	799.32	792.30	805.20	819.68	805.00	1.28 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.155	1.142	1.132	1.150	1.171	1.150	1.28 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	91.70						2.20 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	585.31						2.20 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.50	1.49	1.51	1.49	1.44	1.49	1.99 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	127.32	127.81	126.86	126.99	127.04	127.21	0.30 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	812.66	815.79	809.73	810.56	810.94	811.94	0.30 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	647.30	639.94	634.32	644.64	656.24	64.49	1.29 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	880.30	877.60	898.26	-	-	885.39	1.27 %
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	95.32	94.99	94.87	-	-	95.06	0.25 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	94.55	95.59	99.25	-	-	96.46	2.56 %
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	100.92	97.97	97.50	98.66	97.85	98.58	1.39 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	105.58	106.84	103.28	104.50	105.99	105.24	1.31 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	103.00	107.88	109.54	107.94	105.99	106.87	2.34 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	125.80	126.21	128.25	128.02	127.99	127.25	0.91 %
Maximum load F_{max} under 30° [kN]	120.65	120.56	119.00	119.38	118.18	119.55	0.88 %
Maximum load F_{max} under 45° [kN]	109.88	110.88	108.00	109.56	111.00	109.86	1.11 %
Maximum load F_{max} under 67.5° [kN]	101.48	98.43	100.28	99.26	102.70	100.43	1.70 %

D.1.8 EN ISO 4014 – C1 – M16×110 – A4-70

Table D.8: Specifications, geometrical parameters and tests results of EN ISO 4014 – C1 – M16×110 – A4-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A4	EN ISO 4014	M16×110	C1	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	194.77 mm²	0.38 %	10	156.67 mm²	151.41 mm²	0.68 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	116.80	116.90	115.30	117.00	119.69	117.14	1.36 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	745.52	746.16	735.94	746.79	763.96	747.68	1.36 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.065	1.066	1.051	1.067	1.091	1.068	1.36 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	82.00						1.70 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	523.39						1.70 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.85	1.88	1.84	1.85	1.85	1.85	0.82 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	118.10	119.21	116.91	117.83	117.75	117.96	0.70 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	753.81	760.90	746.22	752.09	751.58	752.92	0.70 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	599.68	600.20	591.98	600.71	614.52	601.43	1.36 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	818.10	806.51	798.22	-	-	807.61	1.24 %
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	91.72	91.40	91.77	91.68	91.89	91.69	0.20 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	119.85	118.86	120.29	120.08	118.39	119.49	0.69 %
Maximum load F_{max} under 30° [kN]	111.14	111.35	112.07	111.16	111.15	111.37	0.36 %
Maximum load F_{max} under 45° [kN]	104.40	103.38	103.75	104.33	104.78	104.13	0.54 %
Maximum load F_{max} under 67.5° [kN]	93.86	94.18	93.62	93.71	93.92	93.86	0.23 %

D.1.9 EN ISO 4014 – C4 – M16×108 – A4-70

Table D.9: Specifications, geometrical parameters and tests results of EN ISO 4014 – C4 – M16×108 – A4-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A4	EN ISO 4014	M16×108	C4	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	198.74 mm²	0.55 %	10	156.67 mm²	151.82 mm²	0.23 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	113.57	114.27	113.16	-	-	113.67	0.49 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	724.90	729.37	722.28	-	-	725.52	0.49 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.035	1.042	1.032	-	-	1.036	0.49 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	73.20						0.80 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	467.22						0.80 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.55	1.54	1.54	-	-	1.54	1.10 %
Failure location	Shank	Shank	Shank	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	571.45	574.97	569.39			571.94	0.49 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	90.18	90.37	89.95	-	-	90.17	0.23 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	115.85	117.78	115.56	-	-	116.39	1.03 %
Maximum load F_{max} under 30° [kN]	111.51	114.12	109.44	-	-	111.69	2.10 %
Maximum load F_{max} under 45° [kN]	102.74	103.51	102.71	-	-	102.99	0.44 %
Maximum load F_{max} under 67.5° [kN]	91.35	92.57	92.89	-	-	92.27	0.88 %

D.1.10 EN ISO 4014 – C2 – M24×130 – A4-70

Table D.10: Specifications, geometrical parameters and tests results of EN ISO 4014 – C2 – M24×130 – A4-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A4	EN ISO 4014	M24×130	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	452.39 mm²	447.84 mm²	0.13 %	10	352.49 mm²	344.05 mm²	0.42 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	246.80						
Ultimate tensile load $F_{mf,exp}$ [kN]	281.75	281.40	280.66	280.42	281.83	281.21	0.23 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	799.31	798.32	796.22	795.54	799.54	797.79	0.23 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.142	1.140	1.137	1.136	1.142	1.139	0.23 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	158.70						
Mean yield load $F_{pf,exp,mean}$ [kN]	204.21						1.10 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	579.34						1.10 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.42	1.42	1.44	1.42	1.39	1.42	1.24 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	246.80						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	629.13	628.35	626.70	626.16	629.31	627.93	0.23 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	230.29	231.50	229.43	230.60	228.72	230.11	0.47 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	291.69	291.97	291.35	290.55	290.67	291.24	0.21 %
Maximum load F_{max} under 30° [kN]	279.16	282.37	277.88	278.43	277.90	279.15	0.67 %
Maximum load F_{max} under 45° [kN]	258.94	260.24	261.03	260.84	260.27	260.26	0.31 %
Maximum load F_{max} under 67.5° [kN]	233.15	228.08	231.18	231.34	231.19	230.99	0.79 %

D.1.11 EN ISO 4014 – C1 – M24×130 – A4-70

Table D.11: Specifications, geometrical parameters and tests results of EN ISO 4014 – C1 – M24×130 – A4-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A4	EN ISO 4014	M24×130	C1	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	452.39 mm²	448.24 mm²	0.14 %	10	352.49 mm²	342.40 mm²	0.33 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	246.80						
Ultimate tensile load $F_{mf,exp}$ [kN]	285.79	286.24	283.42	284.90	284.93	285.06	0.38 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	810.77	812.05	804.05	808.25	808.33	808.69	0.38 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.158	1.160	1.148	1.154	1.154	1.155	0.38 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	158.70						
Mean yield load $F_{pf,exp,mean}$ [kN]	201.90						1.30 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	572.78						1.30 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.33	1.34	1.35	1.33	1.33	1.34	0:71 5
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	246.80						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	637.58	638.59	632.20	635.60	635.66	635.95	0.38 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	227.48	227.43	228.53	227.73	228.73	227.98	0.27 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	290.80	290.76	289.53	290.35	290.55	290.40	0.18 %
Maximum load F_{max} under 30° [kN]	274.60	276.12	275.18	275.75	275.51	275.43	0.21 %
Maximum load F_{max} under 45° [kN]	258.04	259.94	260.87	260.64	260.47	259.99	0.44 %
Maximum load F_{max} under 67.5° [kN]	228.51	231.14	230.96	231.20	228.86	230.14	0.58 %

D.1.12 EN ISO 4014 – C6 – M16×100 – A4-70

Table D.12: Specifications, geometrical parameters and tests results of EN ISO 4014 – C6 – M16×100 – A4-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A4	EN ISO 4014	M16×100	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	196.02 mm²	0.14 %	10	156.67 mm²	154.31 mm²	0.71 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	129.45	129.88	129.41	130.89	129.28	129.78	0.51 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	826.26	829.00	826.00	835.45	825.17	828.38	0.51 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.180	1.184	1.180	1.193	1.178	1.183	0.51 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	84.51						1.69 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	539.41						1.69 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.35	1.35	1.35	1.32	1.35	1.34	1.16 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	660.39	662.59	660.19	667.74	659.52	662.09	0.51 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	102.76	103.32	102.54	102.52	101.66	102.56	0.58 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	131.09	130.32	132.06	-	-	131.15	0.66 %
Maximum load F_{max} under 30° [kN]	125.79	124.23	124.73	-	-	124.92	0.64 %
Maximum load F_{max} under 45° [kN]	113.20	112.57	113.84	-	-	113.20	0.56 %
Maximum load F_{max} under 67.5° [kN]	103.09	101.69	101.80	-	-	102.19	0.76 %

D.1.13 EN ISO 4014 – C6 – M16×100 – A5-70

Table D.13: Specifications, geometrical parameters and tests results of EN ISO 4014 – C6 – M16×100 – A5-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A4	EN ISO 4014	M16×110	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	194.76 mm²	0.35 %	10	156.67 mm²	151.82 mm²	0.44 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	124.11	118.71	120.70	117.67	122.89	120.82	2.25 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	792.17	757.71	770.41	751.07	784.39	771.15	2.25 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.131	1.082	1.100	1.073	1.120	1.101	2.25 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	89.90						2.91 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	573.82						2.91 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	0.65	0.70	0.71	0.74	0.68	0.70	4.76 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 61							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	122.61	122.01	121.47	121.04	122.90	122.01	0.63 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	782.60	778.77	775.32	772.58	784.45	778.75	0.63 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	613.81	602.62	622.90	-	-	613.11	1.70 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	102.84	102.01	102.97	102.51	102.75	102.62	0.37 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	-	-	-	-	-	-	-
Maximum load F_{max} under 30° [kN]	-	-	-	-	-	-	-
Maximum load F_{max} under 45° [kN]	-	-	-	-	-	-	-
Maximum load F_{max} under 67.5° [kN]	-	-	-	-	-	-	-

D.1.14 EN ISO 4014 – C2 – M16×100 – A4-80

Table D.14: Specifications, geometrical parameters and tests results of EN ISO 4014 – C2 – M16×100 – A4-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 80	A4	EN ISO 4014	M16×100	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	196.91 mm²	0.33 %	10	156.67 mm²	151.91 mm²	0.68 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	125.40						
Ultimate tensile load $F_{mf,exp}$ [kN]	137.75	137.95	137.82	136.57	136.61	137.34	0.50 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	879.24	880.51	879.68	871.70	871.96	876.62	0.50 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.098	1.100	1.099	1.089	1.089	1.095	0.50 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	94.01						
Mean yield load $F_{pf,exp,mean}$ [kN]	99.00						1.69 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	631.90						1.69 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	1.28	1.27	1.26	1.30	1.25	1.27	1.37 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	125.40						
$F_{bi,max,exp}$ [kN]	138.11	136.52	136.88	137.67	137.99	137.43	0.51 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	881.53	871.39	873.68	878.73	880.77	877.22	0.51 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	699.56	700.57	699.91	693.57	693.77	697.48	0.50 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	99.84	99.55	97.54	-	-	98.98	1.27 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	99.25	105.26	102.54	-	-	102.35	2.94 %
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	103.39	103.99	103.41	104.29	104.15	103.84	0.41 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	110.46	108.00	110.00	109.54	108.52	109.30	0.94 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	109.50	110.00	114.54	113.94	112.85	112.17	2.05 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	138.28	136.68	136.54	136.71	136.79	137.00	0.53 %
Maximum load F_{max} under 30° [kN]	127.11	126.45	127.73	126.55	126.99	126.97	0.40 %
Maximum load F_{max} under 45° [kN]	117.91	118.87	119.91	117.97	118.93	118.72	0.74 %
Maximum load F_{max} under 67.5° [kN]	104.38	104.88	106.00	104.38	103.99	104.73	0.74 %

D.1.15 EN ISO 4014 – C2 – M16×110 – A4-80

Table D.15: Specifications, geometrical parameters and tests results of EN ISO 4014 – C2 – M16×110 – A4-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 80	A4	EN ISO 4014	M16×110	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	197.94 mm²	0.22 %	10	156.67 mm²	153.85 mm²	0.70 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	125.40						
Ultimate tensile load $F_{mf,exp}$ [kN]	141.90	141.10	142.80	141.53	141.03	141.67	0.51 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	905.73	900.62	911.47	903.36	900.17	904.27	0.51 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.132	1.125	1.139	1.129	1.125	1.130	0.51 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	94.01						
Mean yield load $F_{pf,exp,mean}$ [kN]	98.03						1.31 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	625.71						1.31 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	1.31	1.32	1.31	1.33	1.39	1.33	2.47 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	125.40						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	716.88	712.84	721.43	715.01	712.49	715.73	0.51 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	970.11	975.36	985.10	-	-	976.86	0.78 %
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	650.10	671.21	652.22	-	-	657.84	1.77 %
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	440.13	460.52	465.35	-	-	455.33	2.94 %
Elongation at fracture $A_{exp,6892-1}$ [%]	25.77	25.12	20.12	-	-	23.67	13.06 %

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	106.83	106.68	105.52	107.31	105.73	106.41	0.71 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	141.56	140.24	139.59	142.03	142.01	141.08	0.79 %
Maximum load F_{max} under 30° [kN]	129.06	128.87	129.71	129.59	128.53	129.15	0.38 %
Maximum load F_{max} under 45° [kN]	119.31	119.00	118.36	118.74	118.23	118.73	0.38 %
Maximum load F_{max} under 67.5° [kN]	106.49	107.36	107.52	-	-	107.12	0.52 %

D.1.16 EN ISO 4014 – C2 – M24×130 – A4-80

Table D.16: Specifications, geometrical parameters and tests results of EN ISO 4014 – C2 – M24×130 – A4-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 80	A4	EN ISO 4014	M24×130	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	452.39 mm²	447.66 mm²	0.11 %	10	352.49 mm²	342.75 mm²	0.42 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	282.10						
Ultimate tensile load $F_{mf,exp}$ [kN]	343.36	347.89	349.00	347.08	341.28	345.72	0.94 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	974.10	986.95	990.10	984.65	968.20	980.80	0.94 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.217	1.233	1.237	1.230	1.210	1.226	0.94 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	211.60						
Mean yield load $F_{pf,exp,mean}$ [kN]	263.80						1.80 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	748.39						1.80 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	0.91	0.88	0.87	0.91	0.91	0.90	2.37 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	282.10						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	767.01	777.13	779.61	775.32	762.36	772.29	0.94 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	251.88	254.63	254.98	248.55	250.54	252.12	1.08 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	334.56	331.96	322.11	333.31	330.50	330.49	1.49 %
Maximum load F_{max} under 30° [kN]	296.94	309.17	304.29	302.69	303.25	303.27	1.44 %
Maximum load F_{max} under 45° [kN]	279.14	284.20	281.13	285.72	283.54	282.75	0.92 %
Maximum load F_{max} under 67.5° [kN]	252.36	251.06	247.02	255.05	247.45	250.59	1.35 %

D.1.17 EN ISO 4014 – C6 – M16×100 – A4-80

Table D.17: Specifications, geometrical parameters and tests results of EN ISO 4014 – C6 – M16×100 – A4-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 80	A4	EN ISO 4014	M16×100	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	196.83 mm²	0.22 %	10	156.67 mm²	150.05 mm²	0.70 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	125.40						
Ultimate tensile load $F_{mf,exp}$ [kN]	135.19	136.40	132.08	132.02	134.20	133.98	1.44 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	862.90	870.62	843.05	842.66	856.58	855.16	1.44 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.078	1.088	1.053	1.053	1.070	1.068	1.44 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	94.01						
Mean yield load $F_{pf,exp,mean}$ [kN]	93.00						2.50 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	593.60						2.50 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	1.22	1.25	1.19	1.18	1.24	1.22	2.51 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]							
$F_{bi,max,exp}$ [kN]	133.85	133.51	132.83	131.90	132.10	132.84	0.64 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	854.34	852.17	847.83	841.90	843.17	847.88	0.64 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	686.84	692.98	971.04	670.73	681.81	680.68	1.44 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	940.15	922.45	934.20	-	-	932.27	0.97 %
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	104.84	105.45	105.31	105.68	107.68	105.79	1.04 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	135.19	132.07	131.98	-	-	133.08	1.37 %
Maximum load F_{max} under 30° [kN]	127.02	126.38	125.08	-	-	126.16	0.78 %
Maximum load F_{max} under 45° [kN]	116.17	116.04	115.83	-	-	116.01	0.14 %
Maximum load F_{max} under 67.5° [kN]	104.46	105.83	104.71	-	-	105.00	0.69 %

D.1.18 EN ISO 4014 – C6– M24×130 – A4-80

Table D.18: Specifications, geometrical parameters and tests results of EN ISO 4014 – C6– M24×130 – A4-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 80	A4	EN ISO 4014	M24×130	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	452.39 mm²	449.16 mm²	0.32 %	10	352.49 mm²	344.16 mm²	0.44 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	282.10						
Ultimate tensile load $F_{mf,exp}$ [kN]	310.87	313.57	308.58	309.01	307.99	310.00	0.73 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	881.93	889.59	875.43	876.65	873.76	879.47	0.73 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.102	1.112	1.094	1.095	1.092	1.099	0.73 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	211.60						
Mean yield load $F_{pf,exp,mean}$ [kN]	208.70						1.60 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	592.07						1.60 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	0.99	0.96	1.02	1.00	0.99	0.99	2.34 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	282.10						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	692.11	698.13	687.02	687.97	685.70	690.19	0.73 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	251.57	252.59	248.28	255.68	250.99	251.82	1.07 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	-	-	-	-	-	-	-
Maximum load F_{max} under 30° [kN]	-	-	-	-	-	-	-
Maximum load F_{max} under 45° [kN]	-	-	-	-	-	-	-
Maximum load F_{max} under 67.5° [kN]	-	-	-	-	-	-	-

D.1.19 EN ISO 4014 – C4 – M16×100 – A8-80

Table D.19: Specifications, geometrical parameters and tests results of EN ISO 4014 – C4 – M16×100 – A8-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 80	A4	EN ISO 4014	M16×100	C4	Cut

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	199.15 mm²	0.04 %	10	156.67 mm²	151.66 mm²	0.43 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	125.40						
Ultimate tensile load $F_{mf,exp}$ [kN]	133.29	133.77	133.59	-	-	133.55	0.18 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	850.77	853.83	852.68	-	-	852.43	0.18 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.063	1.067	1.065	-	-	1.065	0.18 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	94.01						
Mean yield load $F_{pf,exp,mean}$ [kN]	97.20						0.80 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	620.41						0.80 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	0.91	0.83	0.84	-	-	0.86	5.30 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	125.40						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	775.12	755.90	775.33	-	-	768.78	1.45 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	104.52	105.14	104.00	-	-	104.55	0.55 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	138.42	138.58	138.51	-	-	138.50	0.06 %
Maximum load F_{max} under 30° [kN]	130.83	135.88	132.64	-	-	133.12	1.92 %
Maximum load F_{max} under 45° [kN]	120.69	120.86	121.94	-	-	121.16	0.56 %
Maximum load F_{max} under 67.5° [kN]	104.52	105.14	104.00	-	-	104.55	0.55 %

D.1.20 EN ISO 4014 – C3 – M16×100 – A4-8.8

Table D.20: Specifications, geometrical parameters and tests results of EN ISO 4014 – C3 – M16×100 – A4-8.8

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 8.8	A4	EN ISO 4014	M16×100	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	197.62 mm²	0.43 %	10	156.67 mm²	152.44 mm²	0.31 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	125.40						
Ultimate tensile load $F_{mf,exp}$ [kN]	140.30	141.28	140.43	-	-	140.67	0.38 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	895.51	901.77	896.34	-	-	897.87	0.38 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.119	1.127	1.120	-	-	1.122	0.38 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	640 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	100.48 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	110.70						1.68 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	706.58						1.68 %
Nominal elongation at fracture A_{nom} [x·d]	0.30 (PC 80)						
Elongation at fracture A_{exp} [x·d]	1.13	1.11	1.14	-	-	1.13	1.34 %
Failure location	Shank	Shank	Shank	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	125.40						
$F_{bi,max,exp}$ [kN]	141.11	140.83	142.66	-	-	141.53	0.70 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	900.68	898.90	910.58	-	-	903.39	0.70 %
Failure location	Shank	Shank	Shank	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	709.95	714.91	710.61	-	-	711.82	0.38 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	1008.01	1002.40	999.01	-	-	1003.14	0.45 %
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	680.21	688.34	670.58	-	-	679.71	1.31 %
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	550.25	520.43	549.01	-	-	539.90	3.12 %
Elongation at fracture $A_{exp,6892-1}$ [%]	19.87	23.65	21.01	-	-	21.51	9.01 %

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	105.50	105.37	103.63	-	-	104.83	1.00 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	136.78	139.44	136.86	-	-	137.69	1.10 %
Maximum load F_{max} under 30° [kN]	128.85	128.89	127.47	-	-	128.40	0.63 %
Maximum load F_{max} under 45° [kN]	115.39	115.52	115.65	-	-	115.52	0.11 %
Maximum load F_{max} under 67.5° [kN]	103.65	103.74	104.07	-	-	103.90	0.22 %

D.1.21 EN ISO 4014 – C3 – M24×130 – A4-8.8

Table D.21: Specifications, geometrical parameters and tests results of EN ISO 4014 – C3 – M24×130 – A4-8.8

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 8.8	A4	EN ISO 4014	M24×130	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	452.39 mm²	444.60 mm²	0.21 %	10	352.49 mm²	342.36 mm²	0.53 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	282.10 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Ultimate tensile load $F_{mf,exp}$ [kN]	319.35	316.70	319.03	317.77	317.98	318.17	0.33 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	905.98	898.47	905.08	901.50	902.10	902.62	0.33 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.132	1.123	1.131	1.126	1.127	1.128	0.33 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	640 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	225.92 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	216.70 (but fulfil PC 80)						1.61 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	614.77 (but fulfil PC 80)						1.61 %
Nominal elongation at fracture A_{nom} [x·d]	0.30 (PC 80)						
Elongation at fracture A_{exp} [x·d]	0.98	0.98	0.98	1.01	0.98	0.99	1.34 %
Failure location	Shank	Shank	Shank	Shank	Shank	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	282.10						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	718.29	712.33	717.57	714.73	715.20	715.62	0.33 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	227.69	228.99	227.44	228.74	227.01	227.97	0.37 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	308.00	309.93	310.04	308.11	306.00	308.42	0.54 %
Maximum load F_{max} under 30° [kN]	269.24	268.21	269.79	267.58	269.71	268.91	0.36 %
Maximum load F_{max} under 45° [kN]	247.55	252.66	243.89	254.89	246.97	232.26	1.80 %
Maximum load F_{max} under 67.5° [kN]	232.59	232.86	232.35	231.68	231.82	232.26	0.22 %

D.1.22 EN ISO 4014 – C3 – M16×100 – A4-10.9

Table D.22: Specifications, geometrical parameters and tests results of EN ISO 4014 – C3 – M16×100 – A4-10.9

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 10.9	A4	EN ISO 4014	M16×100	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
6	201.06 mm²	196.85 mm²	0.04 %	6	156.67 mm²	151.85 mm²	0.43 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	1000 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	156.70 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Ultimate tensile load $F_{mf,exp}$ [kN]	187.13	187.00	186.80	-	-	186.98	0.09 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	1194.42	1193.59	1192.32	-	-	1193.44	0.09 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.194	1.193	1.192	-	-	1.193	0.09 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	141.30 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	145.70						1.10 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	929.98						1.10 %
Nominal elongation at fracture A_{nom} [x·d]	0.20 (PC 100)						
Elongation at fracture A_{exp} [x·d]	0.38	0.38	0.38	-	-	0.38	0.94 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	156.70						
$F_{bi,max,exp}$ [kN]	188.61	189.42	186.83	-	-	188.29	0.70 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	1203.87	1209.04	1192.51	-	-	1201.80	0.70 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	1045.12	1033.34	1035.81	-	-	1038.09	0.60 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	980.11	950.25	970.42	-	-	966.93	1.58 %
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	780.25	790.56	765.12	-	-	778.64	1.64 %
Elongation at fracture $A_{exp,6892-1}$ [%]	14.22	13.10	14.11	-	-	13.81	4.47 %

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	126.33	124.29	128.14	-	-	126.25	1.53 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	178.16	177.73	179.07	-	-	178.32	0.39 %
Maximum load F_{max} under 30° [kN]	157.17	155.91	156.57	-	-	156.55	0.40 %
Maximum load F_{max} under 45° [kN]	142.58	143.03	142.20	-	-	142.60	0.29 %
Maximum load F_{max} under 67.5° [kN]	128.60	128.06	127.07	-	-	127.91	0.60 %

D.1.23 EN ISO 4014 – C5 – M24×130 – D6-70

Table D.23: Specifications, geometrical parameters and tests results of EN ISO 4014 – C5 – M24×130 – D6-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 70	D6	EN ISO 4014	M24×130	C5	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	452.39 mm²	442.19 mm²	0.22 %	10	352.49 mm²	342.52 mm²	0.61 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	246.80						
Ultimate tensile load $F_{mf,exp}$ [kN]	280.06	279.85	278.74	282.43	279.39	280.09	0.50 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	794.52	793.92	790.77	801.24	792.62	794.62	0.50 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.135	1.134	1.129	1.144	1.132	1.135	0.50 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	158.70						
Mean yield load $F_{pf,exp,mean}$ [kN]	226.40						1.30 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	642.29						1.30 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	0.71	0.71	0.72	0.68	0.70	0.70	1.98 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	246.80						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	755.13	758.11	744.52	-	-	752.59	0.95 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	253.30	250.76	249.76	251.86	251.11	251.36	0.53 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	295.09	290.60	289.93	291.82	292.90	292.07	0.70 %
Maximum load F_{max} under 30° [kN]	295.80	294.09	298.22	301.04	295.23	296.88	0.93 %
Maximum load F_{max} under 45° [kN]	281.00	281.16	277.59	282.85	277.01	279.92	0.90 %
Maximum load F_{max} under 67.5° [kN]	254.47	251.14	250.71	254.83	254.91	253.21	0.83 %

D.1.24 EN ISO 4014 – C4 – M16×100 – D6-80

Table D.24: Specifications, geometrical parameters and tests results of EN ISO 4014 – C4 – M16×100 – D6-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 80	D6	EN ISO 4014	M16×100	C4	Cut

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
6	201.06 mm²	197.78 mm²	0.22 %	6	156.67 mm²	154.02 mm²	0.61 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	125.40						
Ultimate tensile load $F_{mf,exp}$ [kN]	141.13	142.16	140.36	-	-	141.22	0.64 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	900.81	907.38	895.90	-	-	901.36	0.64 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.125	1.134	1.119	-	-	1.126	0.64 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	94.01						
Mean yield load $F_{pf,exp,mean}$ [kN]	127.40						1.80 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	813.17						1.80 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	0.61	0.50	0.62	-	-		11.11 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	125.40						
$F_{bi,max,exp}$ [kN]	143.22	142.91	143.70	-	-	143.28	0.28 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	914.15	912.17	917.21	-	-	914.51	0.28 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	825.10	825.32	820.01	-	-	823.48	0.36 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	119.01	118.29	116.61	-	-	117.98	1.04 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	151.64	152.48	153.85	-	-	152.66	0.73 %
Maximum load F_{max} under 30° [kN]	144.76	145.11	145.05	-	-	144.97	0.13 %
Maximum load F_{max} under 45° [kN]	135.14	132.48	132.51	-	-	133.37	1.14 %
Maximum load F_{max} under 67.5° [kN]	118.25	119.41	117.83	-	-	118.50	0.69 %

D.1.25 EN ISO 4014 – C4 – M24×130 – D6-80

Table D.25: Specifications, geometrical parameters and tests results of EN ISO 4014 – C4 – M24×130 – D6-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 80	D6	EN ISO 4014	M24×130	C4	Cut

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
6	452.39 mm²	447.72 mm²	0.17 %	6	352.49 mm²	341.09 mm²	0.37 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	282.10						
Ultimate tensile load $F_{mf,exp}$ [kN]	299.97	292.96	300.74	-	-	297.89	1.44 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	851.00	831.12	853.19	-	-	845.10	1.44 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.063	1.038	1.066	-	-	1.056	1.44 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	211.60						
Mean yield load $F_{pf,exp,mean}$ [kN]	265.40						1.90 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	752.93						1.90 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	0.69	0.68	0.70	-	-	0.69	1.67 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	282.10						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	800.11	790.22	797.80	-	-	796.04	0.65 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	261.65	262.90	263.60	-	-	262.72	0.38 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	310.62	312.75	312.50	-	-	311.96	0.37 %
Maximum load F_{max} under 30° [kN]	300.10	298.78	298.41	-	-	299.10	0.30 %
Maximum load F_{max} under 45° [kN]	279.89	288.77	280.84	-	-	283.17	1.72 %
Maximum load F_{max} under 67.5° [kN]	260.43	261.95	261.50	-	-	261.29	0.30 %

D.1.26 EN ISO 4014 – C5 – M16×100 – D6-100

Table D.26: Specifications, geometrical parameters and tests results of EN ISO 4014 – C2 – M16×110 – A2-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 100	A4	EN ISO 4014	M16×100	C5	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
6	201.06 mm²	194.82 mm²	0.38 %	6	156.67 mm²	152.46 mm²	0.75 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	1000						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	156.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	174.51	173.33	174.24	174.50	174.32	174.18	0.28 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	1113.87	1106.34	1112.15	1113.81	1112.66	1111.76	0.28 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.114	1.106	1.112	1.114	1.112	1.112	0.28 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	800						
Nominal yield load $F_{pf,nom}$ [kN]	125.40						
Mean yield load $F_{pf,exp,mean}$ [kN]	140.70						2.03 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	898.07						2.03 %
Nominal elongation at fracture A_{nom} [x·d]	0.20						
Elongation at fracture A_{exp} [x·d]	0.59	0.59	0.60	0.61	0.52	0.58	6.60 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	156.70						
$F_{bi,max,exp}$ [kN]	175.61	176.82	177.80	177.64	176.88	176.95	0.49 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	1120.89	1128.61	1134.87	1133.85	1129.00	1129.44	0.49 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	850.12	880.15	898.70	-	-	876.32	2.80 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	123.74	122.64	125.28	122.66	123.21	123.51	0.88 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	164.91	165.28	164.87	165.96	166.27	165.46	0.38 %
Maximum load F_{max} under 30° [kN]	147.79	147.93	147.25	147.97	148.36	147.86	0.27 %
Maximum load F_{max} under 45° [kN]	136.11	137.27	136.83	135.73	136.37	136.46	0.44 %
Maximum load F_{max} under 67.5° [kN]	123.51	123.72	124.11	124.96	121.78	123.61	0.94 %

D.1.27 EN ISO 4014 – C3 – M16×100 – D8-10.9

Table D.27: Specifications, geometrical parameters and tests results of EN ISO 4014 – C3 – M16×100 – D8-10.9

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 10.9	D8	EN ISO 4014	M16×100	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
6	201.06 mm²	196.86 mm²	0.08 %	6	156.67 mm²	153.34 mm²	0.45 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	1000 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	156.70 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Ultimate tensile load $F_{mf,exp}$ [kN]	191.90	190.95	191.81	-	-	191.55	0.27 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	1224.87	1218.80	1224.29	-	-	1222.65	0.27 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.225	1.219	1.224	-	-		0.27 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	141.30 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	162.30						2.30 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	1035.94						2.30 %
Nominal elongation at fracture A_{nom} [x·d]	0.20 (PC 100)						
Elongation at fracture A_{exp} [x·d]	0.41	0.40	0.41	-	-	0.40	0.32 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	156.70						
$F_{bi,max,exp}$ [kN]	193.60	194.45	193.77	-	-	193.94	0.23 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	1235.72	1241.14	1236.80	-	-	1237.89	0.23 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	1025.11	1050.12	1018.31	-	-	1031.18	1.62 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	1010.31	980.55	976.14	-	-	989.00	1.88 %
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	823.26	833.45	825.45	-	-	827.33	0.65 %
Elongation at fracture $A_{exp,6892-1}$ [%]	11.65	11.12	9.16	-	-	10.64	12.32 %

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	134.55	136.66	135.88	-	-	135.70	0.79 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	185.37	183.36	183.20	-	-	183.98	0.66 %
Maximum load F_{max} under 30° [kN]	161.45	163.21	160.45	-	-	161.70	0.86 %
Maximum load F_{max} under 45° [kN]	147.29	147.48	146.53	-	-	147.10	0.34 %
Maximum load F_{max} under 67.5° [kN]	130.92	131.98	130.76	-	-	131.22	0.50 %

D.1.28 EN ISO 4762 – C3 – M16×100 – D8-10.9

Table D.28: Specifications, geometrical parameters and tests results of EN ISO 4762 – C3 – M16×100 – D8-10.9

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 10.9	D8	EN ISO 4762	M16×100	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
6	201.06 mm²	196.94 mm²	0.22 %	6	156.67 mm²	152.99 mm²	0.47 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	1000 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	156.70 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Ultimate tensile load $F_{mf,exp}$ [kN]	191.69	192.63	192.90	-	-	192.41	0.33 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	1223.53	1229.53	1231.25	-	-	1228.10	0.33 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.223	1.229	1.231	-	-	1.228	0.33 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	141.30 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	163.00						1.70 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	1040.40						1.70 %
Nominal elongation at fracture A_{nom} [x·d]	0.20 (PC 100)						
Elongation at fracture A_{exp} [x·d]	0.38	0.42	0.42	-	-	0.40	5.69 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	156.70						
$F_{bi,max,exp}$ [kN]	191.52	190.90	192.85	-	-	191.76	0.52 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	1222.44	1218.48	1230.93	-	-	1223.95	0.52 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	1002.11	1050.54	1033.20	-	-	1028.51	2.39 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	139.19	138.38	136.99	-	-	138.18	0.81 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	182.82	182.86	180.90	-	-	182.19	0.61 %
Maximum load F_{max} under 30° [kN]	160.91	158.03	160.11	-	-	159.68	0.93 %
Maximum load F_{max} under 45° [kN]	144.01	146.67	146.26	-	-	145.65	0.98 %
Maximum load F_{max} under 67.5° [kN]	139.19	138.38	136.99	-	-	138.18	0.81 %

D.1.29 EN ISO 4762 – C3 – M16×100 – D6-12.9

Table D.29: Specifications, geometrical parameters and tests results of EN ISO 4762 – C3 – M16×100 – D6-12.9

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 12.9	D6	EN ISO 4762	M16×100	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
6	201.06 mm²	198.15 mm²	0.18 %	6	156.67 mm²	150.85 mm²	0.51 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	1200 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	192.00 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Ultimate tensile load $F_{mf,exp}$ [kN]	207.64	207.31	207.54	-	-	207.50	0.08 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	1325.33	1323.23	1324.70	-	-	1324.42	0.08 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.081	1.080	1.081	-	-	1.081	0.08 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	1080 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	169.56 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	196.20						0.90 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	1252.31						0.90 %
Nominal elongation at fracture A_{nom} [x·d]	- (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Elongation at fracture A_{exp} [x·d]	0.41	0.40	0.42	-	-	0.41	1.70 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	192.00						
$F_{bi,max,exp}$ [kN]	206.81	205.62	208.66	-	-	207.03	0.74 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	1320.04	1312.44	1331.84	-	-	1321.44	0.74 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	1144.22	1135.11	1190.31	-	-	1156.55	2.56 %
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	152.25	152.77	151.34	-	-	152.12	0.47 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	198.56	198.51	199.86	-	-	198.97	0.38 %
Maximum load F_{max} under 30° [kN]	179.86	176.89	176.71	-	-	177.82	1.00 %
Maximum load F_{max} under 45° [kN]	156.73	161.18	162.24	-	-	160.05	1.83 %
Maximum load F_{max} under 67.5° [kN]	147.29	152.77	151.34	-	-	152.12	0.47 %

D.2 Summary of tested fully threaded stainless steel bolts with threaded bolt part in the shear plane at UDE-IML

D.2.1 General

Subsequently, all experimental investigations conducted in the German IGF research project FOSTA P 1386 / IGF-No. 20651 N and as supplementary investigations within this thesis on fully threaded stainless steel bolts with threaded part in the shear plane are summarised.

Table D.30: Summary of tested fully threaded stainless steel bolts with threaded bolt part in the shear plane at UDE-IML

Fully threaded stainless steel bolts with unthreaded bolt part in the shear plane											
Steel type	**Property class acc. to EN ISO 3506-1**	**Corrosion class acc. to EN ISO 3506-1**	**Manufacturer or trader**	**Thread production type**	**Bolt type**	**Bolt geometry**	**Number of tensile tests**	**Number of single-shear tests**	**Number of double-shear tests**	**Number of interaction tests**	**Series designation**
Austenitic	**PC 50**	A4-50	C4	Cut	EN ISO 4017	M16×100	3	3	-	12	EN ISO 4017 – C4 – M16×100 – A4-50
				Cut	EN ISO 4017	M24×130	3	3	-	12	EN ISO 4017 – C4 – M24×130 – A4-50
	PC 70	A2-70	C1	Rolled	EN ISO 4017	M16×100	5	5	-	20	EN ISO 4017 – C1 – M16×100 – A2-70
				Rolled	EN ISO 4017	M24×130	5	5	-	20	EN ISO 4017 – C1 – M24×130 – A2-70
			C6	Rolled	EN ISO 4017	M16×100	5	5	-	12	EN ISO 4017 – C6 – M16×100 – A2-70
		A4-70	C2	Rolled	EN ISO 4017	M16×100	5	5	8	20	EN ISO 4017 – C2 – M16×100 – A4-70
				Rolled	EN ISO 4017	M24×130	5	5	-	20	EN ISO 4017 – C2 – M24×130 – A4-70
			C6	Rolled	EN ISO 4017	M16×100	5	5	-	12	EN ISO 4017 – C6 – M16×100 – A4-70
		A8-70	C4	Cut	EN ISO 4017	M16×100	3	3	-	12	EN ISO 4017 – C4 – M16×100 – A8-70
	PC 80	A4-80	C2	Rolled	EN ISO 4017	M16×100	5	5	8	20	EN ISO 4017 – C2 – M16×100 – A4-80
				Rolled	EN ISO 4017	M24×130	5	5	-	20	EN ISO 4017 – C2 – M24×130 – A4-80
			C6	Rolled	EN ISO 4017	M16×100	5	5	-	12	EN ISO 4017 – C6 – M16×100 – A4-80
	PC 8.8	A4-8.8	C3	Rolled	EN ISO 4017	M16×100	5	5	16	20	EN ISO 4017 – C3 – M16×100 – A4-8.8
				Rolled	EN ISO 4017	M24×120	5	5	-	20	EN ISO 4017 – C3 – M24×120 – A4-8.8
	PC 10.9	A4-10.9		Rolled	EN ISO 4017	M16×100	5	5	16	20	EN ISO 4017 – C3 – M16×100 – A4-10.9
Duplex	**PC 70**	D6-70	C4	Cut	EN ISO 4017	M16×100	3	3	-	12	EN ISO 4017 – C4 – M16×100 – D6-70
				Cut	EN ISO 4017	M24×130	3	3	-	12	EN ISO 4017 – C4 – M24×130 – D6-70
	PC 10.9	D4-10.9	C3	Rolled	EN ISO 4017	M16×100	5	5	16	20	EN ISO 4017 – C3 – M16×100 – D4-10.9
		D6-10.9		Rolled	EN ISO 4017	M16×100	5	5	16	20	EN ISO 4017 – C3 – M16×100 – D6-10.9
		D8-10.9		Rolled	EN ISO 4017	M16×100	5	5	16	12	EN ISO 4017 – C3 – M16×100 – D8-10.9

D.2.2 EN ISO 4017 – C4 – M16×100 – A4-50

Table D.31: Specifications, geometrical parameters and tests results of EN ISO 4017 – C4 – M16×100 – A4-50

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 50	A4	EN ISO 4017	M16×100	C4	Cut

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	6	156.67 mm²	150.30 mm²	0.16 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	500						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	78.34						
Ultimate tensile load $F_{mf,exp}$ [kN]	85.44	85.14	84.83	-	-	85.14	0.36 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	545.35	543.44	541.46	-	-	543.41	0.36 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.091	1.087	1.083	-	-	1.087	0.36 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	210						
Nominal yield load $F_{pf,nom}$ [kN]	32.91						
Mean yield load $F_{pf,exp,mean}$ [kN]	53.51						2.31 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	341.55						2.31 %
Nominal elongation at fracture A_{nom} [x·d]	0.60						
Elongation at fracture A_{exp} [x·d]	1.17	1.21	1.22	-	-	1.20	2.15 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	78.34						
$F_{bi,max,exp}$ [kN]	86.71	87.12	86.42	-	-	86.75	0.41 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	553.46	556.07	551.61	-	-	553.71	0.41 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	69.64	70.71	71.23	-	-	70.53	1.15 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	86.88	87.29	87.00	-	-	87.06	0.24 %
Maximum load F_{max} under 30° [kN]	85.63	85.22	85.25	-	-	85.37	0.27 %
Maximum load F_{max} under 45° [kN]	81.31	81.77	80.44	-	-	81.17	0.83 %
Maximum load F_{max} under 67.5° [kN]	70.75	70.01	71.77	-	-	70.84	1.25 %

D.2.3 EN ISO 4017 – C4 – M24×130 – A4-50

Table D.32: Specifications, geometrical parameters and tests results of EN ISO 4017 – C4 – M24×130 – A4-50

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 50	A4	EN ISO 4017	M24×130	C4	Cut

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	6	352.49 mm²	342.48 mm²	0.22 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	500						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	176.30						
Ultimate tensile load $F_{mf,exp}$ [kN]	202.97	204.78	201.88	-	-	203.21	0.72 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	575.82	580.95	572.73	-	-	576.50	0.72 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.151	1.162	1.145	-	-	1.153	0.72 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	210						
Nominal yield load $F_{pf,nom}$ [kN]	74.03						
Mean yield load $F_{pf,exp,mean}$ [kN]	134.60						2.70 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	381.85						2.70 %
Nominal elongation at fracture A_{nom} [x·d]	0.60						
Elongation at fracture A_{exp} [x·d]	0.77	0.73	0.74	-	-	0.75	2.76 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	176.30						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	175.45	174.95	173.80	-	-	174.74	0.49 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	219.11	217.25	221.39	-	-	219.25	0.95 %
Maximum load F_{max} under 30° [kN]	211.41	213.04	215.58	-	-	213.34	0.98 %
Maximum load F_{max} under 45° [kN]	194.49	203.38	200.15	-	-	199.34	2.26 %
Maximum load F_{max} under 67.5° [kN]	170.22	176.08	171.55	-	-	172.65	1.76 %

D.2.4 EN ISO 4017 – C1 – M16×100 – A2-70

Table D.33: Specifications, geometrical parameters and tests results of EN ISO 4017 – C1 – M16×100 – A2-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A2	EN ISO 4017	M16×100	C4	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.51 mm²	0.49 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	119.18	118.57	119.34	119.04	118.78	118.98	0.26 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	760.71	756.81	761.73	759.81	758.15	759.44	0.26 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.086	1.081	1.088	1.085	1.083	1.085	0.26 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	92.80						3.10 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	592.33						3.10 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.35	1.30	1.50	1.49	1.33	1.39	6.71 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	119.81	120.72	121.82	122.93	123.11	121.68	1.17 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	1.092	1.100	1.100	1.121	1.122	1.109	1.17 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	94.71	87.54	86.53	92.16	89.18	90.03	3.75 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	119.24	118.11	119.81	119.29	120.32	119.36	0.69 %
Maximum load F_{max} under 30° [kN]	114.32	115.29	115.93	115.90	116.91	115.67	0.82 %
Maximum load F_{max} under 45° [kN]	104.30	104.78	101.60	102.84	101.20	102.94	1.54 %
Maximum load F_{max} under 67.5° [kN]	87.75	87.69	86.68	87.22	84.38	86.74	1.60 %

D.2.5 EN ISO 4017 – C1 – M24×130 – A2-70

Table D.34: Specifications, geometrical parameters and tests results of EN ISO 4017 – C1 – M24×130 – A2-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A2	EN ISO 4017	M24×130	C1	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	352.49 mm²	345.37 mm²	0.27 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	246.80						
Ultimate tensile load $F_{mf,exp}$ [kN]	250.39	249.54	253.52	249.15	249.03	250.33	0.74 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	710.35	707.93	719.23	706.83	706.49	710.16	0.74 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.015	1.011	1.027	1.010	1.009	1.014	0.74 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	158.70						
Mean yield load $F_{pf,exp,mean}$ [kN]	192.01						1.90 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	544.72						1.90 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.19	1.24	1.15	1.22	1.23	1.21	2.71 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	246.80						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	188.31	189.79	183.00	192.87	193.13	189.42	2.18 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	261.92	254.93	255.22	260.25	259.59	258.38	1.21 %
Maximum load F_{max} under 30° [kN]	250.73	246.66	253.25	243.00	247.08	248.15	1.59 %
Maximum load F_{max} under 45° [kN]	235.23	232.04	226.48	232.88	223.33	229.99	2.14 %
Maximum load F_{max} under 67.5° [kN]	183.40	189.87	182.20	191.19	190.56	187.45	2.29 %

D.2.6 EN ISO 4017 – C6 – M16×100 – A2-70

Table D.35: Specifications, geometrical parameters and tests results of EN ISO 4017 – C6 – M16×100 – A2-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A2	EN ISO 4017	M16×100	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.11 mm²	0.51 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	115.60	116.03	116.26	115.58	115.74	115.84	0.25 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	737.86	740.60	742.07	737.73	738.75	739.40	0.25 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.054	1.058	1.060	1.054	1.055	1.056	0.25 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	88.30						2.20 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	563.61						2.20 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	0.87	0.87	0.91	1.00	0.97	0.92	6.23 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	86.74	89.21	86.18	89.57	85.67	87.47	2.05 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	120.08	122.10	120.51	-	-	120.90	0.88 %
Maximum load F_{max} under 30° [kN]	116.54	115.80	115.88	-	-	116.07	0.35 %
Maximum load F_{max} under 45° [kN]	104.38	103.60	105.40	-	-	104.46	0.87 %
Maximum load F_{max} under 67.5° [kN]	85.90	86.42	85.91	-	-	86.08	0.35 %

D.2.7 EN ISO 4017 – C2 – M16×100 – A4-70

Table D.36: Specifications, geometrical parameters and tests results of EN ISO 4017 – C2 – M16×100 – A4-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A4	EN ISO 4017	M16×100	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.23 mm²	0.44 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	112.17	111.99	110.31	111.95	112.03	111.69	0.69 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	715.96	714.81	704.09	714.56	715.07	712.90	0.69 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.023	1.021	1.006	1.021	1.021	1.018	0.69 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	79.30						2.90 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	506.16						2.90 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.23	1.21	1.30	1.24	1.26	1.25	2.81 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	110.51	110.90	112.32	109.52	108.90	110.43	1.20 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	705.37	707.86	716.92	699.05	695.09	704.86	1.20 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	74.32	72.15	71.28	-	-	72.58	2.16 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	78.60	74.78	76.20	78.45	75.57	76.72	2.25 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	79.85	80.56	79.81	79.30	81.25	80.15	0.95 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	104.26	106.08	105.69	105.94	105.03	105.40	0.72 %
Maximum load F_{max} under 30° [kN]	100.79	100.19	101.97	99.97	102.19	101.02	1.01 %
Maximum load F_{max} under 45° [kN]	93.58	92.29	91.99	93.33	94.36	93.11	1.04 %
Maximum load F_{max} under 67.5° [kN]	78.60	74.78	76.20	78.45	75.57	76.72	1.04 %

D.2.8 EN ISO 4017 – C2 – M24×130 – A4-70

Table D.37: Specifications, geometrical parameters and tests results of EN ISO 4017 – C2 – M24×130 – A4-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A4	EN ISO 4017	M24×130	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	352.49 mm²	345.94 mm²	0.57 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	246.80						
Ultimate tensile load $F_{mf,exp}$ [kN]	252.85	250.65	246.83	247.72	252.13	250.04	1.06 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	717.33	711.08	700.25	702.77	715.28	709.34	1.06 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.025	1.016	1.000	1.004	1.022	1.013	1.06 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	158.70						
Mean yield load $F_{pf,exp,mean}$ [kN]	198.30						1.10 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	562.57						1.10 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	0.99	1.02	1.06	1.03	0.98	1.01	3.00 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	246.80						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	178.64	175.42	177.66	175.03	182.82	177.91	1.76 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	251.22	251.75	250.90	253.79	251.31	251.80	0.46 %
Maximum load F_{max} under 30° [kN]	242.51	241.81	241.62	238.46	241.77	241.24	0.66 %
Maximum load F_{max} under 45° [kN]	223.99	224.39	221.26	224.00	222.79	223.28	0.57 %
Maximum load F_{max} under 67.5° [kN]	183.18	181.91	180.50	179.99	183.50	183.50	0.86 %

D.2.9 EN ISO 4017 – C6 – M16×100 – A4-70

Table D.38: Specifications, geometrical parameters and tests results of EN ISO 4017 – C6 – M16×100 – A4-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A4	EN ISO 4017	M16×100	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.58 mm²	0.49 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	112.11	110.66	113.19	114.64	113.61	112.84	1.35 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	715.58	706.33	722.47	731.73	725.15	720.25	1.35 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.022	1.009	1.032	1.045	1.036	1.029	1.35 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	82.80						1.33 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	528.50						1.33 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.34	1.39	1.38	1.35	1.48	1.39	4.10 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	112.91	113.83	114.11	114.52	112.82	113.64	0.66 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	720.69	726.56	728.35	730.96	720.11	725.33	0.66 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	82.36	83.87	78.77	79.80	84.41	81.84	3.03 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	109.71	109.75	107.78	-	-	109.08	1.03 %
Maximum load F_{max} under 30° [kN]	104.23	104.32	103.74	-	-	104.10	0.30 %
Maximum load F_{max} under 45° [kN]	98.03	97.52	97.04	-	-	97.53	0.51 %
Maximum load F_{max} under 67.5° [kN]	81.50	83.55	82.01	-	-	82.35	1.30 %

D.2.10 EN ISO 4017 – C4 – M16×100 – A8-70

Table D.39: Specifications, geometrical parameters and tests results of EN ISO 4017 – C4 – M16×100 – A8-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 70	A8	EN ISO 4017	M16×100	C4	Cut

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	6	156.67 mm²	150.79 mm²	0.53 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	109.93	112.05	109.23	-	-	110.40	1.33 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	701.67	715.20	697.20	-	-	704.69	1.33 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.002	1.021	0.996	-	-	1.006	1.33 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	83.60						2.40 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	533.61						2.40 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	1.04	0.97	1.05	-	-	1.02	4.37 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	82.63	82.76	82.36	-	-	82.58	0.24 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	113.45	114.51	115.20	-	-	114.39	0.77 %
Maximum load F_{max} under 30° [kN]	105.41	104.51	107.16	-	-	105.70	1.28 %
Maximum load F_{max} under 45° [kN]	98.79	96.37	97.64	-	-	97.60	1.24 %
Maximum load F_{max} under 67.5° [kN]	80.64	79.52	83.44	-	-	81.20	2.49 %

D.2.11 EN ISO 4017 – C2 – M16×100 – A4-80

Table D.40: Specifications, geometrical parameters and tests results of EN ISO 4017 – C2 – M16×100 – A4-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 80	A4	EN ISO 4017	M16×100	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.35 mm²	0.44 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	125.40						
Ultimate tensile load $F_{mf,exp}$ [kN]	129.29	130.01	129.67	130.32	130.23	129.90	0.33 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	825.24	829.83	827.66	831.81	831.24	829.16	0.33 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.031	1.037	1.034	1.039	1.039	1.036	0.33 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	94.01						
Mean yield load $F_{pf,exp,mean}$ [kN]	111.50						2.31 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	711.69						2.31 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	1.04	0.97	1.05	1.05	1.05	1.03	3.40 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	125.40						
$F_{bi,max,exp}$ [kN]	130.81	132.82	129.80	133.44	132.77	131.93	1.17 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	834.94	847.77	828.49	851.73	847.45	842.08	1.17 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	85.54	87.87	86.56	-	-	86.66	1.35 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	86.55	93.09	89.72	92.24	92.16	90.76	2.94 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	90.89	93.56	90.25	92.26	93.54	92.10	1.64 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	123.85	123.36	123.40	124.42	123.55	123.72	0.35 %
Maximum load F_{max} under 30° [kN]	113.32	114.29	113.09	113.23	113.84	113.56	0.44 %
Maximum load F_{max} under 45° [kN]	100.25	101.61	101.40	102.16	103.77	101.84	1.26 %
Maximum load F_{max} under 67.5° [kN]	84.54	84.64	83.61	82.96	86.90	84.53	1.76 %

D.2.12 EN ISO 4017 – C2 – M24×130 – A4-80

Table D.41: Specifications, geometrical parameters and tests results of EN ISO 4017 – C2 – M24×130 – A4-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 80	A4	EN ISO 4017	M24×130	C2	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	352.49 mm²	345.11 mm²	0.22 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	282.10						
Ultimate tensile load $F_{mf,exp}$ [kN]	328.67	324.29	326.75	325.55	325.97	326.25	0.50 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	932.42	920.00	926.98	923.57	924.76	925.55	0.50 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.165	1.150	1.158	1.154	1.156	1.156	0.50 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	211.60						
Mean yield load $F_{pf,exp,mean}$ [kN]	261.80						1.70 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	742.72						1.70 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	0.61	0.60	0.57	0.59	0.59	0.59	2.09 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	282.10						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	217.85	211.52	221.84	211.27	218.01	216.10	2.12 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	297.97	298.93	295.27	298.57	292.86	296.72	0.87 %
Maximum load F_{max} under 30° [kN]	269.34	265.93	270.34	269.75	269.45	268.97	0.65 %
Maximum load F_{max} under 45° [kN]	221.98	225.11	224.72	223.20	220.13	223.03	0.92 %
Maximum load F_{max} under 67.5° [kN]	203.40	208.70	200.51	205.24	194.87	202.54	2.58 %

D.2.13 EN ISO 4017 – C6 – M16×100 – A4-80

Table D.42: Specifications, geometrical parameters and tests results of EN ISO 4017 – C6 – M10×100 – A4-80

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 80	A4	EN ISO 4017	M16×100	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.21 mm²	0.41 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	125.40						
Ultimate tensile load $F_{mf,exp}$ [kN]	131.68	131.44	131.17	131.06	132.27	131.52	0.37 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	840.49	838.96	837.24	836.54	844.26	839.50	0.37 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.050	1.048	1.046	1.045	1.055	1.049	0.37 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	600						
Nominal yield load $F_{pf,nom}$ [kN]	94.01						
Mean yield load $F_{pf,exp,mean}$ [kN]	108.20						1.80 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	690.62						1.80 %
Nominal elongation at fracture A_{nom} [x·d]	0.30						
Elongation at fracture A_{exp} [x·d]	0.50	0.46	0.47	0.49	0.46	0.48	3.68 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	125.40						
$F_{bi,max,exp}$ [kN]	132.80	134.44	134.72	130.25	131.80	132.80	1.40 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	847.64	858.11	859.90	831.37	841.26	847.65	1.40 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	86.46	82.84	89.64	91.23	86.40	87.32	3.73 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	123.14	124.17	122.58	-	-	123.30	0.65 %
Maximum load F_{max} under 30° [kN]	114.22	115.22	114.58	-	-	114.67	0.44 %
Maximum load F_{max} under 45° [kN]	102.37	103.35	100.94	-	-	102.22	1.18 %
Maximum load F_{max} under 67.5° [kN]	89.54	86.55	88.32	-	-	88.14	1.71 %

D.2.14 EN ISO 4017 – C3 – M16×100 – A4-8.8

Table D.43: Specifications, geometrical parameters and tests results of EN ISO 4014 – C4 – M24×130 – A4-50

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 8.8	A4	EN ISO 4017	M16×100	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.16 mm²	0.27 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	125.40						
Ultimate tensile load $F_{mf,exp}$ [kN]	154.50	154.50	154.10	154.58	153.61	154.26	0.26 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	986.15	986.15	983.60	986.66	980.47	984.60	0.26 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.232	1.232	1.229	1.233	1.225	1.230	0.26 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	640 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	100.48 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	128.50						2.60 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	820.20						2.60 %
Nominal elongation at fracture A_{nom} [x·d]	0.30 (PC 80)						
Elongation at fracture A_{exp} [x·d]	0.50	0.47	0.49	0.51	0.50	0.49	3.30 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	125.40						
$F_{bi,max,exp}$ [kN]	155.71	156.82	154.10	153.95	154.73	155.06	0.78 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	993.87	1000.96	983.60	982.64	987.62	989.74	0.78 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	907.62	892.62	877.34	-	-	892.53	1.70 %
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	748.54	740.56	742.23	-	-	743.78	0.57 %
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	18.12	17.70	16.43	-	-	17.40	5.05 %

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	94.11	93.12	92.99	-	-	93.41	0.66 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	94.82	92.47	96.78	-	-	94.69	2.28 %
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	91.81	95.31	98.03	99.05	93.97	95.63	3.09 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	96.95	97.07	93.91	95.18	96.73	95.97	1.44 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	99.40	95.35	95.22	99.13	98.78	97.57	2.15 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	131.84	132.65	133.48	133.64	135.48	133.42	1.02 %
Maximum load F_{max} under 30° [kN]	123.08	122.83	122.61	122.55	123.24	122.86	0.24 %
Maximum load F_{max} under 45° [kN]	107.90	107.31	109.00	108.89	107.31	108.08	0.76 %
Maximum load F_{max} under 67.5° [kN]	88.96	93.40	90.36	91.96	93.10	91.56	2.05 %

D.2.15 EN ISO 4017 – C3 – M24×120 – A4-8.8

Table D.44: Specifications, geometrical parameters and tests results of EN ISO 4017 – C3 – M24×120 – A4-8.8

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 8.8	A4	EN ISO 4017	M24×120	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	352.49 mm²	345.01 mm²	0.39 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	800 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	282.10 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Ultimate tensile load $F_{mf,exp}$ [kN]	335.00	335.81	334.71	335.52	334.96	335.20	0.13 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	950.38	952.68	949.56	951.86	950.27	950.95	0.13 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.188	1.190	1.186	1.189	1.187	1.188	0.13 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	640 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	225.92 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	295.70						2.10 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	838.89						2.10 %
Nominal elongation at fracture A_{nom} [x·d]	0.30 (PC 80)						
Elongation at fracture A_{exp} [x·d]	0.53	0.52	0.52	0.48	0.46	0.50	5.74 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	282.10						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	204.53	205.10	203.86	205.96	206.85	205.26	0.57 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	305.06	303.78	304.00	301.75	301.50	303.22	0.51 %
Maximum load F_{max} under 30° [kN]	273.42	273.28	269.58	268.49	271.20	271.19	0.81 %
Maximum load F_{max} under 45° [kN]	246.49	246.64	247.14	246.12	245.87	246.45	0.20 %
Maximum load F_{max} under 67.5° [kN]	206.82	207.78	217.01	215.76	213.77	212.23	2.19 %

D.2.16 EN ISO 4017 – C3 – M16×100 – A4-10.9

Table D.45: Specifications, geometrical parameters and tests results of EN ISO 4017 – C3 – M16×100 – A4-10.9

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Austenitic	PC 10.9	A4	EN ISO 4017	M16×100	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.33 mm²	0.28 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	1000 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	156.70 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Ultimate tensile load $F_{mf,exp}$ [kN]	185.10	183.60	184.40	184.27	185.59	184.59	0.42 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	1181.46	1171.89	1177.00	1176.17	1184.59	1178.22	0.42 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.181	1.172	1.177	1.176	1.184	1.178	0.42 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	141.30 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	155.40						1.30 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	991.89						1.30 %
Nominal elongation at fracture A_{nom} [x·d]	0.20 (PC 100)						
Elongation at fracture A_{exp} [x·d]	0.43	0.41	0.41	0.43	0.43	0.42	2.59 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	156.70						
$F_{bi,max,exp}$ [kN]	185.60	186.00	184.99	183.25	183.45	184.59	0.68 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	1184.66	1187.21	1180.76	1169.66	1170.93	1178.64	0.68 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	1158.01	1168.61	1138.17	-	-	1154.93	1.34 %
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	920.31	910.20	903.40	-	-	911.30	0.93 %
Elongation at fracture $A_{exp,6892-1}$ [%]	12.54	14.55	11.30	-	-	12.80	12.82 %

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	101.23	102.35	101.22	-	-	101.60	0.64 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	99.00	99.50	103.54	-	-	100.68	2.47 %
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	105.21	105.33	108.50	107.25	109.11	107.08	1.66 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	108.12	108.65	105.98	106.68	108.75	107.64	1.15 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	110.59	108.02	105.64	109.83	110.62	108.94	1.95 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	161.56	160.98	161.79	161.26	156.88	160.49	1.27 %
Maximum load F_{max} under 30° [kN]	138.03	137.35	138.53	137.36	138.19	137.89	0.38 %
Maximum load F_{max} under 45° [kN]	118.07	119.83	117.86	118.39	120.79	118.99	1.07 %
Maximum load F_{max} under 67.5° [kN]	100.12	99.05	101.71	101.16	101.24	100.66	1.06 %

D.2.17 EN ISO 4017 – C4 – M16×100 – D6-70

Table D.46: Specifications, geometrical parameters and tests results of EN ISO 4017 – C4 – M16×100 – D6-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 70	D6	EN ISO 4017	M16×100	C4	Cut

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	6	156.67 mm²	149.15 mm²	0.22 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	109.70						
Ultimate tensile load $F_{mf,exp}$ [kN]	122.00	118.09	118.82	-	-	119.64	1.74 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	778.71	753.75	758.41	-	-	763.62	1.74 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.112	1.076	1.083	-	-	1.091	1.74 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	70.51						
Mean yield load $F_{pf,exp,mean}$ [kN]	94.00						3.30 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	599.99						3.30 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	0.84	0.95	0.66	-	-	0.82	18.08 %
Failure location	Threads	Threads	Threads	-	-s	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	109.70						
$F_{bi,max,exp}$ [kN]	120.21	121.73	119.80	-	-	120.58	0.84 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	767.28	776.98	764.66	-	-	769.64	0.84 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	86.57	92.47	89.94	-	-	89.66	3.31 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	121.67	122.58	121.47	-	-	121.91	0.48 %
Maximum load F_{max} under 30° [kN]	113.64	113.11	111.58	-	-	112.78	0.95 %
Maximum load F_{max} under 45° [kN]	104.26	103.33	103.46	-	-	103.69	0.48 %
Maximum load F_{max} under 67.5° [kN]	88.21	92.47	89.94	-	-	88.80	0.66 %

D.2.18 EN ISO 4017 – C4 – M24×130 – D6-70

Table D.47: Specifications, geometrical parameters and tests results of EN ISO 4017 – C4 – M24×130 – D6-70

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 70	D6	EN ISO 4017	M24×130	C4	Cut

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	6	352.49 mm²	343.59 mm²	0.51 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	700						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	246.80						
Ultimate tensile load $F_{mf,exp}$ [kN]	273.82	270.54	273.23	-	-	272.53	0.64 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506\text{-}1}$ [N/mm²]	776.82	767.51	775.14	-	-	773.16	0.64 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.109	1.096	1.107	-	-	1.104	0.64 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	450						
Nominal yield load $F_{pf,nom}$ [kN]	158.70						
Mean yield load $F_{pf,exp,mean}$ [kN]	191.30						1.40 %
Mean yield strength $f_{yb,exp,mean,3506\text{-}1}$ [N/mm²]	542.71						1.40 %
Nominal elongation at fracture A_{nom} [x·d]	0.40						
Elongation at fracture A_{exp} [x·d]	0.94	0.92	0.92	-	-	1.104	0.64 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	246.80						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	200.47	211.76	196.88	-	-	203.04	3.83 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	-	-	-	-	-	-	-

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	273.60	274.71	272.17	-	-	273.49	0.47 %
Maximum load F_{max} under 30° [kN]	255.11	253.55	255.50	-	-	254.72	0.41 %
Maximum load F_{max} under 45° [kN]	236.99	231.46	233.27	-	-	233.91	1.21 %
Maximum load F_{max} under 67.5° [kN]	206.82	200.78	208.13	-	-	205.24	1.91 %

D.2.19 EN ISO 4017 – C3 – M16×100 – D4-10.9

Table D.48: Specifications, geometrical parameters and tests results of EN ISO 4017 – C3 – M16×100 – D4-10.9

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 10.9	D4	EN ISO 4017	M16×100	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.04 mm²	0.40 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	1000 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	156.70 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Ultimate tensile load $F_{mf,exp}$ [kN]	174.20	173.40	173.50	173.20	173.91	173.64	0.23 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	1111.89	1106.78	1107.42	1105.51	1110.04	1108.33	0.23 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.112	1.107	1.107	1.105	1.110	1.108	0.23 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	141.30 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	137.70 (but fulfil PC 100)						1.10 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	878.92 (but fulfil PC 100)						1.10 %
Nominal elongation at fracture A_{nom} [x·d]	0.20 (PC 100)						
Elongation at fracture A_{exp} [x·d]	0.55	0.56	0.55	0.54	0.57	0.55	2.16 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	156.70						
$F_{bi,max,exp}$ [kN]	174.51	173.80	176.73	173.22	174.50	174.55	0.76 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	1113.87	1109.34	1128.04	1105.64	1113.81	1114.14	0.76 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	1077.44	1065.59	1078.40	-	-	1073.81	0.66 %
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	799.23	850.20	761.98	-	-	803.80	5.51 %
Elongation at fracture $A_{exp,6892-1}$ [%]	17.90	16.01	14.09	-	-	16.00 %	11.91 %

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	102.55	103.45	105.55	-	-	103.85	1.48 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	103.55	103.55	105.50	-	-	104.20	1.08 %
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	107.58	102.17	107.59	104.70	101.30	104.67	2.81 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	106.96	103.89	105.78	105.66	106.95	105.85	1.19 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	110.40	109.34	102.59	107.65	106.65	107.30	2.82 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	154.95	153.61	154.65	156.50	153.40	154.62	0.80 %
Maximum load F_{max} under 30° [kN]	138.63	140.42	140.82	138.39	138.73	139.40	0.81 %
Maximum load F_{max} under 45° [kN]	121.62	123.10	120.75	121.76	119.99	121.45	0.96 %
Maximum load F_{max} under 67.5° [kN]	102.88	103.33	103.17	100.94	100.28	102.12	1.38 %

D.2.20 EN ISO 4017 – C3 – M16×100 – D6-10.9

Table D.49: Specifications, geometrical parameters and tests results of EN ISO 4017 – C3 – M16×100 – D6-10.9

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 10.9	D6	EN ISO 4017	M16×100	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.35 mm²	0.44 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	1000 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	156.70 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Ultimate tensile load $F_{mf,exp}$ [kN]	177.90	176.50	177.50	178.01	177.74	177.53	0.34 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	1135.51	1126.57	1132.95	1136.21	1134.49	1133.15	0.34 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.135	1.126	1.133	1.136	1.134	1.133	0.34 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	141.30 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	143.10						2.00 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	913.38						2.00 %
Nominal elongation at fracture A_{nom} [x·d]	0.20 (PC 100)						
Elongation at fracture A_{exp} [x·d]	0.54	0.54	0.55	0.54	0.55	0.54	1.17 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	156.70						
$F_{bi,max,exp}$ [kN]	178.50	179.10	177.22	176.55	177.91	177.86	0.57 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	1139.34	1143.17	1131.17	1126.89	1135.57	1135.23	0.57 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	1086.66	1088.28	1091.68	-	-	1088.88	0.24 %
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	860.66	850.50	855.95	-	-	855.70	0.59 %
Elongation at fracture $A_{exp,6892-1}$ [%]	15.75	14.72	13.79	-	-	14.75	6.66 %

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	108.55	107.10	109.45	-	-	108.37	1.09 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	108.44	110.54	110.17	-	-	109.72	1.02 %
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	109.58	110.01	109.76	114.62	110.36	110.87	1.91 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	111.62	111.22	111.10	112.21	110.95	111.42	0.45 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	114.47	114.39	110.83	112.45	113.95	113.22	1.38 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	156.06	155.64	155.61	154.98	151.36	154.73	1.24 %
Maximum load F_{max} under 30° [kN]	133.29	132.34	131.48	132.45	132.28	132.37	0.49 %
Maximum load F_{max} under 45° [kN]	119.04	117.81	117.81	119.89	119.25	118.76	0.78 %
Maximum load F_{max} under 67.5° [kN]	103.36	104.76	104.72	106.48	108.12	105.49	1.75 %

D.2.21 EN ISO 4017 – C3 – M16×100 – D8-10.9

Table D.50: Specifications, geometrical parameters and tests results of EN ISO 4017 – C3 – M16×100 – D8-10.9

General specifications						
Steel type	**Property class**	**Corrosion class**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Duplex	PC 10.9	D8	EN ISO 4017	M16×100	C3	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.46 mm²	0.39 %

Tensile tests on the whole bolt according to EN ISO 3506-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{mf,nom}$ [N/mm²]	1000 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal ultimate tensile load $F_{mf,nom}$ [kN]	156.70 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Ultimate tensile load $F_{mf,exp}$ [kN]	188.46	189.17	188.33	187.95	189.60	188.70	0.35 %
Tensile strength $R_{mf,exp} = f_{ub,exp,3506-1}$ [N/mm²]	1202.91	1207.44	1202.08	1199.66	1210.19	1204.46	0.35 %
Overstrength ratio $F_{mf,exp}$ / $F_{mf,nom}$ [-]	1.203	1.207	1.202	1.199	1.210	1.204	0.35 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Nominal yield load $F_{pf,nom}$ [kN]	141.30 (acc. to EN ISO 898-1, as not regulated in EN ISO 3506-1)						
Mean yield load $F_{pf,exp,mean}$ [kN]	159.00						2.51 %
Mean yield strength $f_{yb,exp,mean,3506-1}$ [N/mm²]	1014.87						2.51 %
Nominal elongation at fracture A_{nom} [x·d]	0.20 (PC 100)						
Elongation at fracture A_{exp} [x·d]	0.53	0.51	0.46	0.51	0.55	0.51	6.91 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	156.70						
$F_{bi,max,exp}$ [kN]	189.91	190.85	188.45	186.21	186.20	188.32	1.12 %
Tensile strength $R_{mf,min} = f_{ub,exp,15048-2}$ [N/mm²]	1212.17	1218.17	1202.85	1188.55	1188.49	1202.04	1.12 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Tensile strength $f_{ub,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892-1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892-1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	113.24	112.25	113.94	-	-	113.14	0.75 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	116.56	114.26	117.84	-	-	116.22	1.56 %
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	116.54	116.77	118.52	117.74	117.05	117.32	0.69 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	117.98	117.44	119.00	119.64	118.95	118.60	0.74 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	121.28	122.55	123.48	120.84	122.56	122.14	0.87 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	163.11	166.87	165.70	-	-	165.23	1.16 %
Maximum load F_{max} under 30° [kN]	139.41	143.13	140.58	-	-	141.04	1.35 %
Maximum load F_{max} under 45° [kN]	125.41	124.5	128.86	-	-	126.27	1.81 %
Maximum load F_{max} under 67.5° [kN]	113.03	111.90	113.32	-	-	112.75	0.67 %

D.3 Summary of tested partially threaded carbon steel bolts with unthreaded bolt part in the shear plane at UDE-IML

D.3.1 General

Below, all experimental investigations as supplementary investigations within this thesis on partially threaded carbon steel bolts with unthreaded part in the shear plane are summarised.

Table D.51: Summary of tested partially threaded carbon steel bolts with unthreaded bolt part in the shear plane at UDE-IML

Partially threaded carbon steel bolts with unthreaded bolt part in the shear plane											
Steel type	**Property class acc. to EN ISO 898-1**	**Surface condition**	**Manufacturer or trader**	**Thread production type**	**Bolt type**	**Bolt geometry**	**Number of tensile tests**	**Number of single-shear tests**	**Number of double-shear tests**	**Number of interaction tests**	**Series designation**
Carbon steel	**PC 8.8**	Galvan.	C6	Rolled	EN ISO 4014	M16×100	5	5	10	20	EN ISO 4014 – C6 – M16×100 – 8.8
	PC 10.9	Galvan.	C6	Rolled	EN ISO 4014	M16×100	5	5	10	20	EN ISO 4014 – C6 – M16×100 – 10.9
		tZn	C7	Rolled	EN 14399-3	M16×100	5	5	10	15	EN 14399-3 – C7 – M16×100 – HR – 10.9
		tZn	C8	Rolled	EN 14399-4	M16×95	3	3	6	14	EN 14399-4 – C8 – M16×95 – HV – 10.9
		tZn	C9	Rolled	EN 14399-4	M16×100	3	3	6	12	EN 14399-4 – C9 – M16×100 – HV – 10.9

D.3.2 EN ISO 4014 – C6 – M16×100 – 8.8

Table D.52: Specifications, geometrical parameters and tests results of EN ISO 4014 – C6 – M16×100 – 8.8

General specifications						
Steel type	**Property class**	**Surface condition**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Carbon steel	PC 8.8	Galvanised	EN ISO 4014	M16×100	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	195.30 mm²	0.22 %	10	156.67 mm²	159.83 mm²	0.47 %

Tensile tests on the whole bolt according to EN ISO 898-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{m,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{m,nom}$ [kN]	130.00 (for structural bolts)						
Ultimate tensile load $F_{m,exp}$ [kN]	138.72	138.22	139.46	136.86	137.12	138.08	0.79 %
Tensile strength $R_{mf,exp} = f_{ub,exp,898\text{-}1}$ [N/mm²]	885.43	882.24	890.15	873.56	875.22	881.32	0.79 %
Overstrength ratio $F_{m,exp}$ / $F_{m,nom}$ [-]	1.067	1.063	1.073	1.053	1.055	1.062	0.79 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	640						
Nominal yield load $F_{p,nom}$ [kN]	100.48						
Mean yield load $F_{p,exp,mean}$ [kN]	127.60						1.41 %
Mean yield strength $f_{yb,exp,mean,898\text{-}1}$ [N/mm²]	814.45						1.41 %
Nominal elongation at fracture A_{nom} [x·d]	-						
Elongation at fracture A_{exp} [x·d]	0.41	0.42	0.40	0.42	0.41	0.41	2.41 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	125.60						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	Assumed as ≈ $f_{ub,exp,threads,meam}$ leading to $F_{m,shank}$ = 172.21 kN						
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	110.82	111.00	112.86	110.88	112.22	111.56	0.83 %
Max $F_{v,exp}$[1)] from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	96.45	95.25	96.66	97.12	95.99	96.29	0.74 %
Max $F_{v,exp}$[1)] from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	99.46	99.00	98.87	97.54	98.45	98.66	0.73 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	146.92	142.58	146.67	146.86	149.67	146.54	1.73 %
Maximum load F_{max} under 30° [kN]	138.51	139.74	141.40	139.11	141.64	140.08	0.99 %
Maximum load F_{max} under 45° [kN]	126.19	126.92	127.42	125.25	125.34	126.22	0.76 %
Maximum load F_{max} under 67.5° [kN]	112.94	113.08	111.99	112.47	113.70	112.84	0.57 %

[1)] Double-shear tests with unthreaded and threaded bolt part in the shear planes

D.3.3 EN ISO 4014 – C6 – M16×100 – 10.9

Table D.53: Specifications, geometrical parameters and tests results of EN ISO 4014 – C6 – M16×100 – 8.8

General specifications						
Steel type	**Property class**	**Surface condition**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Carbon steel	PC 10.9	Galvanised	EN ISO 4014	M16×100	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	195.11 mm²	0.33 %	10	156.67 mm²	152.92 mm²	0.53 %

Tensile tests on the whole bolt according to EN ISO 898-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{m,nom}$ [N/mm²]	1000						
Nominal ultimate tensile load $F_{m,nom}$ [kN]	163.00						
Ultimate tensile load $F_{m,exp}$ [kN]	170.60	179.39	168.31	180.71	177.78	175.36	3.16 %
Tensile strength $R_{mf,exp} = f_{ub,exp,898\text{-}1}$ [N/mm²]	1088.91	1145.02	1074.30	1153.44	1134.74	1119.28	3.16 %
Overstrength ratio $F_{m,exp}$ / $F_{m,nom}$ [-]	1.047	1.101	1.033	1.109	1.091	1.076	3.16 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900						
Nominal yield load $F_{p,nom}$ [kN]	141.30						
Mean yield load $F_{p,exp,mean}$ [kN]	161.10						3.71 %
Mean yield strength $f_{yb,exp,mean,898\text{-}1}$ [N/mm²]	1026.11						3.71 %
Nominal elongation at fracture A_{nom} [x·d]	-						
Elongation at fracture A_{exp} [x·d]	0.34	0.34	0.34	0.21	0.34	0.31	18.42 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	163.00						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	Assumed as ≈ $f_{ub,exp,threads,meam}$ leading to $F_{m,shank}$ = 218.33 kN						
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	138.90	132.78	141.83	130.23	133.99	135.55	3.48 %
Max $F_{v,exp}$[1)] from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	119.80	118.50	114.73	114.98	115.85	116.77	1.93 %
Max $F_{v,exp}$[1)] from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	122.43	121.23	120.66	123.99	122.85	122.23	1.08 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	182.11	187.78	185.51	186.29	183.42	185.02	1.22 %
Maximum load F_{max} under 30° [kN]	172.99	167.09	167.78	171.04	172.99	170.38	1.65 %
Maximum load F_{max} under 45° [kN]	164.92	154.07	160.68	155.55	144.31	155.91	4.99 %
Maximum load F_{max} under 67.5° [kN]	134.58	134.93	133.46	145.84	135.25	136.81	3.72 %

[1)] Double-shear tests with unthreaded and threaded bolt part in the shear planes

D.3.4 EN 14399-3 – C7 – M16×100 – HR – 10.9

Table D.54: Specifications, geometrical parameters and tests results of EN 14399-3 – C7 – M16×100 – HR – 10.9

General specifications						
Steel type	**Property class**	**Surface condition**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Carbon steel	PC 10.9	tZn	EN 14399-3	M16×100	C7	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	192.71 mm²	0.42 %	10	156.67 mm²	153.90 mm²	0.45 %

Tensile tests on the whole bolt according to EN ISO 898-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{m,nom}$ [N/mm²]	1000						
Nominal ultimate tensile load $F_{m,nom}$ [kN]	163.00						
Ultimate tensile load $F_{m,exp}$ [kN]	171.66	173.70	171.11	173.18	173.01	172.53	0.63 %
Tensile strength $R_{mf,exp} = f_{ub,exp,898\text{-}1}$ [N/mm²]	1095.68	1108.70	1092.17	1105.38	1104.30	1101.24	0.63 %
Overstrength ratio $F_{m,exp}$ / $F_{m,nom}$ [-]	1.053	1.066	1.050	1.062	1.061	1.058	0.63 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900						
Nominal yield load $F_{p,nom}$ [kN]	141.30						
Mean yield load $F_{p,exp,mean}$ [kN]	163.11						3.71 %
Mean yield strength $f_{yb,exp,mean,898\text{-}1}$ [N/mm²]	1041.11						3.71 %
Nominal elongation at fracture A_{nom} [x·d]	-						
Elongation at fracture A_{exp} [x·d]	0.34	0.34	0.34	0.33	0.33	0.34	1.68 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	163.00						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	Assumed as ≈ $f_{ub,exp,threads,meam}$ leading to $F_{m,shank}$ = 212.22 kN						
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	128.05	130.89	130.63	130.77	131.87	130.44	1.09 %
Max $F_{v,exp}$[1)] from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	110.54	111.54	110.25	112.55	113.67	111.71	1.27 %
Max $F_{v,exp}$[1)] from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	115.25	114.58	116.99	117.55	118.51	116.58	1.40 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	185.42	182.97	181.81	183.71	180.24	182.83	1.07 %
Maximum load F_{max} under 30° [kN]	165.84	164.67	165.84	160.09	162.22	163.73	1.54 %
Maximum load F_{max} under 45° [kN]	147.08	149.76	149.18	148.51	147.48	148.40	0.76 %
Maximum load F_{max} under 67.5° [kN]	-	-	-	-	-	-	-

[1)] Double-shear tests with unthreaded and threaded bolt part in the shear planes

D.3.5 EN 14399-4 – C8 – M16×95 – HV – 10.9

Table D.55: Specifications, geometrical parameters and tests results of EN 14399-4 – C8 – M16×95 – HV – 10.9

General specifications						
Steel type	**Property class**	**Surface condition**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Carbon steel	PC 10.9	tZn	EN 14399-4	M16×95	C8	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
6	201.06 mm²	199.00 mm²	0.31 %	6	154.71 mm²	159.83 mm²	0.47 %

Tensile tests on the whole bolt according to EN ISO 898-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{m,nom}$ [N/mm²]	1000						
Nominal ultimate tensile load $F_{m,nom}$ [kN]	163.00						
Ultimate tensile load $F_{m,exp}$ [kN]	169.19	168.51	171.47	-	-	169.72	0.91 %
Tensile strength $R_{mf,exp} = f_{ub,exp,898\text{-}1}$ [N/mm²]	1079.91	1075.57	1094.47	-	-	1083.32	0.91 %
Overstrength ratio $F_{m,exp}$ / $F_{m,nom}$ [-]	1.038	1.034	1.052	-	-	1.041	0.91 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900						
Nominal yield load $F_{p,nom}$ [kN]	141.30						
Mean yield load $F_{p,exp,mean}$ [kN]	159.50						1.70 %
Mean yield strength $f_{yb,exp,mean,898\text{-}1}$ [N/mm²]	1018.06						1.70 %
Nominal elongation at fracture A_{nom} [x·d]	-						
Elongation at fracture A_{exp} [x·d]	0.27	0.26	0.26	-	-	0.26	3.19 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	163.00						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	Assumed as ≈ $f_{ub,exp,threads,meam}$ leading to $F_{m,shank}$ = 215.58 kN						
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	127.17	131.16	128.83	-	-	129.05	1.55 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	130.46	129.54	132.26	-	-	130.75	1.06 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	133.45	136.26	129.26	-	-	132.99	2.65 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	177.37	183.10	179.46	-	-	179.98	1.61 %
Maximum load F_{max} under 30° [kN]	165.17	163.24	164.00	-	-	164.14	0.59 %
Maximum load F_{max} under 45° [kN]	146.32	143.81	148.13	-	-	146.09	1.49 %
Maximum load F_{max} under 67.5° [kN]	128.88	129.78	129.65	127.65	128.99	129.44	0.38 %

D.3.6 EN 14399-4 – C9 – M16×100 – HV – 10.9

Table D.56: Specifications, geometrical parameters and tests results of EN 14399-4 – C9 – M16×100 – HV – 10.9

General specifications						
Steel type	**Property class**	**Surface condition**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Carbon steel	PC 10.9	tZn	EN 14399-4	M16×100	C9	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
10	201.06 mm²	190.10 mm²	0.22 %	10	156.67 mm²	154.50 mm²	0.47 %

Tensile tests on the whole bolt according to EN ISO 898-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{m,nom}$ [N/mm²]	1000						
Nominal ultimate tensile load $F_{m,nom}$ [kN]	163.00						
Ultimate tensile load $F_{m,exp}$ [kN]	164.55	164.94	166.52	-	-	165.34	0.63 %
Tensile strength $R_{mf,exp} = f_{ub,exp,898\text{-}1}$ [N/mm²]	1050.30	1052.79	1062.87	-	-	1055.32	0.63 %
Overstrength ratio $F_{m,exp}$ / $F_{m,nom}$ [-]	1.010	1.012	1.022	-	-	1.014	0.63 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900						
Nominal yield load $F_{p,nom}$ [kN]	141.30						
Mean yield load $F_{p,exp,mean}$ [kN]	153.53						1.44 %
Mean yield strength $f_{yb,exp,mean,898\text{-}1}$ [N/mm²]	979.96						1.44 %
Nominal elongation at fracture A_{nom} [x·d]	-						
Elongation at fracture A_{exp} [x·d]	0.37	0.36	0.36	-	-	0.36	1.59 %
Failure location	Threads	Threads	Threads	-	-	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	163.00						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Shank tensile strength $f_{ub,exp,shank}$ [N/mm²]	Assumed as ≈ $f_{ub,exp,threads,meam}$ leading to $F_{m,shank}$ = 200.62 kN						
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	120.48	121.00	121.55	-	-	121.01	0.44 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	122.50	123.80	123.48	-	-	126.26	0.55 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	124.54	124.47	126.25	-	-	125.09	0.80 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	175.32	175.09	176.82	-	-	175.74	0.53 %
Maximum load F_{max} under 30° [kN]	153.77	151.75	151.79	-	-	152.44	0.76 %
Maximum load F_{max} under 45° [kN]	135.97	136.88	135.90	-	-	136.25	0.40 %
Maximum load F_{max} under 67.5° [kN]	122.29	121.96	121.25	-	-	121.83	0.44 %

D.4 Summary of tested fully threaded carbon steel bolts with threaded bolt part in the shear plane at UDE-IML

D.4.1 General

In the further, all experimental investigations as supplementary investigations within this thesis on fully threaded carbon steel bolts with threaded part in the shear plane are summarised.

Table D.57: Summary of tested fully threaded carbon steel bolts with threaded bolt part in the shear plane at UDE-IML

Fully threaded carbon steel bolts with threaded bolt part in the shear plane											
Steel type	**Property class acc. to EN ISO 898-1**	**Surface condition**	**Manufacturer or trader**	**Thread production type**	**Bolt type**	**Bolt geometry**	**Number of tensile tests**	**Number of single-shear tests**	**Number of double-shear tests**	**Number of interaction tests**	**Series designation**
CS	**PC 8.8**	Galvan.	C6	Rolled	EN ISO 4017	M16×100	5	5	10	20	EN ISO 4017 – C6 – M16×100 – 8.8
	PC 10.9	Galvan.	C6	Rolled	EN ISO 4017	M16×100	5	5	10	20	EN ISO 4017 – C6 – M16×100 – 10.9

D.4.2 EN ISO 4017 – C6 – M16×100 – 8.8

Table D.58: Specifications, geometrical parameters and tests results of EN ISO 4017 – C6 – M16×100 – 8.8

General specifications						
Steel type	**Property class**	**Surface condition**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Carbon steel	PC 8.8	Galvanised	EN ISO 4017	M16×100	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	152.90 mm²	0.34 %

Tensile tests on the whole bolt according to EN ISO 898-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{m,nom}$ [N/mm²]	800						
Nominal ultimate tensile load $F_{m,nom}$ [kN]	130.00 (for structural bolts)						
Ultimate tensile load $F_{m,exp}$ [kN]	138.72	138.22	139.46	136.86	137.12	138.08	0.79 %
Tensile strength $R_{mf,exp} = f_{ub,exp,898\text{-}1}$ [N/mm²]	885.43	882.24	890.15	873.56	875.22	881.32	0.79 %
Overstrength ratio $F_{m,exp}$ / $F_{m,nom}$ [-]	1.067	1.063	1.073	1.053	1.055	1.062	0.79 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	640						
Nominal yield load $F_{p,nom}$ [kN]	100.48						
Mean yield load $F_{p,exp,mean}$ [kN]	121.60						0.81 %
Mean yield strength $f_{yb,exp,mean,898\text{-}1}$ [N/mm²]	776.15						0.81 %
Nominal elongation at fracture A_{nom} [x·d]	-						
Elongation at fracture A_{exp} [x·d]	0.61	0.61	0.64	0.60	0.60	0.61	2.53 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	125.60						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	81.38	86.68	81.24	82.11	83.89	83.06	2.74 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	84.12	85.46	84.54	83.99	84.54	84.53	0.68 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	86.05	88.00	88.35	85.35	88.19	86.18	1.46 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	127.25	126.53	128.59	128.76	128.29	127.88	0.75 %
Maximum load F_{max} under 30° [kN]	109.35	110.65	111.25	109.87	111.52	110.53	0.83 %
Maximum load F_{max} under 45° [kN]	95.59	98.48	96.01	95.40	96.15	96.33	1.29 %
Maximum load F_{max} under 67.5° [kN]	82.48	83.65	85.17	83.93	83.68	83.78	1.14 %

D.4.3 EN ISO 4017 – C6 – M16×100 – 10.9

Table D.59: Specifications, geometrical parameters and tests results of EN ISO 4017 – C6 – M16×100 – 10.9

General specifications						
Steel type	**Property class**	**Surface condition**	**Bolt type**	**Bolt geometry**	**Manufacturer or trader**	**Thread production type**
Carbon steel	PC 10.9	Galvanised	EN ISO 4017	M16×100	C6	Rolled

Measured geometrical parameters							
Gross cross-sectional area A_{meas}				**Tensile stress area A_s**			
Number of bolts	**A_{nom}**	**$A_{meas,mean}$**	**COV A_{meas}**	**Number of bolts**	**$A_{s,nom}$**	**$A_{s,meas,mean}$**	**COV $A_{s,meas}$**
-	-	-	-	10	156.67 mm²	153.10 mm²	0.39 %

Tensile tests on the whole bolt according to EN ISO 898-1, Cl. 9							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Nominal tensile strength $R_{m,nom}$ [N/mm²]	1000						
Nominal ultimate tensile load $F_{m,nom}$ [kN]	163.00						
Ultimate tensile load $F_{m,exp}$ [kN]	170.60	179.39	168.31	180.71	177.78	175.36	3.16 %
Tensile strength $R_{mf,exp} = f_{ub,exp,898\text{-}1}$ [N/mm²]	1088.91	1145.02	1074.30	1153.44	1134.74	1119.28	3.16 %
Overstrength ratio $F_{m,exp}$ / $F_{m,nom}$ [-]	1.047	1.101	1.033	1.109	1.091	1.076	3.16 %
Nominal yield strength $R_{pf,nom}$ [N/mm²]	900						
Nominal yield load $F_{p,nom}$ [kN]	141.30						
Mean yield load $F_{p,exp,mean}$ [kN]	146.11						1.30 %
Mean yield strength $f_{yb,exp,mean,898\text{-}1}$ [N/mm²]	932.60						1.30 %
Nominal elongation at fracture A_{nom} [x·d]	-						
Elongation at fracture A_{exp} [x·d]	0.58	0.53	0.55	0.55	0.52	0.55	3.76 %
Failure location	Threads	Threads	Threads	Threads	Threads	-	-

Tensile tests on bolting assemblies according to EN 15048-2, Cl. 6							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
$F_{ub,nom}$ [kN]	163.00						
$F_{bi,max,exp}$ [kN]	-	-	-	-	-	-	-
Tensile strength $R_{mf,min} = f_{ub,exp,15048\text{-}2}$ [N/mm²]	-	-	-	-	-	-	-
Failure location	-	-	-	-	-	-	-

Tensile tests on machined bolts and the separated threaded bolt part + Tensile tests on tensile coupon test specimens machined from bolts according to EN ISO 6892-1							
Parameters	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Mean**	**COV**
Threads tensile strength $f_{ub,exp,threads}$ [N/mm²]	-	-	-	-	-	-	-
Tensile strength $f_{ub,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Yield strength $f_{yb,exp,6892\text{-}1}$ [N/mm²]	-	-	-	-	-	-	-
Elongation at fracture $A_{exp,6892\text{-}1}$ [%]	-	-	-	-	-	-	-

Single- and double-shear tests on bolts and bolting assemblies (shear resistances per shear plane)							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Max $F_{v,exp}$ from double-shear tests on bolting ass. with nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 16 mm (H8)) [kN]	-	-	-	-	-	-	-
Max $F_{v,exp}$ from single-shear tests on bolting assemblies with nut (d = 17 mm) [kN]	107.58	107.10	99.77	99.55	97.97	102.39	4.46 %
Max $F_{v,exp}$ from double-shear tests on bolting assemb. with nut (d_h = 17 mm) [kN]	109.13	109.54	107.24	106.24	105.34	107.50	1.69 %
Max $F_{v,exp}$ from double-shear tests on bolts without nut (d_h = 17 mm) [kN]	110.24	107.55	111.25	108.15	108.95	109.23	1.39 %

Single-shear interaction tests on bolting assemblies							
Parameters	**Bolt 1**	**Bolt 2**	**Bolt 3**	**Bolt 4**	**Bolt 5**	**Mean**	**COV**
Maximum load F_{max} under 15° [kN]	156.15	151.69	153.48	151.86	156.01	153.84	1.41 %
Maximum load F_{max} under 30° [kN]	131.81	132.72	131.88	131.57	131.91	131.98	0.33 %
Maximum load F_{max} under 45° [kN]	115.10	113.74	117.41	106.98	116.06	113.86	3.58 %
Maximum load F_{max} under 67.5° [kN]	100.10	97.56	100.14	101.67	98.47	99.59	1.61 %

Appendix E: Determination of partial safety factors according to EN 1990, Annex D

The partial safety factor γ_M* can be derived according to EN 1990, Annex D. A theoretical resistance function r_t of independent basic variables $\underline{X}$ is required, see (Eq. E.1):

$$r_t = g_{rt}\left(\underline{X}\right) \quad \text{(EN 1090, Eq. D.6)} \qquad \text{(Eq. E.1)}$$

The function r_t should include all basic variables $\underline{X}$ affecting the resistance values of the limit state approach. With the given theoretical resistance function r_t and a set of experimental data, a statistical evaluation is conducted. By comparing individual theoretical resistance value r_{ti}, based on a sufficient number of test results, with the experimental resistance values r_{ei}, an error term δ_i can be calculated for each individual data pair (r_{ti}, r_{ei}), see (Eq. E.2):

$$\delta_i = \frac{r_{ei}}{b \cdot r_{ti}} \quad \text{(EN 1090, Eq. D.10)} \qquad \text{(Eq. E.2)}$$

The resistance function is exact and complete if the data points (r_{ti}, r_{ei}) agree with the angle bisector $\Theta = 0.25 \cdot \pi$. If the data points lie above the angle bisector, the investigated resistance function is on the safe side regarding the design. However, if the data points exceed the angle bisector by far, the resistance function leads to a non-economical result and should be modified. Additionally, b is the mean value correction factor using the “Least Squares” best-fit method to the slope of the angle bisector, see Figure 4.7-3 (Step 2) and (Eq. E.3):

$$b = \frac{\sum r_e r_t}{\sum r_t^2} \quad \text{(EN 1090, Eq. D.8)} \qquad \text{(Eq. E.3)}$$

Considering the error term δ_i and the mean value correction factor b, the standard deviation can be calculated to estimate the coefficient of variation of errors V_δ based on the logarithmic normal probability distribution δ_i :

$$V_\delta = \sqrt{\exp\left(s_\Delta^2\right) - 1} \quad \text{(EN 1090, Eq. D.14)} \qquad \text{(Eq. E.4)}$$

Thus, the determination of the estimated value has to be carried out by (Eq. E.5) under consideration of (Eq. E.6) and (Eq. E.7):

$$s_\Delta^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(\Delta_i - \bar{\Delta}\right)^2 \quad \text{(EN 1090, Eq. D.13)} \qquad \text{(Eq. E.5)}$$

$$\Delta_i = \ln\left(\delta_i\right) \quad \text{(EN 1090, Eq. D.11)} \qquad \text{(Eq. E.6)}$$

$$\bar{\Delta} = \frac{1}{n}\sum_{i=1}^{n}\Delta_i \quad \text{(EN 1090, Eq. D.12)} \qquad \text{(Eq. E.7)}$$

The coefficient of variation of errors indicates the variability of the predictions of the resistance function. If V_δ or the scatter Figure 4.7-3 (Step 2) is too high, the resistance function r_t should be adapted. To improve the resistance function r_t by reducing the coefficient variation of errors V_δ and thus the scatter, further basic variables $\underline{X}$ can be considered, which have been previously neglected. Another method to improve the resistance function can be achieved by dividing the experimental test data into appropriate subsets. However, in general, small sample sizes lead to large partial safety factors due to the non-representative data size. Therefore, to avoid large fractile factors $k_{d,n}$ for the calculation of r_d and thus large safety factors, Annex D of EN 1990 states, that the total test data can be used to determine the fractile factors $k_{d,n}$, which can be applied also for subsets. If further modifications to the derived resistance function

are necessary, additional coefficients of variation V_{Xi} of each basic variable can be determined from the data. Finally, to determine the design value r_d, the coefficient of variation V_r is required. If the derived r_t is a product function, the equation for V_r is presented in (Eq. E.8):

$$V_r^2 = \left(V_\delta^2 + 1\right)\left[\prod_{i=1}^{j}\left(V_{Xi}^2 + 1\right)\right] - 1 \qquad \text{(Eq. E.8)}$$

For small values of and the approximation in (Eq. E.12) for V_r may be applied:

$$V_r^2 = V_\delta^2 + V_{rt}^2 \qquad \text{(Eq. E.9)}$$

$$V_{rt}^2 = \sum_{i=1}^{j} V_{Xi}^2 \qquad \text{(Eq. E.10)}$$

The design resistance value r_d can be determined leading to the evaluation of the partial safety factor γ_M*. EN 1990, Annex D gives two equations to calculate r_d depending on the amount of test data. If a limited number of tests n is available (n < 100), r_d is calculated by (Eq. E.11):

$$r_d = bg_{rt}\left(\underline{X}_m\right) \cdot \exp\left(-k_{d,\infty}\alpha_{rt}Q_{rt} - k_{d,n}\alpha_\delta Q_\delta - 0.5 \cdot Q^2\right) \qquad \text{(Eq. E.11)}$$

However, if equal or more than 100 individual tests are available for , r_d can be evaluated using (Eq. E.12):

$$r_d = bg_{rt}\left(\underline{X}_m\right) \cdot \exp\left(-k_{d,\infty}Q - 0.5 \cdot Q^2\right) \qquad \text{(Eq. E.12)}$$

The weighting factors α_{rt} and α_δ resemble the weighting factors for Q_{rt} and Q_δ, see (Eq. E.13) to (Eq. E.17):

$$Q = \sqrt{\ln\left(V_r^2 + 1\right)} \qquad \text{(Eq. E.13)}$$

$$Q_\delta = \sqrt{\ln\left(V_\delta^2 + 1\right)} \qquad \text{(Eq. E.14)}$$

$$Q_{rt} = \sqrt{\ln\left(V_{rt}^2 + 1\right)} \qquad \text{(Eq. E.15)}$$

$$\alpha_{rt} = Q_{rt}/Q \qquad \text{(Eq. E.16)}$$

$$\alpha_\delta = Q_\delta/Q \qquad \text{(Eq. E.17)}$$

As already stated, the fractile factor $k_{d,n}$ depends on the amount of test data, see Table E.1.

Table E.1: Values for $k_{d,n}$ depending on the amount of test data n according to EN 1990, Annex D

n	1	2	3	4	5	6	8	10	20	30	∞
$k_{d,n}$	-	-	-	11.4	7.85	6.36	5.07	4.51	3.64	3.44	3.04

Appendix F: Technical drawings of the test rigs

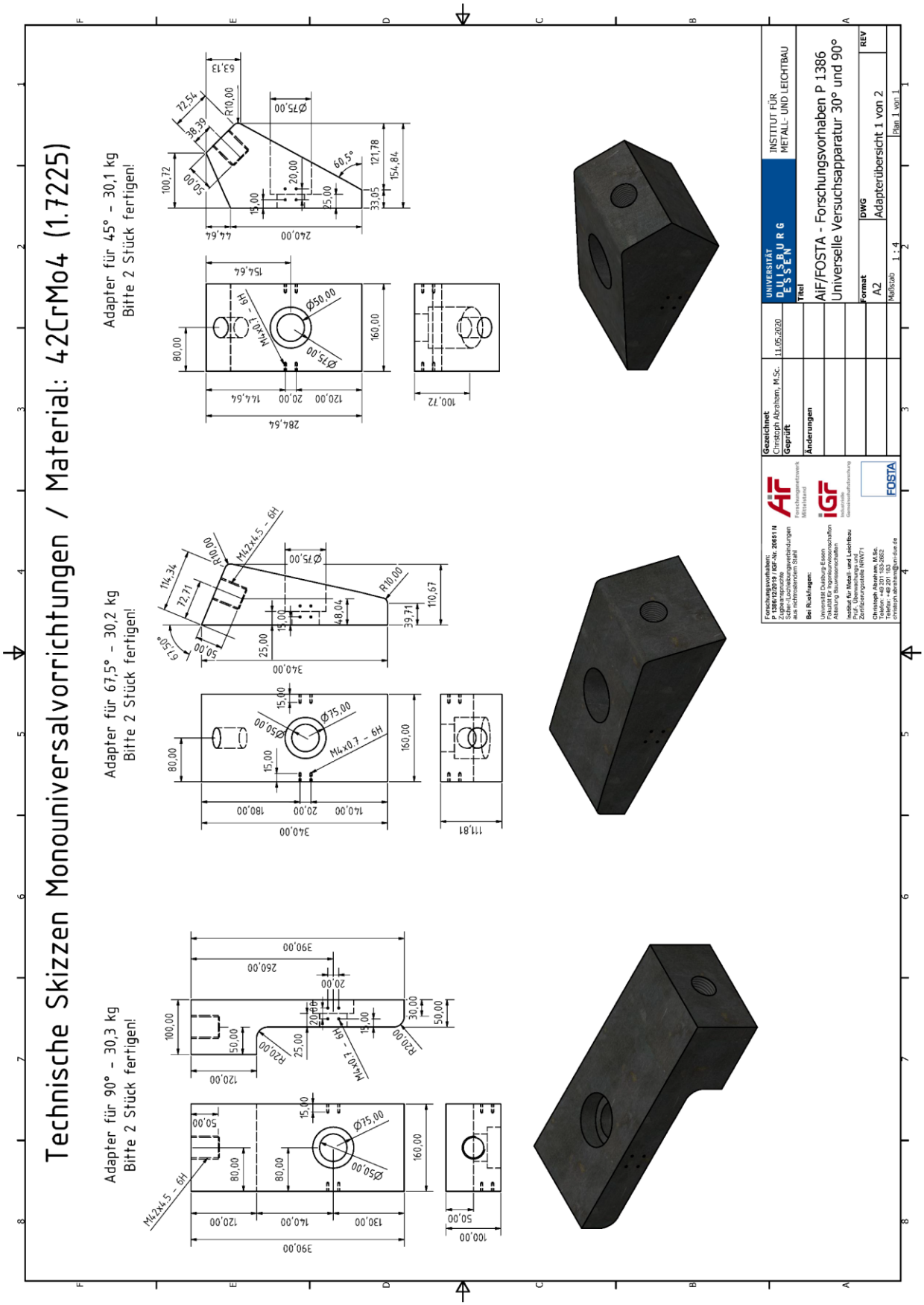


Figure F.1: Test rig for single-shear and interaction tests (45°, 67.5°) according to the German research project FOSTA P 1386 / IGF-No. 20651 N [78]; © UDE-IML

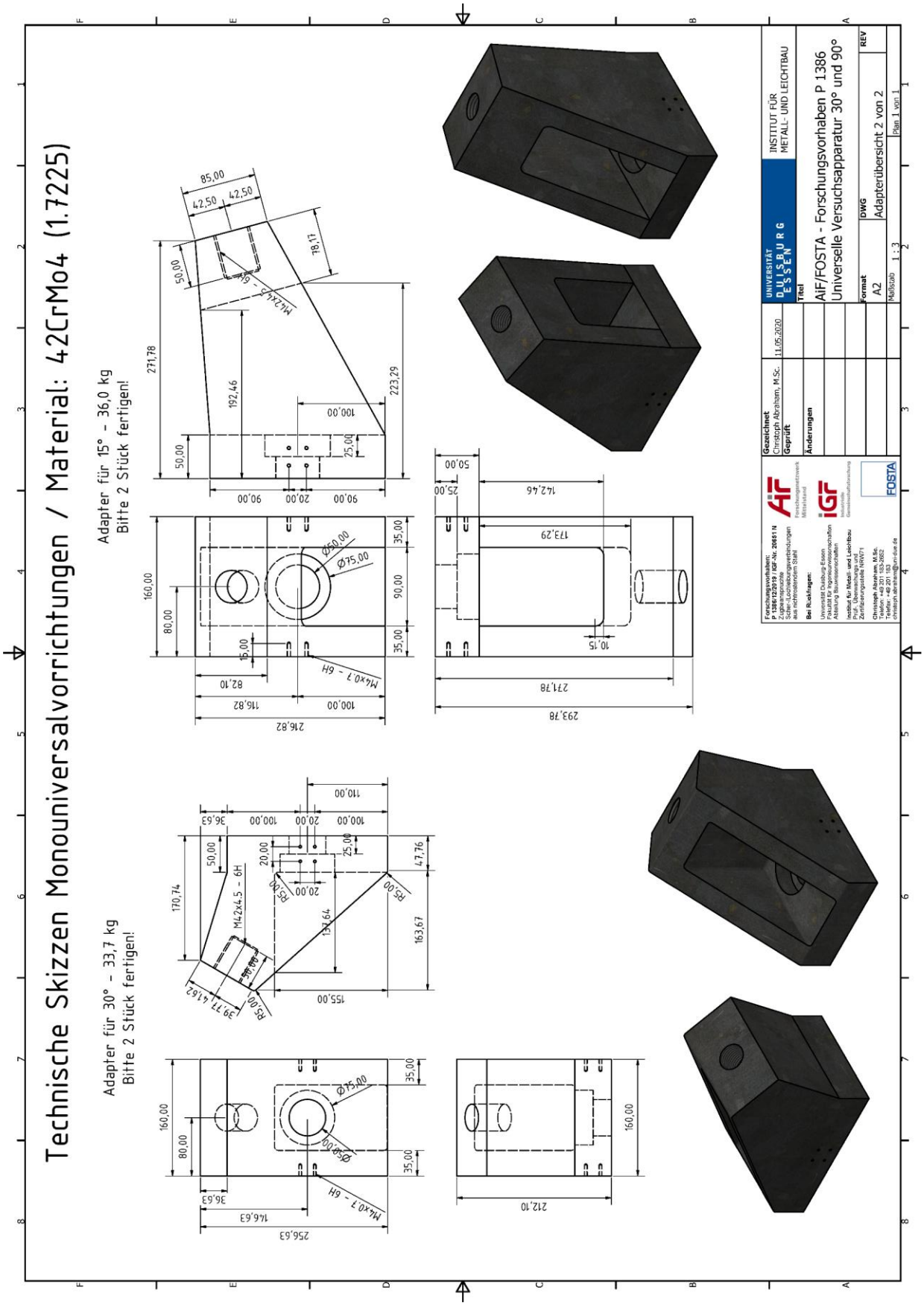


Figure F.2: Test rig for interaction tests (15°, 30°) according to the German research project FOSTA P 1386 / IGF-No. 20651 N [78]; © UDE-IML

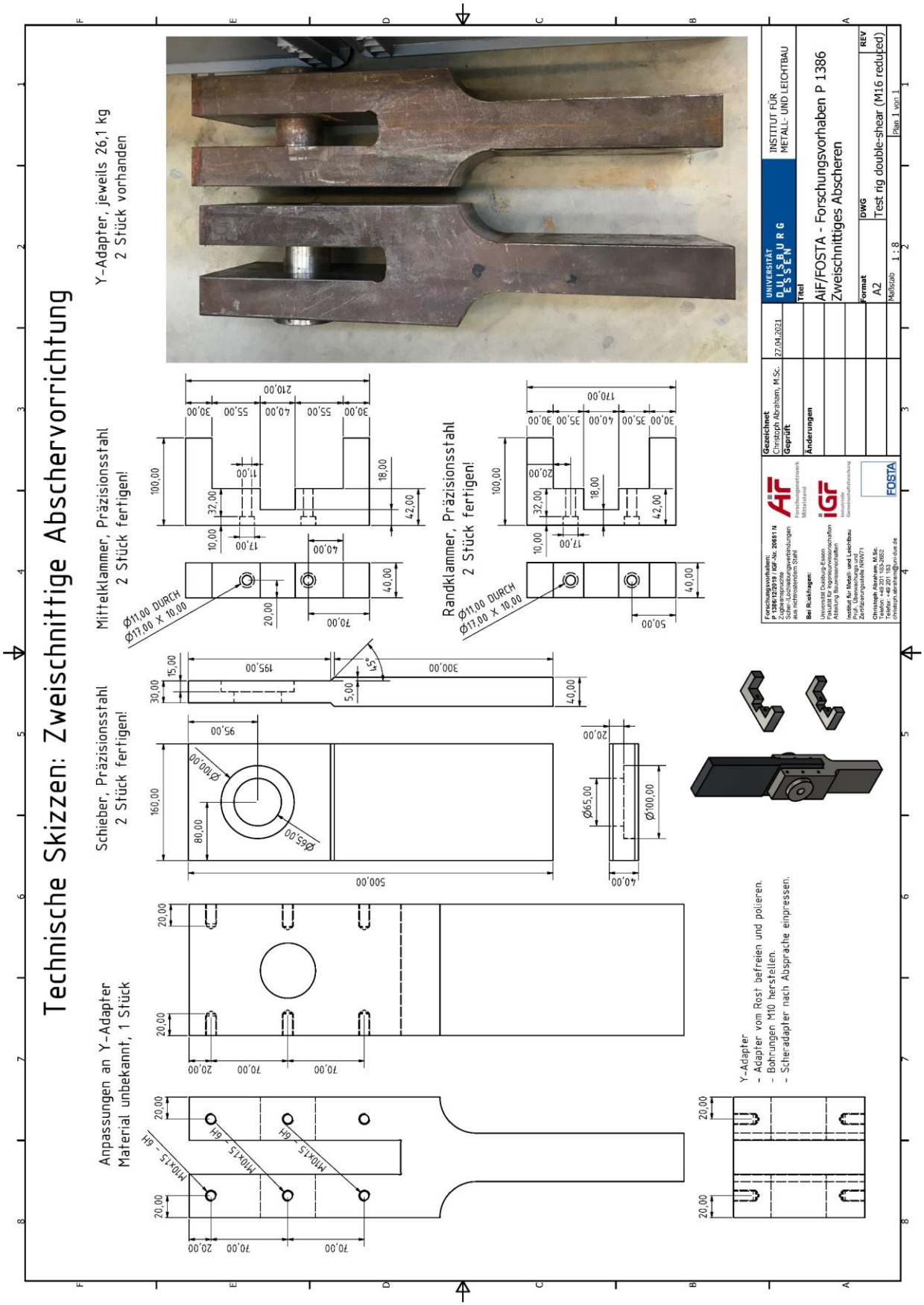


Figure F.3: Double-shear test rig; © UDE-IML

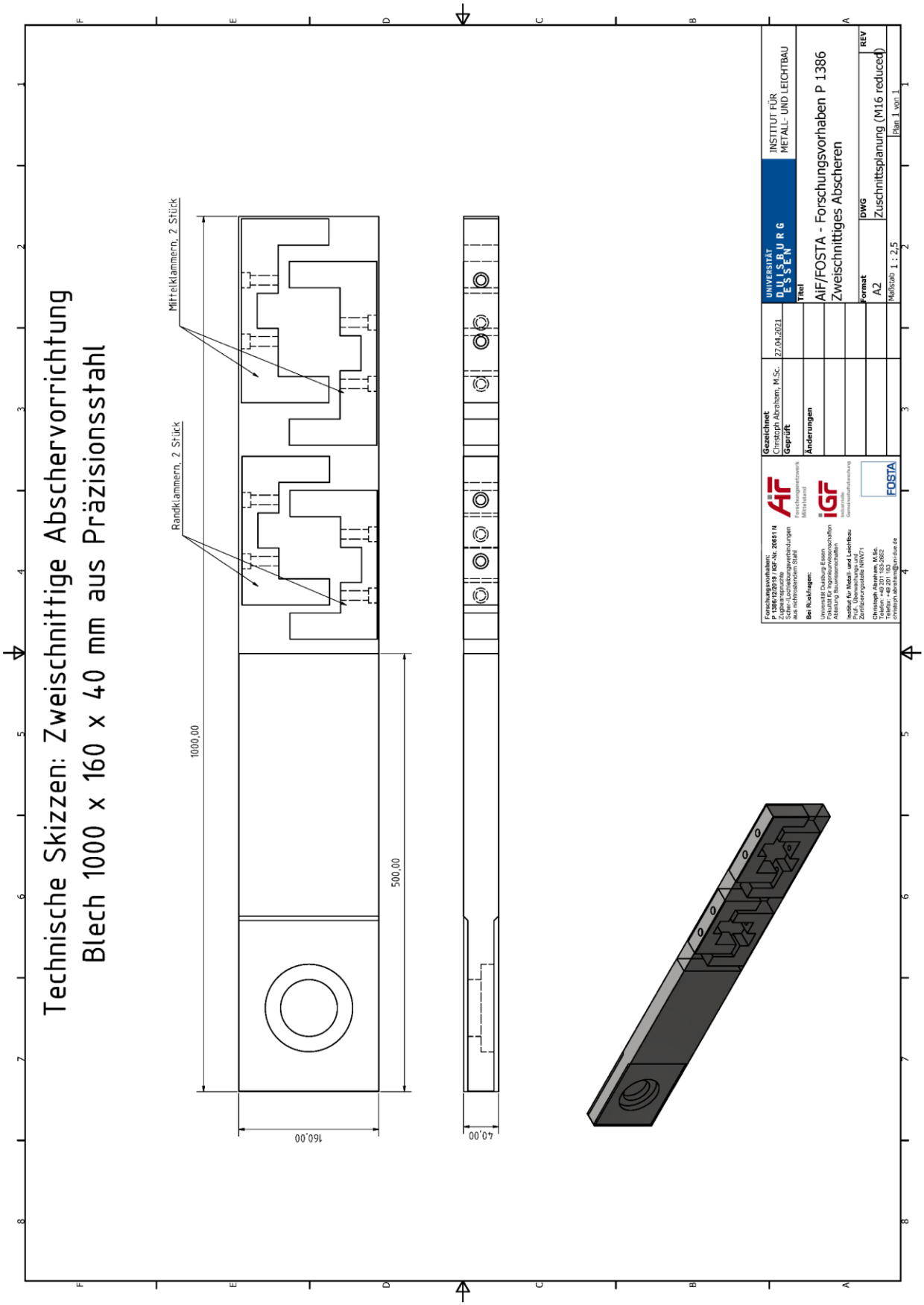


Figure F.4: Inner plate of the double-shear test rig; © UDE-IML

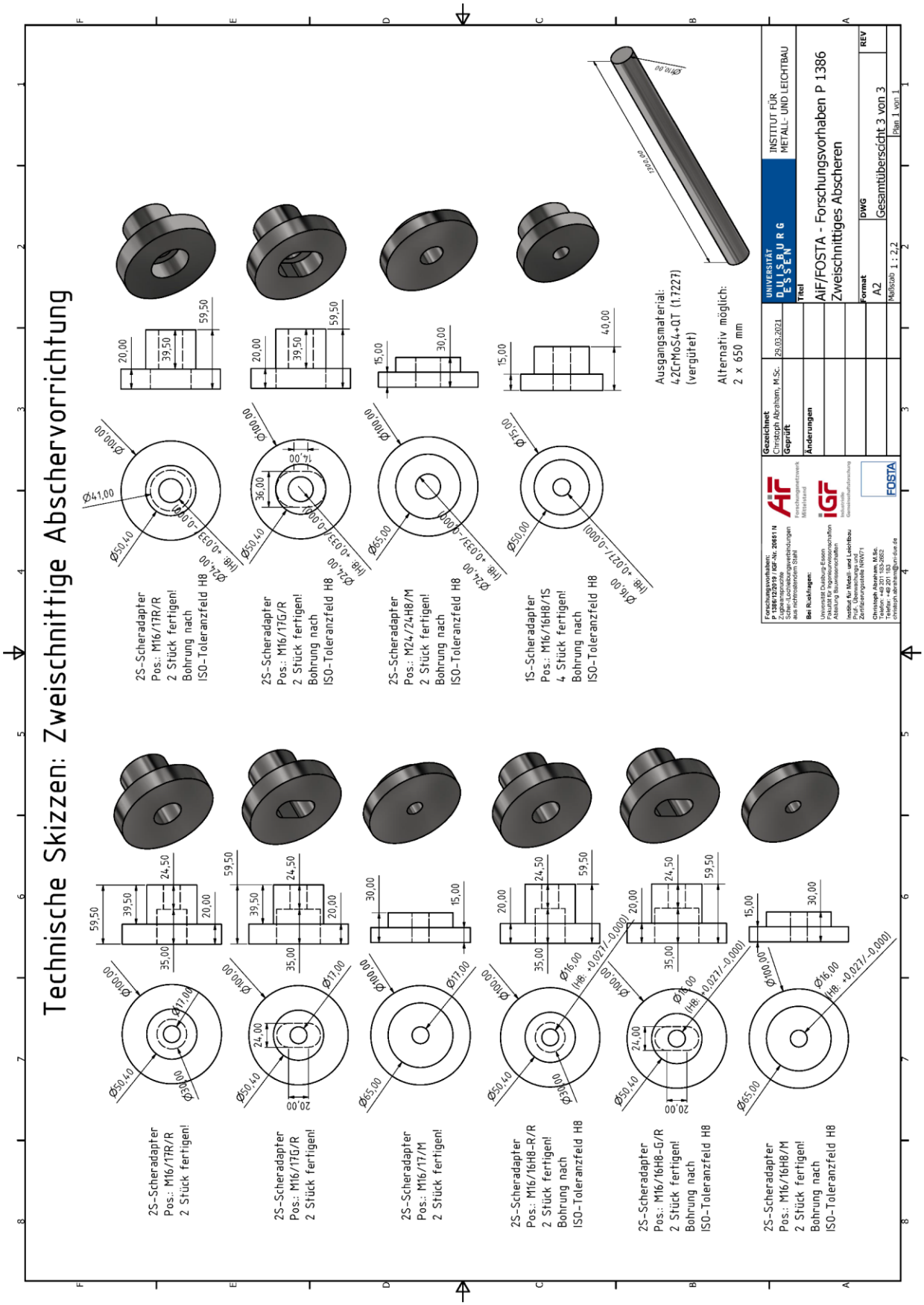


Figure F.5: Different types of shear inserts for the double-shear test rig; © UDE-IML

Appendix G: Derivations of the theoretical and nominal resistance functions for the reliability analyses

G.1 Stranghöner/Abraham for FprEN 1993-1-4 and abZ/aBG Z-30.3-6:2022

G.1.1 Unthreaded bolt part in the shear plane

$$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^{1.7} + \left(\frac{F_{t,Ed}}{1.25 \cdot F_{t,Rd}}\right)^{1.7} \leq 1 \quad \text{with } F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A}{\gamma_{M2}} \text{ and } F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$$

$$\Leftrightarrow \left(\frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot f_{ub} \cdot A}\right)^{1.7} + \left(\frac{r_{t/n} \cdot \cos(\varphi)}{1.25 \cdot k_2 \cdot f_{ub} \cdot A_s}\right)^{1.7} \leq 1$$

$$\Leftrightarrow \left(\frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot A}\right)^{1.7} + \left(\frac{r_{t/n} \cdot \cos(\varphi)}{1.25 \cdot k_2 \cdot A_s}\right)^{1.7} \leq f_{ub}^{\ 1.7}$$

$$\Leftrightarrow r_{t/n,1} \leq \frac{f_{ub}}{\sqrt[1.7]{\left(\frac{\sin(\varphi)}{\alpha \cdot A}\right)^{1.7} + \left(\frac{\cos(\varphi)}{1.25 \cdot k_2 \cdot A_s}\right)^{1.7}}}$$

$$\Leftrightarrow r_{t/n,2} \leq \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3} \leq \min.\left\{\begin{array}{l} \frac{1.25 \cdot k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s \end{array}\right\}$$

$$\longrightarrow r_{t/n} = \min.\left\{\frac{f_{ub}}{\sqrt[1.7]{\left(\frac{\sin(\varphi)}{\alpha \cdot A}\right)^{1.7} + \left(\frac{\cos(\varphi)}{1.25 \cdot k_2 \cdot A_s}\right)^{1.7}}}; \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}; \frac{1.25 \cdot k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)}; F_{mf} = f_{ub} \cdot A_s\right\}$$

G.1.2 Threaded bolt part in the shear plane

$$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^{1.7} + \left(\frac{F_{t,Ed}}{F_{t,Rd}}\right)^{1.7} \leq 1 \quad \text{with } F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A_s}{\gamma_{M2}} \text{ and } F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$$

$$\Leftrightarrow \left(\frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot f_{ub} \cdot A_s}\right)^{1.7} + \left(\frac{r_{t/n} \cdot \cos(\varphi)}{1.25 \cdot k_2 \cdot f_{ub} \cdot A_s}\right)^{1.7} \leq 1$$

$$\Leftrightarrow \left(\frac{r_{t/n} \cdot \sin(\varphi)}{\alpha}\right)^{1.7} + \left(\frac{r_{t/n} \cdot \cos(\varphi)}{k_2}\right)^{1.7} \leq \left(f_{ub} \cdot A_s\right)^{1.7}$$

$$\Leftrightarrow r_{t/n,1} \leq \frac{f_{ub} \cdot A_s}{\sqrt[1.7]{\left(\frac{\sin(\varphi)}{\alpha}\right)^{1.7} + \left(\frac{\cos(\varphi)}{k_2}\right)^{1.7}}}$$

$$\Leftrightarrow r_{t/n,2} \leq \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3} \leq \min.\left\{\begin{array}{l}\dfrac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s\end{array}\right\}$$

$$\longrightarrow r_{t/n} = \min.\left\{\frac{f_{ub} \cdot A_s}{\sqrt[1.7]{\left(\frac{\sin(\varphi)}{\alpha}\right)^{1.7} + \left(\frac{\cos(\varphi)}{k_2}\right)^{1.7}}}; \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}; \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)}; F_{mf} = f_{ub} \cdot A_s\right\}$$

G.2 EN 1993-1-4 and EN 1993-1-8 (bilinear)

G.2.1 Unthreaded bolt part in the shear plane

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.4 \cdot F_{t,Rd}} \leq 1 \quad \text{with } F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A}{\gamma_{M2}} \text{ and } F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$$

$$\Leftrightarrow \frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot f_{ub} \cdot A} + \frac{r_{t/n} \cdot \cos(\varphi)}{1.4 \cdot k_2 \cdot f_{ub} \cdot A_s} \leq 1$$

$$\Leftrightarrow \frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot A} + \frac{r_{t/n} \cdot \cos(\varphi)}{1.4 \cdot k_2 \cdot A_s} \leq f_{ub}$$

$$\Leftrightarrow r_{t/n,1} \leq \frac{f_{ub}}{\frac{\sin(\varphi)}{\alpha \cdot A} + \frac{\cos(\varphi)}{1.4 \cdot k_2 \cdot A_s}}$$

$$\Leftrightarrow r_{t/n,2} \leq \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3} \leq \min.\left\{\begin{array}{l}\dfrac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s\end{array}\right\}$$

$$\longrightarrow r_{t/n} = \min.\left\{\frac{f_{ub}}{\frac{\sin(\varphi)}{\alpha \cdot A} + \frac{\cos(\varphi)}{1.4 \cdot k_2 \cdot A_s}}; \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}; \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)}; F_{mf} = f_{ub} \cdot A_s\right\}$$

G.2.2 Threaded bolt part in the shear plane

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.4 \cdot F_{t,Rd}} \leq 1 \quad \text{with } F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A_s}{\gamma_{M2}} \text{ and } F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$$

$$\Leftrightarrow \frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot f_{ub} \cdot A_s} + \frac{r_{t/n} \cdot \cos(\varphi)}{1.4 \cdot k_2 \cdot f_{ub} \cdot A_s} \leq 1$$

$$\Leftrightarrow \frac{r_{t/n} \cdot \sin(\varphi)}{\alpha} + \frac{r_{t/n} \cdot \cos(\varphi)}{1.4 \cdot k_2} \leq f_{ub} \cdot A_s$$

$$\Leftrightarrow r_{t/n,1} \leq \frac{f_{ub} \cdot A_s}{\frac{\sin(\varphi)}{\alpha} + \frac{\cos(\varphi)}{1.4 \cdot k_2}}$$

$$\Leftrightarrow r_{t/n,2} \leq \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3} \leq \min.\left\{\begin{array}{l}\dfrac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s\end{array}\right\}$$

$$\longrightarrow r_{t/n} = \min.\left\{\frac{f_{ub}}{\dfrac{\sin(\varphi)}{\alpha \cdot A} + \dfrac{\cos(\varphi)}{1.4 \cdot k_2 \cdot A_s}}; \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}; \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)}; F_{mf} = f_{ub} \cdot A_s\right\}$$

G.3 German National Annex DIN EN 1993-1-4/NA (bilinear)

G.3.1 Unthreaded bolt part in the shear plane

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.4 \cdot F_{t,Rd}} \leq 1 \quad \text{with } F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A_s}{\gamma_{M2}} \text{ and } F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$$

$$\Leftrightarrow \frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot f_{ub} \cdot A_s} + \frac{r_{t/n} \cdot \cos(\varphi)}{1.4 \cdot k_2 \cdot f_{ub} \cdot A_s} \leq 1$$

$$\Leftrightarrow \frac{r_{t/n} \cdot \sin(\varphi)}{\alpha} + \frac{r_{t/n} \cdot \cos(\varphi)}{1.4 \cdot k_2} \leq f_{ub} \cdot A_s$$

$$\Leftrightarrow r_{t/n,1} \leq \frac{f_{ub} \cdot A_s}{\dfrac{\sin(\varphi)}{\alpha} + \dfrac{\cos(\varphi)}{1.4 \cdot k_2}}$$

$$\Leftrightarrow r_{t/n,2} \leq \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3} \leq \min.\left\{\begin{array}{l}\dfrac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s\end{array}\right\}$$

$$\longrightarrow r_{t/n} = \min.\left\{\frac{f_{ub}}{\dfrac{\sin(\varphi)}{\alpha \cdot A} + \dfrac{\cos(\varphi)}{1.4 \cdot k_2 \cdot A_s}}; \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}; \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)}; F_{mf} = f_{ub} \cdot A_s\right\}$$

G.3.2 Threaded bolt part in the shear plane

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.4 \cdot F_{t,Rd}} \leq 1 \quad \text{with } F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A_s}{\gamma_{M2}} \text{ and } F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$$

$$\Leftrightarrow \frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot f_{ub} \cdot A_s} + \frac{r_{t/n} \cdot \cos(\varphi)}{1.4 \cdot k_2 \cdot f_{ub} \cdot A_s} \leq 1$$

$$\Leftrightarrow \frac{r_{t/n} \cdot \sin(\varphi)}{\alpha} + \frac{r_{t/n} \cdot \cos(\varphi)}{1.4 \cdot k_2} \leq f_{ub} \cdot A_s$$

$$\Leftrightarrow r_{t/n,1} \leq \frac{f_{ub} \cdot A_s}{\dfrac{\sin(\varphi)}{\alpha} + \dfrac{\cos(\varphi)}{1.4 \cdot k_2}}$$

$$\Leftrightarrow r_{t/n,2} \leq \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3} \leq \min.\left\{\begin{array}{l}\dfrac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{mf} = f_{ub} \cdot A_s\end{array}\right\}$$

$$\longrightarrow r_{t/n} = \min.\left\{\frac{f_{ub}}{\dfrac{\sin(\varphi)}{\alpha \cdot A} + \dfrac{\cos(\varphi)}{1.4 \cdot k_2 \cdot A_s}}; \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}; \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)}; F_{mf} = f_{ub} \cdot A_s\right\}$$

G.4 DIN 18800-1 for carbon steel bolts (quadratic)

G.4.1 Unthreaded bolt part in the shear plane

$$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^2 + \left(\frac{F_{t,Ed}}{F_{t,Rd}}\right)^2 \leq 1 \quad \text{with } F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A}{\gamma_{M2}} \text{ and } F_{t,Rd} = \frac{f_{ub} \cdot A_s}{1.25 \cdot \gamma_{M2}}$$

$$\Leftrightarrow \left(\frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot f_{ub} \cdot A}\right)^2 + \left(\frac{r_{t/n} \cdot \cos(\varphi)}{\dfrac{f_{ub} \cdot A_s}{1.25}}\right)^2 \leq 1$$

$$\Leftrightarrow \left(\frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot A}\right)^2 + \left(\frac{r_{t/n} \cdot \cos(\varphi)}{\dfrac{A_s}{1.25}}\right)^2 \leq f_{ub}{}^2$$

$$\Leftrightarrow r_{t/n,1} \leq \frac{f_{ub}}{\sqrt{\left(\dfrac{\sin(\varphi)}{\alpha \cdot A}\right)^2 + \left(\dfrac{1.25 \cdot \cos(\varphi)}{A_s}\right)^2}}$$

$$\Leftrightarrow r_{t/n,2} \leq \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3} \leq \min.\left\{\begin{array}{l}\dfrac{f_{ub} \cdot A_s}{1.25 \cdot \cos(\varphi)} \\ F_{m,min} = f_{ub} \cdot A_s\end{array}\right\}$$

$$\longrightarrow r_{t/n} = \min.\left\{\frac{f_{ub}}{\sqrt{\left(\dfrac{\sin(\varphi)}{\alpha \cdot A}\right)^2 + \left(\dfrac{1.25 \cdot \cos(\varphi)}{A_s}\right)^2}}; \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)}; \frac{f_{ub} \cdot A_s}{1.25 \cdot \cos(\varphi)}; F_{m,min} = f_{ub} \cdot A_s\right\}$$

G.4.2 Threaded bolt part in the shear plane

$$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^2 + \left(\frac{F_{t,Ed}}{F_{t,Rd}}\right)^2 \leq 1 \quad \text{with } F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A_s}{\gamma_{M2}} \text{ and } F_{t,Rd} = \frac{f_{ub} \cdot A_s}{1.25 \cdot \gamma_{M2}}$$

$$\Leftrightarrow \left(\frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot f_{ub} \cdot A_s}\right)^2 + \left(\frac{r_{t/n} \cdot \cos(\varphi)}{\dfrac{f_{ub} \cdot A_s}{1.25}}\right)^2 \leq 1$$

$$\Leftrightarrow \left(\frac{r_{t/n}\cdot\sin(\varphi)}{\alpha}\right)^2+\left(\frac{r_{t/n}\cdot\cos(\varphi)}{\frac{1}{1.25}}\right)^2\le\left(f_{ub}\cdot A_s\right)^2$$

$$\Leftrightarrow r_{t/n,1}\le\frac{f_{ub}\cdot A_s}{\sqrt{\left(\frac{\sin(\varphi)}{\alpha}\right)^2+\left(1.25\cdot\cos(\varphi)\right)^2}}$$

$$\Leftrightarrow r_{t/n,2}\le\frac{\alpha\cdot A_s\cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3}\le\min.\left\{\begin{matrix}\frac{f_{ub}\cdot A_s}{1.25\cdot\cos(\varphi)}\\ F_{m,min}=f_{ub}\cdot A_s\end{matrix}\right\}$$

$$\longrightarrow r_{t/n}=\min.\left\{\frac{f_{ub}\cdot A_s}{\sqrt{\left(\frac{\sin(\varphi)}{\alpha}\right)^2+\left(1.25\cdot\cos(\varphi)\right)^2}};\frac{\alpha\cdot A_s\cdot f_{ub}}{\sin(\varphi)};\frac{f_{ub}\cdot A_s}{1.25\cdot\cos(\varphi)};F_{m,min}=f_{ub}\cdot A_s\right\}$$

G.5 New interaction approaches of Renner/Lange for carbon steel bolts

G.5.1 Unthreaded bolt part in the shear plane

$$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^{1.5}+\left(\frac{F_{t,Ed}}{1.25\cdot F_{t,Rd}}\right)^{1.5}\le 1 \quad \text{with } F_{v,Rd}=\frac{\alpha\cdot f_{ub}\cdot A}{\gamma_{M2}} \text{ and } F_{t,Rd}=\frac{k_2\cdot f_{ub}\cdot A_s}{\gamma_{M2}}$$

$$\Leftrightarrow \left(\frac{r_{t/n}\cdot\sin(\varphi)}{\alpha\cdot f_{ub}\cdot A}\right)^{1.5}+\left(\frac{r_{t/n}\cdot\cos(\varphi)}{1.25\cdot k_2\cdot f_{ub}\cdot A_s}\right)^{1.5}\le 1$$

$$\Leftrightarrow \left(\frac{r_{t/n}\cdot\sin(\varphi)}{\alpha\cdot A}\right)^{1.5}+\left(\frac{r_{t/n}\cdot\cos(\varphi)}{1.25\cdot k_2\cdot A_s}\right)^{1.5}\le f_{ub}^{1.5}$$

$$\Leftrightarrow r_{t/n,1}\le\frac{f_{ub}}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha\cdot A}\right)^{1.5}+\left(\frac{\cos(\varphi)}{1.25\cdot k_2\cdot A_s}\right)^{1.5}}}$$

$$\Leftrightarrow r_{t/n,2}\le\frac{\alpha\cdot A\cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3}\le\min.\left\{\begin{matrix}\frac{1.25\cdot k_2\cdot f_{ub}\cdot A_s}{\cos(\varphi)}\\ F_{m,min}=f_{ub}\cdot A_s\end{matrix}\right\}$$

$$\longrightarrow r_{t/n}=\min.\left\{\frac{f_{ub}}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha\cdot A}\right)^{1.5}+\left(\frac{\cos(\varphi)}{1.25\cdot k_2\cdot A_s}\right)^{1.5}}};\frac{\alpha\cdot A\cdot f_{ub}}{\sin(\varphi)};\frac{1.25\cdot k_2\cdot f_{ub}\cdot A_s}{\cos(\varphi)};F_{m,min}=f_{ub}\cdot A_s\right\}$$

G.5.2 Threaded bolt part in the shear plane

$$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^{1.5}+\left(\frac{F_{t,Ed}}{F_{t,Rd}}\right)^{1.5}\leq 1 \quad \text{with } F_{v,Rd}=\frac{\alpha\cdot f_{ub}\cdot A_s}{\gamma_{M2}} \text{ and } F_{t,Rd}=\frac{k_2\cdot f_{ub}\cdot A_s}{\gamma_{M2}}$$

$$\Leftrightarrow \left(\frac{r_{t/n}\cdot\sin(\varphi)}{\alpha\cdot f_{ub}\cdot A_s}\right)^{1.5}+\left(\frac{r_{t/n}\cdot\cos(\varphi)}{1.25\cdot k_2\cdot f_{ub}\cdot A_s}\right)^{1.5}\leq 1$$

$$\Leftrightarrow \left(\frac{r_{t/n}\cdot\sin(\varphi)}{\alpha}\right)^{1.5}+\left(\frac{r_{t/n}\cdot\cos(\varphi)}{k_2}\right)^{1.5}\leq \left(f_{ub}\cdot A_s\right)^{1.5}$$

$$\Leftrightarrow r_{t/n,1}\leq \frac{f_{ub}\cdot A_s}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha}\right)^{1.5}+\left(\frac{\cos(\varphi)}{k_2}\right)^{1.5}}}$$

$$\Leftrightarrow r_{t/n,2}\leq \frac{\alpha\cdot A_s\cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3}\leq \min.\left\{\begin{matrix}\frac{k_2\cdot f_{ub}\cdot A_s}{\cos(\varphi)}\\ F_{m.min}=f_{ub}\cdot A_s\end{matrix}\right\}$$

$$\longrightarrow r_{t/n}=\min.\left\{\frac{f_{ub}\cdot A_s}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha}\right)^{1.5}+\left(\frac{\cos(\varphi)}{k_2}\right)^{1.5}}};\frac{\alpha\cdot A_s\cdot f_{ub}}{\sin(\varphi)};\frac{k_2\cdot f_{ub}\cdot A_s}{\cos(\varphi)};F_{m,min}=f_{ub}\cdot A_s\right\}$$

G.6 New interaction approaches of Može for carbon steel bolts

G.6.1 Unthreaded bolt part in the shear plane

$$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^{1.5}+\left(0.9\cdot\frac{F_{t,Ed}}{F_{t,Rd}}\right)^{1.5}\leq 1 \quad \text{with } F_{v,Rd}=\frac{\alpha\cdot f_{ub}\cdot A}{\gamma_{M2}} \text{ and } F_{t,Rd}=\frac{k_2\cdot f_{ub}\cdot A_s}{\gamma_{M2}}$$

$$\Leftrightarrow \left(\frac{r_{t/n}\cdot\sin(\varphi)}{\alpha\cdot f_{ub}\cdot A}\right)^{1.5}+\left(\frac{r_{t/n}\cdot 0.9\cdot\cos(\varphi)}{k_2\cdot f_{ub}\cdot A_s}\right)^{1.5}\leq 1$$

$$\Leftrightarrow \left(\frac{r_{t/n}\cdot\sin(\varphi)}{\alpha\cdot A}\right)^{1.5}+\left(\frac{r_{t/n}\cdot 0.9\cdot\cos(\varphi)}{k_2\cdot A_s}\right)^{1.5}\leq f_{ub}^{\,1.5}$$

$$\Leftrightarrow r_{t/n,1}\leq \frac{f_{ub}}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha\cdot A}\right)^{1.5}+\left(\frac{0.9\cdot\cos(\varphi)}{k_2\cdot A_s}\right)^{1.5}}}$$

$$\Leftrightarrow r_{t/n,2}\leq \frac{\alpha\cdot A\cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3}\leq \min.\left\{\begin{matrix}\frac{k_2\cdot f_{ub}\cdot A_s}{\cos(\varphi)}\\ F_{m,min}=f_{ub}\cdot A_s\end{matrix}\right\}$$

$$\longrightarrow r_{t/n} = \min.\left\{ \frac{f_{ub}}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha \cdot A}\right)^{1.5} + \left(\frac{0.9 \cdot \cos(\varphi)}{k_2 \cdot A_s}\right)^{1.5}}} ; \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)} ; \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} ; F_{m,min} = f_{ub} \cdot A_s \right\}$$

G.6.2 Threaded bolt part in the shear plane

$$\left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^{1.5} + \left(0.9 \cdot \frac{F_{t,Ed}}{F_{t,Rd}}\right)^{1.5} \leq 1 \quad \text{with } F_{v,Rd} = \frac{\alpha \cdot f_{ub} \cdot A_s}{\gamma_{M2}} \text{ and } F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}}$$

$$\Leftrightarrow \left(\frac{r_{t/n} \cdot \sin(\varphi)}{\alpha \cdot f_{ub} \cdot A_s}\right)^{1.5} + \left(\frac{r_{t/n} \cdot 0.9 \cdot \cos(\varphi)}{k_2 \cdot f_{ub} \cdot A_s}\right)^{1.5} \leq 1$$

$$\Leftrightarrow \left(\frac{r_{t/n} \cdot \sin(\varphi)}{\alpha}\right)^{1.5} + \left(\frac{r_{t/n} \cdot 0.9 \cdot \cos(\varphi)}{k_2}\right)^{1.5} \leq \left(f_{ub} \cdot A_s\right)^{1.5}$$

$$\Leftrightarrow r_{t/n,1} \leq \frac{f_{ub} \cdot A_s}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha}\right)^{1.5} + \left(\frac{0.9 \cdot \cos(\varphi)}{k_2}\right)^{1.5}}}$$

$$\Leftrightarrow r_{t/n,2} \leq \frac{\alpha \cdot A_s \cdot f_{ub}}{\sin(\varphi)}$$

$$\Leftrightarrow r_{t/n,3} \leq \min.\left\{ \begin{array}{l} \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} \\ F_{m,min} = f_{ub} \cdot A_s \end{array} \right\}$$

$$\longrightarrow r_{t/n} = \min.\left\{ \frac{f_{ub} \cdot A_s}{\sqrt[1.5]{\left(\frac{\sin(\varphi)}{\alpha}\right)^{1.5} + \left(\frac{0.9 \cdot \cos(\varphi)}{k_2}\right)^{1.5}}} ; \frac{\alpha \cdot A \cdot f_{ub}}{\sin(\varphi)} ; \frac{k_2 \cdot f_{ub} \cdot A_s}{\cos(\varphi)} ; F_{m,min} = f_{ub} \cdot A_s \right\}$$