Summary of Clause 12 (Connections and joints)

Clause 12 encompasses the design of connections and joints as cited in CEN/TS 19101:2022, where the method of connection is by bolting, adhesive bonding and hybrid adhesive bonding and bolting. In Eurocode terminology, a connection is where two components are joined together so that forces can be transmitted between the components. A joint is formed by connecting components to form a joint zone. In the joint zone, there is usually more than one connection (e.g. as is required to form a beam-to-column joint with bolted connections using web cleats and profile members).

Subclause 12.1 provides general rules for the design of connections and joints.

Subclause 12.2 is specific to the design of bolted connections having plate-to-plate configurations and establishes detailing for the “bearing type” or “tension-type” of connections in terms of geometries (e.g. position of bolts and clearance hole size) and bolting (e.g. material, sizes and tightening torque). This subclause provides resistance formulae for several distinct modes of failure for both in- and out-of-plane actions. In Subclause 12.2.3.6, there is design information on how to create slip-resistant bolted connections.

Subclause 12.3 is specific to bolted joints where there is no significant moment transfer between the members on either side of the joint zone.

Subclause 12.4 is for the design of adhesive joints and connections, which, importantly, for the method of connection by adhesive bonding shall be designed as fail-safe, that is, joint failure shall not result in failure of the structure or critical parts thereof. There are three options to determine the resistance of adhesive joints: Subclause 12.4.5.2 is for design assisted by testing, 12.4.5.3 is for design based on stress analysis and 12.4.5.4 is for design based on fracture mechanics.

Subclause 12.5 is for the design of hybrid joints and connections where the method of connection is by bolting and adhesive bonding. Guidance includes that bolting may be used as a backup system in adhesive joints and connections to maintain the fail-safe condition.

Note that there is relevant detailing information for the design of connections and joints in Clause 11, with Subclause 11.4 for bolted connections and 11.5 for adhesive connections.

The Commentary contains 61 background reports for Clause 12, which consists of 107 paragraphs. There is a single report for general rules (Subclause 12.1), 38 reports for background information and provenance to the design of bolted connections and joints (in Subclause 12.2 with 36 reports and 12.3 with two reports), 19 reports for background information and provenance to the design of adhesively bonded connections (Subclause 12.4) and three reports for hybrid connections and joints that combine the methods of connection of adhesive bonding with bolting (Subclause 12.5).

DOI: 10.1201/9781032706948-12

REPORT NUMBER	BR_12.1_PAR_1
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.1 General rules
PARAGRAPH	(1)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT (1) All connections and joints of composite members and components shall have a design resistance such that the structure is capable of satisfying all the requirements given in this document.	

SCOPE OF GENERAL REQUIREMENTS FOR THE DESIGN OF BOLTED CONNECTIONS

Background

If there is no reference to a source for provenance to paragraphs in CEN/TS 19101:2022 for recommendations towards the design of bolted connections, this is because the paragraph is either new or has no known identifiable source in the public domain. Paragraphs and procedures for the design of bolted connections in Section 12 (12.1 to 12.3 inclusive) of CEN/TS 19101:2022 have been prepared using up-to-date knowledge and understanding combined with engineering expertise and judgement from within the drafting team.

Often sources for current knowledge and understanding have been disseminated at the end of previous projects that have been working towards the community having recognized structural design standards for fibre-polymer composite structures. References [1–14] are for such sources of background knowledge and technical understanding that have had, along with journal and conference publications, importance in preparing the content of clauses 12.1–12.3 of CEN/TS 19101:2022.

References are ordered historically and not in order of relevance or importance.

References

[1] Gibbs & Cox Inc. *Marine Design Manual for Fiberglass Reinforced Plastics*. McGraw-Hill, New York, 1960.
[2] Owens, G.W., Cheal, B.D. *Structural Steelwork Connections*. Butterworth-Heinemann, London, 1989.
[3] European Convention for Constructional Steelwork (ECCS). *European Recommendations for Bolted Connections with Injection Bolts*. First Edition, ECCS Publication No. 79, Brussels, Belgium, 1994. Available from: https://tinyurl.com/y68r5agd [viewed 2023-09-15]
[4] Clarke, J.L. (editor). *Structural Design of Polymer Composites. EUROCOMP Design Code and Handbook*. E & F Spon, London, 1996.
[5] EN 1993-1-8:2005. *Eurocode 3: Design of steel structures. Part 1-8: Design of joints*.
[6] Oppe, M. *Zur Bemessung geschraubter Verbindungen von pultrudierten faserverstärkten Polymerprofilen*. Schriftenreihe Stahlbau, Heft 66, Shaker-Verlag Aachen, 2009 (in German).
[7] Italian National Research Council. *Guide for the Design and Construction of Structures Made of FRP pultruded Elements*. CNR-DT 205/2007. Roma: Advisory Committee on Technical Recommendations for Construction (CNR), 2008.
[8] American Society of Civil Engineers (ASCE). *Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures*. Submitted by the American Composites Manufacturers Association (ACMA) to ASCE, ASCE, Reston, VA, 2010.

[9] American Composites Manufacturers Association (ACMA). *Code of Standard Practice for Fabrication and Installation of Pultruded FRP Structures*. Pultrusion Industry Council (PIC), ACMA, Arlington, VA, 2011.

[10] Mosallam, A.S. *Design Guide for FRP Composite Connections*. Manuals of Practice (MOP) 102, American Society of Civil Engineers (ASCE), Reston, WV, 2011.

[11] Ascione, L., Caron, J.F., Correia, J.R., De Corte, W., Godonou, P., Knippers, J., Moussiaux, E., Mottram, T., Oppe, M., Silvestre, N., Thorning, P., Tromp, L. *Prospect for New Guidance in the Design of FRP Structures: Updated Report*. European Composites Industry Association (EuCIA), Available from: www.eucia.eu. 2018.

[12] Mottram, J.T., Henderson, J. (editors). *FRP Bridges – Guidance for Designers*. Composites UK: Construction Sector Group, CIRIA publication C779, London, 2018.

[13] Strongwell. *Design Manual*. Strongwell. Bristol, VA. Available from: http://www.strongwell.com/ [viewed 2023-09-15]

[14] Fiberline Composites. *Fiberline Design Manual*. Fiberline Building Profiles. Middelfart. Available from: https://fiberline.com/design-manual [viewed 2023-09-15]

REPORT NUMBER	BR_12.2.1_PAR_2
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.1 General
PARAGRAPH	(2)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT (2) In composite members and components, bolted connections should be designed for pin-bearing failure (12.2.3.2). NOTE: Designing for pin-bearing failure provides a level of damage tolerance. All other failure modes in bolted connections have a higher probability of giving connections and/or joints a brittle failure mode with no damage tolerance.	

GENERAL FOR BOLTED CONNECTIONS

Background

This is a paragraph with a NOTE which does not have a definite source for its provenance, its underlying principle for the design of bolted connections with fibre-polymer composite components has been known in the community for a long time and comes from practical experience and academic research.

Paragraph 12.2.1(2) is for bolted connections and bolted joints between fibre-polymer composite components and between fibre-polymer composite components and components of another construction material (e.g. steel, timber, concrete).

A bearing-type connection is one where the transfer of connection force is entirely by way of bearing between the shaft(s) of the (steel) bolting and the connecting components, one of which is of fibre-polymer composite material. For the design of bearing-type connections, it is assumed that there is no force transferred through friction between the connected elements in the connection [1]. The bearing mode of failure is the only mode of the “distinct” modes (others are net-tension, shear-out and block shear) for plate-to-plate joints with in-plane loading that does not always result in a brittle mode of failure and can thereby be used to provide the bolted connection with a degree of damage tolerance. This tolerance is desirable because it imparts structural integrity into the resistance design of bolted connections [2–4].

This pragmatic approach to the design of bolted connections has been adopted elsewhere, for example, in [5, 6].

It is noted that failure in bolt shear (for steel yielding) might be a preferable failure mode because it will provide a level of ductility. It is, however, unlikely to be practical to design for unless a low-yield strength bolt material is used.

References

[1] EN 1993-1-8:2005. Eurocode 3: Design of steel structures. Part 1-8: Design of joints.
[2] Mottram, J.T., Turvey, G.J. Physical test data for the appraisal of design procedures for bolted joints in pultruded FRP structural shapes and systems. *Progress in Structural Engineering and Materials*. 2003, **5**(4), 195–222. Available from: https://doi/abs/10.1002/pse.154
[3] Thoppul, S.D., Finegan, J. Gibson, R.F. Mechanics of mechanically fastened joints in polymer-matrix composites – a review. *Composites Science and Technology*. 2009, **69**(11), 301–329. Available from: https://doi.org/10.1016/j.compscitech.2008.09.037

[4] Mottram, J.T., Zafari, B. Pin-bearing strengths for design of bolted connections in pultruded structures. *Structures and Buildings*. 2011, **164**(5), 291–305. Available from: https://doi.org/10.1680/stbu.2011.164.5.291

[5] Italian National Research Council. *Guide for the Design and Construction of Structures Made of FRP pultruded Elements*. CNR-DT 205/2007. Roma: Advisory Committee on Technical Recommendations for Construction (CNR), 2008.

[6] American Society of Civil Engineers (ASCE). *Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures*. Submitted by the American Composites Manufacturers Association (ACMA) to ASCE, ASCE, Reston, VA, 2010.

REPORT NUMBER	BR_12.2.1_PAR_3
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.1 GENERAL
PARAGRAPH	(3)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT (3) Bolted connections with clearance holes shall be treated as "bearing-type" or "tension-type" connections in accordance with the requirements of EN 1993-1-8:- 5.4.1. NOTE: Subclause 12.2.3.6 is for "slip resistant-type" connections where the bolt clearance voiding is either filled with an injected (cured) resin or a metal insert.	

GENERAL FOR BOLTED CONNECTIONS

Background

This is a paragraph which does not have a definite source for its provenance, its underlying principle comes from the long-standing approach to the design of bolted connections/joints in structural steelwork, see references [1–3].

Paragraph 12.2.1(3) is for bolted connections and bolted joints between fibre-polymer composite components and between fibre-polymer composite components and components of another construction material (e.g. steel, timber, concrete). When there is a clearance hole, diameter d_0, it is a pragmatic engineering approach to make the design assumption that there can be **no** transfer of connection force by way of friction between the plates in the bolted connection, even when the bolt tightening is to the recommended torque (refer to Background Report BR_12.2.1_PAR_15). This approach is necessary because viscoelastic relaxation [4] could, and probably does allow, before the end of the design service life of the fibre-polymer composite structure, for the bolt tension to disappear or be relatively low, and maybe with other actions allow the bolting in the connection to become loose. Furthermore, an additional technical issue to consider is that even if a permanent bolt pretension could be relied upon, there is little reliable evidence for there being a "long-term" coefficient of friction between connecting surfaces with fibre-polymer composite materials.

The loose bolting conditions may be prevented by using a lock washer, resin injection or metal insert in the bolting assembly. Resin injected bolting and metal insert to prevent connection slip is scoped in subclause 12.2.3.6 (refer to BR_12.2.3.6_1, BR_12.2.3.6_2, BR_12.2.3.6_3 and BR_12.2.3.6_5).

By 12.2.1(3) we are not saying that bolt torque in execution is not beneficial to the performance of bolted connections. What we must convey in the background report is that the design of bolted connections/joints cannot rely on the benefit of bolt torque to strengths and/or stiffnesses over the design service life of fibre-polymer composite structures. It is possible that any bolt in a bolted fibre-polymer composite structure might become loose such that the connection resistance it contributes to must be based on the transfer of the connection force only in the bolt bearing. We do not and will not, any time, soon have service-life field evidence to overcome this pragmatic and conservative design approach for the design of bolted connections/joints with at least one joining component of a fibre-polymer composite material.

This pragmatic approach to the design of bolted connections has been adopted elsewhere, see [5, 6].

For "bearing-type" or "tension-type" connections it is practical, if not expected, over the design service life of structures for there to be slippage between the plates when the friction force holding them together is overcome and any clearance is closed up by relative plate movement. In, for example, bridge engineering it is necessary to have slip-resistant connections and subclause 12.2.3.6 permits "slip resistant-type" connections where the bolt clearance voiding is either filled with an injected (cured) resin [3, 4, 7], or a metal insert [4, 8]. A second benefit of this type of bolted connection is that they are likely to also possess a higher fatigue resistance.

References

[1] EN 1993-1-8:2005. *Eurocode 3: Design of steel structures. Part 1-8: Design of joint.*

[2] Owens, G.W., Cheal, B.D. *Structural Steelwork Connections*, Butterworth-Heinemann, London, 1989.

[3] European Convention for Constructional Steelwork (ECCS). *European recommendations for bolted connections with injection bolts*. First Edition, ECCS Publication No. 79, Brussels, 1994. Available from: https://tinyurl.com/y68r5agd [viewed 2022-03-31]

[4] Mottram, J.T., Henderson, J. (editors). *FRP Bridges – Guidance for Designers*. Composites UK: Construction Sector Group, CIRIA publication C779, London, 2018.

[5] American Society of Civil Engineers (ASCE). *Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures*. Submitted by the American Composites Manufacturers Association (ACMA) to ASCE, ASCE, Reston, VA. 2010.

[6] Italian National Research Council. *Guide for the Design and Construction of Structures Made of FRP pultruded Elements*. CNR-DT 205/2007. Roma: Advisory Committee on Technical Recommendations for Construction (CNR), 2008.

[7] Zafari, B., Qureshi, J. Mottram, J.T., Rusev, R. Static and fatigue performance of resin injected bolts for a slip and fatigue resistant connection in FRP bridge engineering. *Structures*. 2016, **7**, 71–84. Available from: https://doi.org/10.1016/j.istruc.2016.05.004

[8] Mara, V., Haghani, R., Al-Emrani, M. Improving the performance of bolted joints in composite structures using metal inserts. *Journal of Composites Materials*. 2016, **50**(21), 3001–3018. Available from: https://doi.org/10.1177/0021998315615204

REPORT NUMBER	BR_12.2.1_PAR_5
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.1 General
PARAGRAPH	(5)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT	
(5) The bolt diameter should be in accordance with the requirements of 11.4(1) and should not be less than 6 mm.	

GENERAL FOR BOLTED CONNECTIONS

Background

Paragraph 11.4(1) states the diameter of bolts, *d*, should not be less than the thickness of the thinnest connected composite component, t_{min}.

12.2.1(5) is for bolted connections and bolted joints between fibre-polymer composite components and between fibre-polymer composite components and components of another construction material (e.g. steel, timber, concrete). Provenance for specifying that the minimum bolt size is M6 (for 6 mm diameter (*d*)) is found in Tables 4.1 and 4.2 (for load-bearing capacity of bolts subjected to shear in kN) and in Table 4.3 (for load-bearing capacity of bolts in kN – tensile force perpendicular to the laminate) in the *Fiberline Composites Design Manual*, see section 1.4.15 in [1]. The three tables show that the range of bolt sizes permitted is from M6 to M48 with a range of pultruded fibre-polymer composite thickness from 5 to 20 mm.

The drafting team applied engineering judgment to decide that the minimum fibre-polymer composite thickness specified in CEN/TS 19101:2022 shall be 6 mm (11.4(1) is then satisfied with M6 bolting). The justification for the minimum thickness of 6 mm is to increase durability owing to all forms of actions that can impair the long-term durability of fibre-polymer composite bolted connections and joints, and thereby the structural integrity of the fibre-polymer composite structures.

There is no technical reason known to the drafting team that consideration of bolt sizes and laminate thickness, as reported in [1] for pultruded profiles, cannot be transferred to laminates made from the other composite processing methods, scoped in CEN/TS 19101:2022 (see 1.1(5) and NOTE 3).

Note that the minimum bolt diameter recommended in an American Society of Civil Engineers' LRFD pre-standard [2] for composite structures of pultruded profiles is 9,53 mm (3/8 in.).

There is no minimum bolt diameter specified in the Italian guidance for the design and construction of structures made of FRP pultruded elements [3].

References

[1] Fiberline Composites. *Fiberline Design Manual*. Fiberline Building Profiles. Middelfart. Available from: https://fiberline.com/design-manual [viewed 2023-09-15]

[2] American Society of Civil Engineers (ASCE). *Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures*. Submitted by the American Composites Manufacturers Association (ACMA) to ASCE, ASCE, Reston, VA, 2010.

[3] Italian National REsearch Council. *Guide for the Design and Construction of Structures Made of FRP pultruded Elements*. CNR-DT 205/2007. Roma: Advisory Committee on Technical Recommendations for Construction (CNR), 2008.

REPORT NUMBER	BR_12.2.1_PAR_6
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.1 General
PARAGRAPH	(6)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT (6) Bolts made with composite material shall not be used.	

GENERAL FOR BOLTED CONNECTIONS

Background

Paragraph 12.2.1(6) is essential because there is insufficient knowledge and understanding by way of a lack of test results to provide any reliable guidance for the design of bolted connections using fibre-polymer composite (non-metallic) bolts [1, 2] in constructing joints with fibre-polymer composite components.

Although fibre-polymer composite (non-metallic) bolts are not permitted in design or construction by CEN/TS 19101:2022 for primary structural bolted joints they might be chosen by the designer/client as a method of connection to mitigate against corrosion and maintenance issues in tertiary joints having bolted connections (i.e. these joints are found in relatively low loaded structural assemblies). This approach can provide the designer with assistance towards progress in innovation with field applications.

References

[1] Strongwell. *Design Manual*. Strongwell. Bristol, VA. Available from: http://www.strongwell.com/ [viewed 2023-09-15]

[2] Erki, M.A. Bolted glass-fibre-reinforced plastic joints. *Canadian Journal of Civil Engineering*. 1995, **22**(4), 736–744. Available from: https://doi.org/10.1139/l95-084

REPORT NUMBER	BR_12.2.1_PAR_7
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.1 General
PARAGRAPH	(7)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT (7) For bolting with a smooth shank, the length of thread in contact with any laminate should not exceed 1/3rd of that laminate thickness.	

GENERAL FOR BOLTED CONNECTIONS

Background

Paragraph 12.2.1(7) is for bolted connections and bolted joints between fibre-polymer composite components and between fibre-polymer composite components and components of another construction material (e.g. steel, timber, concrete). This subclause is like 3.6.1(8) in [1]; the provenance of the steel bolted connection paragraph is unknown [2]. The drafting team do not have a justification not to have this requirement. There are no known physical test results with fibre-polymer composite bolted connections having different lengths of thread in bearing to verify this paragraph, which is why the recommendation in 12.2.1(7) is for "should". The designer therefore has the "freedom" to specify longer lengths of thread in bearing; although such a design decision that changes bearing strength ought to be verified by testing (refer to Background Report BR_12.2.3.2_PAR_1).

It may be of use to designers to know that the use of steel bolt sleeves between bolt thread and laminate materials may be useful in preventing thread damage to the fibre-polymer material if it is not considered practical in the construction of fibre-polymer composite structures to achieve this thread limit with the execution of bolted connections.

References

[1] EN 1993-1-8:2005. *Eurocode 3: Design of steel structures. Part 1-8: Design of joints*.
[2] Owens, G.W., Cheal, B.D. *Structural Steelwork Connections*. Butterworth-Heinemann, London, 1989.

REPORT NUMBER	BR_12.2.1_PAR_8
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.1 General
PARAGRAPH	(8)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT	
(8) Steel or stainless steel washers of uniform diameter $d_w > 2d$ (where d is the nominal bolt diameter) and conforming to ISO 7093 should be inserted under each bolt head as well as under each nut (see Figure 11.2 and Figure 11.3).	

GENERAL FOR BOLTED CONNECTIONS

Background

Paragraph 12.2.1(8) is for bolted connections and bolted joints between fibre-polymer composite components and between fibre-polymer composite components and components of another construction material (e.g. steel, timber, concrete). To distribute the bolt tension over a larger surface area (following tightening under bolt torque) it is recommended to have an oversized washer that is in accordance with standard ISO 7093 [1, 2]. This recommendation is to be found in [3–5], with the pultrusion company Fiberline Composites A/S recommending in Table 12.1 of [3] a washer diameter that is 3,4 times the bolt diameter, d. By having a relatively large diameter washer the through-thickness compression stress can be “controlled” and any possible over-tightening is unlikely to cause localised composite damage owing to crushing around the steel (rigid) washer perimeter. Refer also to background report BR_12.2.1_PAR_15 for how to limit the bolt tightening torque in a controlled manner.

The drafting team are aware of field instances where remedial works have been required due to over-tightening on steel bolts with “normal” diameter washers incorrectly used and when larger diameter washers had been specified.

References

[1] ISO 7093-1:2000(en). *Plain washers - Large series – Part 1: Product grade A*.
[2] ISO 7093-2:2000(en). *Plain washers - Large series – Part 1: Product grade C*.
[3] Fiberline Composites. *Fabrication and Repair Manual*. Fiberline Building Profiles. Middelfart. Available from: https://fiberline.com/download-repair-manual/ [viewed 2023-09-15]
[4] Italian National Research Council. *Guide for the Design and Construction of Structures Made of FRP Pultruded Elements*. CNR-DT 205/2007. Roma: Advisory Committee on Technical Recommendations for Construction (CNR), 2008.
[5] American Society of Civil Engineers (ASCE). *Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures*. Submitted by the American Composites Manufacturers Association (ACMA) to ASCE, ASCE, Reston, VA, 2010.

REPORT NUMBER	BR_12.2.1_PAR_10
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.1 General
PARAGRAPH	(10)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT (10) Plate-to-plate connections that subject the bolting to shear (for a "bearing-type" bolted connection) in the plane of the connection (see Figure 11.2) should have bolts with the same nominal diameter, *d*, and of the same grade of steel. NOTE: The resistance formulae in 12.2.3 for when a group of bolts is involved are for bolted connections having constant diameter bolts.	

GENERAL FOR BOLTED CONNECTIONS

Background

Paragraph 12.2.1(10) is for bolted connections and bolted joints between fibre-polymer composite components and between fibre-polymer composite components and components of another construction material (e.g. steel, timber, concrete). There is no provenance to this paragraph that the drafting team have seen. One reason for recommending that within a group of bolts in a connection the bolt diameter is to be a constant is that this is a condition found in a series of physical tests to determine how resistance and failure modes vary for single-bolted and multi-bolted plate-to-plate joints, see [1] for a review of such test series to 2002. The bolting condition that all bolts in a connection are to be of the same size (and the same grade of stainless steel for the same specification) is adopted as a design parameter in both sets of guidelines in [2, 3].

References

[1] Mottram, J.T., Turvey, G.J. Physical test data for the appraisal of design procedures for bolted joints in pultruded FRP structural shapes and systems. *Progress in Structural Engineering and Materials*. 2003, **5**(4), 195–222. Available from: https://doi/abs/10.1002/pse.154

[2] Italian National Research Council. *Guide for the Design and Construction of Structures Made of FRP pultruded Elements*. CNR-DT 205/2007. Roma: Advisory Committee on Technical Recommendations for Construction (CNR), 2008.

[3] American Society of Civil Engineers (ASCE). *Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures*. Submitted by the American Composites Manufacturers Association (ACMA) to ASCE, ASCE, Reston, VA, 2010.

REPORT NUMBER	BR_12.2.1_PAR_12
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.1 GENERAL
PARAGRAPH	(12)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT	
(12) Holes for clearance in laminates should be drilled (or reamed, not punched) to have nominal diameter, d_0, in accordance with the requirements of 11.4(2), that allows the bolt diameter, d, to pass through the laminate thickness without force being applied.	

GENERAL FOR BOLTED CONNECTIONS

<u>Background</u>

Paragraph 12.2.1(12) is for bolted connections and bolted joints between fibre-polymer composite components and between fibre-polymer composite components and components of another construction material (e.g. steel, timber, concrete). What needs to be stated first is that because fibre-polymer composite members and structures can have a relatively lower stiffness than their equivalent components, members or structures made of other construction materials they are more compliant and flexible under installation. This fact, combined with precision in positioning and sizing of holes for bolted connections means that the nominal clearance hole size can be lower than that for the same size bolt in, say, structural steelwork (which is 1 mm for nominal bolts of diameters 12 and 14 mm, 2 mm for bolts with diameters 16–24 mm and 3 mm for diameters 27–36 mm, see [1]). As paragraph 11.4(2) states, the nominal clearance hole size is 1 mm for all bolt diameters covered in CEN/TS 19101:2022 and this size is also to be found in existing European design guidelines [2, 3]. In North America, the clearance hole equivalent to 1 mm is 1/16th inch, which in metric units is 1.58 mm, and this is the nominal clearance hole size recommended in [4, 5]. Tolerances on the sizes of hole diameters are to be found in the *Code of Standard Practice for Fabrication and Installation of Pultruded FRP Structures* guidelines [5].

Fabricators [5, 6] recommend that holes be fabricated by drilling or reaming. Punching is only advised when the thickness of the laminate is 4 mm or less and the minimum thickness recommended in CEN/TS 19101:2022 is 6 mm (refer to 12.2.1(5) and Background Report BR_12.2.1_PAR_5).

It is advisable to consult with a cutter specialist to avoid delamination failures when drilling or using CNC cutters with fibre-polymer composite materials. PolyCrystalline Diamond (PCD) coated cutters with up/down flutes have been developed so that they avoid generating delamination failures during the hole-cutting process. Standard drills and CNC cutters are to be avoided because they can often cause delamination failures in the last couple of laminae (or plies) when pushing through to the other side of the laminate.

References

[1] EN 1090-2:2018. *Execution of steel structures and aluminium structures*.
[2] Fiberline Composites. *Fiberline Design Manual*. Fiberline Building Profiles. Middelfart. Available from: https://fiberline.com/design-manual [viewed 2023-09-15]
[3] Italian National Research Council. *Guide for the Design and Construction of Structures Made of FRP pultruded Elements*. CNR-DT 205/2007. Roma:Advisory Committee on Technical Recommendations for Construction (CNR), 2008.
[4] American Society of Civil Engineers (ASCE). *Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures*. Submitted by the American Composites Manufacturers Association (ACMA) to ASCE, ASCE, Reston, VA, 2010.
[5] American Composites Manufacturers Association (ACMA). *Code of Standard Practice for Fabrication and Installation of Pultruded FRP Structures*. Pultrusion Industry Council (PIC), ACMA, Arlington, VA, 2011.
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REPORT NUMBER	BR_12.2.1_PAR_13
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.1 General
PARAGRAPH	(13)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT	
(13) Bolted connections of composite members and components shall be designed on the assumption that the restraint from bolt torque is not beneficial to connection resistance and that the in-plane connection force (12.2.3(4)) is transferred only in bearing between the bolts and the composite members and components.	

GENERAL FOR BOLTED CONNECTIONS

Background

Paragraph 12.2.1(13) is for bolted connections and bolted joints between fibre-polymer composite components and between fibre-polymer composite components and components of another construction material (e.g. steel, timber, concrete). By way of this paragraph, the drafting team is not saying that bolt torque is not beneficial to a bolted connection's resistance, because it is well-established to be beneficial [1–4]. What is necessary to be understood by designers and other stakeholders is that the structural design of bolted connections cannot rely on bolt tightening to hold components together by a bolt compression force. This installation condition does enable in-plane connection force to be transferred by frictional forces between the connected components and thereby reduces the force in the joint that is to be transferred by bolt bearing. The lateral restraint from bolt tightening also means that the bearing failure mode has a higher strength [4] than that for the pin-bearing condition (when there is no bolt compression force and no lateral restraint [1–5]).

Why therefore can we not take advantage of bolt tightening? Over the design service life of a fibre-polymer composite structure, any one bolt in a bolted joint (comprising of one or more bolted single or multi-bolted connections) might become loose, owing to viscoelastic creep relaxation and other long-term (durability/load) actions [3]. Because of the unknown long-term outcome of creep relaxation, etc., the resistances of bolted connections are based on the transfer of connection force only in bolt bearing; hence why CEN/TS 19101:2022 has 12.2.1(2). We do not and will not for the time being have design service field evidence to overcome this pragmatic and conservatively safe design approach for the design of bolted connections having a least one joining component of a viscoelastic fibre-polymer composite.

It is to be noted that asset owners will have operation and maintenance manuals for their fibre-polymer composite structures and monitoring and inspection requirements will include levels of safety checks on bolting over the design service life of the structure [3].

References

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[2] Mottram, J.T., Turvey, G.J. Physical test data for the appraisal of design procedures for bolted joints in pultruded FRP structural shapes and systems. *Progress in Structural Engineering and Materials*. 2003, **5**(4), 195–222. Available from: https://doi/abs/10.1002/pse.154

[3] Mottram, J.T., Henderson, J. (editors). *FRP Bridges – Guidance for Designers*. Composites UK: Construction Sector Group, CIRIA publication C779, London, 2018.

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REPORT NUMBER	BR_12.2.1_PAR_15
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.1 GENERAL
PARAGRAPH	(15)
AUTHOR(S)	J. Toby Mottram, Matthias Oppe
REVIEWER	Casper Kruger, Lee Canning
DATE	15 September 2023

CONTENT

(15) Bolts should not be over-tightened to prevent compressive crushing failure of laminates in the out-of-plane (z) direction. For non-greased steel bolts, the maximum tightening torque, T, should satisfy the condition in Formula (12.1):

$$T \leq 0{,}15 \cdot \left(n_w^2 - 1{,}2\right) \cdot d^3 \cdot f_{\mathrm{z,c,lim}} \tag{12.1}$$

where

n_{w} is $\dfrac{d_2}{d_1}$;
d_2 is outside diameter of washer;
d_1 is clearance hole (inner diameter) of washer;
d is nominal bolt diameter;
$f_{\mathrm{z,c,lim}}$ is the limiting out-of-plane compressive strength of the laminate, which can be taken as 25 MPa.

GENERAL FOR BOLTED CONNECTIONS

Background

Paragraph 12.2.1(15) is for bolted connections and bolted joints between fibre-polymer composite components and between fibre-polymer composite components and components of another construction material (e.g. steel, timber, concrete).

Collings [1] introduces a relationship for steel bolting between bolt torque (T) and lateral constraint in terms of the generation of bolt tension, N_{b}, and it is

$$N_{\mathrm{b}} = \frac{T}{kd} \tag{1}$$

where

d bolt diameter
k torque coefficient.

The torque coefficient, k, in Formula (1) was measured by Stewart [2] with steel as the plate material and found to be substantially constant at 0,2 for various bolt diameters and for both coarse and fine threads; the steel bolts were lubricated.

Smith *et al.* [3] contributed to our understanding by using test results reported by Crew in [4] to show that the torque coefficient of 0,2 in Formula (1) is acceptable for fibre-polymer composite material. Assuming that the bolt tension is reacted by a uniform compression force over the area of a washer (a washer is between laminate and/or bolt head and/or nut in bolting) of outer diameter d_2

TABLE 1

Extracted from Table 2 in 4.1 Mechanical fastening: Bolting joints in fibreglass [7]

Bolt[a]	**M8**	**M10**	**M12**	**M16**	**M20**
Nominal *d* mm	**8**	**10**	**12**	**16**	**20**
Bolt tightening torque, T in Nm	16,8	33,2	59,0	141	275
Bolt tension, N_b in kN	11,1	17,5	26,2	40,1	73,4
Calculated k by Formula (1)	0,189	0,190	0,187	0,187	0,187
Out-of-plane compression stress f_z in N/mm^2	21,3	21,5	22,4	22,6	22,6
T by (12.1) in Nm	17,0	33,4	60,1	143	280

[a] Nominal bolt diameter and not actual diameter that can be 0,2 mm lower.

and clearance hole (inner diameter) d_1 Formula (1) becomes in terms of T, d_1, d_2 and f_z (for the uniform out-of-plane compression stress):

$$T = 0{,}157 \cdot \left(d_2^2 - d_1^2\right) \cdot d \cdot f_z \tag{2}$$

Noting conservatively that $d_1 = 1{,}2d$ (from standard ISO 7093 [5, 6] is 1,1 to 1,17d) and setting 0,157 = 0,15, $n_w = d_2/d$ and $f_z = f_{z,\mathrm{clim}}$ (the limiting out-of-plane compressive strength of the laminate) we obtain from Formula (2) the final form, that is, Formula (1).

Table 1 in this Background Report is developed from Table 2 in the *Fabrication and Repair Manual* [7] by Fiberline Composites A/S, Denmark. The steel bolts are required to be greased prior to assembly. Presented in Table 1 are values for five bolt diameters for sizes from M8 to M20. Values for both T and N_b in rows 2 and 3 are directly taken from Table 2 in [7]. Calculated values in rows 4 to 6 for k, f_z and T (by Formula (1) with $f_{z,\mathrm{lim}}$ taken to be the f_z values reported in row 4 are made using $n_w = 3{,}4$, as recommended in [7].

Comparing the values for T (Nm) in rows 2 and 6, it is observed that for the five bolt diameters, the two tightening torques are within 1–2%, thereby demonstrating that Formula (1) determines bolt tightening torques that are employed in practice with pultruded profiles [7].

Standard ISO 7093 [5, 6] is for plain washers of large series with Part 1 having two parts for product grade A and product grade C, owing to hardness class. Based on preferred washer dimensions for M6 to M20 bolt sizes that are listed in Table 1 of [5, 6] they have a range of $2{,}82 \le n_w \le 3{,}13$ (see 12.2.1(9)), which does not include the higher ratio n_w of 3,4 that is recommended for bolted connections with pultruded profiles in [7].

12.2.1(16) specifies that the value of $f_{z,c,\mathrm{lim}}$ for laminates in Formula (12.1) may be determined by testing.

References

[1] Collings, T.A. The strength of bolted joints in multi-directional CFRP laminates. *Composites*. 1977. **8**(1), 43–55. Available from: https://doi.org/10.1016/0010-4361(77)90027-1

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[6] ISO 7093-2:2000. *Plain washers - Large series – Part 1: Product grade C*.

[7] Fiberline Composites. *Fabrication and Repair Manual*. Fiberline Building Profiles. Middelfart. Available from: https://fiberline.com/download-repair-manual/ [viewed 2023-09-15]

REPORT NUMBER	BR_12.2.2_PAR_2
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.2 Design criteria for bolted connections
PARAGRAPH	(2)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT (2) For a bolted connection with FRP material subjected to in-plane actions the resistances for the following four failure modes of the FRP material shall be verified: – net-tension (12.2.3.1); – pin-bearing (12.2.3.2); – shear-out (12.2.3.3); – block-shear (12.2.3.4).	

DESIGN CRITERIA FOR BOLTED CONNECTIONS

Background

Paragraph 12.2.2(2) is for bolted connections and joints of fibre-polymer composite components that have in-plane tensile loading such that the fibre-polymer composite material is experiencing deformations associated with the double-lap shear joint configuration. A majority of test results are from double-lap shear joints having a central plate of fibre-polymer composite material sandwiched between two plates of steel. Evaluation of the observed modes of failure from these test results on a wide range of single-bolted double-lap shear connections/joints, such as introduced in reference [1, 2], show that there are three distinct failure modes that deserve to have their own resistance formula. These modes are illustrated by line-drawings in Figure 1, as (a) net-tension (subclause 12.2.3.1), and see Background Reports BR_12.2.3.1_PAR_1, BR_12.2.3.1_PAR_2, BR_12.2.3.1_PAR_3 and BR_12.2.3.1_PAR_5; (b) pin-bearing (subclause 12.2.3.2), and see BR_12.2.3.2_PAR_1, BR_12.2.3.2_PAR_3 and BR_12.2.3.2_PAR_4; (c) shear-out (subclause 12.2.3.3), and see BR_12.2.3.3_PAR_1, BR_12.2.3.3_PAR_2, BR_12.2.3.3_PAR_3 and BR_12.2.3.3_PAR_4.

Pin-bearing is for the failure mode whereby the laminate material adjacent to the bearing bolt (without or with thread) fails locally owing to compression. The word "pin" is important because it signifies that there is no lateral restraint from bolt tightening and that the bolt shaft is plain (or smooth), and that the bearing strength is the lower bound value, which is called the pin-bearing value [3]. In 1988, Chamis [4] presented simplified closed-form formulae for the prediction of strengths based on these three failure modes; in 1988, the bearing strength in resistance calculations was not taken to be the pin-bearing strength value. Chamis [4] is the earliest source presenting resistance formulae for different bolted connection failure modes known to the drafting team.

A fourth distinct mode of failure for fibre-polymer composite laminates in a multi-row bolted connection is that of block-shear (subclause 12.2.3.4), and see BR_12.2.3.4_PAR_1, BR_12.2.3.4_PAR_2, BR_12.2.3.4_PAR_3, BR_12.2.3.4_PAR_4 and BR_12.2.3.4_PAR_5, whereby there is a combination of tension plane(s) and shear plane(s) failures as introduced in [1, 5]. There can be several possible block-shear failure patterns and each of them is to be checked using the design procedure in subclause 12.2.3.4 to establish which has the lowest connection force for the design

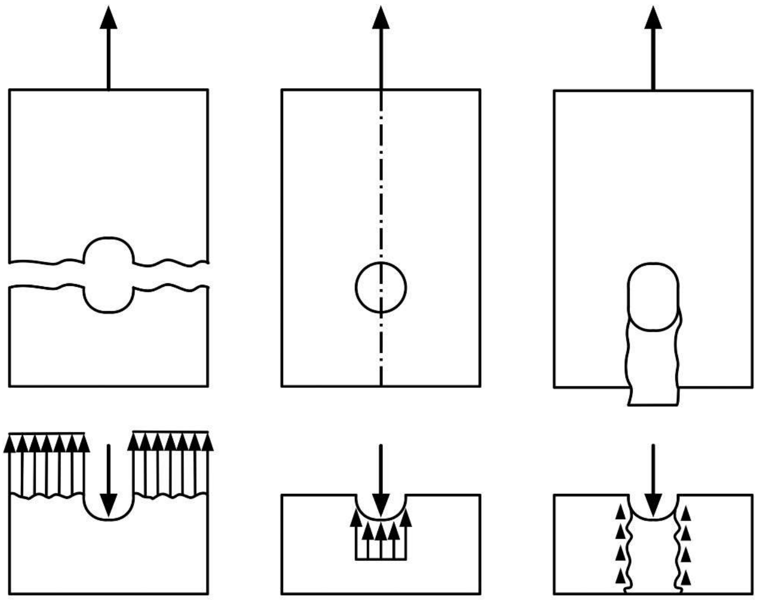

FIGURE 1 Single-bolted connection distinct modes of failure: (a) net-tension; (b) pin-bearing; (c) shear-out.

resistance owing to this distinct mode of failure. The block-shear mode of failure does not occur when the bolted connection has either a single bolt or a single row of bolts.

Publications [6] to [8] are the deliverables of previous projects to prepare a consensus structural design standard for structures of fibre-polymer composite materials. All three sources of guidelines have closed-form formulae (which can have different terms) to determine the resistance for the four distinct failure modes that are introduced in this Background Report (BR_12.2.2_PAR_2).

References

[1] Mottram, J.T., Turvey, G.J. Physical test data for the appraisal of design procedures for bolted joints in pultruded FRP structural shapes and systems. *Progress in Structural Engineering and Materials*. 2003, **5**(4), 195–222. Available from: https://doi/abs/10.1002/pse.154

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[6] Clarke, J.L. (editor). *Structural Design of Polymer Composites. EUROCOMP Design Code and Handbook*. E & F Spon, London, 1996.

[7] Italian National Research Council. *Guide for the Design and Construction of Structures Made of FRP pultruded Elements*. CNR-DT 205/2007. Roma:Advisory Committee on Technical Recommendations for Construction (CNR), 2008.

[8] American Society of Civil Engineers (ASCE). *Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures*. Submitted by the American Composites Manufacturers Association (ACMA) to ASCE, ASCE, Reston, VA, 2010.

REPORT NUMBER	BR_12.2.2_PAR_4
CLAUSE / ANNEX	12. JOINTS AND CONNECTIONS
SUBCLAUSE	12.2.2 Design criteria for bolted connections
PARAGRAPH	(4)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023
CONTENT (4) When bolted connections are for the single lap-shear joint configuration, the resistance calculated by subclauses 12.2.3.1 to 12.2.3.4 shall be multiplied by a factor of 0,6 to take into account the effect of load eccentricity on the internal forces and moments.	

DESIGN CRITERIA FOR BOLTED CONNECTIONS

Background

Paragraph 12.2.2(4) is for a specific type of bolted connections and bolted joints of fibre-polymer composite components. When the connection arrangement is for the single-lap shear configuration the load path creates secondary actions (with a bending moment profile along the connection's overlap length), and their presence in laminates is known to lead to a reduction in bolted connection resistance [1]. Because aerospace laminates are generally not as thick as the laminated components in civil engineering structures, the proposed reduction of 20% for the single-lap situation [1] is likely to be too low. For steel structures, Eurocode 3 Part 1–8 [2] gives the maximum permitted reduction in bearing strength to be 40%. Typical strength losses of 20%, and higher, are expected because the rotation of the bolt under single shear causes a stress concentration near the interface of the laminated components connected together.

With the single-lap geometry failure of bolted connections might **not** be with one of the distinct fibre-polymer composite modes of failure scoped by 12.2.2(2) (refer to Background Report BR_12.2.2_PAR_2). This is because of the additional stresses induced in the overlap length by a combination of axial and flexural deformations. The amount of strength loss in steel connections is a function of the bolt diameter-to-thickness ratio as well as the degree of moment restraint afforded by the tightening and the sizes of the bolt head and nut. Until applicable research is available, it is assumed in CEN/TS 19101:2022 that a reduction factor of 0,6 times the double-lap shear strength, from a distinct mode of failure scoped by 12.2.2(2) and the accompanying resistance subclauses, will be acceptable for the ultimate limit state design of single-lap bolted connections of fibre-polymer composites.

The same reduction of 40% in resistance between the equivalent double-lap and single-lap joints with in-plane (tensile) loading is to be found in [3], see subclauses 8.3.2 and 8.3.3 in [3].

Further work is needed to increase the number of test results that can reliably be employed to verify whether the multiplication factor of 0,6 can be shown to be an excessive reduction or is appropriate. We advise that the 40% reduction can be taken as a minimum and should be used unless a greater reduction is confirmed by the designer (e.g. by either numerical analysis or design by testing).

References

[1] Hart-Smith, L.J. Mechanically-fastened joints for advanced composites, Phenomenological considerations and simple analyses. In: *Fibrous Composites in Structural Design*, Lenoe, M., Oplinger, D.W. and Burke, J.J. (editors). Springer, Boston, MA, 1987. Available from: https://doi.org/10.1007/978-1-4684-1033-4 [Viewed 2023-09-15]

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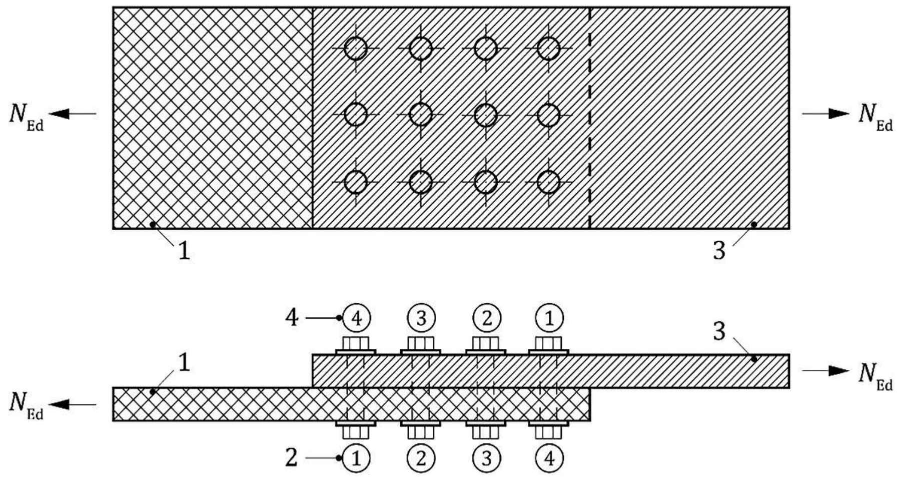
REPORT NUMBER	BR_12.2.3_PAR_3
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.3 Bolted connections subjected to in-plane actions
PARAGRAPH	(3)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023

CONTENT

(3) It is assumed that each bolt in the i^{th} -bolt row transfers an equal part of the design value of the connection force, $N_{\text{Ed},i}$, transferred at the i^{th}-bolt row's section.

NOTE: Figure 12.1 shows that for a multi-bolted joint having four rows ($i = 4$) of three bolts the first row of bolts for the composite material on the left-side is Row 1 ($i = 1$) (numbering below the connection illustration), whereas for the composite or steel material on the right-side it is also Row 1 (number above the connection illustration). Row 1 is the bolt row that first resists the connection force (the furthest away from the free-end of the corresponding side). The number of bolts per row of bolts does not have to be constant.



Key:

(1) Composite,

(2) Row number ordering for composite,

(3) Composite or steel, and

(4) Row number ordering for composite or steel

FIGURE 12.1 Layout of a multi-bolted lap-shear connection in which at least one side (left-side) is of composite material.

BOLTED JOINTS SUBJECTED TO IN-PLANE ACTIONS

Background

Paragraph 12.2.3(3) and Figure 12.1 are for bolted connections and joints of fibre-polymer composite components that for the laminate(s) satisfy the 15 CEN/TS 19101:2022 paragraphs in subclause 12.2.1, except for 12.2.1(11), and the six paragraphs in subclause 12.2.2, except for 12.2.2(5). The bolt force distributions per row of bolts in Table 12.1 of 12.2.3(4) (refer to Background Report

BR_12.2.3_PAR_4) are for bolted connections of both double-lap and single-lap shear configurations. The connection force, N_{Ed}, distribution between bolt rows will clearly be affected by the precise placement of the bolting in the holes, and the size(s) of hole clearance, which in Europe is nominally 1 mm (for fabrication of structures of pultruded profiles). It is assumed that the component of N_{Ed} resisted at each bolt row is equally distributed to the number of bolts in that row.

For two illustrative examples of the bolt force distribution in bolted connections, refer to Background Report BR_12.2.3_PAR_4.

REPORT NUMBER	BR_12.2.3_PAR_4
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.2.3 Bolted connections subjected to in-plane actions
PARAGRAPH	(4)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023

CONTENT

(4) The design value of the connection shear force per bolt at the i^{th}-row of bolts, $V_{\text{b},i,\text{Ed}}$, should satisfy the condition in Formula (12.2):

$$V_{\text{b},i,\text{Ed}} = \frac{c_{\text{r},i}}{n_{\text{b},i}} N_{\text{Ed}} \tag{12.2}$$

where

N_{Ed} is the design value of the axial force for the connection force (tension or compression);
$c_{\text{r},i}$ is the bolt row load distribution coefficient listed in Table 12.1 for the i^{th}-bolt row, with reference to Figure 12.1;
$n_{\text{b},i}$ is the number of bolts at the i^{th} bolt row.

TABLE 12.1

Load distribution coefficients, $c_{\text{r},i}$, for the rows in a multi-bolted lap-shear connection of composite materials of constant thickness components

Row number ordering (composite)	Plate combination	Row 1 $c_{r,1}$	Row 2 $c_{r,2}$	Row 3 $c_{r,3}$	Row 4 $c_{r,4}$
1	composite/composite	1			
	composite/steel	1			
2	composite/composite	0,5	0,5		
	composite/steel	0,6	0,4		
3	composite/composite	0,4	0,2	0,4	
	composite/steel	0,5	0,3	0,2	
4	composite/composite	0,3	0,2	0,2	0,3
	composite/steel	0,4	0,3	0,2	0,1
> 4	Not permitted				

BOLTED JOINTS SUBJECTED TO IN-PLANE ACTIONS

Background

Paragraph 12.2.3(4) and Table 12.1 are for bolted connections and joints of fibre-polymer composite components that for the laminate(s) satisfy the 15 CEN/TS 19101:2022 paragraphs in subclause 12.2.1, except for 12.2.1(11), and the six paragraphs in subclause 12.2.2, except for 12.2.2(5). Table 12.1 is Table 5.3 *Fastener load distribution* in multi-row joint (as a proportion of average fastener load) in [1], with unknown provenance. The bolt force distributions in Table 12.1 of 12.2.3(4) are for