DNV·GL

STANDARD

DNVGL-ST-0361 Edition September 2016

Machinery for wind turbines

DNV GL AS

FOREWORD

DNV GL standards contain requirements, principles and acceptance criteria for objects, personnel, organisations and/or operations.

Any comments may be sent by e-mail to *rules@dnvgl.com*

CHANGES – CURRENT

General

This is a new document.

Contents

Contents

Contents

SECTION 1 INTRODUCTION

1.1 Objectives

This DNV GL standard provides principles, technical requirements and guidance for design and manufacturing of machinery components and structures for wind turbines onshore and offshore in order to maintain safety and function in ultimate and serviceability limit states.

The present DNV GL standard can be applied as part of the technical basis for carrying out a DNV GL certification of wind turbines according to the DNV GL service specifications DNVGL-SE-0441, DNVGL-SE-0190, DNVGL-SE-0073 and DNVGL-SE-0074.

The basis for the machinery standard is the safe life design method. The damage tolerant design approach is not considered within this standard.

Guidance note:
The present DNV GL standard will cover the technical requirements to be applied for the DNV GL certification schemes and it is also intended to cover the requirements implied when using IEC 61400-22 related certification schemes.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

The objectives of this standard are to:

— provide an internationally acceptable level of safety by defining minimum requirements for machinery components and structures in wind turbines (in combination with referenced standards, recommended practices, guidelines, etc.).
— serve as design basis for designers, suppliers, purchasers and regulators.
— specify requirements for wind turbines subject to DNV GL certification.

1.2 Scope and application

This standard is the DNV GL standard for the design of machinery components and structures for the complete wind turbine. The standard assumes a typical wind turbine and a design lifetime of 20 years. However, the content and the requirements stipulated in this standard can be transferred to all types of wind turbines.

Machinery components and structures for wind turbines shall be designed with the aim that:

— the maintaining of normal operational conditions will be ensured
— the safety of personnel and installations will be ensured and risks of injury to human life will be reduced to a minimum
— the machinery components and structures will reach the expected design life time
— sufficiently high reliability is reached for the entire system.

This standard covers:

— materials
— corrosion protection
— bolted connections
— machinery structures
— bearings
— blade pitching systems
— yaw systems
— mechanical brakes and locking devices
— couplings
— elastomer bushings
— hydraulic systems
— gearboxes
— nacelle covers and spinners.

This standard specifies requirements for the design of machinery components and structures for wind turbines intended to ensure a safety level that is deemed acceptable for such systems. Some of these requirements imply certain constraints on the designs that reflect the current practice in the industry and established principles of design and construction of wind turbines. Alternative designs and arrangements that deviate from these requirements may be accepted provided that it is documented that the level of safety is at least as high as that implied by the requirements of this standard. Technology qualification procedures may be helpful in this context.

Guidance note:
A recommended method for identifying risk control options and documenting the safety of alternative designs and arrangements is given in DNV-RP-A203.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

1.3 References

The standards and guidelines in Table 1-1 include provisions, which through reference in this text constitute requirements of this standard.

If not stated explicitly always the latest version/edition of the referenced specifications, standards and guidelines shall be considered.

Table 1-1 Standards and guidelines

Reference	*Title*
DNVGL-SE-0073	Project certification of wind farms according to IEC 61400-22
DNVGL-SE-0074	Type and component certification of wind turbines according to IEC 61400-22
DNVGL-SE-0190	Project certification of wind power plants
DNVGL-SE-0439	Certification of condition monitoring
DNVGL-SE-0441	Type and component certification of wind turbines
DNVGL-ST-0054	Transport and installation of wind power plants (planned published in 2016)
DNVGL-ST-0076	Design of electrical installations for wind turbines
DNVGL-ST-0126	Design of wind turbine support structures
DNVGL-ST-0376	Rotor blades for wind turbines
DNVGL-ST-0437	Load and site conditions for wind turbines (planned published in 2016)
DNVGL-ST-0438	Control and protection systems for wind turbines
DNVGL-RP-0416	Corrosion protection for wind turbines
DNVGL-RP-C203	Fatigue design of offshore steel structures
DNV-RP-A203	Technology qualification
DNVGL-RU-SHIP Part 2	DNVGL Rules for Classification, Ships, Part 2: Materials and Weldings, Chapter 2: Metallic Materials
GL-IV-2	Guideline for the Certification of Offshore Wind Turbines, Edition 2012
DASt-Richtlinie 021	Schraubenverbindungen aus feuerverzinkten Garnituren M39 bis M72 entsprechend EN 14399-4, EN 14399-6
DIN 740-1:1986	Power transmission engineering; flexible shaft couplings; technical delivery conditions
DIN 743	Calculation of load capacity of shafts and axles
DIN 3990-4:1987	Calculation of load capacity of cylindrical gears; calculation of scuffing load capacity
DIN 6892:2012	Drive type fastenings without taper action - Parallel keys - Calculation and design
DIN 7190	Interference fits - Calculation and design rules
DIN 50930	Corrosion of metals - Corrosion of metallic materials under corrosion load by water inside of pipes, tanks and apparatus
EN 362	Personal protective equipment against falls from a height – Connectors
EN 515	Aluminium and aluminium alloys - Wrought products - Temper designations
EN 573	Aluminium and aluminium alloys - Chemical composition and form of wrought products
EN 755-2	Aluminium and aluminium alloys - Extruded rod/bar, tube and profiles - Part 2: Mechanical properties

Table 1-1 Standards and guidelines (Continued)

Reference	*Title*
EN 1011-2	Welding - Recommendation for welding of metallic materials - Part 2: Arc welding of ferritic steels
EN 1090	Execution of steel structures and aluminium structures
EN 1369:1996	Founding - Magnetic particle testing, Edition 1996
EN 1369:2012	Founding - Magnetic particle testing, Edition 2012
EN 1371-1:1997	Founding - Liquid penetrant testing - Part 1: Sand, gravity die and low pressure die castings, Edition 1997
EN 1371-1:2011	Founding - Liquid penetrant testing - Part 1: Sand, gravity die and low pressure die castings, Edition 2011
EN 1559-1:2001	Founding - Technical conditions of delivery - Part 1: General
EN 1559-2:2000	Founding - Technical conditions of delivery - Part 2: Additional requirements for steel castings
EN 1559-3:1997	Founding - Technical conditions of delivery - Part 3: Additional requirements for iron castings
EN 1563:2012-03	Founding - Spheroidal graphite cast irons
EN 1706	Aluminium and aluminium alloys - Castings - Chemical composition and mechanical properties
EN 1993-1-8	Eurocode 3: Design of steel structures - Part 1-8: Design of joints
EN 1993-1-9:2005	Eurocode 3: Design of steel structures - Part 1-9: Fatigue
EN 1993-1-10	Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings
EN 10025	Hot rolled products of structural steels
EN 10083-1	Steels for quenching and tempering - Part 1: General technical delivery conditions
EN 10084	Case hardening steels - Technical delivery conditions
EN 10088-1	Stainless steels - Part 1: List of stainless steels
EN 10088-2	Stainless steels - Part 2: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes
EN 10160	Ultrasonic testing of steel flat product of thickness equal to or greater than 6 mm (reflection method)
EN 10164	Steel products with improved deformation properties perpendicular to the surface of the product - Technical delivery conditions
EN 10204:2005	Metallic products – Types of inspection documents
EN 10213	Steel castings for pressure purposes
EN 10228-1	Non-destructive testing of steel forgings - Part 1: Magnetic particle inspection
EN 10228-2	Non-destructive testing of steel forgings - Part 2: Penetrant testing
EN 10228-3	Non-destructive testing of steel forgings - Part 3: Ultrasonic testing of ferritic or martensitic steel forgings
EN 10228-4	Non-destructive testing of steel forgings - Part 4: Ultrasonic testing of austenitic and austenitic-ferritic stainless steel forgings
EN 10250-1	Open die steel forgings for general engineering purposes – Part 1: General requirements
EN 10250-2	Open die steel forgings for general engineering purposes – Part 2: Alloy special steels Non-alloy quality and special steels
EN 10250-3	Open die steel forgings for general engineering purposes – Part 3: Alloy special steels
EN 10328	Iron and steel - Determination of the conventional depth of hardening after surface heating
EN 12495	Cathodic protection for fixed steel offshore structures
EN 12680-2:2003	Founding - Ultrasonic examination - Part 2: Steel castings for highly stressed components
EN 12680-3:2011	Founding - Ultrasonic testing - Part 3: Spheroidal graphite cast iron castings
EN 12681:2003	Founding - Radiographic examination
EN 13173	Cathodic protection for steel offshore floating structures

Table 1-1 Standards and guidelines (Continued)

Reference	*Title*
EN 14399-3	High-strength structural bolting assemblies for preloading - Part 3: System HR - Hexagon bolt and nut assemblies
EN 14399-4	High-strength structural bolting assemblies for preloading - Part 4: System HV - Hexagon bolt and nut assemblies; German version EN 14399-4:2015
IEC 60721-3-3	Classification of environmental conditions - Part 3: Classification of groups of environmental parameters and their severities; section 3: Stationary use at weatherprotected locations (IEC 60721-3-3:1994)
IEC 61400-22	Wind turbines - Part 22: Conformity testing and certification
IIW	International Institute of Welding – Recommendations for Fatigue Design of welded joints and components, IIW-2259-15 ex XIII-2460-13/XV-1440-13 (2016) and IIW-1823-07 ex XIII-2151r4-07/XV-1254r4-07 (2008)
ISO 76:2006	Rolling bearings - Static load ratings
ISO 281:2007	Rolling bearings - Dynamic load ratings and rating life
ISO 898-1:2009	Mechanical properties of fasteners made of carbon steel and alloy steel - Part 1: Bolts, screws and studs with specified property classes - Coarse thread and fine pitch thread
ISO 945-1:2008	Microstructure of cast irons - Part 1: Graphite classification by visual analysis
ISO 1083:2004	Spheroidal graphite cast irons – Classification
ISO 1219-2	Fluid power systems and components - Graphical symbols and circuit diagrams - Part 2: Circuit diagrams
ISO 1328-1:1995	Cylindrical gears - ISO system of flank tolerance classification - Part 1: Definitions and allowable values of deviations relevant to flanks of gear teeth
ISO 2639	Steels - Determination and verification of the depth of carburized and hardened cases
ISO 3452	Non-destructive testing - Penetrant testing
ISO 3754	Steel; Determination of effective depth of hardening after flame or induction hardening
ISO 4406:1999	Hydraulic fluid power - Fluids - Method for coding the level of contamination by solid particles
ISO 4413	Hydraulic fluid power - General rules and safety requirements for systems and their components
ISO 4967	Steel - Determination of content of non-metallic inclusions - Micrographic method using standard diagrams
ISO 4992-2:2006	Steel castings - Ultrasonic examination - Part 2: Steel castings for highly stressed components
ISO 4993:2009	Steel and iron castings - Radiographic testing
ISO 5579	Non-destructive testing - Radiographic testing of metallic materials using film and X- or gamma rays - Basic rules
ISO 6336-1:2006	Calculation of load capacity of spur and helical gears - Part 1: Basic principles, introduction and general influence factors
ISO 6336-2:2006	Calculation of load capacity of spur and helical gears - Part 2: Calculation of surface durability (pitting)
ISO 6336-3:2006	Calculation of load capacity of spur and helical gears - Part 3: Calculation of tooth bending strength
ISO 6336-5:2003	Calculation of load capacity of spur and helical gears - Part 5: Strength and quality of materials
ISO 6336-6:2006	Calculation of load capacity of spur and helical gears - Part 6: Calculation of service life under variable load
ISO 7010	Graphical symbols - Safety colours and safety signs - Registered safety signs
ISO 8044	Corrosion of metals and alloys - Basic terms and definitions
ISO 8501-1	Preparation of steel substrates before application of paints and related products - Visual assessment of surface cleanliness - Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings

Table 1-1 Standards and guidelines (Continued)

Reference	*Title*
ISO 8501-3	Preparation of steel substrates before application of paints and related products - Visual assessment of surface cleanliness - Part 3: Preparation grades of welds, edges and other areas with surface imperfections
ISO 9016	Destructive tests on welds in metallic materials - Impact tests - Test specimen location, notch orientation and examination
ISO 9712	Non-destructive testing - Qualification and certification of NDT personnel
ISO 10684	Fasteners - Hot dip galvanized coatings (ISO 10684:2004 + Cor. 1:2008)
ISO 12944-1	Paints and varnishes - Corrosion protection of steel structures by protective paint systems – Part 1: General introduction
ISO 12944-3	Paints and varnishes - Corrosion protection of steel structures by protective paint systems - Part 3: Design considerations
ISO 12944-5	Paints and varnishes - Corrosion protection of steel structures by protective paint systems - Part 5: Protective paint systems
ISO 14635-1:2000	Gears - FZG test procedures - Part 1: FZG test method A/8,3/90 for relative scuffing load-carrying capacity of oils
ISO 14919	Thermal spraying - Wires, rods and cords for flame and arc spraying - Classification - Technical supply conditions
ISO 15156	Petroleum and natural gas industries - Materials for use in H?S-containing environments in oil and gas production
ISO 16269-6:2014	Statistical interpretation of data -- Part 6: Determination of statistical tolerance intervals
ISO 16810	Non-destructive testing - Ultrasonic testing - General principles
ISO 20340	Paints and varnishes - Performance requirements for protective paint systems for offshore and related structures
ISO/IEC 17000	Conformity assessment - Vocabulary and general principles
ISO/IEC 17025	General requirements for the competence of testing and calibration laboratories (ISO/IEC 17025:2005)
ISO/TR 13989	Calculation of scuffing load capacity of cylindrical, bevel and hypoid gears - Flash temperature method
ISO/TR 15144-1:2010	Calculation of micropitting load capacity of cylindrical spur and helical gears - Part 1: Introduction and basic principles
ISO/TS 16281:2008	Rolling bearings - Methods for calculating the modified reference rating life for universally loaded bearings; Technical Corrigendum 1
NORSOK M-503	Cathodic protection
NREL DG03	NREL Wind Turbine Design Guideline DG03: Yaw and pitch rolling bearing life, Section 4
SEW 550	Stahl-Eisen-Werkstoffblatt [steel/iron materials data sheet]; Steels for larger forgings; quality regulations
VDG Instruction Sheet P-541	Verein Deutscher Giessereifachleute - VDG Instruction Sheet P-541
VDI 2230	Systematic calculation of highly stressed bolted joints
VDI 2645 part 2	Capability test for fastening technology - Machine capability test – MCT
VDI 2862 part 2	Minimum requirements for application of fastening systems and tools - Applications in plant construction, mechanical engineering, equipment manufacturing and for flange connections in components under pressure boundary

Table 1-2 References to literature

/1/	Haibach, E.: Betriebsfestigkeit [Fatigue Strength], 3rd Edition, VDI-Verlag 2006
/2/	Gudehus, H.; Zenner, H.: Leitfaden für eine Betriebsfestigkeitsrechnung [Guideline for fatigue stength analysis], Stahleisen GmbH, 3rd Edition, 1995

1.4 Informative references

For additional acceptable methods to fulfil the requirements in this standard see also current service documents published on www.dnvgl.com/rules-standards. Other recognized codes or standards may be applied provided it is shown that they meet or exceed the level of safety of the actual standard.

1.5 Definitions

1.5.1 Terminology and definitions

The use of verbal forms is given in Table 1-3, definition of terms in Table 1-4.

Table 1-3 Definitions of verbal forms

Term	*Definition*
shall	verbal form used to indicate requirements strictly to be followed in order to conform to the document
should	verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required
may	verbal form used to indicate a course of action permissible within the limits of the document

Table 1-4 Definitions of terms

Term	*Definition*
certification	refers to third-party issue of a statement, based on a decision following review, that fulfilment of specified requirements has been demonstrated related to products, processes or systems (ISO/IEC 17000:2004)
recommendation	non-mandatory advice
verification	verification consists of evaluating and checking information to establish that an object in question meets a technical requirement or standard Multiple verification activities are performed and successfully completed to support the decision to issue a statement of compliance.
wind turbine	system which converts kinetic energy in the wind into electric energy

1.5.2 Acronyms and abbreviations

Table 1-5 Acronyms and abbreviations

Short form	*In full*
A	fracture elongation
A	abnormal (for partial safety factors)
BIAX	bi-axial
BPA	Bisphenol A
C	carbon
CAD	computer aided design
CEV	carbon equivalent
CRP	carbon fibre reinforced plastic
DLC	design load case
DOF	degrees of freedom
E	extreme (for partial safety factors)
EC	Eurocode
F	fatigue
FFT	fast Fourier transform
FEM	finite element method
FRP	fibre reinforced plastic

Table 1-5 Acronyms and abbreviations (Continued)

Short form	*In full*
FZG	Forschungsstelle für Zahnräder und Getriebebau [Research institute for gears and gearbox design]
GRP	glassfibre reinforced plastic
HB	Brinell hardness
HRC	Rockwell hardness
HV	Vickers hardness
K_v	Charpy impact energy
LDD	load duration distribution
LRF	load relevant control and safety function
MCT	machine capability test
MT	magnetic particle testing
N	normal (for partial safety factors)
PPE	personal protective equipment
PT	liquid penetrant testing
RT	radiographic testing
SCF	stress concentration factor
SRF	stress reserve factor
T	transport, erection and maintenance (for partial safety factors and for the wind speed
U, ULS	ultimate limit state
UT	ultrasonic testing
WPQR	welding procedure qualification records
WPS	welding procedure specifications

1.5.3 Symbols

Table 1-6 Latin characters

A	cross-section area (strength) reference surface (the projected area)
A	elongation at fracture
a	centre distance
a_{ISO}	life modification factor
B_{z0}	tool offset
b	common tooth width
c_{p}	drag coefficient
C_1, C_2, C_3	corrosion class in ISO 12944
D	damage
D, d	diameter (e.g. of rotor, bolt)
D_{admi}	admissible damage sum
D_{PW}	pitch diameter of ball or roller set
D_{W}	nominal ball diameter
d_{a}	tip diameter
d_{f}	root diameter
E	E-modulus (modulus of elasticity, Young's modulus)
F	force
F_{Design}, F_{d}	design load
F_{i}	force acting in the direction i = x, y or z
Fi	impact force
F_{k}	characteristic load

Table 1-6 Latin characters (Continued)

F_{Smax}	max. bolt force under extreme load
F_{test}	load to be applied
$F_{0,2min}$	bolt force at the 0.2% elastic strain limit
$F_{\beta x}$	initial equivalent misalignment
f, f_a	frequency
f_{pe}	normal pitch error
f_f	profile form error
f_{yk}	yield strength
f_{uk}	characteristic tensile strength
g	acceleration due to gravity (= 9.81m/s²)
h	working depth of the teeth
$h_{a0}{}^*$	coefficient of tool addendum
$h_{fP0}{}^*$	coefficient of tool dedendum
$h_{FfP0}{}^*$	utilized dedendum coefficient tool
j	casting quality level
j_0	constant
K_A	application factor for static and fatigue strength analysis
$K_{F\alpha}$	transverse load factor, root stress
$K_{F\beta}$	face load factor, root stress
$K_{H\alpha}$	transverse load factor, contact stress
$K_{H\beta}$	face load factor, contact stress
k_s	reduction factor for the design S/N curve of large bolts
K_v	impact energy
K_v	dynamic factor for internal dynamic loads
K_γ	load distribution factor
L, l, ℓ	length
L_{10}	basic rating life
L_{10m}	modified rating life
L_{10mr}	modified reference rating life
l_{eff}	effective length
M	moment
M	mean stress sensitivity
M_B	braking moment
M_{Bmin}	minimum required braking moment
M_{Bmax}	maximum braking moment
$M_{B\ op\ min}$	minimum operational braking moment
m	slope parameter of the S/N curve
m_G	mass
m_n	normal module
N	total number or revolutions
N_i	permissible load cycle number
N	recurrence period for extreme conditions
n	quantity
n	notch sensitivity
n	operating speed
n_i	number of revolutions
n_r	rated operational speed
n_1	minimal operational speed
n_3	maximal operational speed
n_{ref}	reference load cycle number

Table 1-6 Latin characters (Continued)

P	power
P	probability
P	equivalent load
P_i	dynamic equivalent load
P_s	survival probability
p	pressure
p_{max}	maximum contact stress
pr	protuberance
p_{sk}	wind pressure/suction
pl	number of balancing planes
Q	accuracy according to ISO
q	machining allowance
q_i	time share on the i-th load level
R	stress or strain ratio
R, r	radius
$\mathrm{R_a}$	arithmetic surface roughness
$\mathrm{R_{aF}}$	mean peak to valley roughness of root
$\mathrm{R_{aH}}$	mean peak to valley roughness of flank
R_d	design strength
R_k	characteristic strength
R_m	tensile strength
$R_{p0.2}$	characteristic yield strength (0.2% proof test)
$\mathrm{R_z}$	surface roughness
S	safety factor
S_d	reduction factor – casting quality
S_{min}	minimum safety factor
S_A	safety factor for micropitting
S_B, S_{intS}	safety factors for scuffing
S_F	safety factor for tooth breakage
S_H	safety factor for pitting
S_{Ps}	reduction factor – survival probability
S_0	static safety factor acc. to ISO 76:2006
T	temperature
T_g	glass transition temperature
t	thickness (component, wall, plate)
U	generally permissible residual imbalance per balancing plane of the respective part
V	wind speed
v_{wind}	highest extreme wind speed
w	displacement in the z direction
x	coordinate
y	coordinate
Y_{NT}	life factor (tooth breakage)
z	number of teeth
z	coordinate
Z_{NT}	life factor (pitting)

Table 1-7 Greek characters

α_0	nominal contact angle
α_k	stress concentration factor
α_n	normal pressure factor
α_{pr}	protuberance angle
β	helix angle
γ_{1t}	factor accounting for scattering of the component characteristics in series production
γ_F	partial safety factor for the loads
γ_M	material partial safety factor
γ_N	partial safety factor for consequence of failure
δ_{Oil}	oil temperature
ν	kinematic viscosity
ρ	density
ρ_{a0}	coefficient of tool tip radius
σ	stress
σ_a, σ^*_A	stress amplitude
σ_{HP}	Hertzian stress
$\Delta\sigma_A$, $\Delta\sigma^*_A$	reference value of the S/N curve
$\Delta\sigma_D$	fatigue limit
$\Delta\sigma_i$	stress range
$\sigma_{H\ lim}$	endurance limit for contact stress
$\sigma_{F\ lim}$	endurance limit for bending stress
σ_{lim}	limiting stress
σ_m	mean stress
σ_{Rc}	corrected fatigue strength reference value of S/N curve at $2 \cdot 10^6$
σ_S	structural or hot spot stress

Table 1-8 Subscripts

A	amplitude
air	air
cyl	cylinder
d, D	design value
F	load, action
fat	fatigue
M	material, mean value
m	mean value
max.	maximum
min.	minimum
p	pre-stress
R	resisting
x	coordinate designation
y	coordinate designation
z	coordinate designation

SECTION 2 MATERIALS

2.1 General requirements

2.1.1 General

2.1.1.1 Only suitable materials with guaranteed properties (e.g. strength, toughness – at low temperatures if appropriate, cold deformability, suitability for welding, corrosion resistance etc.) shall be used for load carrying components of a wind turbine.

2.1.1.2 Materials chosen shall be matched to the demands on the component, particularly the type of load (shock load, oscillating load) as well as the external conditions (see DNVGL-ST-0437), and to the design. The materials chosen shall be named clearly and comprehensively in the documents (drawings, specifications, parts lists, etc.) to be submitted for approval.

2.1.1.3 All materials not listed in this section shall be treated in accordance with the relevant standards as regards quality requirements and test conditions. The special environmental and operational conditions of the wind turbine shall be taken into account.

2.1.1.4 The temperature range for the materials to be used is laid down in DNVGL-ST-0437. The use of materials outside this temperature range necessitates separate assessment by DNV GL.

2.1.1.5 Where tests are required, these shall be performed by the manufacturer unless specified otherwise in this standard. The material tests shall be carried out by an accredited testing laboratory (ISO/IEC 17025) or witnessed by DNV GL.

2.1.2 Categories of structural members

2.1.2.1 In the selection of materials for the different members of the structure, the criteria explained below shall be observed:

— importance of the member within the structure (consequence of failure, redundancy)
— character of load and stress level (static or dynamic loads, residual stresses, stress concentrations, direction of stresses in relation to the rolling direction of the material etc.)
— cesign temperature
— chemical composition (suitability for welding, chemical compatibility with other materials)
— yield strength and tensile strength of the material (dimensioning criteria)
— ductility of the material (resistance to brittle fracture at given design temperature)
— through-thickness properties (resistance to lamellar tearing).

Additional properties, such as corrosion resistance, shall be considered.

2.1.2.2 Depending on the importance of the structural member and on the type of load and the stress level, a structure may be subdivided into the following component categories: primary structural, secondary structural and special structural members, see DNVGL-ST-0126 [4.2.3.3] Table 4-1.

Guidance note:
For the components of machinery structures commonly the categories primary and secondary apply. In case the category "special" is used the requirements defined in DNVGL-ST-0126 and the additional requirements in Table 2-5 shall be applied.

Main frame, generator carrier, main bearing housings, hub, torque arm, and planet carrier are categorised as primary structural members.

Secondary structural members are e.g. non-structural walls, stairs, pedestals, mountings for cables etc.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

2.1.3 Material tests

Classification of materials for components

2.1.3.1 The type and extent of material testing depends on the importance of the component and stress in a component. If nothing else has been determined in detail, the following requirements shall apply.

2.1.3.2 Material tests shall be documented in accordance with EN 10204:2005. The material certificates shall contain the results of the tests as required in the reference material standards or additionally agreed or requested on the basis of the design requirements. Material certificates shall furthermore contain data of the unique marking of the material batch to permit reliable tracing to components.

2.1.3.3 The general requirements for material certificates shall be defined with respect to the importance of the component. Therefore, the material certificate is related to the significance of the structural member, see [2.1.2] and DNVGL-ST-0126 [4.2.8] Table 4-5.

2.1.3.4 In cases of doubt, the classification of the materials for components or assemblies shall be agreed with DNV GL. In the case of components not obtained with material certificates, the scope of the substitute requirements shall be agreed with DNV GL.

2.1.3.5 For special materials, production processes or components, DNV GL may extend the scope by additional material testing accordingly. The approach shall be agreed together with DNV GL in advance.

Statistical interpretation of material test results

2.1.3.6 Suitable statistical methods shall be employed to guarantee that the required survival probability is attained with the required level of confidence. The method shall be agreed in advance with DNV GL. The interpretation of the test results shall incorporate a determination of the systematic error and a description of the random error (statistical interpretation).

2.1.3.7 Unless requested otherwise and provided that a normal distribution of the test results is given, the statistical interpretation shall be carried out using a confidence level of $1-\alpha = 0.95$ for a probability of $P = 95\%$ and an unknown variance of the population at least (e.g. ISO 16269-6:2014).

2.2 Metallic materials

2.2.1 General

2.2.1.1 Metallic materials to be employed for wind turbine components shall fulfil the minimum requirements detailed below. Beyond this, other codes and standards should be observed as far as applicable.

2.2.1.2 Metallic materials used for the force- and moment-transmitting components of a wind turbine shall have guaranteed properties (e.g. strength and toughness – at low temperatures if appropriate, cold deformability, suitability for welding etc.), as mentioned in the next section.

2.2.1.3 The use of materials according to other regulations or standards may require the consent of DNV GL.

Guidance note:

Metallic materials are generally differentiated into ductile (e.g. S235 J2+N), semi-ductile (e.g. EN-GJS- 400-18U-LT) and non-ductile (e.g. EN-GJS-700-2U) materials. A material is seen as brittle in case one of the following requirements is met: fracture elongation $A < 12.5\%$, impact energy $K_{V\ mean} < 10$ J (mean value of three tests).

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

2.2.1.4 Material tests shall be performed in accordance with [2.1.3].

2.2.1.5 For the machinery components such as gears, bearings, brakes, couplings etc., materials suitable for these components shall be used. Quality requirements and test conditions shall be taken from the relevant standards, taking into account the environmental operational conditions (see DNVGL-ST-0437). Further special requirements are listed in Sec.6, Sec.7 and Sec.8.

2.2.1.6 The actual material qualities of the component shall be taken into account in fatigue verification by using related reduction factors for S/N curves in accordance with the specified quality (e.g. j and j0, see [4.5.2]). If the quality is defined differently in specific areas of the component, it shall be assured that areas of different quality are covered by the analysis.

2.2.1.7 Surface preparation measures applied before corrosion protection shall not degrade the specified surface roughness. A surface roughness value R_z shall be specified for raw and cleaned (non-machined) areas of structural components made from materials such as cast iron, cast steel and forged steel. This shall correspond to the assumptions of the computational analyses as per [4.4].

2.2.1.8 For complex cast structural components, a casting simulation shall be used to determine casting-critical component areas and to justify the specified cast quality of the respective component. If results from the casting simulation are used for design calculations, it is necessary to calibrate the results of the casting simulation with the cast component. The procedure shall be agreed with DNV GL in advance.

Guidance note:
The following components e.g. are regarded as complex cast structural components:

Hub, main frame, bearing housing, main shaft and tower top adapter.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

2.2.2 Selection criteria of steels for welded structures

2.2.2.1 Structural steels are subdivided, depending on their minimum yield strength, into the strength classes normal strength, high strength and extra high strength, see Table 4-2 in [4.2.4] of DNVGL-ST-0126.

Guidance note:
In particular for reasons of resistance to fatigue, for primary structures, fine-grained structural steels suitable for welding with nominal yield strengths not exceeding 355 N/mm^2 are recommended. High-strength steels having nominal yield strengths (or 0.2% proof stresses) exceeding 460 N/mm^2 may be employed in exceptional cases only, with the corresponding technical justification and with DNV GL consent.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

2.2.2.2 The strength class chosen for the respective structural member and/or the kind of material corresponding to it is to be indicated in the design documentation. The same applies to the special requirements possibly having to be met by the material.

2.2.2.3 Steels with improved through-thickness properties shall be employed where structural members are rigid and/or particularly thick and where high residual welding stresses are to be expected, e.g. due to T-joints, large-volume single-bevel butt joints or double-bevel butt joints with full root penetration, simultaneously implying high stresses acting in the through-thickness direction of the materials.

2.2.2.4 Depending on the structural member category, the design temperature and the material thickness, all steels to be employed for the structure shall meet the requirements listed in [2.2.3], in particular those for impact energy.

2.2.2.5 Table 4-4 [4.2.5] of DNVGL-ST-0126 contains thickness limitations of structural steels for different structural categories and design temperatures. The grade of steel to be used shall in general be selected according to the design temperature and the thickness for the applicable structural category.

2.2.3 Requirements for steels for welded structures

Manufacturing procedures

2.2.3.1 The requirements in DNVGL-ST-0126 [4.2.4] apply in general.

2.2.3.2 The following deoxidation practice shall be applied as a minimum:

— steels with an impact test temperature of ≥ 0°C shall at least be semi-killed, i.e. equivalent to the deoxidation method FN according to EN 10025.
— steels with an impact test temperature of < 0°C shall be fully killed, FF according to EN 10025.
— steels with requirements for the through-thickness properties (see [2.2.2.3]) shall be fully killed and fine grained. Special requirements for the material composition shall be agreed (see [2.2.3.9]).

Supply condition and heat treatment

2.2.3.3 Steels intended for primary structural members shall be supplied normalized/normalized rolled (N), thermomechanically rolled (M) or quenched and tempered (QT), as for example defined in EN 10025.

2.2.3.4 The steels shall fulfil the requirements for the general thickness limits prescribed in EN 10025. Beyond this, the thickness limits acc. to [4.2.5] Table 4-4 of DNVGL-ST-0126 shall apply.

Guidance note:

The thickness limits are specified in [4.2.5] Table 4-4 of DNVGL-ST-0126 and are, for example, applicable in cases where high local stresses occur, especially in connection with the negative influences due to the heat-affected zone of a welding (e.g. thick butt or fillet welds).

For unaffected base material, the general thickness limits as specified above apply, e.g. for the flange body of ring flanges with neck.

Steel structures exceeding the general thickness limits may be employed in exceptional cases for technical reasons, subject to additional requirements on material testing and with DNV GL's prior consent.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

Chemical composition and suitability for welding

2.2.3.5 Table 4-2 [4.2.4] of DNVGL-ST-0126, contains a selection of appropriate steels for plates and sections. It shall be checked from case to case, whether the envisaged material complies with the impact energy requirements as laid down in the present standard and in the design specification.

2.2.3.6 Steels produced in accordance with other standards may be employed, provided they have equivalent properties. In that case, they shall be correlated to the steel grades listed in Table 4-2 [4.2.4] of DNVGL-ST-0126 in accordance with their properties.

2.2.3.7 Steels not listed in DNVGL-ST-0126 or not being part of EN 10025 shall fulfil the requirements for the chemical composition with respect to the carbon equivalent CEV as listed in Table 2-1:

$$CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}$$

Table 2-1 Maximum carbon equivalent CEV in %

Steel strength class	Material quality N [1]		Material Quality M + Q [1]	
	$t \leq 40$ mm	$t > 40$ mm	$t \leq 40$ mm	$t > 40$ mm
High strength	0.42	0.45	0.42	0.45
Extra high strength	0.45		0.43	
Normal strength	0.42		0.38	
[1] N, M and Q see EN-10025				

2.2.3.8 If the values listed in Table 2-1 are exceeded, the chemical composition with respect to weldability (CEV) shall be verified in accordance with EN 1011-2 appendix C.2. The limitations for hydrogen content, preheating temperature, plate thickness and heat input in dependence of the CEV shall be observed. This is applicable for fine grained, non-alloyed and low alloy steels. The suitability of welding for other steel grades shall be agreed with DNV GL.

2.2.3.9 Steels with requirements for the through-thickness properties (see [2.2.2.3]) shall not exceed the limit value of 0.010% for sulphur, as determined by heat analysis.

Thickness limitations of structural steels

2.2.3.10 Table 4-4 [4.2.4] of DNVGLST0126 contains thickness limitations of structural steels for different structural categories and design temperatures. The grade of steel to be used shall in general be selected according to the design temperature and the thickness for the applicable structural category.

2.2.3.11 Post-weld heat treatment should generally be performed at structural welds of joints exceeding the thickness limitations given in Table 4-4, [4.2.4] of DNVGL-ST-0126, unless adequate fracture toughness can be proven in the as-welded condition by an evaluation based on fracture mechanics testing and analysis. For restrained joints of complicated design, post-weld heat treatment may be required for thicknesses less than those given in Table 4-4, [4.2.4] of DNVGL-ST-0126.

Mechanical properties

2.2.3.12 For steels with required impact test temperatures ≤ -20°C, the yield strength ratio f_{yk}/f_{uk} respectively $R_{p0,2}/f_{uk}$ as defined in Table 2-2 shall not be exceeded.

Table 2-2 Maximum yield strength ratio

<table>
<tr><th rowspan="2">Steel strength class</th><th colspan="2">Material quality N [1]</th><th colspan="2">Material Quality M + Q [1]</th></tr>
<tr><th>t ≤ 16 mm</th><th>t > 16 mm</th><th>t ≤ 16 mm</th><th>t > 16 mm</th></tr>
<tr><td>Normal strength</td><td>0.80</td><td>0.80</td><td>0.80</td><td>0.80</td></tr>
<tr><td>Extra high strength</td><td rowspan="2">0.87</td><td rowspan="2">0.85</td><td rowspan="2">0.93</td><td rowspan="2">0.90</td></tr>
<tr><td>High strength</td></tr>
<tr><td colspan="5">[1] N, M and Q see EN-10025</td></tr>
</table>

Guidance note:
This requirement is fulfilled in general by all steel grades as listed in EN 10025.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

2.2.3.13 If impact tests shall be performed for welds, the specimen position of the notched bar impact test shall be in line with ISO 9016:2012.

2.2.3.14 The minimum values listed in Table 2-3 shall be observed in compliance with the test temperature as prescribed in [2.2.3.10] to [2.2.3.11].

Table 2-3 Impact energy[1]

<table>
<tr><td colspan="2">Minimum nominal yield strength[2] [N/mm²]</td><td>235</td><td>275</td><td>355</td><td>420</td><td>460[3]</td></tr>
<tr><td>Minimum impact energy [J] (Charpy V notch test specimen)</td><td>Longitudinal: primary and secondary category</td><td>27</td><td>30</td><td>40</td><td>47</td><td>50</td></tr>
<tr><td colspan="7">1 Average values of 3 specimens; one of the values may be below the average value, but not less than 70% of the average value.
2 Intermediate values may be interpolated.
3 Impact energy requirements for steels with nominal yield strengths exceeding 460 N/mm² shall be agreed with DNV GL in advance.</td></tr>
</table>

Through-thickness properties

2.2.3.15 If properties are to be proven in the through-thickness direction (see [2.2.2.3]), the testing shall be carried out in the final heat treatment condition. Testing is not required for a product thickness below 15 mm. The test shall be in accordance with EN 10164 and the test results shall meet the requirements in accordance with EN 1993-1-10.

Internal defects

2.2.3.16 Regarding their internal defects (flaws), plates and wide flats for which through-thickness property requirements exist shall meet at least the requirements listed in the relevant standards, e.g. EN 10160 quality class S2/E2 or equivalent.

2.2.3.17 All flange materials shall be tested additionally with respect to being free of laminations and internal defects by means of ultrasonic testing.

Inspections

2.2.3.18 Unless otherwise fixed or agreed, the requirements as stated in [2.1.3] shall apply.

2.2.3.19 Materials for special structural members of offshore wind turbines shall be inspected according DNVGL-ST-0126.

Identification and marking

2.2.3.20 All products shall be marked such as to enable their clear identification and correlation to the inspection documentation. The minimum information for marking is the manufacturer’s symbol, heat No. and steel grade.

2.2.3.21 Products which cannot be clearly identified shall be rejected during the incoming goods inspection, unless the stipulated properties can be determined by re-inspection.

2.2.4 Requirements for cast steels

General

2.2.4.1 Where cast steels are intended to be employed for primary structural members, relevant materials specifications containing all details required for assessment shall be submitted to DNV GL for evaluation. For secondary structural members, appropriate materials in accordance with the standards may be employed.

2.2.4.2 For structures and components in accordance with Sec.4, Sec.7 and Sec.8, cast steels of the grades listed in Table 2-4 may be used.

Table 2-4 Applicable steel grades

Steel grades	Applicable standard
GE200 GE240 GE300	EN 10293
GP240GH+QT GP280GH+QT G17Mn5 G20Mn5+N G20Mn5+QT	EN 10213

Cast steel grades according to other specifications or standards may also be used with the consent of DNV GL, provided they are proven to be equivalent to the grades listed above with respect to their mechanical properties and, if appropriate, weldability and also provided that proof has been furnished of their suitability for the intended application. For this purpose, a once-only suitability test may be required.

2.2.4.3 Unless agreed otherwise, the quality requirements and test conditions in accordance with the above-mentioned standards apply to steel castings. Furthermore, the provisions set out in EN 1559-1:2011 and EN 1559-2:2000 shall be observed.

Approval test

2.2.4.4 An approval test shall be assessed by DNV GL in case cast steels and non-standardized materials are to be employed for primary structural members. Such kind of verification is based on 30 probes picked randomly of different heats for each wall thickness range acc. to standard (component specific).

Supply conditions

2.2.4.5 All products shall be supplied in heat-treated condition. Heat treatment may comprise:

— normalizing
— normalizing and tempering
— quenching and tempering.

Chemical composition

2.2.4.6 The composition of cast steel grades suitable for welding shall meet the requirements according to [2.2.3.7]. Alloyed steels shall comply with the requirements listed in the approved specification.

Strength properties

2.2.4.7 The tensile and yield strength values of forgings and castings shall be adapted to those of rolled steels employed for the remaining structure. In general, steel castings with a yield strength exceeding 355 N/mm^2 shall not be employed.

Toughness requirements

2.2.4.8 Steel castings shall show adequate resistance to brittle fracture at design temperatures. Unless otherwise stipulated, the minimum requirements for impact energy, as listed in Table 2-5, apply.

Table 2-5 Minimum impact energy requirements[1] for steel casting

Minimum impact energy (Charpy-V-notch) [J] min.	Test temperature[2] [°C]	
	Special structural members	Primary structural members
30	-40	-20

1 Products employed for secondary structural members are subject to the requirements listed in the standards
2 If the design temperatures are below the specified test temperatures, special requirements shall be agreed

Scope of testing

2.2.4.9 Unless otherwise stipulated in the approved specification, the products shall be combined into heats of up to 10 t each and shall be subjected to tensile and notched bar impact tests.

2.2.4.10 For cast components that are predominantly dynamically stressed, quality level 3 in conjunction with EN 12681:2003 or ISO 4993:2009 (Radiographic test), EN 12680-2:2003 or ISO 4992-2:2006 (Ultrasonic test), EN 1371-1:2011 (Dye penetration test) and EN 1369:1996 (Magnetic particle test) is the minimum permitted. The quality levels shall correspond to the assumptions of the computational analyses as per [4.5.2].

2.2.4.11 Steel castings may not exhibit any faults which might adversely affect their use and appropriate processing.

2.2.4.12 The removal of faults through fabrication welding or repair welding is permissible only with specifications approved by DNV GL. The qualification of the welding workshop and the welder performing the work shall be verified in accordance with DNVGL-ST-0126.

2.2.5 Stainless steels

2.2.5.1 Stainless steels shall be selected with respect to their resistance to corrosion, taking into account the processing conditions (e.g. welding). Unless agreed otherwise for individual cases, suitable steels, e.g. according to EN 10088 (Stainless steels) and EN 10213 (Steel castings for pressure purposes) may be selected.

2.2.5.2 Only those grades suitable for welding with guaranteed resistance to intercrystalline corrosion may be used for welded structures. Only grades of cast steel that are corrosion-resistant shall be used, e.g. cast steels stabilized or containing not more than 0.03% C.

2.2.5.3 Other grades of cast steel conforming to other standards or material specifications may be used, provided that they are comparable to the grades of cast steel described in EN 10213-4 with respect to their delivery condition, heat treatment, chemical composition, mechanical properties and weldability, and provided that proof has been furnished of their suitability for the intended application. For this purpose, a first-time suitability test may be required.

2.2.5.4 The limits for the lowest design temperatures according to [2.1.1] shall be observed.

2.2.6 Forging steels

Standards

2.2.6.1 Forgings and bar stock for structures and components as per Sec.6 and Sec.7 shall be selected in accordance to EN 10083, in the case of larger cross-sections (i.e. thicknesses greater than 100 mm/250 mm; see EN 10083) according to Stahl-Eisen-Werkstoffblatt (Steel/Iron Materials Data Sheet) SEW 550 or EN 10250 Part 1-3. Further notes on selecting suitable materials may also be taken from DNVGL Rules for Classification, Ships, Part 2: Materials and Weldings, Chapter 2: Metallic Materials. For tempering and case-hardening steels, e.g. for manufacturing of gear- wheels and pinions, EN 10083 and EN 10084 apply; for stainless steels, EN 10088 applies. Forgings and bar stock in accordance with other standards or manufacturers' material specifications may be used if properties equivalent to those in the standards listed above can be guaranteed, and if proof has been furnished of their suitability for the intended application. For this purpose, a first-time suitability test may be required. If the dimensions or mechanical properties of the forgings are not covered by the above-mentioned standards, a material qualification shall be agreed with DNV GL.

Production processes

2.2.6.2 Forging steels shall be produced by basic oxygen steelmaking processes in an electric furnace or by other processes approved by DNV GL and shall be fully killed. Cleanliness shall be tested according to ISO 4967, Method A. Forgings with specified minimum tensile strength of 800 N/mm^2 shall be vacuum treated prior to or during pouring of the ingot, in order to remove gases and improve steel cleanliness. Other processes may be accepted provided that an adequate obtained cleanliness is documented. On request, DNV GL shall be informed of the steelmaking process used. A sufficient amount of material shall be cropped from the top and bottom ends of ingots to ensure that the forgings are free from any harmful segregations. This term includes all inhomogeneties liable to impair the required characteristics.

2.2.6.3 Given a reasonable machining allowance, work pieces shall as far as possible be forged to the final dimensions. Excessive machining to give the forging its final shape which may impair its characteristics, e.g. by laying open the core zone, is not allowed. Necks of shafts, pinions and journals exceeding 1/10 of the outer diameter shall be produced as far as possible by stepped forging. The degree of deformation shall be such that the core zone of the forging undergoes sufficient plastic deformation.

2.2.6.4 *L* and *D* are the length and diameter respectively of the part of the forging under consideration. Annular and hollow shapes shall be produced from sections cut from the ingot or bloom which have been suitably punched, drilled or trepanned before the parts are rolled or expanded over a suitable mandrel.

2.2.6.5 Unless otherwise approved, the total reduction ratio shall be at least:

— for forgings made from ingots or from forged blooms or billets, 3:1 where $L > D$ and 1.5:1 where $L < D$
— for forgings made from rolled products, 4:1 where $L > D$ and 2:1 where $L < D$
— for forgings made by upsetting, the length after upsetting shall not be more than one-third of the length before upsetting or, in the case of an initial forging reduction of at least 1.5:1, not more than one-half of the length before upsetting.
— for rolled bars, 6:1
— for continuous cast material, the minimum reduction is 5:1.

Heat treatment

2.2.6.6 All forgings shall be heat-treated in a manner appropriate to the material. The treatment shall be carried out in suitable furnaces, maintained effectively and regularly. These shall be equipped with a means for controlling and indicating the temperature. The dimensions of the furnace shall make it possible to bring the entire forging uniformly to the required annealing temperature. Where, in the case of very large forgings, the furnace dimensions do not permit total normalizing in one step, alternative heat treatment processes shall be agreed with DNV GL.

2.2.6.7 All hot-forging work shall be completed before the final heat treatment. If a forging has for any reason to be reheated for further hot working, the final heat treatment shall be repeated.

2.2.6.8 If a forging is hot- or cold-straightened after final heat treatment, subsequent stress-relieving to remove the residual stress may be required.

2.2.6.9 Forgings which, after forging, undergo large changes in cross-section by machining may be hardened and tempered only after adequate pre-treatment. The weight at hardening and tempering shall not be more than 1.25 times the finished weight.

General forging quality

2.2.6.10 All forgings shall be free from any faults which may impair use and processing to more than an insignificant extent, e.g. flakes, cracks, shrinkage holes, segregations, peripheral blowholes and major non-metallic inclusions. Forgings to be delivered unmachined shall have a smooth surface appropriate to the production process.

2.2.6.11 Small surface faults may be removed by pointing and/or grinding. Complete removal of the fault shall be demonstrated by a magnetic crack detection test or a dye penetration test.

2.2.6.12 The removal of defects by welding is permissible only in exceptional cases with the agreement of DNV GL if the defects are of limited extent and occur at points which are subject to low operating loads. The removal of faults by fabrication welding or repair welding is only permissible with approved procedure testing. With regard to the qualification of the welding workshop and the welder performing the work, DNVGL-ST-0126 shall be observed. Prior to the start of welding work of this type, the welding process, the heat treatment and the scope of the testings shall be agreed with DNV GL.

2.2.6.13 Proof of the chemical composition: The manufacturer shall determine the chemical composition of every melt and submit a corresponding certificate in accordance with [2.1.3]. This certificate shall state the chemical composition of the melt which characterizes the steel grade.

2.2.6.14 Grain refining elements and elements designated as residual elements in the individual specification shall be reported.

2.2.6.15 If there is any doubt as to the composition, or if the correspondance between certificate and forging cannot be proven, a product analysis shall be carried out.

Mechanical-technological testing

2.2.6.16 Tensile testing: The mechanical properties shall be checked by means of the tensile test, in which the tensile strength, the yield limit or 0.2% elastic strain limit, the elongation at fracture and the reduction of the sectional area at fracture are to be determined.

2.2.6.17 Charpy impact testing: A Charpy impact test shall be carried out. Unless otherwise specified, the Charpy impact energy shall be verified on every forging or test piece by Charpy impact testings, and the minimum requirements for impact energy, as listed in Table 2-6, apply.

Table 2-6 Minimum impact energy requirements[1] for forgings

Minimum impact energy (Charpy-V-notch) [J] min.	Test temperature[2] [°C]	
	Special structural members	Primary structural members
longitudinally: 40 transversely: 30	-40	-20

1 Products employed for secondary structural members are subject to the requirements listed in the standards
2 If the design temperatures are below the specified test temperatures, special requirements are to be agreed

2.2.6.18 Samples: As a rule, samples from forgings shall be taken by forging-on sample sections outside the forging dimensions. The position, shape and size of the samples shall be chosen to achieve forming ratios and cooling rates similar to those in the dynamically highly stressed regions of the component. The sample section may generally be separated from the forging only after the final heat treatment. Subsequent stress relieving need not be taken into account in this connection. Premature separation is permitted only if unavoidable for production reasons. In this event, the forging and the sample section shall be heat-treated together.

2.2.6.19 Deviating from this provision, in the case of series-production drop forgings, the samples may be taken from items surplus to requirements or separately forged sample sections; these shall belong to the same melt and be heat-treated together with the associated items under test. The test batch sizes laid down in the standards apply with respect to the sample selection.

2.2.6.20 All sample cut-offs shall be forged with the same degree of deformation of a cross-section which is also representative of the forging's typical cross-section. The sample cut-offs shall be large enough to provide specimens for all tests which might be necessary as well as those required for any repeated testing.

2.2.6.21 All test sections and samples shall be so marked that they can be clearly related to the forgings or test batches which they represent.

2.2.6.22 The test specimens may be taken from the samples in the longitudinal, tangential or transverse direction in relation to the fibre pattern; see Figure 2-1.

2.2.6.23 The location of the test specimens in the cross-section of the heat-treated region shall be taken starting from the surface at a distance of 1/4 of the diameter or the (wall) thickness, but max. 80 mm, and at a corresponding distance from a further, adjacent surface.

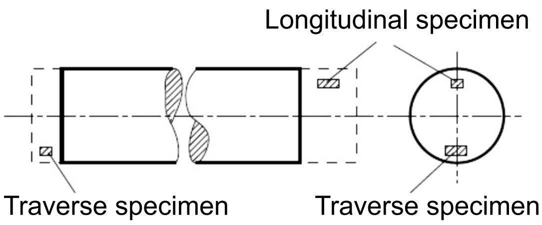

Figure 2-1 Position of test specimens

2.2.6.24 First article inspection: The mechanical properties of the test specimens shall be verified by a first article inspection (FAI) extracted of a representative component. Results of the FAI shall be made available to DNV GL on request. In special cases DNV GL might request to witness the FAI.

Non-destructive testing

2.2.6.25 If surface crack testing is required, it shall preferably be performed by means of the magnetic crack detection method according to EN 10228-1, except in the case of austenitic steels. The tests shall generally be carried out on forgings which have undergone final heat treatment, if possible after machining. If current flow is being used, care shall be taken that no penetration points are caused by the contact electrodes. The effective tangential field intensity shall be at least 2 kA/m (25 Oe) at the workpiece surface, but shall not exceed 5 kA/m (62.5 Oe).

2.2.6.26 Surface crack tests using the liquid dye penetration method shall preferably be performed for austenitic steels or for other materials only in exceptional and well documented cases. The tests shall be carried out with a testing-medium combination comprising penetrant, intermediate cleaner and developer in accordance with the instructions of the manufacturer of the testing-medium. A surface crack test by the dye penetration method shall be performed prior to any sandblasting or shot peening processing of the component. EN 10228-2/ISO 3452 shall be applied.

2.2.6.27 For ultrasonic testing, the general principles of the ISO 16810, EN 10228-3, and EN 10228-4 shall be applied. Ultrasonic testing shall preferably be carried out while the component still has a simple geometric shape, the components to be tested having been at least normalized. Provided it is permitted by the shape and size of the component, the component shall be inspected both radially and axially. Technical data relating to the test, such as method, type of appliance, probe type, appliance adjustment, recording threshold and error margins shall be laid down and made known by the manufacturer according to ISO 16810. The qualification of the tester shall be demonstrated according to ISO 9712. The company shall prepare a report on the ultrasonic testing according to ISO 16810 containing the assessment of the readings and a listing of all readings above threshold level.

Requirements for surface finish and dimensions

2.2.6.28 The manufacturer shall inspect each forging for surface finish and compliance with the dimensional and geometrical tolerances. The surface of the forgings shall be clean and properly prepared for inspection, and surface defects shall be removed. This condition shall be achieved wherever necessary, unless the parts are to be submitted in the rough-machined condition.

2.2.7 Cast iron

2.2.7.1 For structures and components in accordance with Sec.4, Sec.7 and Sec.8, cast iron with spheroidal graphite (EN-GJS) according to EN 1563:2012-03 may be used, depending on the mechanical properties required. The provisions set out in EN 1559-1:2011 and EN 1559-3:1997 shall be observed.

2.2.7.2 Without additional verification, cast iron with a fracture elongation A < 12.5% or an impact energy $K_{V\ mean}$ < 10 J (mean value of three tests) shall not be used for components that play a significant role in the transmission of force and are under high dynamic loading, e.g. rotor hub, gearbox housing with integrated rotor bearings, main bearing housing and machine foundations.

2.2.7.3 Load-carrying structures, which are made of non-ductile high-strength cast iron with a fracture elongation A < 12.5% or an impact energy $K_{V\ mean}$ < 10 J (mean value of three tests) with spheroidal graphite, require an extension of the common design calculations by an adequate qualification procedure, in case calculated SRF factors are 1.0 < SRF <= 1.5. The details of the qualification procedure shall be agreed with DNV GL. No qualification procedure is needed in case the following requirements are fulfilled:

— critical areas of the component regarding stresses from fatigue and ultimate loads or experiencing high strain rates shall fulfil quality level 01 of EN 12680-3:2011 with reference to volume and surface testing.
— 100% quality testing of these critical areas is required in series production of the component.
— component areas prone to casting defects shall not overlap with critical areas of the component regarding stresses. This can be determined by evaluating the cast simulation of the respective component or by NDT testing.
— the requirements listed above have to be fulfilled during the design assessment of the component, e.g. by component specifications.
— an inspection of the implementation of above mentioned requirements at the respective component manufacturer shall be performed during manufacturing evaluation of the component.

2.2.7.4 An alternative qualification procedure shall be applied, e.g. by fracture mechanics calculations, if the aforementioned items will not be considered. Fracture mechanics calculations shall be based on material properties derived from material testing of specimens taken from the respective structure. The details of the qualification procedure shall be agreed in advance with DNV GL.

2.2.7.5 The Charpy impact energy shall be verified at a temperature corresponding to the minimum design temperature (see [2.1.1.4]). If Charpy impact testing at the minimum design temperature is not applicable for a chosen material, an alternative evaluation procedure to verify the suitability of the material at the minimum design temperature shall be agreed with DNV GL.

Guidance note:
A correlation between the results of the toughness tests (agreed beforehand with DNV GL) and those of the Charpy tests may be used in order to define the minimum test temperature to perform the Charpy impact test in series production.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

2.2.7.6 For the determination of the microstructure, ISO 945-1:2008 shall be applied. The manufacturing process of cast iron with spheroidal graphite shall ensure that 90% of the graphite has been segregated in the spheroidal form V and VI and in the spheroidal size between 3 (5 for the rim zone) and 7 according to ISO 945-1:2008. For the ferritic types, the pearlite proportion within the grain structure of the metallic base material shall not exceed 10% following ISO 1083:2004.

2.2.7.7 The use of other types of cast iron according to other standards or material specifications shall be agreed with DNV GL.

2.2.7.8 For the assessment of the casting quality of components with consideration of internal flaws, non-destructive testing methods such as ultrasonic (according to EN 12680-3:2011) and/or radiographic tests (according to EN 12681:2003) shall be applied. For radiographic tests, the radiation source shall be selected in relation to the maximum wall thicknesses in accordance with ISO 5579. If no satisfactory rear-panel or error echo is obtained for the ultrasonic test, a combination with the radiographic testing shall be performed.

2.2.7.9 For components that are predominantly dynamically stressed and made of cast iron with spheroidal graphite, a quality level requirement shall be set according to EN 12680-3:2011 (Ultrasonic test) and VDG instruction sheet P-541 (Verein Deutscher Giessereifachleute) in conjunction with EN 12681:2003 (Radiographic test), EN 1369:1996 (magnetic crack detection test) and EN 1371-1:1997 (Dye penetration test). These shall correspond to the assumptions of the computational analyses as per ?4.5.2. For machined surfaces, the worst acceptable are quality levels SM/LM/AM 2 according to EN 1369:1996 or SP/CP/LP/AP 2 according to EN 1371-1:1997. The quality levels LM/AM according EN 1369:2012 and LP/AP according EN 1371-1:2011 shall be converted acc. to Annex A of the respective standard if the new versions are applied.

2.2.7.10 The flaw types blowholes (flaw class A), non-metallic inclusions (B) and enclosed shrinkage holes (C) shall be classified according to their quality after the radiographic test (see also Table 2-7). Here the worst acceptable is quality level 3 according to VDG instruction sheet P-541. Dross or shrinkage holes cut by mechanical processing are fundamentally inadmissible and shall be removed by mechanical means, taking into account the permissible reduction in wall thickness. Dross shall be evaluated by ultrasonic test for the entire component, a quality level 01 according to EN 12680-3:2011, table 2, shall be achieved. All other types of flaws shall, if applicable, be assessed separately and possible countermeasures shall be coordinated with DNV GL.

Table 2-7 Allocation of the flaw class to wall thicknesses and quality levels for radiographic testing of EN-GJS on the basis of VDG instruction sheet P-541

Quality level	Flaw classes		
	Wall thickness up to 100 mm	Wall thickness >100 – 250 mm	Wall thickness >250 – 400 mm
1	A1, B1, C1	A1, B1, C2	A1, B1, C3
2	A2, B2, C2	A2, B2, C3	A2, B2, C4
3	A3, B3, C4	A3, B3, C5	A3, B3, C6

2.2.7.11 For components that are predominantly dynamically stressed and made of cast iron with spheroidal graphite, a quality level requirement shall be set according to EN 12680-3:2011 for indications to be reported. Here the worst acceptable is quality level 3.

2.2.7.12 For the flaws which are near to the surface of components predominantly under dynamic stress, a quality level requirement shall be set according to EN 1369:1996 (Magnetic crack detection test) or EN 1371-1:2011 (Dye penetration test) for indications to be reported. Here the worst acceptable is quality level 3.

2.2.7.13 The removal of sample cut-offs or test specimens for determining the mechanical-technological properties and the grain and graphite structures, and for determining the casting quality, shall be so executed that the typical characteristics of the component are registered properly. In many cases, it is necessary to prescribe varying sampling points on the component.

2.2.7.14 All sample cut-offs and test specimens shall be so marked that they can be clearly assigned. The corresponding specifications shall be submitted to DNV GL.

2.2.7.15 The test results shall be documented in accordance with [2.1.3].

2.2.7.16 Mixed welding of dynamically stressed components is inadmissible. Dross or shrinkage holes cut by mechanical processing are fundamentally inadmissible in highly stressed areas and shall be removed by mechanical means, taking into account the permissible reduction in wall thickness. All other types of flaws shall, if applicable, be assessed separately and possible countermeasures shall be coordinated with DNV GL. The removal of faults by fabrication welding or repair welding is permissible only with approved welding procedure specifications (WPS) and welding procedure qualification records (WPQR).

2.2.7.17 The removal of faults by fabrication welding or repair welding is permissible only with approved procedure testing. With regard to the qualification of the welding workshop and the welder performing the work, DNVGL-ST-0126 shall be applied. Prior to the start of welding work of this type, the welding process, the heat treatment and the scope of the tests shall be agreed with DNV GL. DNV GL shall be involved at a very early stage of the process.

2.2.7.18 The limits for the lowest design temperatures according to [2.1.1] shall be observed.

2.2.8 Aluminium alloys

2.2.8.1 Only those aluminium alloys that are suitable for the intended purpose and have been approved by DNV GL shall be used. If applicable, proof of suitability for welding shall be furnished for the alloys.

2.2.8.2 With respect to fatigue strength and sensitivity to notches, aluminium is comparable to high-tensile steels, and therefore demands careful design and manufacturing.

2.2.8.3 Proper processing and suitable corrosion protection shall be applied in order to prevent contact corrosion and particularly corrosion in a marine atmosphere.

2.2.9 Wrought alloys

2.2.9.1 For the chemical composition of the aluminium alloys, EN 573 shall be observed, for the mechanical properties EN 755-2, and for the definition of the material conditions of semifinished products EN 515.

2.2.9.2 Compliance with the tolerances and the requirements for the general condition lies within the responsibility of the manufacturer.

2.2.10 Cast alloys

2.2.10.1 The chemical composition and mechanical properties of castings made of aluminium and aluminium alloys shall comply with the values given in EN 1706.

2.2.10.2 All castings shall be free from any internal or external faults which may impair use and competent processing to more than an insignificant extent.

2.2.10.3 If defects are to be removed by welding, the manufacturer shall compile a welding specification and obtain the consent of DNV GL. Furthermore, in the case of doubts concerning the freedom from defects of the castings, non-destructive tests shall be initiated by the casting manufacturer and performed at the relevant points. Repaired defects as well as areas that are critical from the viewpoint of casting technology shall be included in the tests.

2.2.10.4 The results of the tests shall be documented in accordance with [2.1.3].

SECTION 3 CORROSION PROTECTION

3.1 Machinery for wind turbines

3.1.1 General

3.1.1.1 Corrosion protection shall be taken into account by the selection of suitable materials and appropriate coatings and protective films, plus regular inspection. The assessment of mechanical and electrical components shall take into account not only the integrity but also the influence of corrosion on functioning, e.g. jamming of rusted joints or failure of sensors. In particular, freedom from corrosion is assumed for fatigue calculations.

3.1.1.2 In general the recommendations given in DNVGL-RP-0416 or equivalent shall be followed.

3.1.1.3 Offshore wind turbine components are exposed to aggressive environmental conditions and are not easily accessible. Because of the operational conditions the repair of protective coating is not possible in many cases. Special importance therefore relates to the design, choice of material and corrosion protection measures.

3.1.1.4 Offshore wind turbines shall be classed in "marine atmosphere" with respect to corrosion attack.

3.1.1.5 Recognized codes and standards of institutions such as NACE, DIN, BSI, NORSOK, ISO may be used for the design, if the classification of the risk potential is applied in a correct manner.

3.1.1.6 The basic terms and definitions for corrosion of metals and alloys in ISO 8044 and ISO 15156 and coating systems in ISO 12944 shall be applied. For the different structure types, the terms and definitions according to EN 12495, EN 13173 and NORSOK M-503 shall be applied.

3.1.1.7 Corrosion damage may be prevented by the following corrosion protection measures:

— designing the systems and components through the application of suitable structural measures according to ISO 12944-3; see [3.1.3].
— influencing the characteristics of the reaction partners and/or modification of the reaction conditions
— separating metallic material from the electrolyte by protective layers
— electrochemical action, see [3.2.4].

3.1.1.8 For the accessible areas within the atmosphere, an appropriate coating or a metallic coating according to ISO 12944 or an equivalent standard shall be taken.

3.1.1.9 For novel corrosion protection systems not yet proven for the envisaged application, proof of suitability, e.g. by experiments, is required.

3.1.1.10 A structural design which takes into account corrosion protection and reduction has a significant effect on the ease of implementation, the effectiveness and the repairability of the corrosion protection. Basic rules are addressed in e.g. ISO 12944-3 and ISO 12944-5.

3.1.1.11 Surfaces prone to corrosion should be designed to be as smooth as possible. Any necessary stiffenings, fittings, pipes etc. are, wherever possible, to be located in low-corrosion regions. Inaccessible hollow components are to be welded airtight.

3.1.1.12 Areas in which water or aggressive media can accumulate (water pockets) shall be avoided by means of suitable measures such as slopes, passages or run-offs. Condensation shall be reduced by means of design measures such as ventilation.

3.1.1.13 Residues from welding, such as slag, loosely attached splashes and beads, shall be removed. Splashes or beads melted onto the surface shall be removed if the coating system makes this necessary. ISO 8501-3 shall be observed. Normally P2 or P3 according to ISO 8501-3, Table 1, are taken into account. This shall be agreed with DNV GL beforehand.

3.1.1.14 For all parts of the structure to be coated, burrs are to be removed and sharp edges rounded off to fulfil the preparation grade "good" according to ISO 12944-3, Fig. D5.

3.1.1.15 For areas which cannot be protected by coatings or protective coverings, suitable materials shall be used. The corrodibility of various materials is described in DIN 50930.

3.1.2 Coatings

3.1.2.1 Coatings may be selected in accordance with ISO 12944-5, which lists the stressing and the coating system to be used.

3.1.2.2 For coating systems, different guidelines and standards may be applied after consultation with DNV GL.

3.1.2.3 Surfaces to be protected by coating shall be designed to be accessible for the necessary activities such as surface preparation, application, inspection and maintenance. Surface preparation shall be effected in accordance with ISO 12944 or an equivalent standard.

3.1.2.4 For all coating systems that do not conform with any recognized standard, it is possible to apply for an approval at DNV GL. It is necessary to provide sufficient evidence to DNV GL that the coating material is suitable for the intended purpose.

3.1.2.5 Proof of efficiency of coating materials shall be furnished either by many years' proven practical use under the expected conditions or by well-justified experimental results.

3.1.2.6 The choice of materials, coating thicknesses, workmanship, testing etc. shall comply with the ISO 12944 series or an equivalent standard. The durability of the coating system shall correlate with the design life of the structure. Coatings shall not be susceptible to hydrolysis or saponification.

3.1.2.7 Coatings shall be sufficiently resistant to the respective corrosion medium under the given service conditions.

3.1.2.8 Special attention shall be paid to the presence of soluble salts. The chosen coating system shall tolerate the expected contamination with soluble salts.

3.1.2.9 The application of the coating system should be supervised by qualified personal, i.e. FROSIO-, NACE-, DIN-certified paint inspectors (or equivalent).

3.1.2.10 The coatings in the atmospheric zone shall be inspected on the occasion of the usual periodical surveys of the structure, according to an agreed inspection plan. Any damage shall be repaired.

3.1.3 Metallic coatings and platings

3.1.3.1 Metallic coatings may have a more positive or a more negative free corrosion potential than the base material, which in general is unalloyed or low-alloy steel. They should be free from cracks and pores.

3.1.3.2 With coatings using materials having a more positive potential (e.g. nickel and copper alloys, stainless steel), there is a risk of bimetal corrosion at pores in the coatings and at the transition to the base material. Therefore, the coatings shall be free from cracks and pores. The transitions to the base material shall be coated. The risk of contact corrosion of the base metal does not exist in the case of cathodic protection.

3.1.3.3 Coatings made of materials with a more negative potential (e.g. zinc or aluminium alloys) are well suited for temporary protection of equipment in the atmospheric zone. Depending on their thickness and composition, and on their working environment, coatings undergo uniform wear and have a limited life in the atmospheric zone.

3.1.3.4 In the surface preparation and application and testing of the metallic coatings, the ISO 12944 series or equivalent standards shall be observed.

3.1.3.5 The plating of steels shall show perfect bonding with the base material, proof of which may be furnished by ultrasonic testing.

3.1.4 Corrosion protection of bolts

3.1.4.1 The corrosion protection of bolts shall be equivalent to the protection system of the steel structure.

3.1.4.2 For further details regarding corrosion protection of bolts, see [5.4.2].

3.2 Offshore application

3.2.1 General

3.2.1.1 As the accessibility in offshore applications is heavily dependent on the weather conditions, the maintenance interval of components should be at least 1 year.

3.2.2 Atmosphere

3.2.2.1 It shall be described what kind of atmosphere is required inside the offshore wind turbine (e.g. nacelle, hub and other rooms where components that are needed for the operation of the offshore wind turbine are located) and how these requirements are being met. This shall be done according to IEC 60721-3-3.

3.2.2.2 As the corrosion rate increases exponentially with increased relative humidity, the relative humidity inside the offshore wind turbine should be below 60%. This could be met by e.g. keeping the inside temperature higher than the outside temperature.

3.2.2.3 The internals of the rooms shall be protected against the outside air (offshore atmosphere). Documentation (e.g. drawings, functional description, data sheets) of the systems/designs used (e.g. filter, heating or air dryer systems) shall be submitted. These systems/designs shall be monitored by the control system of the offshore wind turbine and considered in the maintenance.

3.2.2.4 The air-flow, cooling and heating concept of the offshore wind turbine and of its components shall be explained by e.g. drawings, functional description, data sheets.

3.2.2.5 For all components which have an indirect contact by e.g. a breather (for e.g. bearings or gearbox) with the outside air, documentation shall be submitted, wherein it is stated that these components and materials are adequate for use in the offshore atmosphere and that the function of the components will not be disturbed.

3.2.2.6 For all operating materials (e.g. lubricants, oil) which are in contact – directly or indirectly – with the offshore atmosphere, documentation shall be submitted, wherein it is stated that these materials are adequate for the use in the offshore atmosphere and that the function of the components will not be disturbed.

3.2.2.7 For all components which are neither protected by a corrosion protection system nor covered and which are in contact with the offshore atmosphere (e.g. sealings, elastomer components, hoses, components outside of the nacelle), documentation shall be submitted, wherein it is stated that these components and materials are adequate for use in the offshore atmosphere and that the function of the components will not be disturbed.

3.2.3 Corrosion protection

3.2.3.1 For all metal parts, an appropriate coating or metallic coating according to ISO 12944 series or an equivalent standard shall be provided.

3.2.3.2 Parts which are protected according to ISO 12944 series shall fulfil the following corrosion classes:

— outside components, hub, fittings, sensors etc. shall be protected against corrosion according to class C5-M (ISO 12944 series)
— inside surfaces directly exposed to outside air shall be protected against corrosion according to class C4 (ISO 12944 series)
— inside surfaces directly exposed to desalinated and dehumidified air only shall be protected against corrosion according to class C3 (ISO 12944 series). In this case, the functional efficiency of an air conditioning system has to be shown by appropriate documentation. In case of grid-loss of the wind turbine, the air conditioning system shall keep up its operability for a reasonable amount of time.

3.2.3.3 The protective coating shall fulfil the durability level "high" (>15 years) according to the ISO 12944 series.

3.2.3.4 For thermally sprayed metallic coatings, Zn99.99 alloy according to ISO 14919 shall be applied. The application of other alloys than Zn99.99 for thermal sprayed metallic coatings shall be agreed with DNV GL.

3.2.3.5 The corrosion protection shall be described or named.

3.2.3.6 The corrosion protection shall be considered in the maintenance.

3.2.4 Surface preparation for protective coatings

3.2.4.1 The surface preparation degree before application of the coating system shall be in accordance with ISO 8501-1.

3.2.4.2 For the preparation of steel substrates before application of paints, the regulations of ISO 85013 shall be applied. For guidance, the preparation grade for corrosivity category C3 and C4 shall be at least P2, whereas for C5-M preparation grade P3 is advised.

3.2.4.3 Edges and welding surfaces of components to be coated shall achieve the level “good” according to ISO 12944-3, Annex D.

SECTION 4 MACHINERY STRUCTURES

4.1 General

4.1.1 General requirements

4.1.1.1 The following requirements in particular apply to the force- and moment-transmitting machinery structures of a wind turbine, or of wind turbine components made of metallic materials as per Section ?2.2.

4.1.1.2 For the components listed below (if applicable), insofar as they are important for the integrity of the wind turbine and also present a potential danger for human health and life, a structural assessment is required:

— rotor hub
— rotor shaft and axis
— main bearing housing
— gear box structures (e.g. torque arm, planet carriers and housing, if load-transmitting)
— torque arm
— main frame
— generator frame
— tower top adapter
— bolted connections
— direct drive turbine generators
— structural aspects of pitch and yaw system
— structural aspects of breaking and locking devices
— structural aspects of large diameter bearings.

4.1.1.3 Components of a wind turbine shall be subjected to verification of their ultimate, fatigue, and serviceability limit states (cf. [4.2.2.11]). For this, the design loads (cf. [4.1.2.5]) for the load cases determined according to DNVGL-ST-0437 shall be applied.

4.1.1.4 The basis for the structural machinery component standard is the safe life design method. The damage tolerant design approach is not considered within this standard (see also [1.1]).

4.1.1.5 The strength of a component shall be verified in accordance with this section. The strength depends on the material, on the shape of the loaded structure and on the type of loading (tension, compression, shear, bending, torsion).

4.1.1.6 As a rule, analyses shall be performed by calculation. However, for fatigue analysis, component tests under simulated operating conditions are also permitted.

4.1.1.7 Dynamic loading, such as resonance effects or impact forces, affecting the strain and stress levels of the wind turbine to an extent which cannot be disregarded shall be accounted for in a suitable manner (see also [7.1]).

4.1.1.8 Local plastic and elastic deformation can adversely affect the functionality of a component. Both its function and that of the adjacent components shall be verified (e.g. bearings, gear box housings). The analyses to be made with regard to the limiting of deformation are described in detail in the relevant sections (e.g. [2.2] or [7.1]).

4.1.1.9 The loads of a generator short circuit shall be considered for the verification of ultimate strength of the generator frame. Detailed information on the short circuit loads is laid down in DNVGL-ST-0437.

Guidance note:
The generator short-circuit torque will not be reduced by a slip coupling. Hence, design calculations for the generator frame need to consider the full load from the short-circuit event.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

4.1.1.10 The generator carrier shall be designed with sufficient stiffness in lateral direction with reference to its integrity. The generator carrier shall withstand high lateral accelerations that can occur during operation. The adjacent components shall not be affected adversely.

4.1.1.11 For thick-walled steel connection plates (e.g. generator frame to main frame connection) the minimum required through-thickness properties shall be determined and specified (cf. [2.2.2.3] and [2.2.3.15]).

4.1.1.12 For the assessment of the strength and serviceability of machinery structures of wind turbines, the following documents are required:

a) documents on the components with e.g. material properties, references to relevant standards in case of standardized parts, references to the specifications and drawings used etc. In addition, parts lists may be necessary in case of welded structures.
b) design documentation (e.g. assembly drawings, and if necessary work instructions and specifications), also of the primary adjacent components, executed in standard form and with clear identification (parts designation, drawing number, modification index), shall be submitted. These shall contain
    - in the case of cast and forged structures, all necessary data on the delivery conditions, such as surface finish, microstructure, heat treatment, corrosion protection, etc.
    - in the case of welded structures, data on material designations, type of welding seam, heat treatment, corrosion protection etc.
c) technical data sheets are generally sufficient for machinery structures, which form part of mass-produced components. However, further documentation/verification may be necessary in individual cases for such parts.

4.1.1.13 Strength calculations shall prove the ultimate strength, fatigue strength and serviceability for the machinery structures in a thorough, clear and comprehensible manner. They shall contain sufficient information on

- design loads
- static systems (analogous models) and general boundary conditions applied (also the influence of adjacent components)
- materials
- permissible stresses
- references used.

4.1.1.14 From a technical and analysis point of view, the documentation of the computational analyses shall form a unified whole together with all other documents (drawings, specifications). Here it shall be observed that the references of the adjacent components and structural areas which are mentioned in the computational analyses shall be included in the documentation.

4.1.1.15 Analysis concepts of different standards and guidelines shall not be mixed.

4.1.2 Limit states

4.1.2.1 The integrity of a structure or its components shall be proven by the investigation of limit states. The limit states are divided into three groups, the ultimate limit states, the fatigue limit state and the serviceability limit states, which in turn may be subdivided further.

4.1.2.2 Ultimate limit state
The ultimate limit state, which generally corresponds to the maximum load-bearing capacity, includes for example the following states:

- rupture of critical parts of a structure comprising components, cross-sections and connections, for instance by:
    - fracture/exceedance of yield strength
    - loss of stability (buckling)

— loss of the static equilibrium of a structure or its parts (e. g. overturning as a rigid body or capsizing)
— transformation of the structure into a mechanism (collapse or excessive deformation)
— loss of station keeping (free drifting)
— sinking.

4.1.2.3 Fatigue limit state
The fatigue limit state corresponds to the life time capacity of a structure. The typical design life time for wind turbines is assumed to be 20 years.

4.1.2.4 Serviceability limit state
Depending on design and function, the serviceability limit state is determined by various limiting values which are oriented towards the normally envisaged use of the wind turbine. Limits to be observed are, amongst others:

— deformations or movements that affect the efficient use of structural or non-structural components
— motions that exceed the limitations of equipment
— vibration amplitudes and accelerations
— crack widths
— stresses and strains
— water tightness
— corrosion that reduces the durability of the structure and affects the properties and geometrical parameters of structural and non-structural components.

4.1.2.5 Partial safety factors for loads
The partial safety factors for the loads γ_F shall effect that, taking into account the probability of the load occurring, certain limiting values will not be exceeded with a given probability. These partial safety factors reflect the uncertainty of the loads and their probability of occurrence (e.g. normal and extreme loads), possible deviation of the loads from the representative/characteristic values, plus the accuracy of the load model (e.g. gravitational or aerodynamic forces).

The partial safety factors for the loads are independent of the materials used and are stated for all load components in DNVGL-ST-0437.

To ensure reliable design values, the uncertainties and variances of the loads are covered by the partial safety factors for the loads:

$$F_d = \gamma_F F_k$$

where:

F_d = design values of the loads
γ_F = partial safety factors for the loads
F_k = characteristic values of the loads. In this standard, the alternative term "representative value" is used in cases for which the characteristic value cannot easily be determined by statistical means.

These varying uncertainties are in some cases considered by means of individual partial safety factors. In this standard, as in most other codes, the load-related factors are grouped together in a partial safety factor γ_F.

4.1.2.6 Partial safety factors for materials
The partial safety factors for materials γ_M (cf. [4.7]) take into account e.g. the dependence on the type of material, the processing, component geometry and, if applicable, the influence of the manufacturing process on the strength.

The design strength R_d to be used for the strength analyses are derived by division of the characteristic strength R_k by the partial safety factor for materials:

$$R_d = R_k / \gamma_M$$

4.2 Determination of stresses

4.2.1 General notes on the loading of the structure

4.2.1.1 For the strength analyses, component-specific critical loading conditions shall be considered as a rule. For assessments of fatigue strength, loading conditions which generate dynamic cyclic stresses at the critical regions shall be considered. The design situations (i.e. operating conditions) and design load cases are given in DNVGL-ST-0437.

4.2.1.2 Loads and loading conditions shall generally be treated in accordance with DNVGL-ST-0437. More specific or especially adapted load criteria/values shall be well-documented and agreed upon with DNV GL. The load cases and combinations to be considered in the design calculations shall cover the most unfavourable conditions likely to occur in a specified time.

4.2.1.3 Non-linearities in the load components shall, if relevant, be taken into account. For this, it shall be observed that the linear superposition principle does not apply here. In certain cases, forces which only arise due to particular deformations (for example through the contact of structural areas) may be analysed in the form of additional load cases and superposed with consideration of the non-linear structural behaviour (e.g. radial compressive loads at the bearings).

4.2.1.4 As an alternative to the approach using general strength analyses with selected load cases, special methods particularly suited to the complete consideration of the movements and loads (so-called time-series calculations) may be used.

4.2.1.5 In calculations with time series, the loading or stressing process shall be generated from the characteristic data of the design load cases (see DNVGL-ST-0437). The time series and the statistical frequencies for the structural analysis shall be chosen in accordance with DNVGL-ST-0437. The validity of selected simplifications for the computational model shall be documented in a plausible manner.

4.2.1.6 Loading conditions occurring during construction, transport or sea installation have to be considered in the design; see also DNVGL-ST-0054 or Chapter 12 of GL-IV-2, Edition 2012.

4.2.2 Methods of analysis

General

4.2.2.1 Strength/stress analysis may be carried out according to recognized methods and standards. However, in any case it shall be ascertained that the design fundamentals and standards used are consistent and compatible for the individual structure or installation.

4.2.2.2 Requirements and recommendations regarding the definition of objective, type and scope of a strength analysis using the finite element method (FEM) as well as calculation and details on evaluation and documentation are given in the GL IV, Part 2, Ed. 2012, Appendix 5.A.

4.2.2.3 In general, the stress calculation may be carried out using conventional static theory. Where the decisive stresses cannot be calculated sufficiently accurately using these methods, calculations using numerical procedures (e.g. finite element method) shall be applied. In special cases, the procedure shall be agreed with DNV GL in advance.

4.2.2.4 The calculation procedures shall ensure the state of equilibrium.

4.2.2.5 The state of equilibrium can often be analysed on the basis of the non-deformed structure (first-order linear theory).

4.2.2.6 For the strength analyses, the effects resulting from loads acting on the components are usually characterized by stresses. At the failure-critical region, the nominal stress or the structural stress shall be determined according to the currently accepted rules of technology, as reflected in the applicable standards and codes. The criteria and selection of the failure-critical regions shall be documented.

4.2.2.7 Structural redundancy shall be considered at an early stage. As redundancy is not explicitly taken into account in the design methods currently in use, with the exception of the grouping of categories of structural elements (see [2.1.2]), the consequence of a failure shall be considered specifically.

4.2.2.8 The use of modifications to the analysis procedures listed in the following shall be agreed with DNV GL. Here it shall be ensured that a consistent analysis concept is applied.

Design methods and criteria

4.2.2.9 Structural strength calculations may generally be based on linear elastic theory. However, non-linear relations between loads and load effects shall be properly accounted for, where they are found to be important. Where plastifications occur, the limitations described in [4.3.2] are to be observed.

4.2.2.10 Influences that are based on the type of load, the geometry or the material shall be considered in the strength analyses. This also applies for non-linear influences of

— loading (e.g. solely compressive loading for roller or sliding bearings)
— geometry (second-order linear theory; consideration of large deformations)
— material (plasticity theory and yield hinge theory).

4.2.2.11 A structure may become unsafe or unfit for use by damages or other changes of state according to different criteria. They may be defined by "limit states", i.e. states of loading, straining (deformation) or other impairment, at which a structure, or structural component, loses its planned operability or function (cf. [4.1.2]).

Nominal stress approach

4.2.2.12 The nominal stress is the stress determined by means of the basic theories of linear elastic mechanics. Stress components caused by the notch effect are not included. They shall be considered by stress concentration factors (SCFs) and fatigue notch factors that are related to the nominal stresses. Stress concentration factors shall be chosen in accordance with current guidelines and standards. Alternatively, they can be derived from tests or numerical calculations.

4.2.2.13 The nominal stress concept is limited to slender bars and beams and to such structures which can be idealized with a close approximation as component details having a strip, bar or beam shape.

4.2.2.14 In the case of fatigue analysis of non-welded components, S/N curves containing the detail categories or geometrical discontinuities to be considered shall be used. If in welded components there is a geometric discontinuity that is not fully covered by the detail category which was selected to evaluate the respective design detail, the nominal stress shall be modified (see e.g. IIW).

4.2.2.15 In the case of combined types of stresses, [4.4.4] and [4.4.5] shall be observed.

Structural stress approach

4.2.2.16 The stress which fully describes a stress condition is termed structural stress. It includes effects from complex component shapes (spatially curved structures) and from design-related notches (e.g. grooves, steps, drill-holes) and local influences at load introduction. In welded structures, the structural stress is known as the "structural hot-spot stress". The term indicates that this stress includes the nominal stress and the influence of local stress-concentrating effects of the weld detail but not the peak stress of the notch.

4.2.2.17 In the case of fatigue analyses, material-dependent S/N curves shall be used for non-welded components if the calculated structural stresses include all local influences of the notch effect. The fatigue verification shall be carried out by using S/N curves that correspond to the actual qualities of the component. The quality-related factors shall be chosen in accordance with the specified quality (e.g. j and j0; see [4.5.2]). If the quality is defined differently in specific areas of the component, it shall be assured that areas of different quality are covered by the analysis.

4.2.2.18 In case of structural hotspot concept stress concentration factor (α_k) shall only be considered in case the modelling is not sufficiently reflecting the geometry. The consideration of fatigue notch factor (β_k) shall be agreed case by case together with DNV GL.

Guidance note:

For the main structural components like hub, main frame, main shaft, bearing housing etc. it is recommended to consider α_k = 1 and β_k = 1. The assumption for the fatigue notch factor is based on thick walled components experiencing rather axial fatigue than bending fatigue within the cross section.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

4.2.2.19 For welded joints, the structural hot-spot stresses (geometric stresses) are decisive in the fatigue analysis. When the structural hot-spot stress approach is used for the assessment of welded joints, it is recommended to carry out the finite element modelling in terms of the choice of element type and mesh quality in accordance with IIW or DNVGL-RP-C203. It is recommended to calculate structural hot-spot stresses for the assessment of welded joints in accordance with IIW or DNVGL-RP-C203.

4.2.2.20 In the case of combined types of stresses, [4.4.4] and [4.4.5] shall be observed.

4.2.2.21 Generally, components that are located in the force flow should not be subject to plastification.

4.2.2.22 In case plastification occurs in combination with failure-critical areas of the component, the directions given in [4.3.2] shall be observed.

Modelling of the structure

4.2.2.23 The analysis model ("idealization") used shall account for all main load bearing and stiffening components, and for the relevant supporting and constraining effect. The degree of subdivision (detailing) shall take into account the geometry of the structure and its influence on the load distribution and introduction, of the distribution of external loads, and of the expected stress pattern. Elements or members considered as being of "secondary" importance may nevertheless have to be accounted for where they have an influence on stress distribution or dynamic properties of the structure.

4.2.2.24 Where modelling is made by means of beam elements, the actual stiffness shall be accounted for as precisely as practicable, particularly in way of connections (joints). The effective width of associated plating should be chosen according to accepted standards.

4.2.3 Dynamic calculation

4.2.3.1 Within a dynamic calculation, the vibration-related system response of structures and components resulting from time-variant loads is determined including the influence of the structural dynamics of the entire wind turbine (see DNVGL-ST-0437).

4.2.3.2 The requirements for the dynamic calculations of individual structures and components are given in the relevant sections of this document.

4.3 Static strength analysis

4.3.1 General

4.3.1.1 The general strength analysis shall be carried out on the basis of European or equivalent international codes in consultation with DNV GL.

4.3.1.2 Machinery components whose dimensioning is not covered by standard codes shall be designed and analysed according to the currently accepted rules of technology. For the dimensioning of bolted connections, the requirements set out in Sec.5 shall be observed.

4.3.1.3 Welded machinery structures shall be preferably verified according to IIW in combination with the specific considerations for wind turbines stated in this standard. The static and fatigue strength analysis of welded machinery structures may be verified according IIW, DNVGL-RP-C203 or Eurocode together with the specific considerations for wind turbines stated in this standard, see e.g. item [4.5.1.3], [4.5.1.5], [4.5.1.6].

4.3.1.4 The components shall be dimensioned for the design loads with regard to the corresponding design strength (cf. [4.1.2]).

4.3.2 Method for static strength analysis

4.3.2.1 The dimensioning of a structure or component depends primarily on the type of possible failures. If two or more types of loading occur simultaneously, the combined resulting stresses shall be assessed. As a rule, the ultimate limit state verifications shall be carried out with regard to the material and loading, using the following equivalent stress hypotheses.

4.3.2.2 For ductile materials, the maximum shear strain energy hypothesis or the maximum shear stress hypothesis may be used. Other hypotheses, such as the shear stress intensity hypothesis, may be used as an alternative if adequate proof of their usefulness is given.

4.3.2.3 For brittle materials (e.g. EN-GJS-700-2U), the behaviour of the material is described by the maximum principal stress hypothesis. In the case of semiductile materials (e.g. EN-GJS-400-18U-LT), either the maximum principal stress hypothesis or the maximum shear strain energy hypothesis (e.g. von Mises) may be applied.

4.3.2.4 Minor local plastification, limited to local notches, is usually permissible for components made of ductile and semiductile materials. If, for structures consisting of such materials, the local stress values are located above the elastic limit (start of yielding), it shall be observed that the local stress distribution and thus the local strains have to be considered for assessment of the static component strength. Here it shall be taken into account that the local stress and strain distribution depends both on the component shape (e.g. notch) and on the type of loading (tension/compression, bending, torsion). The total permissible notch base strain may not exceed 1.0% for ductile (e.g. S235 J2+N) and semiductile materials (e.g. EN-GJS-400-18U-LT). In all cases, this is limited to minor plastifications, resulting from extreme load cases at local notches.

4.3.2.5 In addition, the permissible strain depends on the function of the structure, so that, in the case of permanent elongation, proof of operativeness shall be given for the component and its adjacent components. The procedure shall be defined in consultation with DNV GL.

4.3.2.6 Any plastifications in combination with failure-critical areas of the component (e.g. areas subjected to high fatigue stressing) should be avoided. The superposition of local plastification limited to notched areas with fatigue critical areas can be accepted, provided that the influence is evaluated by adequate means.

4.3.2.7 The approach for the evaluation of the superposition of plastified areas caused by extreme loads with fatigue critical areas shall be agreed with DNV GL in advance. For the evaluation the static strength verification shall be supplemented by an elasto-plastic calculation. The stress state of the respective hotspot and the residual stresses caused by the extreme events shall be evaluated. The stress time series of the fatigue and extreme load events should be analysed to detect any stress conditions which exceed the static yield limit or lead to a reversal of the plastification. To verify the fatigue strength of the affected area the analysis may be based on strains. The plastification and its damaging effect shall be considered as pre-existing. A positive effect of the residual stresses on the fatigue life time shall be neglected.

4.3.2.8 Linear extrapolation of stress reserve is permissible only for linear design calculations. In case of non-linear design calculations it shall be assured that the structural detail behaves linearly within the applied load range otherwise a full recalculation is necessary.

4.4 Fatigue strength analysis

4.4.1 General

4.4.1.1 In the following, components under variable cyclic loading are referred to as “dynamically loaded”.

4.4.1.2 For the predominantly dynamically loaded metallic components of wind turbines, a fatigue analysis shall be carried out. As a rule, this applies to the drive-train components from the blade connection to the generator, the main frame including its connection to the tower, the generator frame, the connecting elements and other turbine-specific components (e.g. blade pitch mechanism).

4.4.1.3 The fatigue analysis may be carried out by component testing, computational analyses or analytical analysis, if applicable. Component tests shall be carried out with loads relevant to operation and using DNVGL-ST-0437 as a basis. Evaluation of the test results shall be such that the effects of those influences which cannot be taken into consideration directly (large number of load cycles > $10E^9$, scattering of the test results etc.) are reliably covered; cf. Haibach /1/).

4.4.1.4 The analysis of adequate fatigue strength, i.e. the resistance against crack initiation under dynamic operational loads, serves the assessment and reduction of the crack initiation probability of components within the scope of the structural design. Owing to incalculabilities in the loading process, involving material- and production-related variances and ageing effects, crack initiation in later operation cannot completely be ruled out, necessitating measures such as periodical inspections and other appropriate actions, cf. [4.1.1.4].

4.4.1.5 The technical crack initiation shall be taken as a general failure criterion, i.e. a crack that is detectable on site with the usual non-destructive inspection methods.

4.4.1.6 In special cases, the remaining lifetime of an initiated crack that is growing steadily may, in consultation with DNV GL, be used for limited continued operation of a wind turbine. For this, the remaining lifetime shall be verified with suitable and recognized analysis methods. In addition, periodical inspections at appropriate intervals shall be laid down in consultation with DNV GL.

4.4.2 Methods for fatigue strength analysis

4.4.2.1 Depending on the required computational accuracy, fatigue analysis by calculation may be performed with the aid of one of the following procedures:

— by using stress-time series and damage accumulation to account for the complex interaction between the external loadings and the structural responses as accurately as possible, or

for stress reserve calculations (SRF):

— by using stress spectra and damage accumulation. The superposition of the various load effects shall include the worst physical meaningful combination. Effects of variations in the mean load level shall be considered.
— with equivalent constant-range spectra as a simplified form of the fatigue analysis ([4.4.2.5] through [4.4.2.10]) in case of predominantly uni-axial stressed components. Here the equivalent constant-range spectra shall be used in accordance with DNVGL-ST-0437. Additionally the effects on non-zero mean load levels shall be considered adequately.

4.4.2.2 The procedure and the applied loads shall be documented adequately.

4.4.2.3 If not defined otherwise in referenced standards, the influence of the mean stress shall be considered in accordance with [4.4.6].

4.4.2.4 For complex components subjected to combined loading (see Figure 4-1), adequate procedures for the hot-spot localization shall be applied. In general, stress-time series shall be used and the entire component shall be analysed.

4.4.2.5 A simplified fatigue analysis, which is generally applied when considering safety margins by stress reserve calculation (e.g. comparison of turbine variants with different rotor diameters and hub height), is only permissible in case of predominantly uni-axial loaded components. For bi- and multi-axial loaded components it is not permissible without further verifications. The approach shall be agreed together with DNV GL.

4.4.2.6 For the simplified fatigue analysis equivalent constant-range spectra are commonly used. In the following, it will be assumed that the determination of equivalent constant-range spectra on the basis of the Palmgren/Miner method has already been performed. Explanations of this method can be taken from e.g. Haibach /1/.

4.4.2.7 When generating the equivalent constant-range spectrum, the slope parameter of the S/N curve corresponding to the material used shall be applied. The decisive slope parameter of the design S/N curve is given in [4.5].

4.4.2.8 When generating the equivalent constant-range spectrum the effect of mean loads, respectively mean stresses, and the mean stress sensitivity of the materials shall be considered adequately.

4.4.2.9 When using the simplified fatigue analysis for considering safety margins, it shall be observed that the assumed reference load cycle number generally does not correspond with the assumed design lifetime of the component.

4.4.2.10 Influences reducing the fatigue resistance (such as probability of survival P_S, surface influence etc.) shall be taken into account analogously to the evaluation of the S/N curves according to [4.5].

4.4.3 Damage calculation

4.4.3.1 The details of the execution of fatigue verifications via damage accumulation may for instance be taken from IIW or Haibach /1/.

4.4.3.2 When working out a damage accumulation, all stress ranges $\Delta\sigma_i$ due to operational loads in accordance with DNVGL-ST-0437 shall, as a matter of principle be used in conjunction with their associated stress cycle numbers n_i. The damage sum D from the fatigue strength calculation is dependent on the material, type of loading and structural geometry. The damage sum shall not exceed the following value:

$$D \leq 1,$$

e.g. when using the Palmgren/Miner linear damage accumulation hypothesis:

$$D = \sum_i n_i / N_i \leq D_{\mathrm{admi}}$$

where:

n_i = number of stress cycles in one bin of stress ranges
N_i = number of tolerable stress cycles in one bin of stress ranges

4.4.3.3 Here the number of tolerable stress cycles N_i is the permissible number of stress cycles of the relevant S/N curve for the stress range $\Delta\sigma_i \cdot \gamma_M$.

4.4.3.4 The partial safety factor γ_M is given in [4.7].

4.4.3.5 For the damage accumulation the design S/N curves given in [4.5] and the equivalent stresses described in [4.4.5] shall be used.

4.4.3.6 For stress superposition in the case of multi-axial stress conditions, see [4.4.4].

4.4.4 Superposition of multi-axial stress conditions

4.4.4.1 For multi-axially stressed components (see Figure 4-1), it is necessary to consider the complex stress conditions in a realistic manner and to model them for the damage accumulation calculation in a physically meaningful manner. For this, the relevant time series of the fatigue loads are applied in accordance with DNVGL-ST-0437.

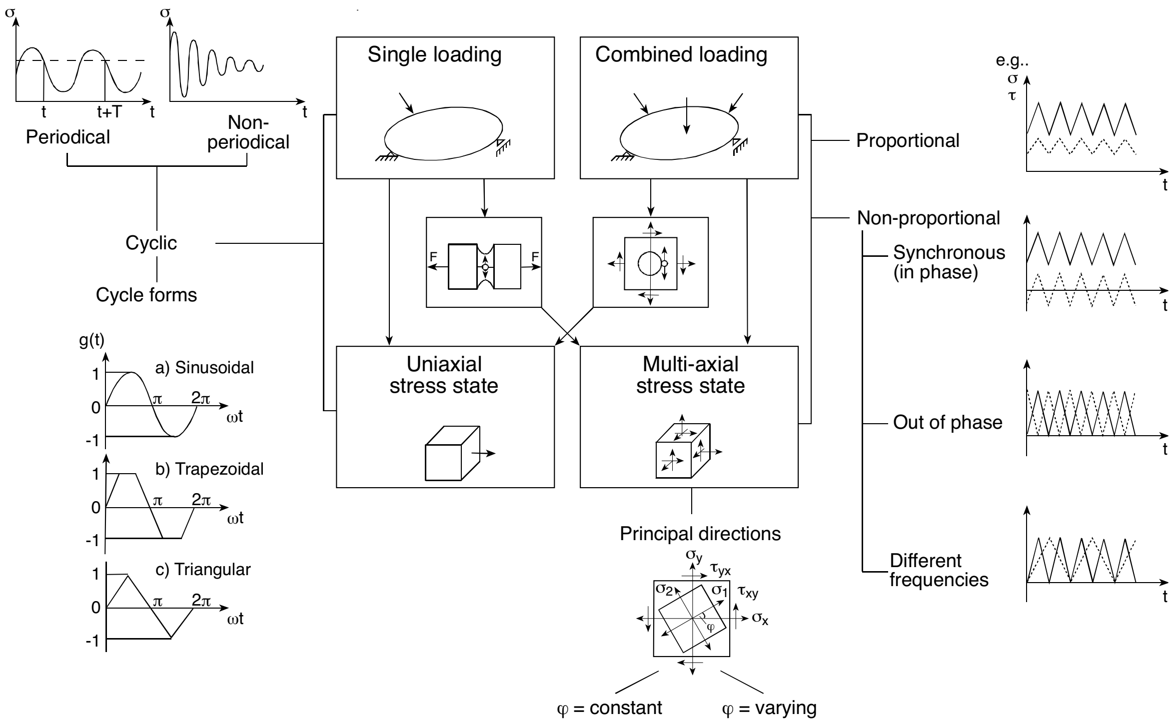

Figure 4-1 Relationship of various terms in the field of multi-axialities

4.4.4.2 When analyzing multi-axial stresses, it is recommended that the dominating (damage-relevant) stress distribution or stress combination be established for the critical regions via consideration of the principal stresses and principal-stress directions. Occasionally, the presence of a dominating load component, or the combination of load components, may lead to a stress condition that is close to uni-axial. In such cases, this may allow a possible simplification that is appropriate for the problem.

4.4.4.3 The applicable procedure depends on the material, the type of loading and the structural geometry and shall be defined in consultation with DNV GL.

4.4.5 Equivalent stress hypotheses

4.4.5.1 In cases of multi-axial stress conditions, the fatigue-relevant stress components that define a three-dimensional stress state shall be transformed to an equivalent mono-axial stress state by means of an adequate stress hypothesis.

4.4.5.2 For ductile materials, an equivalent stress hypothesis (e.g. maximum shear strain energy hypothesis, maximum shear stress hypothesis) may be applied as a method of the critical plane. Other hypotheses, such as the shear stress intensity hypothesis for ductile materials, may be used as an alternative, provided that adequate proof of their usefulness is given.

4.4.5.3 For brittle and semiductile materials (e.g. EN-GJS-400-18U-LT belongs to the semiductile materials), the normal stress hypothesis may be applied as a method of the critical plane. Other hypotheses shall be used if it can be predicted that the component will fail due to the effects of other kinds of stresses.

4.4.5.4 If the nominal stress approach is chosen for the assessment of welded joints, the decisive stresses are those transverse or parallel to the weld seam. If normal and shear stresses occur simultaneously in welded joints, their combined effects shall be considered (guidance is e.g. given in IIW).

4.4.5.5 If the structural hot-spot stress approach is chosen for the assessment of welded joints, principal stresses shall be analysed. In cases where the direction vector of the principal stress is approximately perpendicular to the weld seam and does not change significantly over time, this stress may be used in combination with the fatigue resistance values of the code chosen. If the direction vector varies significantly, the other principal stresses need to be analysed as well. Their combined effects shall be considered (guidance is e.g. given in IIW).

4.4.6 Mean stress correction

4.4.6.1 In general, the material's fatigue strength is sensitive to mean stresses. The influence of the mean stress shall be considered by means of Haigh diagrams (Figure 4-2).

4.4.6.2 An additional mean stress correction is not necessary if the correction is already considered within the detail category.

4.4.6.3 When using stress-time series for the fatigue analysis, the damage-equivalent amplitude σ^*_A (R) corresponding to a S/N curve of the same stress ratio R shall be calculated for each given combination of stress amplitude σ^*_A and mean stress σ_m.

4.4.6.4 Alternatively, the S/N curve may be adjusted in a corresponding manner.

4.4.6.5 If stress spectra or equivalent constant-range spectra are used (cf. [4.4.2]), the influence of the mean stress shall be considered in a demonstrably conservative manner.

4.4.6.6 The conversion of stress amplitudes shall be carried out by one or two lines parallel to the fatigue life line in the Haigh diagram (see dashed line in Figure 4-2).

4.4.6.7 The mean stress sensitivity M shall be chosen depending on the material. For cast iron, the mean stress sensitivity M shall be used for $-\infty \leq R \leq 1$. In case of ductile steel materials, a slope $M/3$ may be applied for $0 \leq R \leq 1$. Other methods shall be agreed with DNV GL in advance.

4.4.6.8 The procedure of mean stress correction depicted in [4.6] is applicable as well.

4.4.6.9 In general for welded components, positive effects from mean stress corrections may only be applied if no significant residual stresses occur (e.g. after post-weld heat treatment).

4.4.6.10 The limiting stress level is defined by the admissible yield stress (e.g. $R_{p0.2} / \gamma_M$). The mean stress occurring plus the stress amplitude σ_a shall not exceed the limiting stress level ($\sigma_m + \sigma_a \leq \sigma_{lim}$).

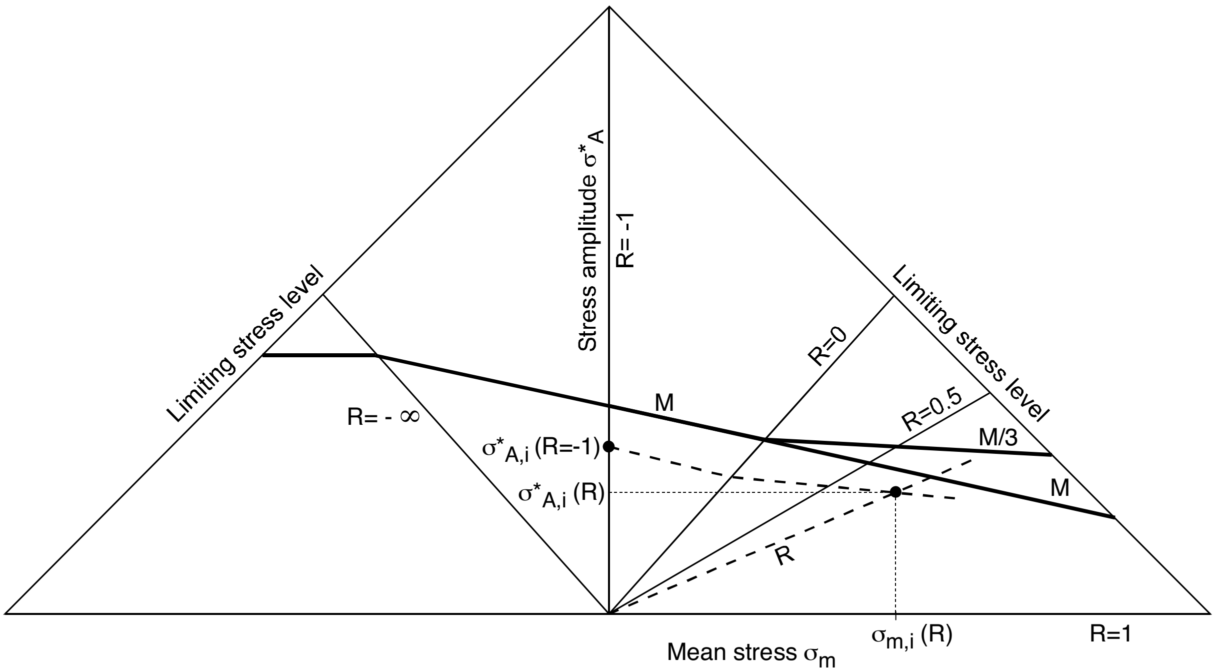

Figure 4-2 Haigh diagram

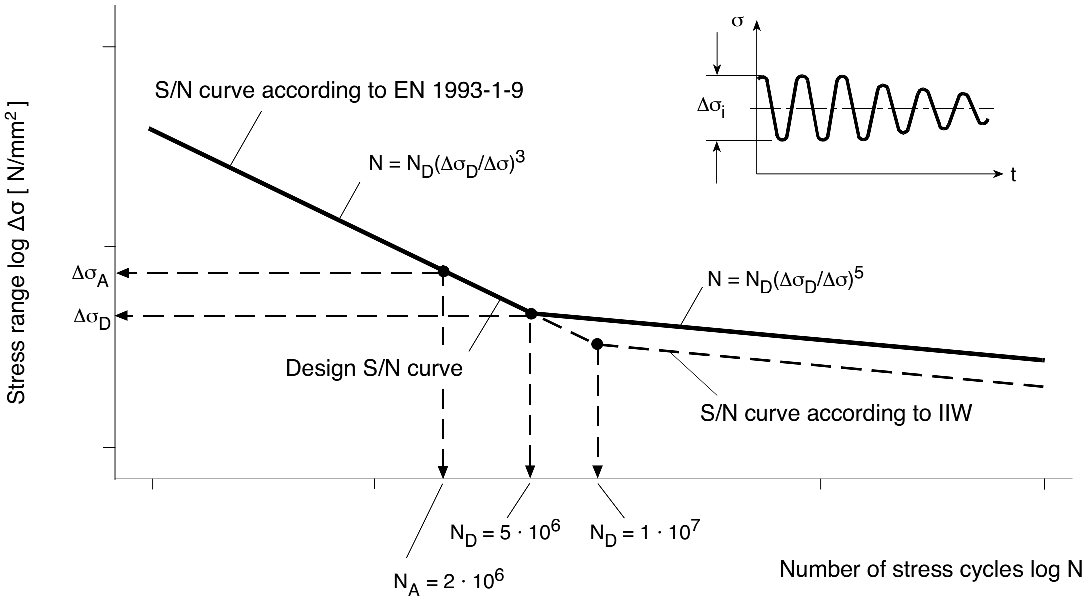

Figure 4-3 S/N curve for welded structures, general shape

4.5 S/N curves for metallic materials

4.5.1 S/N curves for welded steel structures

4.5.1.1 For welded machinery structures the S/N curve for the strength verification shall preferably be in accordance with the IIW recommendations. Alternatively DVNGL-RP-C203 or Eurocode may be applied together with the specific considerations for wind turbines stated in this standard, see e.g. item [4.5.1.3], [4.5.1.5] and [4.5.1.6].

4.5.1.2 Reducing influences, e.g. because of the material thickness or insufficient alignment of the two joints to be welded, shall be observed in accordance with the chosen code.

4.5.1.3 The thickness correction shall be applied according to the chosen code. In the case of Eurocode the thickness correction shall be applied in accordance with IIW, when applying the hot-spot stress approach.

4.5.1.4 Post-weld improvement techniques shall be agreed with DNV GL.

4.5.1.5 S/N curve according to IIW recommendations:
When machinery structures are assessed, the following applies to the S/N curve:

— region I:
slope parameter of the S/N curve $m_1 = 3$, stress cycle numbers $N_i < 1 \cdot 10^7$
— region II:
slope parameter of the S/N curve $m_2 = 5$, stress cycle numbers $N_i \geq 1 \cdot 10^7$

For the analysis of damage contribution caused by shear stresses the following applies to the S/N curve:

— region I:
slope parameter of the S/N curve $m_1 = 5$, stress cycle numbers $N_i < 1 \cdot 10^8$
— region II:
slope parameter of the S/N curve $m_2 = 9$, stress cycle numbers $N_i \geq 1 \cdot 10^8$

Guidance note:

In case the S/N curve is based on EN 1993-1-9:2005 (cf. DNVGL-ST-0126):

In the case of loading by normal stresses, the following additional requirement applies to the S/N curve as per EN 1993-1-9:2005:

– region I:

slope parameter of the S/N curve m_1 = 3, stress cycle numbers $N_i < 5 \cdot 10^6$

– region II:

slope parameter of the S/N curve m_2 = 5, stress cycle numbers $N_i \geq 5 \cdot 10^6$

For predominantly shear-stress loaded components, the S/N curves of EN 1993-1-9:2005 shall be used with a constant (region I + II) slope parameter m = 5.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

4.5.1.6 In all cases, a threshold value of the fatigue strength (cut-off) is not permissible. Figure 4-3 shows the general shape of the S/N curve to be used as a basis.

4.5.1.7 When establishing the tolerable number of stress cycles N_i (see [4.4.3]), account shall be taken of the partial safety factors γ_M according to Table 4-3.

4.5.2 S/N curves for cast steel, cast, forged and rolled parts

4.5.2.1 Selection: In principle, statistically assured material S/N curves shall be used. Requirements for material testing shall be defined prior to the design assessment in consultation with DNV GL. If such S/N curves are not available for the material to be used, synthetic S/N curves in accordance with [4.6.3] may be used as a basis for a comprehensive fatigue analysis.

4.5.2.2 Reducing influences: The following reducing influences on the fatigue resistance shall be considered:

— type of loading
— significant residual stresses (e.g. shot peening, plastifications)
— stress ratio
— stress concentration factor
— notch effect factor
— component size
— surface quality
— influence of technological parameters
— survival probability
— environmental conditions (corrosion etc.).

4.5.2.3 Survival probability: Usually, S/N curves are assigned a survival probability of P_s = 50%, see e.g. Haibach /1/ and Leitfaden /2/. The fatigue analysis shall be performed with a survival probability of P > 97.7%. Unless determined otherwise, the S/N curve reference value $\Delta\sigma_A$ shall be reduced to

$$\Delta\sigma^*_A = \Delta\sigma_A \cdot S_{Ps} \text{ where } S_{Ps} = 2/3$$

which corresponds to a survival probability of P_s > 97.7% (mean value – 2 · standard deviation), see also Table 4-2. If S/N curves with a survival probability of P_s > 50% are used, a reduction factor S_{Ps} > 2/3 may be assumed after consultation with DNV GL.

4.5.2.4 Admissible stress range: The fatigue strength line of the S/N curve shall be limited by the elastic properties of the material including the partial safety factor for material γ_M. The respective mean stress level shall be considered when determining the upper limit of the fatigue strength line.

4.5.2.5 Reduction factors: The influence of large wall thicknesses and surface roughness shall be taken into account. In the case of S/N curves determined from specimens taken from equally thick component regions, the influence of large wall thickness is included in the S/N curves. When determining synthetic S/N curves according to [4.6.3], both the thickness-dependent mechanical characteristic values (guaranteed minimum tensile strength and yield point) as well as the reduction through the existing surface roughness shall be observed. The assumed surface roughness for the determination of the S/N curve shall be consistent with the specified surface roughness.

4.5.2.6 Stress cycle numbers: For stress cycle numbers $N_i > N_D$, the S/N curves shall be extended from $\Delta\sigma^*_A$ with the slope parameters $2m_1$-1, where m_1 is the slope parameter of the fatigue strength line (Figure 4-5). Here the limiting stress cycle number N_D is that number at which, under optimum test conditions (no corrosion effect, etc.), the endurance limit is given. Where synthetic S/N curves are used, N_D results from its calculation.

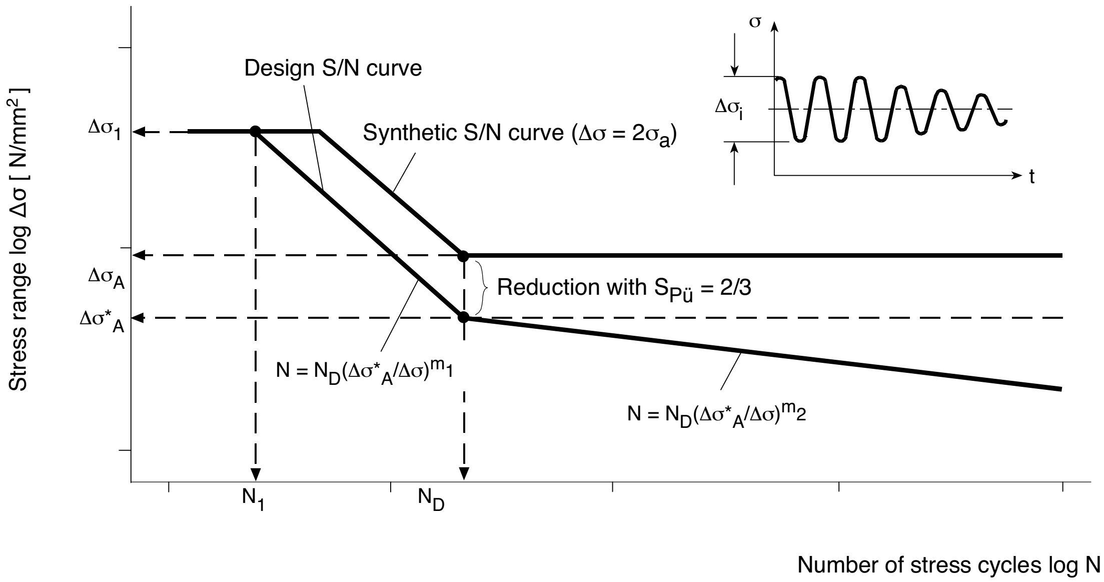

Figure 4-4 S/N curve example „Synthetic S/N curve"; general shape

4.5.2.7 In case of unfinished (raw and cleaned) casting surfaces a value of at least R_z = 200 μm shall be assumed for the calculation, if no other value is specified.

4.5.2.8 In using synthetic S/N curves for cast iron, the influence of the quality levels (cf. [2.2.4] and [2.2.7]) shall be considered through the factor

$$S_d = 0.85^{\,(j-j0)}$$

where:

j the quality level for the component or component detail to be designed with adequate fatigue strength, (01, 2, 3 acc. to EN 12680-3:2011; cf. [2.2.4], [2.2.7])

j_0 constant depending on the test method (0 or 1), with the following values:

ultrasonic (UT) or radiographic (RT) testing	j_0 = 0
additional testing liquid penetrant (PT) or magnetic particle (MT) surface testing	j_0 = 1

For the assessment of the casting and surface quality and the testing techniques to be applied, the requirements listed in [2.2.4] and [2.2.7] shall be observed. MT/PT quality level is limited to level 3 in general. For the UT quality level 1 area, MT/PT quality level will be limited to level 2. This will ensure that, in the UT quality level 1 area, the more critical surface flaws detected by MT/PT are not allowed to be bigger than internal flaws detected by UT.

4.5.2.9 The classification into quality levels shall be documented consistently in the drawings, calculations and specifications and submitted to DNV GL for assessment within the scope of the design assessment and associated inspections. The requirements of [2.2.4] and [2.2.7] shall be observed.

4.5.2.10 Design S/N curve for cast material: The reference stress range to be used as a basis for the S/N curve is

$$\Delta\sigma^*_A = S_{Ps} \cdot S_d \;\; \Delta\sigma_A$$

as the ideal fatigue limit at the stress cycle number N_D (see Figure 4-4). For stress cycle numbers $N > N_D$, the S/N curves shall be extended from $\Delta\sigma^*_A$ with the slope $2m_1$-1, where m_1 is the slope parameter of the fatigue strength line (see Figure 4-4).

4.5.3 S/N curves for the design of aluminium parts

4.5.3.1 In principle, statistically assured S/N curves shall be used.

4.5.3.2 For detail categories, the detail category selection shall be in accordance with the chosen code. In cases of doubt, the procedures shall be agreed with DNV GL.

4.6 Calculation of synthetic S/N curves

4.6.1 General

4.6.1.1 In general, statistically assured and representative S/N curves for the raw material should be used as a basis for the fatigue analysis. If such S/N curves are not available for the material to be used, synthetic S/N curves may be used.

4.6.1.2 The procedures depicted in the flow charts of this section are applicable for non-welded forged and rolled parts (cf. Figure 4-5), cast steel and spheroidal graphite cast iron (cf. Figure 4-6).

4.6.1.3 The fatigue verification shall be carried out by using S/N curves that correspond to the local qualities of the component. The reduction factors shall be chosen in accordance with the specified quality (e.g. j and j_0; see [4.5.2]). If the quality is defined differently in specific areas of the component, it shall be assured that areas of different quality grades are covered by the analysis.

4.6.2 Non-welded forged and rolled parts

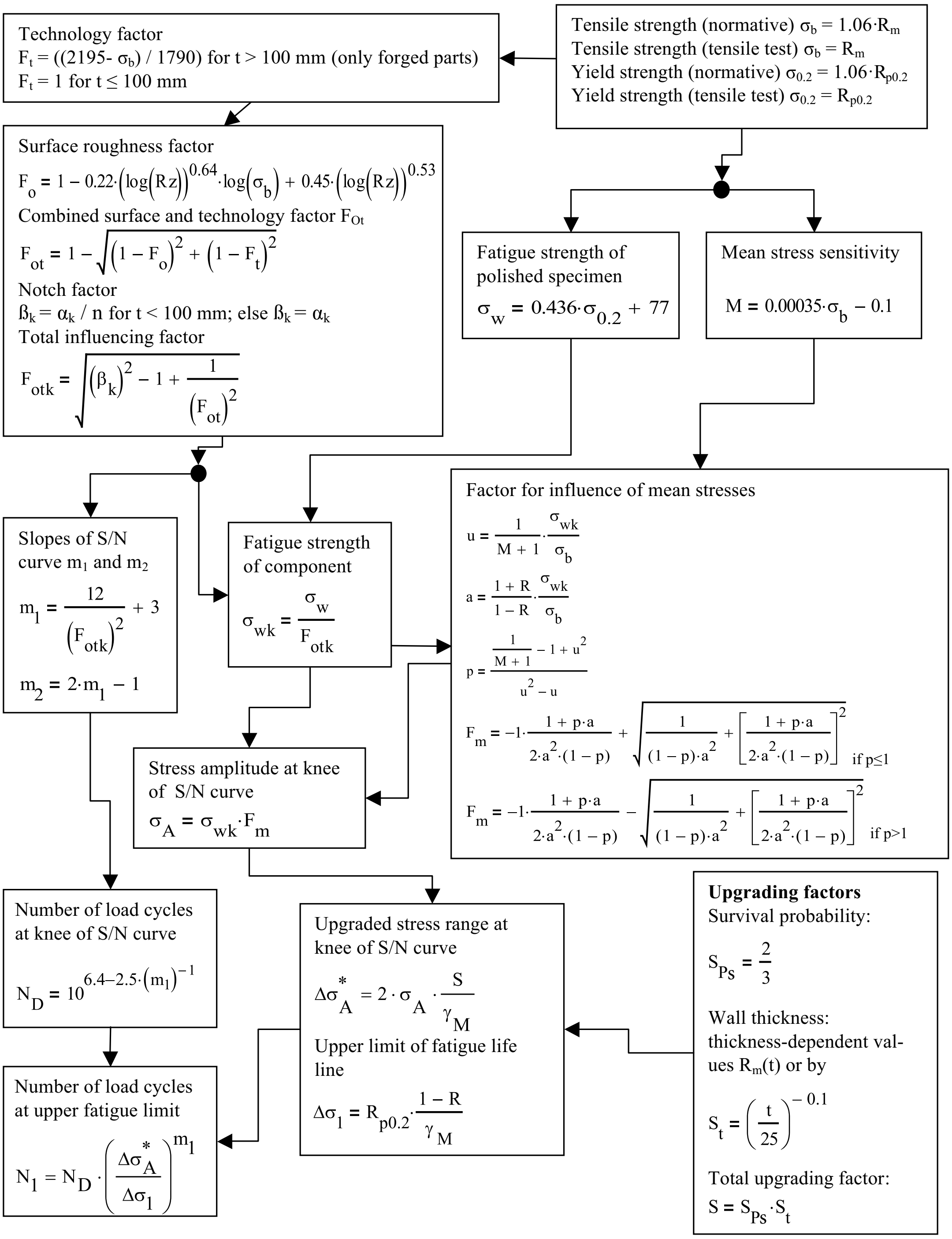

Figure 4-5 Calculation of synthetic S/N curve for non-welded forged and rolled parts

4.6.3 Cast steel and spheroidal graphite cast iron

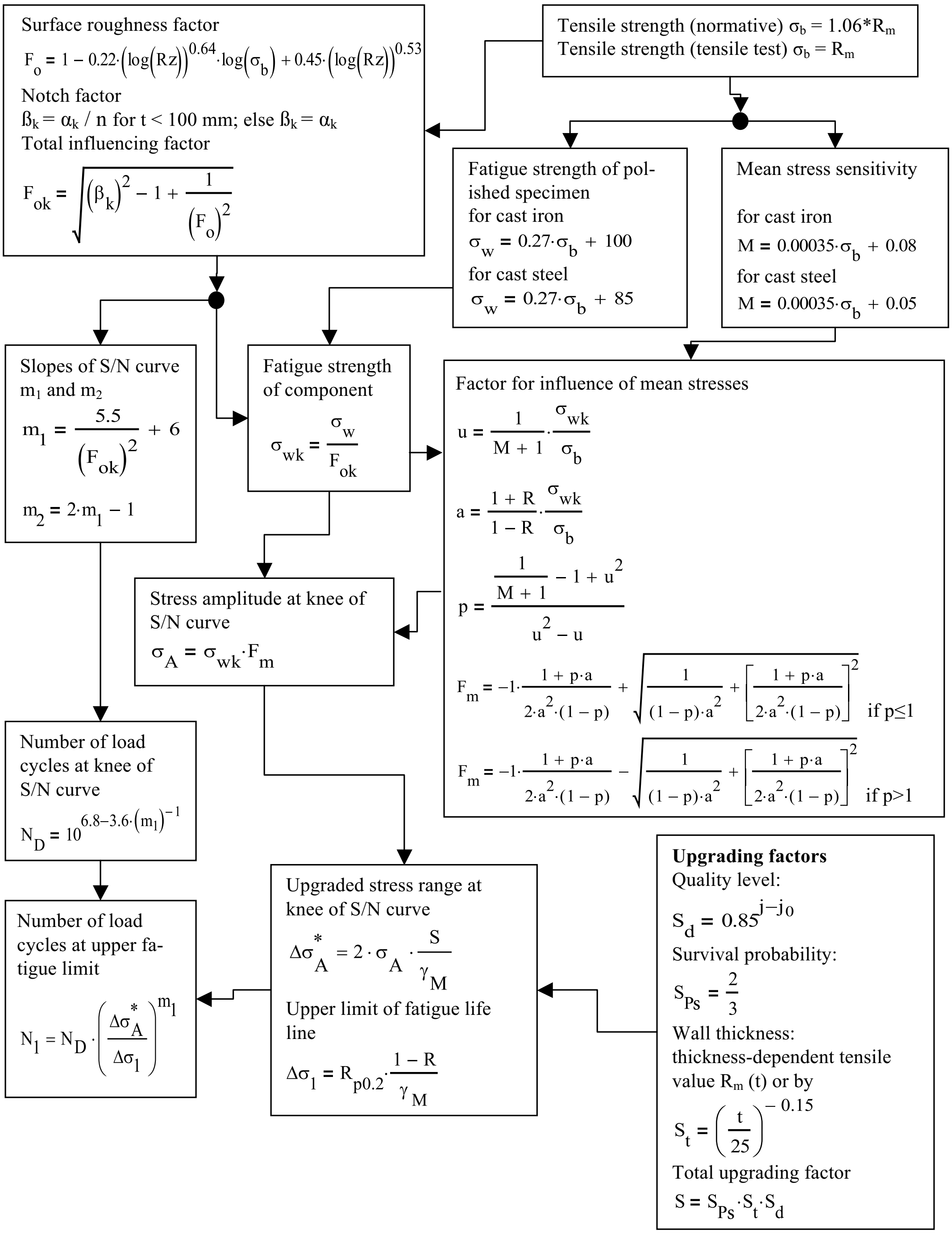

Figure 4-6 Calculation of synthetic S/N curve for cast steel and spheroidal graphite cast iron

4.6.4 Documentation of input parameters

The documentation of input parameters shall be performed on the basis of Table 4-1.

Table 4-1 Input parameters for the calculation of synthetic S/N curves

Symbol	Meaning	Unit	Value
R_m	Tensile strength	N/mm²	
$R_{p0.2}$	Yield strength	N/mm²	
R	Stress ratio	-	
α_k (see [4.2.2.18])	Stress concentration factor	-	
n	Notch sensitivity caused by stress gradient influence and localized plastic deformation at the notch base	-	
R_z	Surface roughness	µm	
γ_M	Partial safety factor for material	-	
j	Quality level for component	-	
j_0	Constant for material and test method	-	
t	Wall thickness	mm	

4.6.5 Documentation of result parameters

The documentation of key parameters defining the synthetic S/N curve shall be performed on the basis of Table 4-2. A graphical presentation of the S/N curve shall be part of the documentation as well (Figure 4-7).

Table 4-2 Result parameters defining the synthetic S/N curve

Symbol	Meaning	Unit	Value
$\Delta\sigma_1$	Upgraded upper limit of fatigue life line (stress range)	N/mm²	
N_1	Number of load cycles at upper fatigue limit	-	
$\Delta\sigma^*_A$	Upgraded stress range at knee of S/N curve	N/mm²	
N_D	Number of load cycles at knee of S/N curve	-	
m_1	Slope of S/N curve for $N_1 < N \leq N_D$	-	
m_2	Slope of S/N curve for $N > N_D$	-	

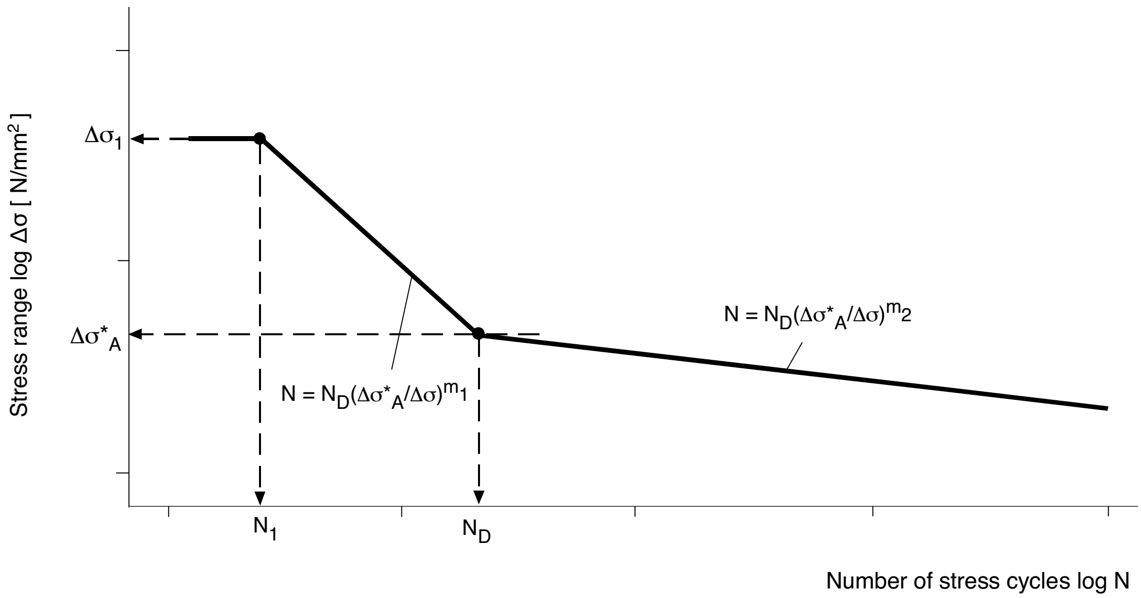

Figure 4-7 Graphical presentation of the synthetic S/N curve

4.7 Partial safety factors

4.7.1 Ultimate limit state

Ultimate limit state: the partial material safety factor γ_M to be used as a basis for metallic components of all load case groups is γ_M = 1.1.

4.7.2 Fatigue limit state

Fatigue limit state: the following partial safety factor γ_M shall be applied in relation to the criteria given in Table 4-3. Examples can be found in Table 4-4.

Table 4-3 Partial safety factor γ_M for fatigue verification

Component failure results in the destruction of the wind turbine or endangers people	Component failure results in wind turbine failure or consequential damage	Component failure results in interruption of operation
1.25	1.15	1.0

Table 4-4 Example for the partial safety factor γ_M

Failed component	Inspection or accessibility	
Bearing collar of the rotor shaft	Cannot be inspected without removing the shaft	γ_M = 1.25
Planet carrier of main gearbox	Cannot be inspected; failure can lead to destruction of wind turbine	γ_M = 1.25
Bolted connection of hub/rotor shaft (multiple bolt connection)	A single bolt failure in a multiple bolt connection can be detected before complete failure of the connection.	γ_M = 1.15
Fixture for control cabinets Fixture of accumulators	Operation of wind turbine will be interrupted	γ_M = 1.0

In case the S/N curve is derived based on material and component specific test data a γ_M = 1.15 can be considered. The approach shall be agreed with DVN GL in advance.

For fatigue strength analysis of welded structures the safety factor shall be increased by an additional safety factor of γ_M = 1.2 in case of multi-axially loaded hotspots.

In case of brittle material with a fracture elongation A < 12.5% or an impact energy of K_{Vmean} < 10 J (mean value of three tests) the requirements defined in [2.2.7.3] shall be considered.

4.7.3 Serviceability limit state

Serviceability limit state: For verifications in the serviceability limit states, the partial safety factor shall be γ_M = 1.0.

A limitation of the deformations is not required if it can be demonstrated that the deformation does not affect the safe operation of the wind turbine (cf. [4.3.2.5]).

Guidance note:
The safety factors mentioned in this section [4.7] define the safety level in combination with the overall calculation concept. In general we recommend not to mix our standard with other standards or guidelines as each one of the standards or guidelines has its individual safety concept. In case the calculation concept depicted in this standard is combined with IEC standards the safety factors used (γ_M and γ_N according to IEC61400-1) should not be lower than the ones mentioned in this standard. In case γ_M and γ_N according to IEC61400-1 lead to a higher safety factor these factor shall be considered to fulfil IEC guideline.

Plastification of the rotor lock under extreme load should be avoided, otherwise functionality of the rotor lock system can be compromised.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

SECTION 5 BOLTED CONNECTIONS

This chapter refers primarily to carbon or alloy steel fasteners used in load carrying components of a wind turbine.

5.1 Assessment documents

For the assessment of bolted connections, at least the following documents shall be submitted:

a) design calculations of the bolted connections according to [5.3].
b) work instruction for making the bolted connection (assembly instructions). These instructions shall contain at least the following:

   — pretreatment or checks of the surfaces to be joined
   — if additional activities at the flanges (e.g. underpinning) during the connecting work are already intended in the design, these shall be described together with the necessary materials. If these activities only become necessary if certain criteria are exceeded (e.g. maximum gap widths), the criteria and measurement procedures shall be stated.
   — lubrication condition of thread and bolt/nut
   — tightening procedure and all data needed for manufacture (e.g. preloading, torque required, tightening tool)
   — tightening sequence

c) work instruction for checking the bolted connection (maintenance instruction), with statement of at least the test intervals and test procedure; see [5.4.3].
d) drawings and/or specifications providing the remaining parameters for the design of the bolted connection, such as:

   — dimensions and tolerances
   — data on possible coatings of the flange surfaces or parts thereof
   — designation of the bolts, nuts and any washers
   — corrosion protection.

5.2 Tensioning of bolted joints

5.2.1 General

Bolted joints used in wind turbines shall be installed using an adequate amount of preload. Due to increased danger of stress corrosion cracking for higher strength steels, only bolts of the strength category 8.8 or 10.9 according to ISO 898-1:2009 are permissible for preloaded bolted connections in load carrying components of wind turbines.

The pre-tensioning procedure shall be categorized according to VDI 2862 part 2. Moreover, the requirements of VDI 2645 part 2 shall apply.

5.2.2 Yielding

The technique of tensioning bolts beyond the area of elasticity shall be agreed in detail with DNV GL.

Guidance note:
The following requirements for the technique of tensioning bolts beyond the area of elasticity may be applied in order to obtain acceptance by DNV GL and are valid for both, the case of yielding during the tensioning process (at the installation/mounting) and the case of yielding due to an extreme load during the operational life of the bolted connection:

a) The plastic deformation during the tensioning process is determined in that section of the bolt where the yielding occurs most heavily (mostly the tensioned part of the free thread). For this section the most unfavourable values of all data (data of the tensioning process, frictional coefficients, material data of the bolts material, etc.) shall be considered.
b) The amount of plastic deformation during the occurrence of a possible extreme load shall be determined if the calculations show that such plastification shall be expected. For this situation the most unfavourable values of all data shall be considered.
c) The plastification during the tensioning as per item a) shall be added to the additional plastification during an extreme load as per item b). This sum (total plastification) shall be lower than or equal to 1% of the length of that section of the bolt exposed to yielding. In this context, the partial safety factor for materials shall be: γ_M = 1.0.

d) The minimum pre-tensioning force in the bolt shall be determined (calculations or tensioning tests/measurements) according to the tensioning procedure. A possible occurrence of an additional plastification during an extreme load (see item b) might reduce the tensioning force in the bolt and shall therefore be considered accordingly. For this situation the most unfavourable values of all data shall be considered.

e) The minimum pre-tensioning force determined as per item d) shall be reduced by 10% to account for inaccuracies. This reduced pre-tension shall be used for the bolt fatigue calculation and the considerations of proper function of the bolted connection.

f) When choosing the detail category as per [5.4.1], the values for “bolts rolled before heat treatment” (detail category 50 or 71) shall be used.

Limitations within national requirements shall be considered additionally in the case of tensioning bolts beyond the elastic area of the bolt.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

5.3 Strength analysis of preloaded bolted joints

Strength of the bolted connection may be assessed either with analytical or numerical calculation method. Regardless of the method, the assessment of the bolt strength shall be based on the nominal stress hypothesis.

Bolted joints in wind turbines should be generally designed against the following limit states:

Ultimate limit states:

— yielding of bolting element critical section
— slipping at interface of adjacent parts
— yielding of mating parts
— thread shearing.

Fatigue limit states:

— fatigue of bolting element critical section
— fatigue of mating parts (bolt hole).

Ensuring an adequate preloading is a fundamental prerequisite to avoid failure of the bolted connection. The assembly preload allows to proportionally sharing the transmitted working loads and moments between the mated parts and the bolt.

The load share of the bolt is determined by the stiffness of the adjacent parts and the application point of the force or moment. Influences from loading eccentricity, possible gaps in the joints and imperfections shall be taken into account. In the strength assessment, relaxation of the bolt preload due to surface setting effects shall be taken into account. Relaxation of the bolt preload may be prevented by inspecting the bolts and retightening them, if necessary, during the first months following the installation.

5.3.1 Analytical strength assessment of preloaded bolted joints

Strength analysis of preloaded bolted joints may be based on analytical calculations when the stiffness of the adjacent parts is considered symmetrical and uniform.

Shear loaded bolted connections

5.3.1.1 Analytical calculations of transversally loaded bolted joints should be performed on the basis of EN 1993-1-8 or other design codes and analytical methodologies agreed with DNV GL in advance. Bolted connections of components belonging to primary supporting structures or machinery components should be calculated as slip-resistant at ultimate limit states (e.g. according to Category C: EN 1993-1-8).

Guidance note:
Designing the bolted joint against slipping at an interface of adjacent parts at ULS also ensures design against bolt shearing and plate bearing as per EN 1993-1-8.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

Axially loaded bolted connections

5.3.1.2 Analytical calculations of axially loaded bolted joints should be performed on the basis of VDI 2230 or other widely recognized design codes and analytical methodologies. Limitations and shortcomings of the analytical assessments shall be taken into account when selecting a calculation method.

5.3.2 Numerical strength assessment of bolted joints

For bolted connections with non-uniform stiffness of the adjacent parts, a numerical or experimental analysis may be required in addition to or in substitution of the analytical calculation. Here the finite element method may be used.

Guidance note:
Calculation of ring flange connections may also be performed with the aid of the finite element method (FEM) or other calculation methods leading to comparable results. In that case, imperfections and gaps at the flanges need to be considered.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

In design calculations for the static strength of bolted connections at machinery components done in accordance with [4.3], the partial safety factor for the bolt material may be set to: γ_M = 1.0 if the torsional loading of the bolt as well as the tensional and bending loading is taken into account in the calculations. This does not influence the requirements on fatigue analysis in other sections of this standard.

All friction coefficients that are used in calculations shall be verified, either by established written sources or by tests. The tests shall be carried out by laboratories accredited according to ISO/IEC 17025 or shall be witnessed by DNV GL.

5.4 Requirements on materials and corrosion protection of bolting elements

In general, material characteristics for bolting elements shall be defined according to ISO 898-1. For metric bolts exceeding M39, ISO 898 may be applied as long as the material meets the corresponding strength requirements.

For HV bolts with sizes larger than M36 used in primary supporting structures, requirements given in DASt-Richtlinie 021 and EN 14399-3/-4 shall be observed.

5.4.1 Fatigue strength of bolts

Fatigue strength of bolts under variable amplitude axial loading may be described by S/N curves with the form as given in DNVGLRP0005 and categorized in the Table 5-1:

Table 5-1 Table ?51 Fatigue strength under variable loading

Fatigue strength at 2x10^6 cycles [MPa]	Negative inverse slope (N < 5x10^6 cycles)	Negative inverse slope ($N \geq$ 5x10^6 cycles)	Comments
detail category $71*(2-\frac{F_{S\max}}{F_{0,2\min}}) \leq 85$	m_1 = 6	m_2 = 11	Rolled after heat treatment, no thermal coating
71	m_1 = 3	m_2 = 5	Rolled before heat treatment, no thermal coating
50	m_1 = 3	m_2 = 5	Rolled threads, thermal coating

where:

$F_{S\ max}$ = maximum bolt force

$F_{0.2\ min}$ = bolt force at the 0.2% elastic strain limit

Guidance note:
The maximum bolt force may be calculated under the same preload assumptions as used for the bolt fatigue strength assessment.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

For bolts larger than M30, a reduction of the S/N curve by the factor k_s shall be taken into account, with:

$$k_s = (30 \text{ mm}/d)^{0,25}$$

where d is the nominal diameter of the bolt

The previous S/N curves provide a 97.7% probability of survival with 75% level of confidence.

Nominal stress levels in the bolts shall be established taking into account bending in the bolt due to prying effects and/or other sources, such as eccentric loading. Alternatively, the bolt shall be assessed using detail category 36.

5.4.2 Corrosion protection

In general, bolted joints shall be protected against corrosive environments to the same extent as the adjacent parts, see Sec.3.

For steel structures following the provisions of EN 1090, corrosion protection of bolts shall be equivalent to the protection system of the steel construction. To this purpose, hot dip galvanized fasteners according to ISO 10684 should be used.

However, certain corrosion protection systems may have a detrimental effect on the fatigue strength, in terms of hydrogen embrittlement and loss of compressive residual stresses on the threads, if these are cold rolled after heat treatment.

In case the bolts are protected against corrosion by hot dip galvanization, no beneficial effects from residual compressive stresses from thread rolling shall be assumed.

If different corrosion protection systems are used instead of hot-dip galvanization, the tightening procedure and application of the preload shall be ensured by appropriate procedure tests in agreement with DNV GL.

Furthermore, the manufacturer should provide evidence that the fatigue properties of the bolts remain unaffected by the thermal coating process. This shall be proven with S/N curves based on fatigue tests for both cases.

5.4.3 Inspection of bolted connections

5.4.3.1 During the operating life of the wind turbine, the bolted connections shall be inspected as part of regular preventive maintenance on the wind turbine. These inspection procedures shall be specified in the maintenance manual. Here the following shall be observed:

5.4.3.2 All bolted connections which rely on a defined preload level and were tightened using a torque-controlled or tensioning-force-controlled method shall be retightened at least once after the commissioning (within 6 months but not directly after the installation). The original tightening torque or the original tensioning force on the bolts should be applied. The retightening time shall be specified in the manual.

5.4.3.3 An interval for regular visual inspections and looseness checks during the life cycle of the wind turbine shall be specified. The intention of looseness checks is to detect if bolts have failed or have totally lost their design preload.

5.4.3.4 In the case of bolted connections which were tightened by other methods or which were brought into the plastic zone when tensioned, special inspection procedures shall be defined for each individual case.

5.4.3.5 In the case of bolted connections for which GRP or CRP is included in the tensioned material, special inspection procedures shall be defined for each individual case.

SECTION 6 BEARINGS

6.1 General

The requirements of this section apply to rolling contact bearings intended as rotor, gearbox or generator bearings in the drive train of a wind turbine, as well as to blade or yaw bearings, and to rolling contact bearings for other load-transmitting components. The requirements for plain bearings shall be determined for each individual case in consultation with DNV GL.

6.2 Assessment documents

The following assessment documents shall be submitted for the bearings listed in Section ?6.1:

a) assembly drawings of relevant application
b) calculation documents
c) relevant detail drawings including number of rolling elements and geometry of the rolling elements and raceways (as listed in ISO 281:2007) if the bearings are not of a standard type
d) data sheet of lubricant including necessary oil flow or necessary amount of grease
e) in case of integrated bearings in planetary gears the documentation shall be agreed on with DNV GL.
In order to assess the structural integrity of surface hardened large diameter roller bearings ($D_{PW}/D_W \geq 20$) intended to be used as main bearings, yaw and blade bearings the documentation shall include the following information:

f) mechanical properties of bearing ring base material: Core hardness HB or HV, yield strength $R_{p0,2}$, tensile strength R_m, elongation at fracture A_5, Charpy impact energy K_v (test temperature 20°C or 40°C depending on survival temperature specified for the respective wind turbine)
g) surface hardness of raceways
h) surface roughness of the raceways (if not specified DNV GL will anticipate R_a = 1.6 μm)
i) case depth of raceway according to EN 10328, ISO 3754 or ISO 2639
j) diameter D_W of the bearing balls (diameter D_W and effective length l_{eff} for rollers respectively)
k) amount of rolling elements per raceway
l) cage guided/non cage guided rolling elements
m) grease- or oil-lubricated raceway system
n) track diameter D_{PW} of the raceways
o) osculation; i.e. ratio between cross sectional raceway groove radii r_i and r_a for inner and outer ring respectively (ball bearings only)
p) nominal contact angle α_0
q) assembly drawing of bearing including details of corrosion protection.

The influences of the surrounding structure on the raceway stresses of blade, yaw and main bearings with similar characteristics shall be included in the strength analysis of the bearing raceways.

Thus, the impact of pre-tensioned bolted connections or shrink fits as well as temperature gradients shall be taken into account. In any case, frictional contact shall be considered between the bearing rings and the mating structures. Furthermore, the tangential hoop stress of the bearing rings shall be analysed and documented for static and fatigue loads respectively

For each bearing in the drive train and for blade and yaw bearings, the bearing manufacturer shall be named clearly. If a bearing is supplied by two or more bearing manufacturers, the assessment documents shall be provided for each bearing manufacturer.

6.3 Materials

6.3.1 Approved materials

The scope of material tests (insofar as the bearings are of a standard type) shall be determined in consultation with DNV GL.

6.3.2 Assessment of materials

6.3.2.1 The scope of the material tests (insofar as the bearings are not of a standard type) shall be determined in consultation with DNV GL and with due consideration of [2.1.3].

6.3.2.2 The verifications of the bearing materials for the blade and yaw bearings shall be provided as per 2.1.3. For these bearings, which are predominantly loaded by small back-and-forth motions, the following shall be fulfilled:

— The notched-bar impact work in the case of the ISO-V test shall have a 3-test mean value ≥ 27 Joule at 20°C; the lowest individual value shall be more than 70% of the mean value. Deviation from these values is possible in consultation with DNV GL if a lower stress level can be proven or on the basis of test results.
— The minimum hardness of the bearing raceway surfaces is 55 HRC.

6.4 Loads to be applied

6.4.1 General

6.4.1.1 For the static rating, the extreme load (positive and negative) shall be applied. Blade and yaw bearings are designed for a certain static load-bearing capacity. For the static load-bearing capacity, the extreme load shall be applied according to [7.2.3] and [7.3.3].

6.4.1.2 For the dynamic rating (determination of the rating life and determination of the contact stress), the equivalent operating load shall be used. Using a duration counting method, the representative loads for the calculation of the rating life and the contact stress shall be determined from the time series of the fatigue loads as per DNVGL-ST-0437. With this counting method the sum of revolutions n_i of the bearing is determined, during which the equivalent dynamic bearing load P_i acts within the individual class limits.

6.4.2 Analysis

6.4.2.1 For the analysis of the basic rating life according to ISO 281:2007, the equivalent bearing load averaged over the lifetime can be calculated as follows:

$$P = \sqrt[p]{\frac{\sum P_i{}^p n_i}{N}}$$

where:

P_i = equivalent dynamic bearing load
p = 10/3 for roller bearings; 3 for ball bearings
n_i = number of revolutions during which P_i acts
N = total number of revolutions for the design lifetime of the wind turbine.

6.4.2.2 Alternatively, the rating life can be calculated using the time series of the fatigue loads (normal operating load conditions) as per DNVGL-ST-0437.

6.4.2.3 Using a duration counting algorithm, the representative load levels and load cycles shall be derived and used as input to derive, for each load bin i, the sum of the revolutions n_i for which each bearing is loaded with an equivalent dynamic bearing load P_i. Both P_i and n_i are used to compute, for each load bin and each bearing, the corresponding rating life. The raceway contact stress shall be calculated for a Miner’s sum equivalent from the derived duration load set (P_i, n_i).

6.4.2.4 The operating loads on generator bearings and on gearbox output shaft bearings shall be superposed by the calculated reaction forces due to the maximum permissible dynamic misalignment between the generator and gearbox.

6.4.2.5 For calculation of the operating loads on the generator bearings the tower top acceleration acting on the generator shall be considered.

6.4.2.6 The extreme loads on generator bearings and on gearbox output shaft bearings shall be superposed by the calculated reaction forces from the maximum permissible static misalignment between the generator and gearbox.

6.5 Calculations

6.5.1 Static rating under extreme load

6.5.1.1 For bearings used in the drive train, a static rating according to ISO 76:2006 shall be submitted. The static safety factor S_0 shall be at least 2.0.

6.5.1.2 For blade and yaw bearings, which are predominantly loaded by small back-and forth-motions, the static rating is derived directly from the calculated maximum contact stress between rolling elements and raceway. The maximum permissible Hertzian contact stress shall be defined by the bearing manufacturer with consideration for the material, surface hardness and hardening depth, and shall be documented in the design calculation. A proof against core crushing shall be supplied for the yaw and blade bearing raceways.

6.5.1.3 The static safety factor for blade and yaw bearings is the ratio between the maximum permissible Hertzian contact stress and the maximum contact stress, and shall be at least 1.1.

6.5.1.4 For the bearings in the actuators of pitch and yaw systems, the static safety factor S_0 according to ISO 76:2006 shall be at least 1.1.

6.5.1.5 For all other bearings, the static safety factor shall be defined in consultation with DNV GL.

6.5.2 Rating life

6.5.2.1 For bearings used in the drive train, the following analyses shall be submitted:

— basic rating life calculation (L_{10}) according to ISO 281:2007.
— modified rating life calculation (L_{10m}) according to ISO 281:2007.
— modified reference rating life calculation (L_{10mr}) according to ISO/TS 16281:2008. Alternatively, proprietary calculation methods developed by bearing manufacturers may be used if agreed with DNV GL.

Alternatively, proprietary calculation methods developed by bearing manufacturers can be used if agreed with DNV GL.

6.5.2.2 For blade and yaw bearings, the ISO 281:2007 rating life calculation shall be modified according to NREL Wind Turbine Design Guideline DG03, Section 4.

6.5.2.3 For all other bearings, the basic or modified rating life calculation according to ISO 281:2007 may be performed if agreed with DNV GL.

6.5.3 Contact stress

6.5.3.1 For bearings used in the drive train, the contact stress shall be calculated taking into account the internal load distribution.

6.5.3.2 The contact stress using the Miner's sum dynamic equivalent bearing load should not exceed the values listed in Table 6-1.

6.5.4 Boundary conditions

6.5.4.1 In the calculation of the modified rating life according to ISO 281:2007 and the modified reference rating life according to ISO/TS 16281:2008, the probability of failure shall be set to 10%. The life modification factor a_{ISO} shall be limited to 3.8.

6.5.4.2 The calculated modified rating life according to ISO 281:2007 may not be less than 130,000 hours. The calculated modified reference rating life according to ISO/TS 16281:2008 shall not be less than 175,000 hours or the operating life of the wind turbine.

Table 6-1 Recommended values for maximum contact stress at Miner's sum dynamic equivalent bearing load

Bearing position	Maximum contact stress p_{max} in N/mm^2
High-speed shaft	1300
Intermediate shafts	1650
Planets	1500
Low-speed shaft	1650
The recommended values apply for bearings manufactured from contemporary, commonly used, high-quality hardened bearing steel, in accordance with good manufacturing practice and basically of conventional design regarding the shape of rolling contact surfaces. Values in this table are valid for a design lifetime of 20 years and shall be adjusted for designs with different design lifetime.	

6.5.4.3 The following input parameters required for the modified rating life according to ISO 281:2007 shall be set out in the calculation:

— bearing temperature
— type of lubricant (oil, grease, additives etc.)
— lubricant viscosity at operating temperature
— operating lubricant cleanliness according to ISO 4406:1999.

6.5.4.4 The modified reference rating life calculation according to ISO/TS 16281:2008 shall consider at least the following effects in addition to the loads:

— internal design of bearings
— operating internal clearance
— deformation of bearings and shafts
— load sharing between rolling elements
— load distribution along roller length, considering actual roller and raceway profiles
— bearing temperature
— type of lubricant (oil, grease, additives etc.)
— lubricant viscosity at operating temperature
— operating lubricant cleanliness according to ISO 4406:1999
— dead-weight of components where necessary.

6.5.4.5 The calculation of the modified reference rating life according to ISO/TS 16281:2008 shall be performed for each load level of the load duration distribution or for the equivalent load. A reduction of the specified spectrum to 10 load levels in accordance with Miner's rule is permissible to minimize the computational effort. The life exponent for reducing the number of load levels shall correspond to the exponent used in the bearing calculation.

6.5.4.6 The combined modified rating life according to ISO/TS 16281:2008 for the corresponding bearing is then obtained as:

$$L_{10mr} = \frac{\sum q_i}{\sum \frac{q_i}{L_{10mr\ i}}}$$

where:

L_{10mr} = combined modified rating life of the bearing
q_i = time share on the *i*-th load level
$L_{10mr\ I}$ = modified rating life of the bearing on the *i*-th load level

6.5.4.7 The modified rating life calculation according to ISO 281:2007 as well as the modified reference rating life calculation according to ISO/TS 16281:2008 shall be based on an oil cleanliness class of /17/14 according to ISO 4406:1999 for filtered systems. For unfiltered systems a cleanliness class of /21/18 shall be assumed.

6.5.5 Minimum loading

Compliance with the minimum load shall be agreed between the component manufacturer and the bearing supplier in accordance with the general structural and operational conditions.

6.6 Miscellaneous

In principle, the oils and greases recommended by the wind turbine manufacturer shall be used, whereby these shall comply with the prescribed component manufacturer’s specification.

During assembly, the bearing manufacturer’s instructions shall be observed. The transport of bearings shall be undertaken in such a way that damage to rolling elements and raceways is prevented.

The bearing shall be sealed if this ensures its function or protects the function of adjoining components.

Owing to the special operating conditions for wind turbines, it should be possible to exchange generator bearings on site.

SECTION 7 MACHINERY COMPONENTS AND SYSTEMS

7.1 General

7.1.1 Assessment documents

7.1.1.1 The following documents are required for assessment of the ultimate and serviceability limit states of machinery components of wind turbines.

7.1.1.2 For the important components, i.e. force or torque transmitting parts as well as safety relevant components, specifications and/or parts lists are required with data about materials, data from the manufacturer in the case of mass-produced parts, about the standard in the case of standardized parts etc.

7.1.1.3 Engineering drawings (assembly drawings and individual-part drawings) of the important elements of the wind turbine, executed in standard form are required; clear identification shall be assured (parts designation, drawing number, and modification index). They shall contain data about surface finish, heat treatment, corrosion protection etc.

7.1.1.4 For mass-produced parts which have proven their suitability for use by successful service in comparable technical applications, type/data sheets are generally sufficient. However, further documentation/verification may be necessary in individual cases for such parts. E.g. main gearboxes do not count as mass-produced in this sense.

7.1.1.5 Strength calculations for all components and means of connection shall verify the ultimate limit states and serviceability limit states totally, clearly and confirmably. The analyses shall be complete and unified in themselves. They shall contain adequate data concerning:

— design loads
— static systems (analogous models)
— materials
— permissible stresses
— references used.

7.1.1.6 Fatigue analysis shall be carried out in accordance with [4.4] using the codes and technical literature listed therein.

7.1.1.7 From the technical and calculation viewpoint, the documentation of the computational analyses shall form a unified whole together with all other documents (drawings, specifications). Here it shall be observed that the references of the adjacent components and structural areas that are mentioned in the computational analyses shall be included in the documentation.

7.1.1.8 If analysis concepts of different standards and guidelines are applied, these shall not be mixed.

7.1.1.9 Operations associated with moving or transportation of machinery components or parts thereof during the construction or installation may have decisive influence on the overall design. These operations concerning the integrity are therefore included in the design review (design assessment).

7.1.1.10 All lubricants and hydraulic fluids shall be specified with the corresponding type sheets. Oil collecting trays for the possible spilling of operating media shall be provided in the wind turbine (hub and nacelle).

7.1.1.11 The design of the cooling and heating systems for the operation of the wind turbine shall be specified.

7.1.1.12 The specifications (requirements) from the manufacturer of the wind turbine for the design of the machinery components shall be appended to the documents.

7.1.2 Materials

Requirements, verification and inspection certification are laid down in Sec.2. Additional data are to be found in the following sections of this chapter.

7.2 Blade pitching system

7.2.1 General

7.2.1.1 This section applies to the blade pitching systems of wind turbines as described below. In the event of other designs, the wording shall apply with the necessary changes.

7.2.1.2 In systems with rotary actuation, the torque needed for the pitching of the rotor blades is applied by a motor with the associated rotary drive. The torque is transmitted by the pitch teeth to the blade bearing fixed to the rotor blade.

7.2.1.3 In systems with a blade pitching mechanism actuated e.g. by one or more hydraulic cylinders, the torque needed for the pitching of the rotor blades is applied by a hydraulic cylinder. The torque is transmitted by the piston rod directly or indirectly to a linking point fixed to the rotor blade.

7.2.1.4 A locking device shall be provided for the blade pitching system (see [7.5] and furthermore DNVGL-ST-0438). This device shall lock the pitch system in place during maintenance and repair work in order to exclude the risk of personal injury. This locking device does not need to be located permanently at the blade pitching system; it may also be an external lock which is mounted whenever required.

7.2.2 Assessment documents

7.2.2.1 General information on the assessment documents to be submitted is given in [7.1].

Assembly and sectional drawings, including the associated parts lists and if applicable individual part drawings, shall be submitted together with a description explaining the functional principle of the blade pitching system.

a) The calculations for the verification of the components of the blade pitching system shall be presented including input data for the calculation and presentation of the results with the relevant safety margins.
b) In case of a pitch system with a pitch gearbox, individual part drawings of the pitch pinion, the pitch pinion shaft and the blade bearing teeth are required. Individual parts drawings of the planet carrier and the gearbox housing at the output are required as per [7.2.4].
c) For pitch systems with a pitch gearbox, the strength analysis of the pitch system shall include

   — the pitch gearbox teeth
   — the blade bearing teeth
   — the load capacity considering the fatigue loads
   — static strength against tooth breakage and pitting
   — fatigue strength and static strength for the output shaft of the pitch gearbox and for the connecting elements of the pitch gearbox as described in [7.2.4].

d) In case of systems with a blade pitching mechanism, actuated e.g. by one or more hydraulic cylinders, dimensioned drawings shall be submitted in which the pitching mechanism is shown with various blade angle positions. At least the maximum and minimum positions and the positions in which the greatest loads act on the blade pitching mechanism shall be shown.
e) For components of the blade pitching mechanism, actuated e.g. by one or more hydraulic cylinders, a fatigue strength analysis and a static strength analysis shall be assessed for all load-transmitting components and connecting elements. A buckling analysis for the pitch cylinders shall be included.

7.2.3 Loads to be applied

7.2.3.1 For the calculation of the loading of the blade pitching system, the design loads as per DNVGL-ST-0437 shall be applied.

7.2.3.2 The static and load-dependent bearing friction moments shall be taken into account.

7.2.3.3 For the fatigue analysis, the load duration distributions (LDD) and the load spectra shall be applied. A distinction shall be made between operation with and without blade pitching. Here additional inertial loads resulting from the rotor rotation and dynamic excitation loads shall also be considered.

7.2.3.4 The static strength analysis – with and without blade pitching operation – shall be performed for the design loads of the dimensioning load case as per DNVGL-ST-0437. If the maximum torque about the blade axis obtained from the dimensioning load case is exceeded by the application of the pitch motor brakes or limited by the hydraulic pressure, then the maximum torque generated by the pitch system shall be used for static strength analysis of the pitch system.

7.2.3.5 The teeth of the blade bearings are stressed predominantly on a very small part of their circumference during operation. The maximum rotational angle between start and stop procedures is approx. 90°. According to this the calculative number of load cycles per teeth shall be taken into account for fatigue calculation.

7.2.3.6 In systems with a rotary drive, an application factor of K_A = 1.0 is used for the static and fatigue strength analyses.

7.2.4 Verification of the blade pitching system

Pitch gearbox

7.2.4.1 In case of pitch systems with a pitch gearbox, the gear load capacity calculation of the pitch gearbox and pitch teeth shall be based on the ISO 6336 series.

7.2.4.2 The calculation of the fatigue load capacity of gears shall be performed according to ISO 63366:2006 using the LDD or using an equivalent torque derived from the LDD according ISO 63366:2006, Annex A. The Palmgren-Miner sum used in the service life calculation shall be less than or equal to D = 1.

7.2.4.3 Furthermore, an analysis of the fatigue strength in compliance with the safety factors according to is required.

7.2.4.4 Furthermore, an analysis of the fatigue and static strength against tooth breakage and pitting in compliance with the safety factors according to Table 7-1 and Table 7-2 is also required.

7.2.4.5 According to ISO 6336-5:2003, the predominant alternating load on the gears shall be considered. A reduction factor of 0.7 for the respective S/N curve shall be applied. More favourable values may be used, e.g. based on ISO 6336-3:2006, Annex B.

Table 7-1 Safety factors for the fatigue strength analysis

Minimum safety factors for the pitch gearbox and the blade bearing teeth	Gearbox	Pitch teeth
Surface durability (pitting) S_H	1.0	1.1
Tooth root breakage S_F	1.15	1.25

Table 7-2 Safety factors for the static strength analysis

Minimum safety factors for the pitch gearbox and blade the bearing teeth	Gearbox	Pitch teeth
Surface durability (pitting) S_H	1.0	1.0
Tooth root breakage S_F	1.1	1.2

7.2.4.6 For the output shaft of the pitch gearbox and for the connecting elements a fatigue strength analysis and a static strength analysis shall be submitted. The analyses shall be performed in accordance with DIN 743 series, DIN 6892:2012 and DIN 7190, or equivalent standards.

7.2.4.7 Strength analyses for rotary drive housings and planet carriers may be demanded if necessary (see also [7.1.1.4]).

Guidance note:
The output pinion of the rotary drive should be forged-on.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

Connecting elements

7.2.4.8 Strength analyses for bolted connections are necessary wherever the bolts are essential for the transmission of loads (see Sec.5).

Blade bearing

7.2.4.9 With regard to the calculation and execution of the blade bearing reference is made to Sec.6.

7.2.4.10 The turbine manufacturer and/or the supplier of the blade bearing shall verify that the surrounding construction of the blade bearing is considered in the evaluation of the bearing components at least by implementing stiffness matrixes of surrounding structures into bearing calculations.

7.2.4.11 The seals shall be protected in a way that they are not damaged by the prevailing environmental conditions.

Guidance note:
A single seal is not deemed an adequate protection against external influences for the rolling body and track surface. The level of protection can be increased e.g. by a spinner or an additional seal.

It should be possible to exchange the seals of the blade bearing in the installed condition.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

Lubrication system

7.2.4.12 It shall be shown that an adequate film of lubricant is always provided on the flanks of the blade bearing teeth and also between the balls or rollers and the track surface of the blade bearing for all operational modes of the wind turbine.

7.2.4.13 For the teeth of the blade bearing, a lubrication system is mandatory in general. The functionality of the lubrication system shall be documented (installation plan, lubrication intervals, lubricant distribution).

7.2.4.14 If necessary, this requirement may be met by means of a test run e.g. taking place once within 24 hours. During this test run the rotor blades and thus also the blade bearings are rotated by a pitching angle sufficient for providing relubrication of blade bearing raceways and gear.

7.2.4.15 Appropriate collecting reservoirs shall be provided to accommodate excess quantities of lubricant from the blade bearing teeth as well as from the blade bearing.

Additional verifications

7.2.4.16 For the verification of the electrical system, DNVGL-ST-0076 shall be considered.

7.2.4.17 For the verification of the hydraulic system, [7.8] shall be considered.

7.2.4.18 If other systems than described in [7.2.1.2] or [7.2.1.3] are applied for blade pitching, the verification process of those systems shall be agreed with DNV GL.

7.3 Yaw system

7.3.1 General

7.3.1.1 This section applies for the yaw system of wind turbines as described below. In the event of other designs, the wording shall apply with the necessary changes.

7.3.1.2 The design of the yaw system shall be verified for proper function in accordance with the system concept.

7.3.1.3 The torque necessary to align the nacelle with the wind direction is provided by a yaw motor with the associated yaw gearbox (rotary drive). The torque is transmitted by the yaw teeth from the yaw pinion to the yaw bearing.

7.3.1.4 The nacelle is supported on the tower head either by a friction yaw bearing or by a roller yaw bearing. The rotating of the nacelle around the tower axis is usually braked either by a brake in the yaw motor and/or by yaw brakes acting on a brake disc fixed to the tower head or the nacelle.

7.3.1.5 To exclude damages caused by alternating stresses at the yaw teeth due to oscillating motions around the tower axis, a constantly acting residual brake torque should be applied, either by the inherent and load-dependent friction torque of the yaw bearing or by an additional yaw brake system.

7.3.1.6 A locking arrangement shall be provided for the yaw system (see also DNVGL-ST-0438), with which the system is locked in place during maintenance and repair work, in order to exclude the risk of personal injury. This locking arrangement does not necessarily need to be located permanently at the yaw system; it may also be an external lock which is mounted whenever required.

7.3.1.7 Appropriate collecting troughs shall be provided to accommodate excess quantities of lubricant from the toothing of the yaw ring and the drive pinion as well as from the nacelle bearing.

7.3.2 Assessment documents

7.3.2.1 General information on the assessment documents to be submitted is given in [7.1].

7.3.2.2 For the components of the yaw system, type sheets, specifications and assembly drawings shall be submitted.

7.3.2.3 Assembly and sectional drawings, including the associated parts lists and if applicable individual part drawings, shall be submitted together with a description explaining the functional principle of the yaw system.

7.3.2.4 The calculations (including input data for the calculation, presentation of the results with the relevant safety margins) for the verification of the components of the yaw system shall be presented.

7.3.2.5 For the evaluation of the yaw teeth, the single part drawings of the yaw pinion shaft and the yaw bearing teeth are required, as well as single part drawings of the planet carrier and the gearbox housing at the output of the yaw gearbox. For the output housing and the final stage planetary carrier of the pitch gearbox, a fatigue strength analysis and a static strength analysis shall be submitted. (see [7.1.1.5] and [7.1.1.6]).

7.3.2.6 The analysis of a yaw system with a yaw gearbox shall meet the requirements stated within the documentation as per [7.3.4] for:

— the yaw gearbox teeth
— the yaw bearing teeth
— the load capacity considering the fatigue loads
— the static strength against tooth breakage and pitting
— fatigue and static strength analysis for the output shaft of the yaw gearbox and for the connecting elements.

7.3.3 Loads to be applied

7.3.3.1 For the calculation of the loading of the yaw system, the design loads as per DNVGL-ST-0437 shall be applied.

7.3.3.2 For the fatigue strength analysis of the yaw gears, the load duration distributions (LDD) and the load spectra shall be used. A distinction shall be made between operation with and without yawing. For operation with yawing, inherent and load-dependent yaw bearing friction torque as well as gyroscopic torque of the rotor at rated yaw and rotor speed shall be considered in the fatigue strength analysis (see DNVGL-ST-0437).

7.3.3.3 The static strength analysis – with and without operation of the yaw system – shall be performed for the design loads of the dimensioning load case as per DNVGL-ST-0437. If applicable, the following additional dimensioning loads shall be considered:

— the maximum torque of the yaw motor brakes for the static strength analysis of the yaw gearbox, the yaw bearing teeth and the connecting elements according to [7.3.4]
— if inductive yaw motors are directly switched to the grid without application of soft-start switches or frequency converters, the static strength analysis for the teeth and the shaft connections of the first two

gear stages of the yaw gearbox shall be performed by applying three times the rated yaw motor torque. For the remaining yaw gears, T_{max} and T_{stall} of the motor shall be considered. The occurrence of peak torques at three times the rated motor torque in direct-switched inductive yaw motors shall be considered also in the fatigue strength analysis of the gears and their shaft connections.

7.3.3.4 For the static strength analysis, an application factor of K_A = 1.0 is used.

7.3.3.5 When determining the number of load cycles or the load duration per tooth occurring during yawing, the specifications in DNVGL-ST-0437 shall be applied as a basis. Operation of the yaw system shall be considered to occur at least during 10% of the turbine's service life.

7.3.4 Verification of the yaw system

Yaw gearbox

7.3.4.1 The gear load capacity calculation of the yaw gearbox and yaw teeth shall be based on ISO 6336 series.

7.3.4.2 The calculation of the load capacity from the fatigue loads shall be performed according to ISO 6336-6:2006 using the LDD or using an equivalent torque derived from the LDD according to ISO 6336-6:2006, Annex A. The Palmgren-Miner sum obtained in the service life calculation shall be less than or equal to 1.

7.3.4.3 Furthermore, an analysis of the fatigue and static strength against tooth breakage and pitting in compliance with the safety factors according to Table 7-3 and Table 7-4 is required.

7.3.4.4 According to ISO 6336-5:2003, the predominant alternating load on the gears shall be considered. A reduction factor of 0.7 for the respective S/N curve shall be applied. More favourable values may be used, e.g. based on ISO 6336-3:2006, Annex B.

Table 7-3 Safety factors for the fatigue strength analysis

Minimum safety factor for the yaw gearbox and the yaw bearing teeth	Gearbox	Yaw teeth
Surface durability (pitting) S_H	1.0	1.1
Tooth root breakage S_F	1.15	1.25

Table 7-4 Safety factors for the static strength analysis

Minimum safety factors for the yaw gearbox and the yaw bearing teeth	Gearbox	Yaw teeth
Surface durability (pitting) S_H	1.0	1.1
Tooth root breakage S_F	1.1	1.2

7.3.4.5 For the output shaft of the yaw gearbox and for the connecting elements, a fatigue strength analysis and a static strength analysis shall be submitted. The analyses shall be performed in accordance with DIN 743 series, DIN 6892:2012 and DIN 7190, or equivalent codes.

7.3.4.6 For the output housing and the final stage planetary carrier of the yaw gearbox, a fatigue strength analysis and a static strength analysis shall be submitted (see [7.1.1.5] and [7.1.1.6]).

Connecting elements

Strength analyses for bolted connections are necessary wherever the bolts are essential for the distribution of forces (see Sec.5).

Yaw bearing

7.3.4.7 With regard to the calculation and execution of the yaw bearing, except for yaw sliding bearings, reference is made to Sec.6.

7.3.4.8 The wind turbine manufacturer and/or the supplier of the blade bearing shall verify that the surrounding construction of the yaw bearing is adequate for the function of the yaw bearing.

7.3.4.9 The seals shall be so protected that they are not damaged by the prevailing environmental conditions.

Guidance note:
It should be possible to exchange the seal of the yaw bearing in the installed condition.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

Lubrication system

7.3.4.10 It shall be shown that an adequate film of lubricant is always provided on the flanks of the yaw bearing teeth and also between the balls or rollers and the track surface of the yaw bearing for all operational modes of the wind turbine.

7.3.4.11 For the teeth of the yaw bearing, a lubrication system is mandatory in general. The functionality of the lubrication system shall be documented (installation plan, lubrication intervals, lubricant distribution).

7.3.4.12 Appropriate collecting reservoirs shall be provided to accommodate excess quantities of lubricant from the yaw teeth as well as from the yaw bearing.

Yaw brake

7.3.4.13 Notes on the calculation of brakes are given in [7.4].

7.3.4.14 If a permanent application of a braking torque is required according to the system concept, the function of the brakes shall also be ensured in the event of a failure of the power supply.

Additional verifications

7.3.4.15 In the case of systems with electrical actuation drives, DNVGL-ST-0076 shall also be considered.

7.3.4.16 For the verification of the hydraulic system, [7.8] shall be considered.

7.3.4.17 The design of the drives and brakes shall be verified for proper function in accordance with the system concept.

7.4 Mechanical brakes

7.4.1 General

The following applies to the mechanical brakes of the rotor, the electrical pitch system and the yaw system.

7.4.2 Assessment documents

The following assessment documentation is required:

a) general arrangement and installation drawings and instructions, single-part drawings of all force-transmitting parts, circuit diagrams of the hydraulic, pneumatic and electrical equipment including a parts list
b) data sheet of the brake stating the operational conditions (permissible pressure/current/voltage, permissible temperatures)
c) data sheet of the lining, stating the material, friction coefficient (static and dynamic), permissible temperatures and wear characteristics, data regarding the material combination of lining and brake drum/disc
d) verifications as given in [7.4.4] to [7.4.6].

7.4.3 Materials

Reference is made to Sec.2.

7.4.4 Verification of pitch brake

7.4.4.1 A calculation of the minimum and maximum braking moment shall be carried out, taking into account the variation of friction coefficient, warming and wear of the lining.

7.4.4.2 The minimum and maximum braking moment shall be in accordance with the requirements of the control system.

7.4.4.3 For all force- or moment-transmitting components and joints, a general strength analysis shall be carried out, using the maximum force that the brake can achieve. In case of standard components, data sheets or similar documents can be accepted if agreed with DNV GL

7.4.4.4 The general strength analysis is described in Sec.4.

7.4.5 Verification of rotor brake

7.4.5.1 The mechanical brake is important in order to bring the rotor to a standstill (see DNVGL-ST-0438).

7.4.5.2 Due to the heat generation and the wear arising from continuous operation of mechanical brakes, it is not possible just to limit the rotational speed of the rotor with these brakes. Therefore the brakes shall be designed such that they are capable of bringing the rotor to a standstill. Depending on the safety concept (see DNVGL-ST-0438), standstill may be attainable in combination with the pitch system.

7.4.5.3 For the torques in the drive train that are relevant for the design of the mechanical brake, the following terms apply (see Figure 7-1):

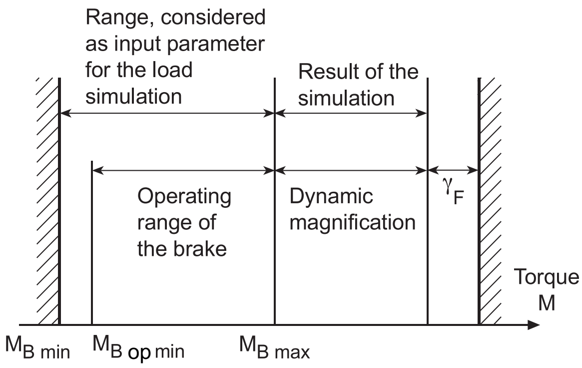

Figure 7-1 Sketch of the relevant torques in the drive train

7.4.5.4 The minimum required braking moment M_{Bmin} and the maximum braking moment M_{Bmax} are input parameters for the load simulations of the wind turbine as per DNVGL-ST-0437.

7.4.5.5 A calculation of the minimum and maximum braking moment ($M_{\mathrm{B\ op\ min}}/M_{\mathrm{Bmax}}$) shall be carried out, taking into account the variation of brake pressure, friction coefficient, warming and wear of the lining.

7.4.5.6 During the braking process, a moment is produced in the drive train which exceeds the maximum braking moment by the dynamic magnification. The magnification is obtained by the load simulation as described in DNVGL-ST-0437. It shall be shown that the magnified maximum braking moment times the safety margin γ_F does not damage the structure of the turbine (see DNVGL-ST-0437 for γ_F). This is the limiting condition of the maximum braking moment M_{Bmax}.

7.4.5.7 The minimum required braking moment M_{Bmin} shall be such that the rotor is brought to standstill (see also [7.4.5.2]). This is analysed by the load simulation as described in DNVGL-ST-0437.

7.4.5.8 It shall be shown that $M_{\mathrm{B\ op\ min}}$ is at least 1.1 times bigger than M_{Bmin}. This is the limiting condition of the minimum braking moment $M_{\mathrm{B\ op\ min}}$.

7.4.5.9 For all force- or moment-transmitting components and joints, a general strength analysis shall be carried out, using the maximum force that the brake can achieve. In case of standard components, data sheets or similar documents can be accepted if agreed with DNV GL.

7.4.5.10 The analysis shall include the brake caliper support and the drum/disc.

7.4.5.11 The general strength analysis is described in Sec.4.

7.4.5.12 It shall be shown that the permissible temperatures are not exceeded during the braking process. The proof shall be provided with the least favourable braking moment.

7.4.5.13 Automatic monitoring of the brake may be necessary; see DNVGL-ST-0438.

7.4.5.14 Additional proofs may be required in individual cases (e.g. spring calculations for spring-actuated brakes).

7.4.6 Verification of yaw brake

7.4.6.1 A calculation of the minimum and maximum braking moment shall be carried out, taking into account the variation of brake pressure, friction coefficient, warming and wear of the lining.

7.4.6.2 The minimum and maximum braking moment shall be in accordance with the requirements of the control system.

7.4.6.3 For all force- or moment-transmitting components and joints, a general strength analysis shall be carried out, using the maximum force that the brake can achieve. In case of standard components, data sheets or similar documents can be accepted if agreed with DNV GL.

7.4.6.4 The analysis shall include the brake support and the drum/disc.

7.4.6.5 The general strength analysis is described in Sec.4.

7.4.7 Miscellaneous

7.4.7.1 The brake surfaces shall be protected against undesirable influences (e.g. lubricants) by means of covers, splashguards or suchlike.

7.4.7.2 The brake shall be capable of holding the rotor blade, the rotor or the nacelle even if there is no power supply. The period of time for which the grid failure shall be assumed is specified in DNVGL-ST-0438.

7.4.7.3 The function of the brakes shall be described in the maintenance instructions.

7.5 Locking devices

7.5.1 General

7.5.1.1 The following applies to the locking devices of the rotor, the pitch system and the yaw system. DNVGL-ST-0438 shall be observed.

7.5.1.2 The locking devices shall be so designed that even with a brake removed they can reliably prevent any rotation of the rotor, nacelle or the rotor blade. The locked (engaged) and the unlocked (disengaged) position of the locking devices shall be secured against unintentional locking and unlocking.

7.5.1.3 At least one rotor lock shall act on the low speed side of the drive train and shall have form-fit. In case of more than one rotor locks the unequal load distribution has to be regarded.

7.5.2 Assessment documents

The following assessment documentation is required:

a) general arrangement and installation drawings and instructions, single-part drawings of all force-transmitting parts, circuit diagrams of the hydraulic, pneumatic and electrical equipment, including a parts list
b) verifications as given in [7.5.4.2].

7.5.3 Materials

Reference is made to Sec.2.

7.5.4 Verifications

7.5.4.1 The locking devices shall be capable of holding the rotor blade, the rotor or the nacelle against

a) a gust during erection or maintenance (DNVGL-ST-0437, DLC 8.1; personnel is present in the nacelle and/or hub)
b) an annual gust (DNVGL-ST-0437, DLC 8.2; personnel has left the turbine).

Requirement b) may be omitted for dimensioning of the rotor lock if the following two prerequisites are fulfilled:

— The turbine and the maintenance procedures are designed such, that it is always tolerable to disengage the rotor lock upon upcoming wind speeds that exceed the wind speed considered in DLC 8.1 (even in cases of unfinished work as e.g. exchange of larger drive train components).
— The maintenance and safety procedures are designed such, that the rotor lock is always disengaged when personnel leaves the nacelle.

7.5.4.2 A general strength analysis using these forces and moments shall be carried out for all force- and moment-transmitting parts of the locking devices.

7.5.4.3 Non-redundant locking devices, based on loads from DLC 8.1, shall be designed considering a safety factor for the consequence of failure of at least $\gamma_N = 1.15$, see also DNVGL-ST-0437. The consequence of failure factor shall be multiplied with the respective safety factor on materials as per [4.7].

7.5.4.4 The general strength analysis is described in Sec.4.

7.5.4.5 The locking bolt shall be verified regarding the shear, bending and surface pressure.

7.5.4.6 If necessary, the locking disc shall be verified against buckling.

7.5.4.7 When using two or more locking devices simultaneously, the distribution of the moment on the individual devices shall be calculated.

7.5.4.8 The function of the locking devices shall be described in the maintenance instructions.

7.5.4.9 The following applies to the locking devices of the pitch and yaw system only:

— The locking device need not necessarily be located permanently at the pitch or yaw system; it may also be an external lock which is mounted whenever required.
— The yaw locking device can also be provided by two independent brake systems.

7.6 Couplings

7.6.1 General

The following applies to couplings in the drive train.

7.6.2 Assessment documents

The following assessment documentation is required:

a) assembly and individual-part drawings of all torque-transmitting components
b) parts lists with data on materials
c) installation drawings and instructions
d) documents as per DIN 740-1:1986, Section 4.12
e) a record (by way of example) of the function test performed on a slipping coupling
f) verifications as given in [7.6.4].

7.6.3 Materials

Reference is made to Sec.2.

7.6.4 Verifications

7.6.4.1 For all torque-transmitting components, a general strength analysis, a fatigue analysis and an analysis of the stress through periodic torque fluctuations shall be submitted. Here the axial, radial and angular misalignment shall be taken into account.

7.6.4.2 In the general strength analysis, the maximum moment resulting from the design loads as per DNVGL-ST-0437 shall be used as the basis.

7.6.4.3 Continuous transmission of that maximum moment is not necessary, but the loading caused by its occurrence shall not result in damage to the coupling. If a reduction in that maximum value is achieved by design measures (e.g. a slipping coupling), the reduced value may be used for the coupling design. Here the tolerance of the slipping moment shall be considered.

7.6.4.4 The general strength analysis is described in Sec.4.

7.6.4.5 The fatigue verification may be carried out by component testing under conditions resembling operation or by computational analyses.

7.6.4.6 For computational analyses, the fatigue loads as per DNVGL-ST-0437 shall be used as a basis. The calculation shall be performed in accordance with Sec.4.

7.6.4.7 If it can be expected that excitation by the rotor or the driven machine may cause alternating torques when passing through a resonance range or when operated at the rated speed, it shall be verified that the coupling is not damaged by these torques.

7.6.4.8 The constancy of the slipping torque over the lifetime or until the next maintenance shall be proven for each torque limiter design. The results may be transferred to torque limiters with other sizes but with the same design.

7.6.4.9 The balance quality shall be agreed upon between the wind turbine manufacturer and the coupling manufacturer.

7.6.4.10 If rubber elements are used, these shall be verified in accordance with [7.7].

7.6.4.11 The temperature influence of a brake disc (if present) on non-metallic coupling components shall be considered (e.g. fire hazard, damage to the rubber elements of the coupling).

7.7 Elastomer bushings

7.7.1 General

The following applies to elastomer bearings which are important for the structural integrity of the turbine, whose failure presents a high potential danger for human health and life, or whose failure results in a severe consequential damage with a long-term break-down of the turbine.

7.7.2 Assessment documents

a) single-part drawing of the elastomer bearing
b) load-deformation diagram for main loading directions
c) type sheet of the elastomer with the following statements:
   - shore hardness, density, elongation at tear, modulus of shear, permissible static deformation
   - permissible operating conditions (chemical resistance, operating temperatures)
   - creep properties of the elastomer bearings (see also design lifetime of the wind turbine, DNVGL-ST-0437)

d) verifications as given in [7.7.4].

7.7.3 Loads to be applied

For the calculation of the loading of the elastomer bearings, the design loads as per DNVGL-ST-0437 shall be applied.

7.7.4 Verifications

7.7.4.1 It shall be shown that the elastomer bearings provide adequate safety against the extreme and fatigue loads.

7.7.4.2 The safety factors of [4.3] and [4.4], Table 4-3, shall be observed.

7.7.4.3 Elastomer bearings shall preferably be subjected to compressive and/or shear loading.

7.7.4.4 If the extreme and fatigue load analyses are carried out with the aid of test results, the test procedure and the results derived from the tests shall be presented in a plausible manner.

7.7.4.5 When transferring test results to the actual application, the assumed reduction factors shall be documented.

7.7.4.6 For the selection of the elastomer bearings, the environmental conditions (e.g. temperature, humidity, ozone) at their place of installation within the wind turbine shall be taken into account. Conditions occurring rarely shall be observed as well.

7.7.4.7 The effects on the spring characteristic shall be described up to the typical loading of the elastomer bearing and for the temperature range from -20°C to +50°C (but at least for -20°C, +20°C and +50°C) or for the extreme temperatures to be expected at the place of installation for the elastomer bearing within the wind turbine.

7.7.4.8 If contamination with aggressive media can be expected during normal operation, it shall be proven that the bearing can safely resist such an exposure for a period not less than the minimum maintenance period.

Guidance note:
For the determination of the lifetime of the elastomer, no generally valid computation standard is currently available, since the dynamic characteristics of the elastomer usually depend strongly on

- the frequency
- the environmental conditions
- the load amplitudes
- the mean load
- the relationship between surface area and volume.

For this reason, it may often be necessary to make use of test results when performing the analysis.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

7.7.5 Miscellaneous

7.7.5.1 Due to the dynamic loading of the elastomer bearings, an annual inspection is necessary according to the maintenance instructions of the suppliers (e.g. visual inspection). Thus possibilities for inspecting, and if necessary exchanging, the elastomer bearing easily shall be provided.

7.7.5.2 For the metallic parts and the bolted joints of the bearings, the requirements of [2.2] and Sec.5 shall be observed.

7.7.5.3 It shall be noted that, due to dynamic loading, the internal temperature of the elastomer bearings can exceed the ambient temperature at the place of the installation, thereby possibly exceeding the permissible operating temperature of the elastomer bearings.

7.8 Hydraulic systems

7.8.1 General

7.8.1.1 This section applies to hydraulic systems necessary for operation (e.g. yaw motion and rotor blade pitch control) or forming part of a braking system (e.g. blade pitch adjustment in fault situations and rotor brakes).

7.8.1.2 In addition to the statements made here, national requirements shall also have to be observed, if relevant.

7.8.2 Materials

7.8.2.1 In the selection of materials for the force-transmitting components, it shall be taken into account that they are possibly subjected to dynamic loading.

7.8.2.2 Seamless or longitudinally welded steel pipes shall be used for piping. Suitable high-pressure hoses in accordance with international codes shall be used as flexible pipe connections.

7.8.2.3 All components not made of corrosion-proof materials shall be provided with a corrosion protection system.

7.8.3 Design and construction

The following points shall be taken into account:

7.8.3.1 The design and construction of hydraulic systems shall be in accordance with recognized rules (see e.g. ISO 4413).

7.8.3.2 The components (e.g. pumps, piping, valves, actuators, accumulators) shall be dimensioned adequately to guarantee the desired reaction times, actuation speeds and actuating forces.

7.8.3.3 The hydraulic system shall be so designed that the wind turbine is in a safe condition in case of no pressure or of failure of the hydraulics.

7.8.3.4 A clear separation is required for the components and assemblies of the independent braking systems.

7.8.3.5 The ambient environmental conditions under which the wind turbine is intended to operate (oil/fluid viscosity; possible cooling, heating etc.) shall be taken into account.

7.8.3.6 If the functionality requires absence of enclosed air in the system, devices shall be provided that allow for air bleeding during and after the process of filling the system with the hydraulic medium, during maintenance and after replacement operations.

7.8.3.7 Leakage shall not impair the system's ability to function. If leakage occurs, this shall be recognized and the wind turbine shall be controlled accordingly.

7.8.3.8 In the layout of piping, it shall be taken into account that components may move relatively to one another and thereby dynamically stress the pipes.

7.8.3.9 All components shall be protected in a suitable manner against accidental loads not considered in the dimensioning (e.g. weight of a person on pipes).

7.8.3.10 Adequately large oil troughs shall be provided to ensure that hydraulic fluid does not pollute the environment in the event of leakage in the hydraulic system, but runs into the collecting troughs instead.

7.8.3.11 Hydraulic accumulators fixed to the hub shall be suitable for the special requirements resulting from the rotating movements of the hub.

7.8.4 Assessment documents

The following assessment documentation is required:

a) hydraulic functional diagram in standard form (e.g. as per ISO 1219-2) with associated parts list
b) electrical circuit diagrams showing the actuation of the hydraulic system valves, insofar as electro-hydraulic control and regulation is planned
c) data sheet of the safety-related components
d) calculations and data for the actuators (e.g. piston diameter, moments acting on servomotors, design of articulated joints and levers), accumulators and valves (e.g. flow rates and reaction times)
e) data concerning pump unit design (flow and pressure rating, storage volume, limitation of pressure, fluid level check, etc.)

f) data on the design of filters
g) data sheets of pipelines and hoses
h) details on the service life of the component used (e.g. hoses, accumulators), if these are shorter than the design lifetime of the wind turbine (see DNVGL-ST-0437).

SECTION 8 GEARBOXES

8.1 General

The requirements in this section apply to gearboxes intended for installation in the drive train of wind turbines.

8.2 Assessment documents

Assembly and sectional drawings of the gearbox, drawings of the housing, part drawings of all torque- and load-transmitting components plus parts list with data on materials shall be submitted for the assessment.

The individual part drawings of the gears shall contain at least the data as per Table 8-1; otherwise this table shall be completed and appended to the assessment documents for each mesh. If the profile modifications cannot be obtained from the original drawings, these values shall also be given in tabular form for each gear. Data tables with data not listed in the part drawings shall include the number, revision status and date of issue of the part drawing.

Strength analyses shall be provided for all torque-transmitting components. Deformation shall be considered for those parts which influence the size and position of the gear contact patterns and bearing alignments. Verification of the adequate dimensioning of bearings and of all bolted connections that play a significant part in the transmission of loads shall be provided.

Also required are specifications for the lubricant used and admissible temperature ranges, instructions for envisaged maintenance work and intervals, plus information about the monitoring appliances and auxiliary units (oil cooler, oil pump, oil filter etc.) installed. A specification of the corrosion protection provided shall be included. Furthermore, the gearbox specification of the wind turbine as well as the operating and maintenance manual (see [8.11]) shall be appended.

8.3 Materials

8.3.1 Approved gear materials

All gears shall be made of materials complying at least material quality MQ according to ISO 6336-5:2003 (see also Sec.2).

8.3.2 Approved shaft materials

8.3.2.1 Pinion shafts shall be manufactured from hardened and tempered alloy steels. The shafts shall be stress-relieved after heat treatment.

8.3.2.2 Materials for the shafts shall fulfil the strength requirements according to [8.6.1] and the quality requirements according to [8.3.3].

8.3.3 Assessment materials

8.3.3.1 All torque-transmitting components of the gearbox shall be tested in accordance with the DNV GL Rules for materials or equivalent standards. Appropriate verification according to EN 10204:2005 shall be provided for the materials. The material test documents (statements of compliance) as per [2.1.3] shall be available at the manufacturer and shall be submitted on request.

8.3.3.2 The tests laid down in the regulations for materials may be truncated with the consent of DNV GL, if execution of the prescribed tests is not practicable because of the small size or particular manufacturing processes of individual components. For such components, DNV GL shall be provided with quality verification in some other way.

8.4 Loads to be applied

8.4.1 General

8.4.1.1 The load-transmitting parts of the gearbox are statically and dynamically loaded by the rotor torque. The dynamic portion depends on the characteristics of the driving side (rotor) and the driven side (generator, oil pump) and also on the masses, stiffnesses and damping values in the driving and driven portions (shafts and couplings) and the external operating conditions imposed on the wind turbine. Depending on the drive train concept of the wind turbine, additional loads in the form of forces and bending moments may be introduced at the gearbox input shaft and the gearbox output shaft, and these shall be taken into account.

8.4.1.2 The fatigue and extreme loads shall comply at least with the requirements set out in DNVGL-ST-0437.

8.4.2 Fatigue loads

8.4.2.1 Using the time series of the fatigue loads (e.g. torque), the load duration distribution (LDD) shall be determined for the calculation of gears, bearings, shafts etc. These specify the sums of the times during which the torque remains within the defined class limits.

8.4.2.2 In the LDD, all operating conditions described in DNVGL-ST-0437 shall be considered for the determination of the fatigue loads to be applied. Apart from normal operating conditions, these also include connections and disconnections, load shedding of the generator, use of the mechanical brake and also standstill loading of the wind turbine. The torque levels shall have a clear relation to the rotational speed. Additional loads, e.g. through deformations, alignment errors and asymmetrical arrangements of the mechanical brakes, shall also be taken into account if applicable. Planet carrier(s) and gearbox housing (torque arm) shall be verified according to Sec.4.

8.4.3 Extreme load

The maximum loads occurring in the drive train of the wind turbine as per DNVGL-ST-0437 shall be used.

8.4.4 Scuffing load

The decisive load for the scuffing calculation is the highest torque of the LDD described in [8.4.2].

8.4.5 Avoidance of unacceptable stand-stills

The wind turbine manufacturer shall ensure that unacceptable gearbox loads caused by pendulousness of the rotor are avoided during stand-still of the wind turbine. Devices shall be provided, which prevent long lasting alternating standstill loads of the gearbox not requiring the presence of service personnel.

Guidance note:
This may for instance be a parking brake, mounted at the low speed rotor shaft or a rotor lock, which can be activated via remote control.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

Table 8-1 List of input data for gear rating

Gearbox						Certification No.			
Manufacturer					Stage				
Wind turbine					Gear stage □		Planetary stage □		
Rated power	P			kW	No. of planets				
Rated speed	n			1/min	Load distribution factor	K_{γ}			
Application factor	K_A			-	Dynamic factor	K_V			-
Face load factors	$K_{H\beta}$			-	Transverse load factors	K_{Ha}			-
	$K_{F\beta}$			-		K_{Fa}			-
Geometrical data		Pinion	Wheel		**Tool data**		Pinion	Wheel	
Number of teeth	z			-					-
Normal module	m_n			mm	Coefficient of tool tip radius	ρ_{a0}^{*}			-
Normal press. angle	α_n			°	Coefficient of tool addendum	h_{a0}^{*}			-
Centre distance	a			mm	Coefficient of tool dedendum	h_{fP0}^{*}			-
Profile shift coeff.	x			-					
Helix angle	β			°	Protuberance	pr			mm
Face width	b			mm	Protuberance angle	α_{pr}			°
Tip diameter	d_a			mm	Machining allowance	q			mm
Root diameter	d_f			mm	Utilized dedendum coefficient of tool	h_{FfP0}^{*}			-
Lubrication data					Tool offset	B_{z0}			mm
Kin. viscosity 40 °C	ν_{40}			mm^2/s	**Accuracy**				
Kin. viscosity 100 °C	ν_{100}			mm^2/s	Accuracy acc. to ISO	Q			-
Oil temperature	δ_{Oil}			°C	Accuracy/tolerance sequence				
FZG load stage				-	Mean peak to valley roughness of flank	R_{aH}			µm
Material data					Mean peak to valley roughness of root	R_{aF}			µm
Material type					Initial equivalent misalignment	$F_{\beta x}$			µm
Endurance limit for contact stress	$\sigma_{H\,lim}$			N/mm^2	Normal pitch error	f_{pe}			µm
Endurance limit for bending stress	$\sigma_{F\,lim}$			N/mm^2	Profile form error	f_f			µm
Surface hardness				HV	Date:				
Core hardness				HV					
Heat treatment method				-	Signature:				

8.5 Calculation of load capacity of gears

8.5.1 General

8.5.1.1 For torque-transmitting gears, a service life calculation according to ISO 6336-6:2006 (pitting, tooth breakage) using the LDD or a load capacity calculation using an equivalent torque derived from the LDD according to ISO 6336-6:2006 Annex A shall be submitted. The Palmgren-Miner's sum obtained in the service life calculation shall be less or equal to 1. The endurance limits for the gear materials shall comply with ISO 6336-5:2003. Sufficient load capacity shall be verified for all meshes in the main gearbox of the wind turbine. The required minimum safety factors are listed in Table 8-2.

8.5.1.2 For torque-transmitting gears, a static strength analysis according to ISO 6336-2/3:2006 (pitting, tooth breakage) shall be submitted. Sufficient load capacity shall be verified for all meshes in the main gearbox of the wind turbine. The required minimum safety factors are listed in Table 8-2.

8.5.1.3 A scuffing analysis according to DIN 3990-4:1987 or ISO/TR 13989 series shall be submitted. This analysis shall cover calculations according to the flash temperature method and according to the integral temperature method. The scuffing capacity of the oil shall be determined by the scuffing test FZG A/8.3/90 according to ISO 14635-1:2000. If the scuffing temperature is determined from FZG tests, one stage lower than the fail load stage shall be used for the scuffing analysis. If this load stage is larger than 12, load stage 12 shall be used. Sufficient load capacity shall be verified for all meshes in the main gearbox of the wind turbine. The required minimum safety factors are listed in Table 8-2.

8.5.1.4 A micropitting analysis according to ISO/TR 15144-1:2010 using the design load shall be submitted. Sufficient load capacity shall be verified for all meshes in the main gearbox of the wind turbine. The required minimum safety factor is listed in Table 8-2.

8.5.1.5 A load distribution analysis (contact analysis) shall be submitted. The load distribution shall be verified by numerical evaluation with an advanced contact analysis that allows analysis of the load distribution in the helix direction and profile direction simultaneously, providing full information of the local loading in the entire contact area.

8.5.1.6 Additionally, maximum operating loads and tolerance combinations in accordance with ISO 6336-1:2006 shall be checked with their resulting contact stress. Special care shall be taken to avoid stress raisers at the extremities of the contact area.

Table 8-2 Minimum safety factors

	Safety factor for pitting S_H	Safety factor for tooth breakage S_F	Safety factors for scuffing S_B and S_{intS}	Safety factor for micropitting S_A
Rated load (LDD)	1.25	1.56	-	1.2
Extreme load	1.0	1.4	-	-
Highest torque from LDD	-	-	1.3	-

8.5.2 Influence factors for the load capacity calculations

Application factor K_A

8.5.2.1 The gears for wind turbines are subjected to additional load fluctuations which are superposed on the load increments or the constant rated load. These load fluctuations, acting at the gearbox input and output, result in additional dynamic loads in the teeth. The application factor K_A accounts for these and other loads, additional to nominal loads, which are imposed on the gears from external sources.

8.5.2.2 For a service life calculation according to ISO 6336-6:2006 using the LDD (see [8.4.2]), K_A equals 1.0.

8.5.2.3 For a load capacity calculation using an equivalent torque, the application factor K_A shall be determined according to ISO 6336-6:2006 Annex A from the LDD for each mesh.

8.5.2.4 The static strength analysis for the gears shall be carried out using the extreme load and K_A = 1.0.

Dynamic factor K_v

8.5.2.5 The dynamic factor K_v accounts for internal dynamic loads.

8.5.2.6 The dynamic factor K_v shall be calculated ac-cording to ISO 6336-1:2006 Method B. Without a detailed dynamic analysis, K_v < 1.05 is not permissible.

Load distribution factor K_γ

8.5.2.7 The load distribution factor K_γ accounts for deviations in load distribution e.g. in gearboxes with dual or multiple load distributions or in the case of planetary stages with more than two planet wheels.

8.5.2.8 For planetary stages, the values given in Table 8-3 apply in relation to the number of planet wheels.

8.5.2.9 If lower values than those given in Table 8-3 are used in analyses, they shall be verified by measurements with strain gauges applied beyond the active profile in the tooth root after consultation with DNV GL. Calculations may be accepted, as long as the underlying model has been verified by measurements.

Table 8-3 Load distribution factor K_γ

Number of planet wheels	3	4	5	6	7
K_γ	1.0	1.2	1.35	1.43	1.5

Face load factors $K_{H\beta}$, $K_{F\beta}$ and $K_{B\beta}$

8.5.2.10 The face load factors account for the effects of non-uniform load distribution over the gear face width.

8.5.2.11 The face load factors shall be determined by sophisticated calculation models as described in ISO 6336-1:2006 Annex E. These models shall at least take into account

- gear accuracy and tooth modifications
- alignment of axes
- elastic deformation and deflections of gears, shafts, bearings, housing and foundation
- bearing clearances.

8.5.2.12 $K_{H\beta}$ < 1.15 is not permissible.

8.5.2.13 A comparison of the calculated load distribution with the real contact pattern during prototype testing is mandatory. For planetary stages, this comparison may only be done by strain gauge measurements or similar. A further comparison after a reasonable period of operation in the wind turbine is recommended.

Transverse load factors $K_{H\alpha}$, $K_{F\alpha}$ and $K_{B\alpha}$

8.5.2.14 The transverse load factors take into account the non-uniform distribution of transverse load between several pairs of simultaneously contacting gear teeth.

8.5.2.15 For gears with accuracy as required in [8.5.3], the transverse load factors can be set to 1.0.

Life factors

8.5.2.16 The life factors Z_{NT} according to ISO 6336-2:2006 and Y_{NT} according to ISO 6336-3:2006 shall be set to 0.85 at $N_L = 10^{10}$.

8.5.3 Design requirements

8.5.3.1 Gear accuracy as per ISO 1328-1:1995 shall comply with at least accuracy grade 6 for surface-hardened external and internal gears and at least accuracy grade 8 for through-hardened internal gears.

8.5.3.2 For ground external and internal gears, the maximum arithmetic surface roughness shall be $R_a \leq 0.8$ µm. The maximum arithmetic surface rough-ness for through-hardened internal gears shall be $R_a \leq 1.6$ µm.

8.5.3.3 The design load for the involute profile and helix modifications should correspond to that load level of the LDD that contributes most to surface durability.

8.5.3.4 Integer ratio designs, e.g. z_1/z_2 = 21/63, are not allowed.

8.5.3.5 DNV GL reserves the right to call for proof of the accuracy of the gear-cutting/gear-grinding machines used and for testing of the procedure used to harden the gear teeth.

8.6 Strength analysis for shafts and connecting elements

8.6.1 General

8.6.1.1 Fatigue and static analyses (general stress analyses) shall be carried out for all shafts. For connecting elements (e.g. keys, slip joints, press fits), only a static analysis is required.

8.6.1.2 The analyses shall be performed for shafts in accordance with DIN 743 series, for keys in accordance with DIN 6892:2012 and for press fits in accordance with DIN 7190:2001, or equivalent codes.

8.6.2 Analysis of the fatigue strength

8.6.2.1 If a representative load spectrum is available, a fatigue analysis shall be carried out. Further notes for the fatigue analysis are given in [4.4].

8.6.2.2 The fatigue analysis may also be carried out in a simplified form using fatigue limits as per DIN 743 series. Here rated loads shall be used for computation, with consideration of the application factor determined for the gear calculation. The theoretical safety factor S shall then in each case be equal to or greater than the minimum safety factor S_{min} = 1.3. The theoretical safety factor is determined with consideration of bending, tension/compression and torsion, assuming phase balance.

8.6.3 Analysis of the static strength

8.6.3.1 The analysis of the static strength against forced rupture shall be based on the load case in DNVGL-ST-0437 that produces the highest load on the component.

8.6.3.2 The component loads shall have a partial safety factor $\gamma_M \geq 1.1$ relative to the yield point of the material.

8.6.4 Balancing

8.6.4.1 Gear wheels, pinions, shafts, gear couplings and, where applicable, high-speed flexible couplings have to be assembled in properly balanced condition.

8.6.4.2 The generally permissible residual imbalance U per balancing plane of the respective part, for which static or dynamic balancing is rendered necessary due to the method of manufacture and the operating and loading conditions, can be determined by applying the equation:

$$U = \frac{9.6\, Q\, m_G}{pl\, n} \text{ [kg mm]}$$

where:

m_G = mass of body to be balanced [kg]

n = operating speed of body to be balanced [min^{-1}]

pl = number of balancing planes [-]

Q = degree of balance [-]:

= 6.3 for low speed parts

= 4.4 for medium speed parts

= 2.5 for high speed parts

8.6.5 Calculation of tooth couplings

8.6.5.1 Adequate load capacity of the tooth flanks of straight-flanked tooth couplings requires that the following conditions be satisfied:

$$p = \frac{2.55 \cdot 10^4 P\, K_A}{b\, h\, d\, z\, n} < p_{\text{zul}}$$

where:

p = actual contact pressure of the tooth flanks [N/mm^2]

p_{zul} = 0.7 R_{eH} for ductile steels

= 0.7 R_m for brittle steels

P = driving power at coupling [kW]

d = pitch circle diameter [mm]

K_A = application factor = equivalent torque from LDD/nominal torque

z = number of teeth [-]

n = speed [min^{-1}]

h = working depth of the teeth [mm]

b = common tooth width [mm]

Where methods of calculation recognized by DNV GL are used for determining the Hertzian stress on the flanks of tooth couplings with involute tooth flanks, the permissible Hertzian stresses are equal to 75% of the values of σ_{HP}.

8.7 Additional verifications

8.7.1 Gearbox bearings

For the design, calculations, assessment documentation and e.g. oil filtration details to be submitted for gearbox shaft bearings, refer to Sec.6.

8.7.2 Bolted connections

Strength analyses are required for bolted connections playing a significant part in the transmission of loads (see Sec.5).

8.7.3 Housing, torque arm and planet carrier

Regarding the gearbox housing, torque arm and planet carrier, fatigue strength analyses and/or deformation analyses shall be performed, insofar as these parts play a significant part in the transmission of power (e.g. introduction of rotor blade loads into the housing, in the case of a hub affixed directly to the gearbox input shaft). General requirements for strength analyses are stated in Sec.4. The influence of deformations of these components on the meshes and the bearings shall be taken into account. If applicable, deformations determined by computation shall be taken into account for the calculation of the mesh and the bearings.

8.7.4 Analysis of the cooling system

A heat balance for the gearbox shall be submitted for verification of the thermodynamics of the design. Sufficient cooling of the gearbox shall be proven in this balance.

8.8 Equipment

For checking the oil level, a mechanical arrangement (e.g. oil level gauge, oil dip-stick) shall be provided. The temperature shall be monitored. For gearboxes with pressure lubrication, the oil pressure shall be monitored after the cooler and before entry into the gearbox. Plain bearings shall be fitted with temperature indicators. Adequate lubrication of all teeth and bearings shall be ensured in every operating state of the wind turbine. For operation at low temperatures, a heating system shall be provided.

An oil filtering system shall be provided to meet the requirements for the rating life of the gearbox bearings. Flanged oil pumps shall be mounted accessibly at the gearbox and shall be exchangeable.

The sealings for the gearbox shall be suited to the operating conditions of the wind turbine and the installation position of the gearbox. Verification shall be provided of the compatibility of the gaskets with the gearbox oil used.

The housing of the main gearbox in wind turbines shall be provided with removable inspection hole covers, so that it is possible to check the teeth of all meshes, for gears in planetary stages at least by the use of an endoscope.

On the torque arm and on the gearbox housing in the area of the high speed shaft vibration sensors or at least tapped holes for the application of vibration sensors in radial and axial direction shall be applied, see DNVGL-SE-0439.

8.9 Inspection of gearboxes

Gearboxes for wind turbines shall be inspected in the manufacturer's works. The final inspection of series-produced gearboxes shall take place after a test run under partial load lasting several hours. The detailed test plan (also regarding noise assessment) shall be agreed between the gearbox manufacturer and the wind turbine manufacturer.

New designs of main gearboxes for wind turbines shall be subjected to a prototype test at a suitable test bench and also in operation on a wind turbine. The precise procedure for the tests of gearboxes for wind turbines is described in Sec.10.

Following a successful prototype test, the tests of identical series-produced gearboxes may be reduced to testing for sufficient production quality.

The detailed scope of the prototype test shall be specified in consultation with DNV GL before the test commences. The reduced extent of series testing shall be defined in the documentation of the prototype test.

8.10 Running-in

For the gearboxes in wind turbines, a running-in period after commissioning shall be defined in consultation with the gearbox manufacturer. During this period, the power output by the rotor shall be limited by the control system. If no malfunctions are detected, the gearbox load may be increased to full load after several hours of operation and with constant checking. During the running-in period, the oil and bearing temperatures (planet bearings not mandatory) shall be monitored and the lubrication system shall be kept in constant operation.

Furthermore, after a prolonged outage, the output shall be limited with due regard for the oil sump temperature (see DNVGL-ST-0438). Because the transmitted power through the gearbox influences the oil temperature, the limitations specified by the gearbox manufacturer shall be followed.

8.11 Manuals

The gearbox manufacturer shall define in a written manual the relevant maintenance, monitoring and precautionary measures for erection, transport and operation of the gearboxes, with the aim to ensure that the design lifetime of the gearbox is reached. According to [8.2], the manual forms part of the assessment documents for the certification of wind turbine gearboxes and shall contain binding statements on at least the following points:

— characteristic values and properties of permissible lubricants

- intervals required for oil analyses (also for oil purity) and oil changes
- required maintenance and inspection intervals, as well as a description of the measurements to be performed in each case. These shall be incorporated into the maintenance manual of the wind turbine.
- operating parameters to be logged, and the corresponding limiting values
- notes on the proper assembly of the gearbox
- notes on the transport by sea, air or land (rail or road), both as separate component and within the nacelle of the wind turbine
- notes on the storage of the gearbox over periods exceeding half a year.

SECTION 9 DRIVE TRAIN DYNAMICS

9.1 General

9.1.1 Scope

This section applies to the dynamic analysis of wind turbine drive trains. The purpose of the analysis is the investigation of load-increasing resonances of the main drive train components using a detailed simulation model of the drive train. These resonance phenomena are usually not included in the global simulation model used for the determination of the design loads.

9.1.1.1 When determining the design loads (see DNVGL-ST-0437), the dynamic behaviour of the drive train shall be considered in a suitable manner. For this, the drive train is modelled in an idealized form within the load simulation by a system comprising a few rotating masses and torsional springs. The reduction of the complex drive train system and the determination of the values of torsional springs, rotating masses, and possibly damping values shall be presented during the assessment of drive train dynamics.

9.1.1.2 The drive train is reckoned all torque-transmitting components from the rotor to the generator including the elastic mounting of the drive train. The wind field and the wind turbine's control and electrical system are not part of the investigation.

9.1.1.3 The dynamic behaviour of the drive train depends mainly on the mass, inertia and stiffness properties of the drive train components. Varying drive train configurations might cause variations of these properties. Hence, a new analysis of the drive train dynamics is required if different types of the following components are installed in the same type of wind turbine:

— rotor blades
— main shaft
— gearbox
— elastic gearbox and generator supports
— generator coupling
— generator
— type of main or gearbox bearings.

For minor differences of the respective components, an analysis of the resulting impact on the drive train dynamics may be adequate.

9.1.1.4 A sensitivity analysis may be carried out in order to identify the contribution of individual components to the overall dynamic behaviour of the drive train. As a result, it might be possible to reduce the number of combinations to be investigated by separate analyses of the drive train dynamics.

9.1.1.5 Results of the analyses are Campbell diagrams showing eigenfrequencies related to excitations. The investigation of the eigenfrequencies shall include an analysis of the energy distribution for each mode shape. In the case that the evaluation of these results shows potential resonances, more detailed investigations shall be carried out in time domain. The increase of the local loads to individual parts shall be evaluated regarding the load-carrying capacity.

9.1.1.6 The assumptions for the design load simulation model shall be compared to the results obtained by means of the detailed model of the drive train.

For vibration measurements within the scope of the drive train dynamics analysis, information is laid down in [9.3] and in Sec.10.

9.1.2 Method of analysis

For the analysis of the dynamic drive train behaviour, numerical simulation procedures shall be applied (e.g. multi-body approaches). The analysis shall be carried out in the frequency and/or time domain.

For the assessment of resonance frequencies, a modal analysis is mandatory. The analysis requires a linearized model for determining eigenfrequencies and mode shapes. In the case of non-linear simulation models, an adequate number of linearization states shall be considered.

Torsional, axial and bending modes shall be considered. A model with only torsional degrees of freedom may be used if supplementary measurements during prototype testing on the gearbox test bench are carried out. For details, see [9.3].

For the evaluation of resonances, the excitations shall be considered.

For the detailed evaluation of potential resonances, the distribution of energies needs to be analysed for each mode shape. Other means of analysis shall be agreed with DNV GL.

The analysis shall cover the operating range of the wind turbine from n_1 to n_3 (see DNVGL-ST-0438).

For the detailed investigation of potential resonances, a run-up shall be simulated in time domain (see [9.2.6]).

Further recommendations and requirements regarding modelling aspects are given in [9.2].

9.1.3 Documentation

The configuration of the drive train analysed shall be documented by a listing of wind turbine type, grid frequency and type information for all major components as well as relevant drawing numbers.

Stiffness, mass, inertia and damping values of all drive train components shall be documented.

Eigenfrequencies and relevant excitation frequencies shall be presented. A detailed listing of excitation frequencies that shall be considered is given in [9.2].

The results of modal analyses and the excitation frequencies shall be combined in Campbell diagrams. Furthermore, mode shapes and energy distributions shall be illustrated.

The assumptions for parameterization of the drive train model for global load assumptions shall be compared to the results obtained from the detailed model of the drive train.

A detailed interpretation of the results with an in-depth evaluation of potential resonances shall be carried out.

9.2 Dynamic analysis of wind turbine drive trains

9.2.1 General

Recommendations regarding the definition of objective, type and scope required for the analysis of drive train dynamics as well as modelling aspects and details on documentation are given in the following. The necessary extent of analysis and modelling detail level depends on the particular project and may vary from the recommendations defined here.

9.2.2 Scope

The objective of this section is to provide information and instructions on the dynamic analysis of wind turbine drive trains using numerical simulation procedures such as multi-body system analyses.

The aim is to provide support for the selection of the appropriate method, in the modelling and performing of the analysis, and in the interpretation of the results. This chapter [9.2] is to be considered as an application-related supplement to the general requirements for dynamic analyses of wind turbine drive trains formulated in this standard.

The following refers primarily to conventional drive train designs using a gearbox to increase the rotational rotor speed. For drive trains using a slow speed generator or other methods of power transmission, the statements shall apply with the necessary adaptations. In general, the analysis consists of the following steps:

— simplification of the complex drive train into an equivalent model
— determination of the required input for stiff-ness, mass, inertia and damping values
— set-up of the simulation model
— execution of the analysis
— verification of the model
— evaluation, assessment and documentation of the results.

9.2.3 Modelling of the system

The technical data from the component manufacturers shall be used to build the simulation model.

9.2.4 Discretization of the model

9.2.4.1 The simulation model shall include all major drive train components. The individual component is subdivided into segments represented by rigid bodies. Gears and bearings may be modelled as single bodies, whereas for shafts and rotor blades finer discretizations are recommended. Interaction between the bodies is modelled by force elements (e.g. spring/damper elements). For shafts and complex parts, the use of elastic bodies is recommended. Table 9-1 lists the major drive train components which shall be considered at least.

9.2.4.2 All relevant eigenfrequencies of the drive train shall be considered. Thus, all relevant mechanical properties (mass, inertia, stiffness) shall be included in the model.

9.2.4.3 The discretization of the major drive train components shall be attuned to the shape of the respective component. Moreover, it shall be selected in a way that allows identification of all eigenfrequencies of the component at or below the third harmonic of the highest excitation frequency. The discretizations given in Table 9-1 should be taken as guidance.

Table 9-1 Major drive train components and requirements for modelling

Major drive train components	Minimum requirements for modelling structure of components	Minimum requirements for modelling degrees of freedom of components
Rotor blades	Minimum three bodies per blade; elastic recommended	Edgewise and flapwise
Hub	Rigid body	Torsional, axial, bending
Main shaft	Minimum two rigid bodies; elastic recommended	Torsional, axial, bending
Low-speed shaft coupling	Rigid body	Torsional, axial, bending
Gearbox housing	Rigid body; elastic recommended	Torsional, axial, bending
Planet carrier	Rigid body; elastic recommended	Torsional, axial, bending
Gearbox shafts	Minimum three rigid bodies, elastic recommended	Torsional, axial, bending
Gearbox gears	Rigid bodies	Torsional, axial, bending
Elastic gearbox support	Connecting spring-damper element	Translational
Brake disc	Rigid body	Torsional, axial, bending
Generator coupling	Minimum three rigid bodies; elastic recommended	Torsional, axial, bending
Generator shaft and rotor	Rigid body; elastic recommended	Torsional, axial, bending
Generator housing	Rigid body	Torsional, translational
Elastic generator support	Spring-damper element	Translational
Main frame	Rigid body; elastic recommended	In compliance with model of component
Bearings	Spring damper element	Full stiffness matrix recommended

9.2.4.4 Depending on the excitation mechanisms, the extent regarding the number of degrees of freedom (DOF) of each individual component shall be chosen adequately. Torsional, axial and bending DOFs shall be considered as a general rule.

9.2.4.5 A model with only torsional degrees of freedom may be used if supplementary measurements during the prototype testing on the gearbox test bench are carried out. For details, see [9.3].

9.2.4.6 If elastic bodies are used for the modelling, the boundary conditions shall be consistent in both model domains (e.g. finite element method, multi-body system).

9.2.5 Model input parameters

9.2.5.1 The model input data shall include the mass, inertia, stiffness and damping values of the components. The required input for masses and inertias should be derived from computer aided design (CAD) data, by analytical calculation or by measurement. The elasticity of complex parts should be determined by finite element analysis, by measurement or, in cases of simple geometries, by analytical formulae.

9.2.5.2 For the gears, the meshing stiffness should be calculated on the basis of ISO 6336-1, Method B, or by measurement.

9.2.5.3 Stiffness properties of bearings should be provided by the bearing supplier(s). The stiffness properties shall be represented by:

— stiffness matrices linearised for the operational point for simulations in frequency domain, e.g. calculation of eigenfrequencies
— non-linear stiffness functions for simulations in time domain, e.g. calculation of load amplifications. However, in most cases it might be sufficient to represent the stiffness of a bearing by its stiffness matrix which has been linearized at a suitable point of operation (e.g. at rated load level). Thus, only in cases where the stiffness cannot be represented appropriately by a matrix, non-linear functions or even the characteristic stiffness field shall be used for the simulation in time domain.

9.2.5.4 Damping properties should be determined by measurements or, if applicable, data from literature may be used. The final adjustment should be made by measurements on the actual drive train. Damping should only be applied to parts of the model where it occurs in wind turbines, e.g. bearings, toothings.

9.2.5.5 If the analysis is carried out in time domain, sources of excitation due to variations in the component stiffness and component inertia values shall be considered:

— blade passing
— variations in tooth meshing stiffness
— imbalance of major drive train components (rotor, brake disc, coupling, and rotor of generator)
— communication frequencies of controllers (e.g. pitch and yaw controller).

9.2.6 Boundary conditions

9.2.6.1 The frequency range for the analysis in frequency domain shall be chosen wide enough to cover the excitation frequencies according to Table 9-2.

9.2.6.2 The analysis range for time domain simulation shall be chosen in accordance with the operating range of the wind turbine.

9.2.6.3 The interaction of the mechanical and electrical part of the wind turbine should be considered adequately, e.g. by applying the generator's speed-dependent torque characteristics and by implementing the wind turbine's controller algorithm.

9.2.6.4 In order to impose all operating conditions on the drive train, the simulation of a run-up by steadily increasing the rotational speed is an appropriate procedure. The run-up can be carried out in the speed- or torque-driven mode (see Figure 9-1). The torque-driven mode is recommended.

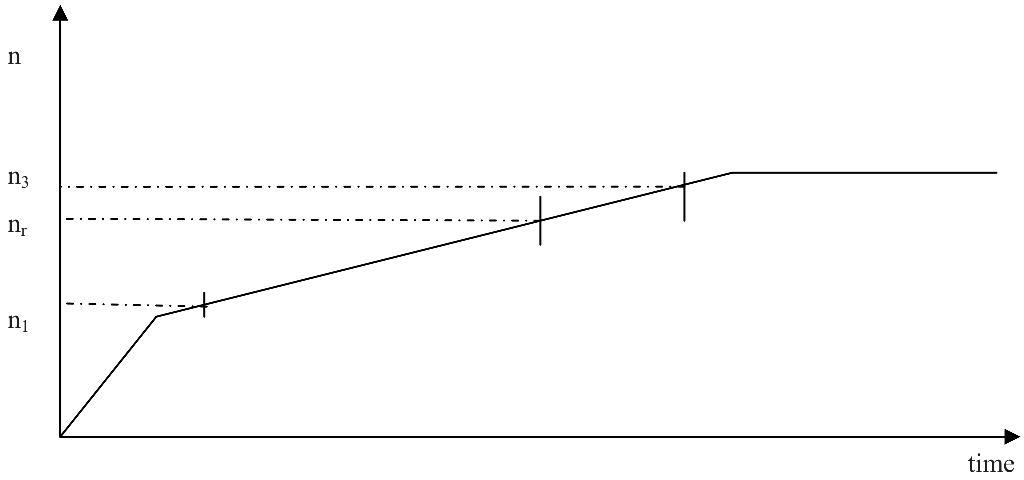

Figure 9-1 Example for a synthetic run-up load case

9.2.7 Check of the model and input data

9.2.7.1 The input data used for the modelling of the drive train shall be checked thoroughly for errors. The effectiveness of the data check can be increased by visualization of the data.

9.2.7.2 The interconnection of components forming the assembled drive train model shall be re-viewed by visual inspection of e.g. animations and by plausibility checks of the modal results. It has been found that the comparison of damped and undamped eigenfrequencies is an effective procedure for locating defects in the model.

9.2.7.3 The simulation model should be adequately validated, e.g. by evaluating the results of gearbox test runs on a test bench, to ensure plausible behaviour in relation to the actual drive train.

9.2.8 Verification of the global drive train parameters

9.2.8.1 To verify the drive train model parameters used within the global load assumptions, the detailed drive train model shall be analysed in this regard. In most cases, these parameters are "resulting drive train stiffness" and "moment of inertia of generator rotor". The verification may also be performed by comparing the first eigenfrequency obtained from the detailed model of the drive train with the corresponding value derived from the global simulation model. The deviation may not exceed ±10%. Otherwise the influence on the load assumptions shall be evaluated.

9.2.8.2 Depending on the model set-up and simulation possibilities, other assessment techniques are permitted, if plausible.

9.2.9 Calculation and evaluation of the results

9.2.9.1 For the time domain calculation, the time range and sampling rate shall be chosen large enough such that, for each level of rotational speed, a steady state will be reached and reliable Fast Fourier transform (FFT) with 2^n supporting points can be performed. *n* shall be chosen in such a way that an appropriate resolution will be obtained and that the necessary frequency range can be analysed.

9.2.9.2 Calculated time series of e.g. rotor speed and torque and the load levels in all springs shall be checked with respect to the correct reproduction of e.g. transmission ratio, rotational direction, angular displacement of shafts etc.

9.2.9.3 The results shall be checked for plausibility. This involves checking of eigenfrequencies and mode shapes to see whether their magnitude and shape, respectively, are credible in comparison to similar drive train layouts and to experience.

9.2.10 Extended evaluation

9.2.10.1 In the event that the analysis shows abnormalities in terms of e.g. resonances that occur in the operating range of the wind turbine, extended evaluations become necessary. These may be performed by applying a more detailed simulation model (see [9.2.4]) or by measurement on the actual drive train (see [9.3]).

9.2.10.2 It is recommended that the simulation model of the drive train is used to analyse transient dynamic loading caused by extreme load cases (e.g. low voltage ride through, grid loss, generator short circuit, emergeny brake; see DNVGL-ST-0437) that are relevant for the drive train.

9.2.10.3 The results of bearing and gearing forces for stationary operational points should be checked with the assumed bearing and gearing forces in the verifications of the main gearbox.

9.2.11 Documentation

9.2.11.1 The formal and content-related requirements relating to the documentation of the analyses of drive train dynamics for the certification of wind turbine machinery components are set out in the following. The necessary scope may deviate from that described here.

9.2.11.2 The requirements for the documentation are to a large extent presented independently of the analysis approach (multi body system, hybrid approaches etc.).

9.2.11.3 From the technical and calculation point of view, the documentation of the computational analysis shall form a unified whole together with all other documents, such as component-related drawings, data sheets and wind turbine type information.

9.2.11.4 The objective, the type (methods used and theories applied) as well as the extent of the calculation shall be described.

9.2.11.5 Reference shall be made to the wind turbine type and configuration and the grid frequency. A listing of the type information for all major components and the relevant assembly and single-part drawings is required.

9.2.11.6 Rotational operating speed ranges of the wind turbine defining the range for the analysis shall be documented according to DNVGL-ST-0438.

9.2.11.7 The relevant frequencies should be named according to Table 9-2.

Table 9-2 Naming of frequencies

Frequency identification	Symbol	Orders that should be analysed
Eigenfrequencies	f_N1, f_N2, f_N3, …	-
Excitation frequencies (shafts)	f_E1, f_E2, f_E3, …	Rotor shaft: 1P, 2P, 3P, 6P Gearbox shafts: 1P, 2P
Excitation frequencies (gear meshes)	f_ZLSS_0, f_ZLSS_1, …, f_ZIMS_0, f_ZIMS_1, …, f_ZHSS_0, f_ZHSS_1, …	Fundamental frequency (1P), 2nd harmonic (2P), 3rd harmonic (3P)

9.2.11.8 The mass, stiffness and damping properties of all components that are considered in the drive train model shall be documented. Depending on the chosen simulation approach, not all of these data may be directly available. In this case, other forms of documentation shall be agreed with DNV GL.

9.2.11.9 Excitation frequencies and their harmonics originating from shafts and gear meshes shall be documented with reference to the rated speed of the wind turbine.

9.2.11.10 The analogous model that represents the simplified drive train and serves as basis for the simulation model shall be demonstrated (see Figure 9-2). The model shall include all major drive train components and their interconnections.

9.2.11.11 The following requirements shall be applied especially for the documentation of analyses applying multi-body, finite element or hybrid approaches. The documentation shall contain the following data:

- identification of the programme used (name, variant and version designation; if applicable, designations of various software packages for pre-processing, post-processing and the solution phase)
- description of the degrees of freedom applied to the individual body
- description of the elements used (e.g. rigid body, type of beam element)
- properties of the interconnecting elements, such as joints, constraints, force elements
- description of the elements used to model the excitation mechanisms
- description of flexible bodies, the underlying finite element models and the modal reduction procedure (if applicable)
- solver settings of the individual multi-body system.

9.2.11.12 Eigenfrequencies of the linearized system and excitation frequencies shall be documented in Campbell diagrams (see Figure 9-3). The frequency range that needs to be analysed shall be chosen wide enough so that the excitation frequencies according to Table 9-2 are covered. The operating speed range and rated speed of the wind turbine shall be indicated in the diagram.

9.2.11.13 In order to analyse the excitability of eigenfrequencies, mode shapes and energy distributions shall be taken into account in the analysis. Components/bodies with large portions of the total kinetic energy (> 20%) shall be mentioned for each eigenfrequency.

9.2.11.14 The identification of potential resonances by means of Campbell diagrams and energy distributions should be supplemented by frequency response calculations. Results should be documented in frequency response plots.

9.2.11.15 Simulation results of a run-up shall be evaluated by Campbell diagrams depicting the amplitude as a function of frequency and excitation (e.g. rotational speed). Frequency and excitation should be displayed in two dimensions, and the amplitude as a coloured spectrum. All stages of the drive train shall be analysed by these means.

9.2.11.16 The "resulting drive train stiffness" calculated by using the detailed drive train model and the "moment of inertia of the generator" shall be compared to the parameters used within the global load assumptions. The verification may also be performed by comparing the first eigenfrequency derived from the detailed model of the drive train with the corresponding value derived from the global simulation model.

9.2.11.17 A detailed interpretation of the documented results shall be carried out in terms of an in-depth evaluation of potential resonances.

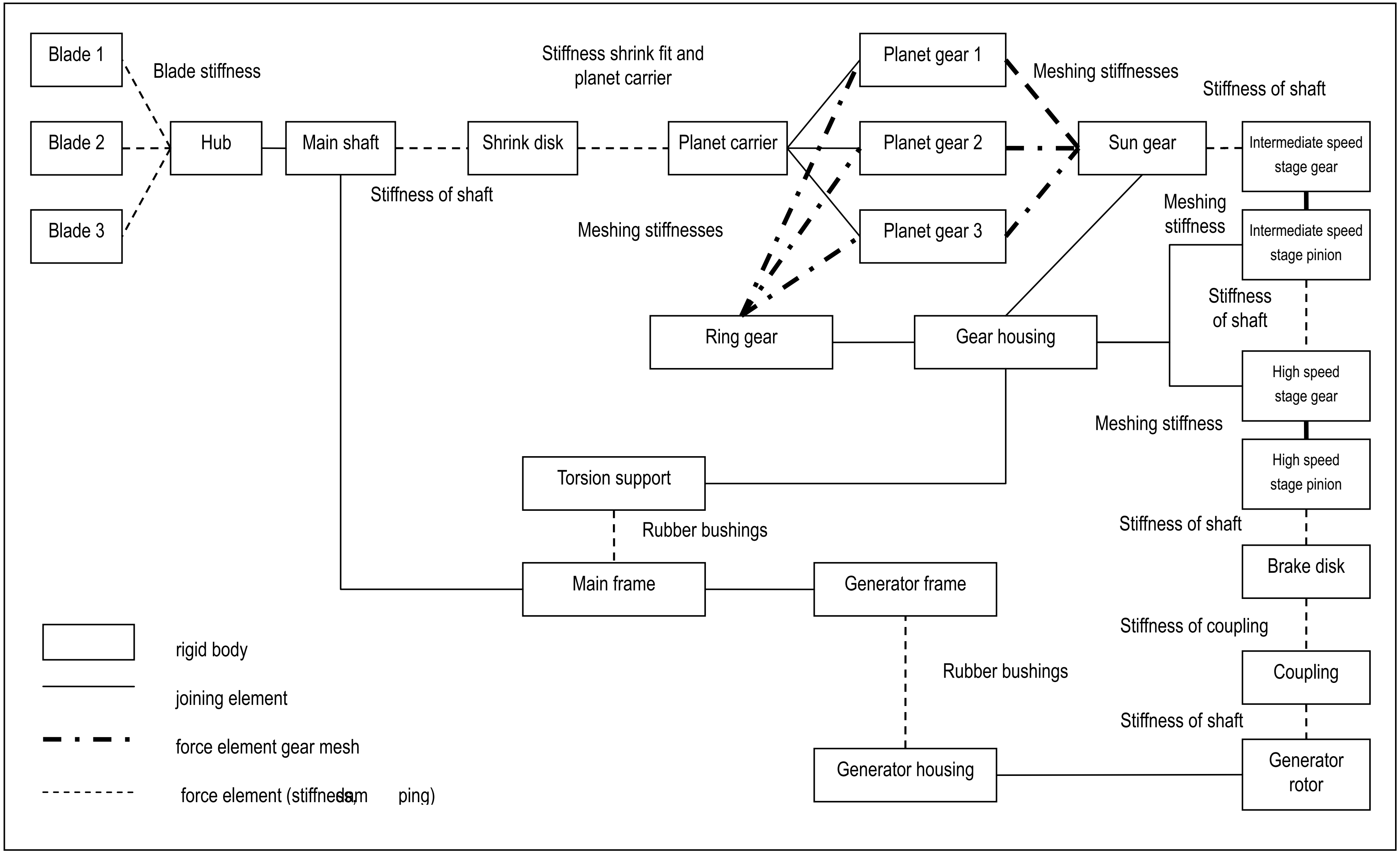

Figure 9-2 Analogous model of a generic drive train (bearing force elements not shown)

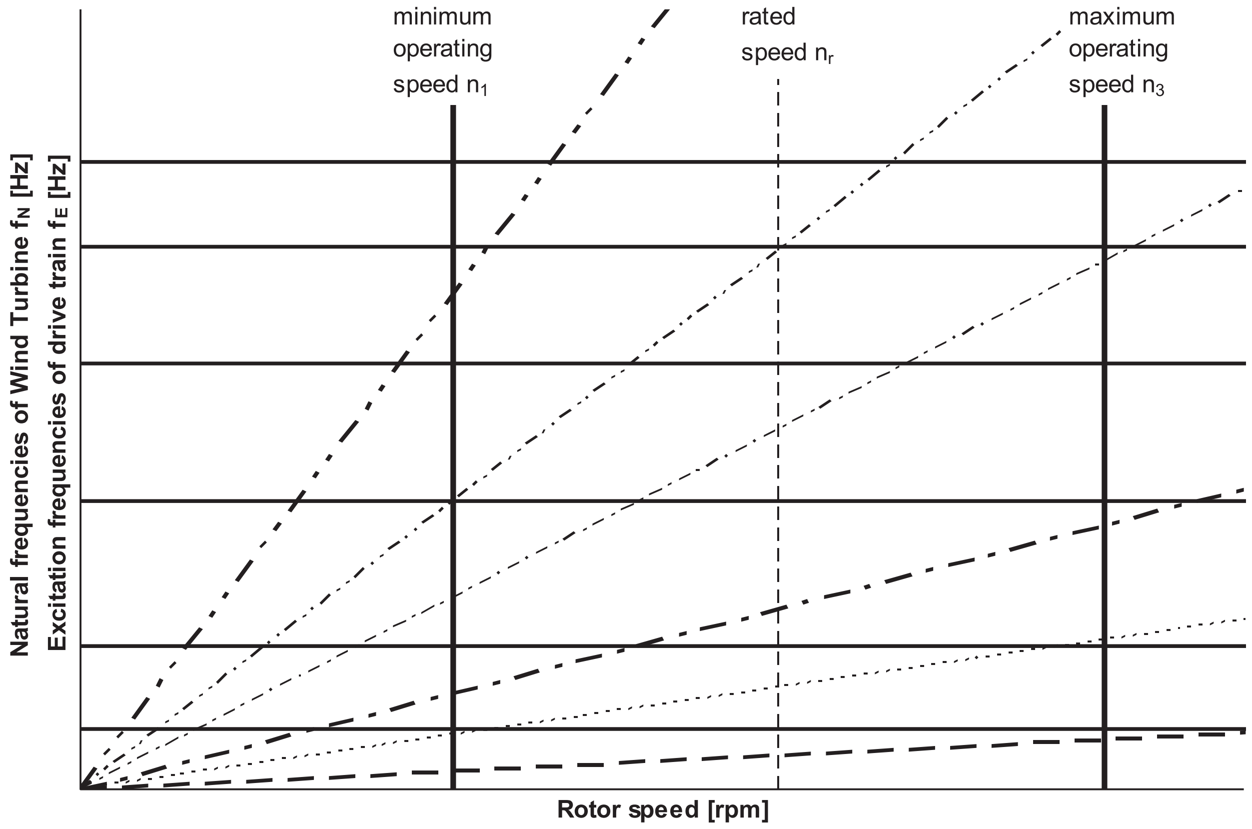

Figure 9-3 Campbell diagram

9.3 Supplementary measurements for the evaluation of the drive train dynamics

9.3.1 Scope

9.3.1.1 The scope of this section is to provide support and recommendations for the analysis of vibrations in the drive train with the additional aid of measurements.

9.3.1.2 The assessment of the dynamic behaviour of the wind turbines drive train is based on numerical simulation procedures. In general, all steps of the analysis shall be performed using a multi-body or similar model as described in this Section.

9.3.1.3 In addition to this numerical simulation procedure, supplementary measurements may become necessary for the evaluation of the drive train dynamics.

9.3.2 Applications

9.3.2.1 In general, measurements for the verification of the assumptions made in the simulation model are advisable.

9.3.2.2 The verification may be performed by comparing identified eigenfrequencies and, if applicable, amplitudes. In order to verify the assumptions, differences regarding the topology of numerical and experimental system shall be taken into account.

9.3.2.3 Other means of simulation model verification shall be agreed upon with DNV GL.

9.3.2.4 In specific cases, measurements may become mandatory for the evaluation of the drive train dynamics.

9.3.2.5 In more detail, these cases are described in [9.3.3] and [9.3.4]:

9.3.3 Case A: Complementary measurements for a 1-dimensional simulation model

9.3.3.1 If a 1-dimensional simulation model is used, the measurements shall serve as a basis for the verification of the assumptions made in the analysis and provide additional mode shapes and eigenfrequencies for the degrees of freedom not covered by the simulation model, e.g. shaft axial and bending modes (cf. [9.1.2]).

9.3.3.2 If agreed with DNV GL, the measurements may be limited to the components of the gearbox if no additional benefit is expected from the results of the other drive train components.

9.3.3.3 If agreed with DNV GL, it may be accepted to perform the measurements during the prototype test on the gearbox test bench (cf. Sec.10). In this case the set-up shall include the high speed coupling that is intended to be installed in the wind turbine or at least a coupling with similar mechanical properties.

9.3.3.4 A 1-dimensional simulation model of the test set-up, representing the actual test bench configuration, shall be used to verify the assumptions made for the gearbox simulation model.

9.3.3.5 In case of deviations of the results, the simulation model shall be refined with the help of the measurements. All relevant changes shall be transferred to the simulation model of the whole drive train accordingly.

9.3.3.6 With the aid of the measurements, additional eigenfrequencies for the degrees of freedom not covered by the simulation model shall be identified for all torque transmitting gearbox components.

9.3.3.7 The results of the 1-dimensional drive train model shall be used in combination with the additional eigenfrequencies derived by the measurements to identify possible resonances.

9.3.3.8 All possible resonances shall be evaluated in an appropriate way. Since the additional eigenfrequencies cannot be evaluated by a simulation in time domain, measurements on the drive train are mandatory in case of possible resonances.

9.3.4 Case B: Evaluation of possible resonances/verification for type certification using wind turbine measurements

9.3.4.1 The vibrational behaviour of possible resonance points in the wind turbine's speed range of normal operation shall be investigated. This can include the determination of the coupled modes, magnitude of vibration and modal damping (see [9.2.10] and Sec.10).

9.3.4.2 It has to be ensured that all relevant components modelled in the analysis are identical to the components of the turbine used for the measurements. This applies especially for the components listed in [9.1].

9.3.4.3 In case of deviations regarding component properties, it has to be demonstrated in a suitable way that the transfer of the results is applicable.

9.3.4.4 The measurements shall be performed using an appropriate instrumentation for the given task. During the planning of the measurement campaign, it shall be clarified whether qualitative results (frequencies) or quantifiable values (amplitude at resonance frequency) are desired since this may have an influence on the equipment to be used.

9.3.4.5 The specification below applies to a standard gearbox design with helical and planetary stages. For different designs the specification shall be adapted accordingly.

- the rotational speed of the system shall be logged during all measurements
- measurement of power
- for the gearbox housing, sensor positions shall be selected in close proximity to the bearings of all load transmitting shafts and the torque support. If sufficient data can be acquired in this way, the sensor positions might be limited to the shaft bearings accessible at the outside of gearbox housing
- measurement of the torque at the high speed side of the system is recommended
- main bearing housing: measurement of vibration at outer ring of all bearings

— main frame: measurement of vibration in close proximity to the gearbox torque support. This applies, if a system for the reduction of vibrations is used at the interface between gearbox and main frame
— generator: measurement of vibration at outer ring of upwind bearing.

9.3.4.6 Additional sensors might be useful in order to evaluate further relevant mode shapes that were identified in the simulation. The instrumentation shall be adapted to the specific measurement task.

9.3.5 System state for measurement

9.3.5.1 The measurement shall cover the entire relevant speed range of the wind turbine. For the range of power production between the rotor speeds n_1 and n_3, the torque on the drive train shall be representative for real power production conditions. The measurements of normal power production cases shall be performed at a representative load condition, i.e. at least 70% of rated power shall be reached.

9.3.5.2 During the run-up measurement, the speed gradient shall be chosen in a way providing sufficient samples required for the evaluation of a given speed level. The merging of variable rotor speeds for the analysis of a given resonance point shall be kept at a minimum.

9.3.5.3 For the investigation of specific rotor speeds, additional measurements at constant speeds might be useful.

9.3.6 Documentation

9.3.6.1 Besides the documentation listed in [10.4] the following items shall be included additionally.

9.3.6.2 Sample plots of unprocessed time domain data of selected sensors shall be included. All applied filter and data manipulation steps shall be documented, accompanied by illustrating examples based on acquired data.

9.3.6.3 The time-domain data obtained during the measurements shall be kept for record. Upon request, this data shall be made available to DNV GL.

9.3.6.4 The results from the system run-up shall be illustrated by means of waterfall-diagrams for each signal according to [9.3.4.5], plotting amplitude over frequency and time. For special points of investigation, results from measurements at constant rotor speed shall be plotted as amplitude over frequency.

9.3.6.5 The results of the measurements shall be interpreted with respect to the applicable reference values obtained from specifications and standards.

9.3.6.6 In order to allow an overview, identified eigenvalues shall be plotted against the excitation frequencies in a 2D-Campbell-plot. This plot shall cover the relevant operational speed range n_1 to n_3 of the wind turbine.

9.3.6.7 The findings of the simulation model validation shall be included in the documentation. These shall include a comparison of frequencies obtained from simulation and measurements. If applicable mechanical properties like mass, inertia, stiffness and damping shall be included.

9.3.6.8 Conclusions regarding the safe operation of the turbine shall be drawn.

SECTION 10 PROTOTYPE TESTS OF GEARBOXES

10.1 General

A gearbox type intended for installation in the drive train of a wind turbine (main gearbox) shall be subjected to a prototype test at a suitable test bench and also to a prototype test at the wind turbine for which this gearbox was developed. The prototype test at the test bench serves to check the assumptions made in the design of the gearbox and also to obtain important parameters for the execution of series tests during the production of wind turbine gearboxes. The fundamental suitability of the gearbox for use in the wind turbine shall be verified through a prototype test at the wind turbine by measuring the bearing temperatures, sound and/or vibration behaviour and inspecting the gear contact patterns.

In the event of design modifications (e.g. alteration of the gear ratio) which exert an appreciable effect on the dynamic characteristics of the gearbox or on the load distribution of individual components of the gearbox, a renewed prototype test is necessary. The corresponding scope shall be determined in relation to the design modification and agreed with DNV GL.

The test plan shall be assessed by DNV GL prior to the prototype test. The prototype test at the test bench and the subsequent inspection of the disassembled gearbox shall be assessed by DNV GL.

The detailed scope of the prototype tests shall be agreed with DNV GL before the tests commence.

The prototype test at the wind turbine shall be carried out by DNV GL or by a testing laboratory accredited for vibration measurements at wind turbines, or shall be verified and witnessed by DNV GL.

The measurement report and the verification by the accredited testing laboratory (if applicable) shall be submitted to DNV GL for assessment.

10.2 Scope of the prototype test at the test bench

At least the following items shall be observed before and during the test of wind turbine gearboxes at the test bench:

— The gearbox under test and its essential components shall be uniquely identifiable. The relevant quality records shall be made available by the time of the test.
— The prototype test at the test bench shall also include the function of the cooling system and the lubrication system. A realistic test bench set-up and the simulation of extreme operating conditions shall be provided.
— The purity of the lubricant used shall be ensured and monitored constantly before and during the test at the test bench. The cleanliness limit stated in [6.5.4.7] shall be met.
— The test torque shall be applied in a minimum of 4 steps up to the nominal torque as defined in the gearbox specification.
— The test shall dwell at each torque step until the sump and bearing temperatures are stable with normal cooling.
— After each torque step, the contact pattern shall be documented. For inaccessible meshes, other methods for the validation of the contact pattern shall be applied e.g. tooth root strain gauges. These contact patterns shall be compared with the assumptions made in the design.
— At planetary stages, the dynamic load share (the product of $K_v \cdot K_\gamma$) at each torque step shall be measured e.g. using tooth root strain gauges.
— Measured parameters such as temperatures, pressures and vibration shall be comprehensively logged. The data shall be stored with an unambiguous relationship to each other and, as far as possible, in a format which can be processed electronically.
— On completion of the prototype test at the test bench, the gearbox shall be so disassembled that the condition of all bearings, gears, shafts etc. can be assessed and documented.
— If the test results do not meet the criteria listed in the gearbox specification, then recalculations/ redesign shall be performed.

10.3 Scope of the prototype test at the wind turbine

The following items at least shall be observed before and during the test of wind turbine gearboxes at the wind turbine:

— If the test results do not meet the criteria listed in the gearbox specification, then a redesign shall be performed.
— The duration of the operation at the wind turbine shall be agreed with DNV GL. The test shall continue at least until the nominal load of the gearbox is reached. If this load cannot be reached, a lower load may be accepted if agreed with DNV GL.
— Relevant operational parameters such as temperatures, pressures and vibration shall be comprehensively logged and evaluated, together with parameters concerning the load on the gearbox. In addition to the torque, these shall include the loads resulting from the integration of the gearbox into the wind turbine.
— After the test, the gearbox shall be visually inspected, including a check of contact patterns and an oil analysis.

10.4 Documentation of the prototype tests

All phases of the prototype tests shall be comprehensively documented and evaluated, e.g. by means of measurement data files, photographs, oil analyses, and inspection or assembly reports. As an important part of the evaluation, an appropriate plan shall be defined for the tests of the series gearboxes. The documentation and evaluation shall be submitted, together with the plan for the tests of series gearboxes, to DNV GL for assessment.

SECTION 11 NACELLE COVERS AND SPINNERS

11.1 Introduction

The strength and serviceability of nacelle covers and spinners of wind turbines with horizontal axes can be analysed based on the contents of this section.

The basis for analysis of unusual designs shall be agreed with DNV GL.

11.2 Requirements for certification

11.2.1 Lightning protection systems of nacelle covers and spinners

For requirements for the assessment of lightning protection systems for nacelle covers and spinners, refer to Sec.10 of DNVGL-ST-0076.

11.2.2 Manufacturers of nacelle covers and spinners

For requirements for manufacturers of nacelle covers and spinners made of fibre-reinforced plastics (FRP), refer to Sec.5 of DNVGL-ST-0376.

11.2.3 Materials used in nacelle covers and spinners

11.2.3.1 For requirements for metallic materials, refer to Sec.2.

11.2.3.2 For requirements for fibre reinforced plastic material, refer to Sec.3 of DNVGL-ST-0376.

11.2.4 Simplified approach for design allowables for FRP materials

For deriving design allowables for FRP materials used in nacelle covers and spinners, a simplified approach may be used. This simplified approach avoids the effort for material testing programmes in the design phase. The responsibility for achieving the material properties assumed for the design in serial production later-on is with the manufacturer and/or purchaser.

With the simplified approach, plausible values for the design-relevant properties of FRP materials may be assumed without the necessity of further verification during the design phase.

Guidance note:
Plausible in this context means that the assumed material values are comparable to those of similar materials as published in the literature.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

At least the following properties shall be specified for each FRP-material used:

— Young’s moduli of the material in its main load bearing direction and the perpendicular in-plane direction
— in-plane shear modulus of the material
— tensile and compressive strengths of the material in its main load bearing direction and perpendicular in-plane direction
— in-plane shear strength of the material
— Poisson’s ratios of the material in its main load bearing direction and perpendicular in-plane direction
— heat deflection temperature of the material or at least glass transition temperature (T_g) of the matrix resin (minimum required value: 65°C)
— density of the material (composite).

In any case, the following parameters of the each FRP material used shall be stated in the design documentation/material specification:

— type of fibre product used (e.g. E-Glass, H-Glass, etc.) including filament diameter and sizing basis
— type of fabric (woven, roving, chopped strand mat, etc.)
— area weight of fabric and ratio of fibre weight in each fibre direction (e.g. BIAX 800 g/m² with 50% +45° fibres and 50% -45° fibres)

- type of matrix resin used (e.g. BPA-based epoxy, amine cured or by mentioning the trade name of resin, hardener and catalyst - if applicable)
- nominal fibre volume content and allowable tolerance
- production process (e.g. resin infusion, hand lay-up, etc.)
- description of curing cycle.

11.2.5 Safety attachment points

Areas within or outside nacelle cover and spinner, that exhibit the hazard of falling from height (e.g. the nacelle cover roof) shall be equipped with suitable safety attachment points.

The safety attachment points shall fulfil the following requirements, if this is not contrary to applicable national requirements:

- All safety attachment points that are intended to act as an anchor point for personal protective equipment (PPE) shall be painted in signal colour (yellow, as a rule, e.g. RAL 1003).
- Safety attachment points shall offer an opening to accommodate large hooks, which shall be sufficient to accommodate at least two double action scaffold hooks conforming to EN 362.
- Safety attachment points shall be positioned in a way that personal protective equipment (PPE) which is attached does not touch any sharp edges which might damage the PPE.
- Safety attachment points shall be fixed in a way that loosening is ruled out. This shall be ensured by applying suitable measures such as screw locking, bolt adhesive etc.

11.2.6 Analysis concept

11.2.6.1 It shall be verified by calculation or suitable testing that nacelle cover and spinner are sufficiently designed in order to withstand the design loads as per [11.2.7]. All loads applied or introduced shall be traced to the main load bearing structure (primary structural members such as e.g. main machine frame, hub). The respective partial safety factors for the loads and for the allowables of the materials shall be taken into account. For the component resistances, plastic reserves and large displacements may be utilized as long as this does not imply a risk to the structural integrity of the component and this can be suitably verified.

11.2.6.2 If the verification of safety attachment points by means of calculation reveals any plastic deformation (or exceedance of allowable stress/strain for FRP-parts), the safety attachment points shall additionally be subject to full-scale testing as per [11.2.6.4].

11.2.6.3 For parts made from fibre reinforced plastics (FRP), the analyses for inter-fibre failure and for stability (buckling) may be omitted, as a rule.

11.2.6.4 Entire components or specific aspects (e.g. safety attachment points) may also be verified by full-scale testing. Such tests shall be witnessed by a representative of the certifying body. If agreed with the certifying body prior to commencing the testing, the tests may also be performed without being witnessed by a representative of the certifying body. In this case the testing institution needs to be acknowledged by the certifying body (e.g. if it is accredited for the respective testing procedure according to ISO 17025).

The component to be tested shall be randomly selected from the components that have already been produced at the time of the testing. It may be the first component produced, but relevance to series production shall be ensured.

Before commencing of the testing, a test specification shall be agreed with the certifying body.

The magnitude of the test load for full scale testing shall be determined as follows:

$$\mathrm{F}_{\mathrm{test}} \geq \mathrm{F}_{\mathrm{Design}} \cdot \gamma_{1\mathrm{t}}$$

where

F_{test} = load to be applied in the test,

F_{Design} = design load and

γ_{1t} = factor accounting for scattering of the component characteristics in series production, γ_{1t} = 1.1.

11.2.6.5 It is recommended that the maximum bending deflection of a structural member under characteristic loads shall not exceed 1/200 of its maximum free span (for frames or cantilevers: 1/150). These ratios may be exceeded only in case this does not imply any hazards for personnel working on the wind turbine or any danger for the functionality of the wind turbine.

11.2.7 Design loads

11.2.7.1 The values given for all design loads are minimum values. If guidelines or regulations applicable at the installation site of the wind turbine (e.g. national labour safety regulations) demand higher values, these shall be authoritative.

Dead weight

11.2.7.2 The partial safety factor for dead weights of nacelle covers and spinners is γ_{1t} = 1.1.

The weight of nacelle cover and spinner as well as of all components permanently applying a dead load onto nacelle cover and spinner shall be stated in the design documentation.

Live load

11.2.7.3 The partial safety factor for all live loads is γ_F =1.5.

All surfaces that are potentially loaded by live loads (e.g. persons stepping onto them, goods being put onto them etc.) such as floor plates, platforms, landings, roofs, walkable cover parts etc. shall be subject to both, global and local verification. The load values shall be as follows:

— for global verification: 3 kN/m² to be applied onto all above-mentioned surfaces at the same time

Guidance note:
For the global verification, the total load onto some parts of nacelle cover and spinner (e.g. the nacelle cover roof) can be reduced in justified cases.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

— for local verification: 1.5 kN to be applied onto a surface of 200 mm x 200 mm at the least favourable position. For that verification, the mentioned concentrated load shall be applied to different positions of the component that are assumed to be unfavourable.

Structural elements which are intended to offer horizontal resistance (height of the load application over the floor or standing level = 1.1 m) shall also be subject to both, global and local verification. The load values shall be as follows:

— for global verification: line load of 1 kN/m to be applied onto all structural elements intended to offer horizontal resistance at the same time.
— for local verification: 1.5 kN to be applied onto a surface of 200 x 200 mm at the least favourable position. For that verification, the mentioned concentrated load shall be applied to different positions of the components intended to offer horizontal resistance in order to find out the most unfavourable position.

Loads on safety attachment points

11.2.7.4 The partial safety factor for loads on safety attachment points is γ_F =1.0.

All safety attachment points mounted to nacelle cover and spinner shall withstand a load of 20 kN in the direction of the attachment bolt and perpendicular.

Wind loads

11.2.7.5 The wind pressure (suction) onto the external surfaces of nacelle cover and spinner shall be determined as follows:

$$p_{\mathrm{Sk}} = \frac{1}{2} \cdot \rho_{\mathrm{air}} \cdot v_{\mathrm{wind}}^2 \cdot c_{\mathrm{p}}$$

where

p_{Sk}	=	the wind pressure/suction to be applied on the respective side of the cover part,
ρ_{air}	=	is the air density applicable for the design of the wind turbine,
v_{wind}	=	is the highest extreme wind speed that the wind turbine is designed for (v_{e50} as a rule)
c_{p}	=	is the drag coefficient for the respective side of the cover part.

For the drag coefficient c_{p}, the following values may be used for simplification:

— c_{p} = 0.8 (pressure) for cover parts facing the wind

— c_{p} = -0.6 (suction) for cover parts with surface parallel to the wind direction, the suction shall be applied perpendicular the surface

— c_{p} =-0.5 (suction) for cover parts facing away from the wind.

Other (less conservative) drag coefficients (e.g. for nacelle covers with rounded edges, spinners) may be used in case they are comprehensively verified (e.g. by referencing internationally acknowledged standards or consistent calculations stating the origin of all approaches and formulas used).

Snow and ice loads

11.2.7.6 Snow and ice loads are included in the live loads on the nacelle cover roof as determined in [11.2.7.3]. If guidelines or regulations applicable at the installation site of the wind turbine (e.g. national labour safety regulations) require higher values, these shall be authoritative.

Loads and load combinations to be considered for the verification

11.2.7.7

As a rule, the following loads and load combinations shall be taken into account for the verification of nacelle cover and spinner:

— Dead weight + global live load:
The dead weight as per [11.2.7.2] shall be superposed with the global verification for vertical and horizontal live loads (both simultaneous as per [11.2.7.3]).

— Dead weight + local live load:
Each relevant case of local live load verification as per [11.2.7.3] shall be superposed with the dead weight as per [11.2.7.2].

— Dead weight + loads on safety attachment points
Each relevant case of load applied to the safety attachment points as per [11.2.7.4] shall be superposed with the dead weight as per [11.2.7.2].

— Dead weight + extreme wind hitting the covers from the front (rotor side):
The dead weight as per [11.2.7.2] shall be superposed with the extreme wind load as per [11.2.7.5] (wind hitting the covers while wind turbine faces the wind).

— Dead weight + extreme wind hitting the covers from the side (90°):
The dead weight as per [11.2.7.2] shall be superposed with the extreme wind load as per [11.2.7.5] (wind hitting the covers while wind turbine is oriented in 90° compared to the wind direction).

11.3 Documents required for certification

11.3.1 Documents describing the design

As a rule, drawings of all parts of nacelle cover and spinner that are relevant for the structural integrity shall be submitted to DNV GL in order to describe the design of the component clearly without ambiguity.

11.3.1.1 Drawings of FRP-parts shall at least include the following details:

— detailed dimensions
— laminate lay-up and main fibre directions
— detailed representation of fixings and connections, e.g. additional reinforcement layers etc.
— allowable tolerances for manufacturing.

11.3.1.2 Drawings of metal parts shall at least include the following details:

— detailed dimensions
— clear designation of the material according to an acknowledged material standard
— detailed representation of welding seams, fixings and connections, this shall comprise details like welding seam specifications and acceptance criteria, pre-load of bolted connections etc.
— allowable tolerances for manufacturing
— specification of the corrosion protection system, if applicable.

11.3.1.3 In all cases, additional specifications that are helpful or required to fully describe the design shall be submitted to DNV GL as well.

11.3.2 Documents for verification

11.3.2.1 The documentation of verification as per the requirements in [11.2.7.1] shall be structured to be complete, comprehensive and clear. The origin of unusual equations and calculation methods shall be stated. For verification by means of finite element analysis all input parameters and a description of the FE-model used shall be included besides the results.

11.3.2.2 If components or sub-components are verified by means of testing as described in [11.2.7.4], comprehensive test reports shall be submitted to DNV GL.

11.4 General hazards to be considered for the design

In general, nacelle covers and spinners for wind turbines fulfil two main functional purposes:

— provide a safe working environment for persons working inside the wind turbine
— protect the machinery of the wind turbine from environmental influences.

Thus the design of nacelle covers and spinners shall take into consideration the following hazards.

11.4.1 Hazards to human beings (personal safety)

The hazards to human beings at wind turbines are:

— falling (from height) hazard
— shearing hazard
— cutting or severing hazard
— entanglement hazard
— drawing in or trapping hazard
— stabbing or puncture hazard
— friction or abrasion hazard
— electrical hazards, e.g. by contact of persons with live parts
— thermal hazards resulting in burns by a possible contact of persons

— hazard generated by neglecting ergonomic principles in design as hazards from too small free height or inadequate consideration of hand-arm or foot-leg anatomy
— hazards caused by inadequate local lighting.

11.4.2 Risks towards the machinery of the wind turbine

Risks towards the machinery are:

— damage to machinery by environmental influences caused by insufficient sealing, damages to the cover (e.g. water ingress)
— damage to machinery by contact of moving parts with the cover

11.4.3 Warning signs/caution labels

All areas of nacelle cover and spinner that exhibit an increased risk of one of the above-mentioned hazards shall be equipped with respective warning signs. This includes areas that are not designed to withstand the full distributed live load of 3 kN/m² (see [11.2.7.3]). The warning signs shall comply with the requirements of ISO 7010.

11.5 Superstructural parts

11.5.1 Helicopter and heli-hoist platforms

11.5.1.1 Helicopter and heli-hoist platforms that are installed on the roof of the nacelle cover shall comply with the aviation regulations at the erection site of the wind turbine.

11.5.1.2 The design of heli-hoist platforms shall be verified on the basis of [11.2.6] if this is not contrary to other applicable regulations.

11.5.1.3 The live loads on a heli-hoist platform according to [11.2.7.3] may be reduced in justified cases.

11.5.1.4 The maximum allowable load on a heli-hoist platform shall be visibly designated on the platform. The labelling shall be done in a way that it can be clearly seen from an approaching helicopter (from any possible angle of approach).

11.5.2 Met mast

11.5.2.1 The design of met masts to be installed on the nacelle cover, and their fixture to the nacelle cover structure, shall be verified on the basis of [11.2.6].

11.5.2.2 Contrary to [11.2.7.5], conservative assumptions shall be made for determining the wind loads on the met mast structure. Turbulence effects shall be taken into account.

11.5.2.3 Increased wind loads caused by the enlargement of cross-sections due to icing shall be considered. The assumptions for the enlargements of cross-sections by ice formation shall be according to DNVGL-ST-0437.

DNV GL
Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16 000 professionals are dedicated to helping our customers make the world safer, smarter and greener.

SAFER, SMARTER, GREENER