PULL-OUT FAILURE

Background

Paragraph 12.2.4.1(1) with Figure 12.8 is for bolted connections and joints of fibre-polymer composite components only. Should one component thickness in bolted connections be of another construction material, then 12.2.4.1(1) is invalid, and the pull-out failure strength should be determined by testing, in accordance with 4.5(1) in CEN/TS 19101:2022. Note that the pull-out failure mode is known also by the descriptor "pull-through" failure mode.

Resistance Formula (12.33) appears with a reduction factor of 0,5 as Equation (5.6) in the EUROCOMP Design Code and Handbook [1]. PhD thesis by Oppe [2] (in German language) gives specific technical information from which 12.2.4.1(1) was prepared. Formula (12.33) is Equation (3.5) in [2], developed using a test matrix of strength measurements for the pull-out failure mode, which in [2] is Table 4–10. These test results with pultruded materials are plotted in Figure 6–13 of the PhD thesis and have an accompanying evaluation discussion presented in Section 6.4 [2]. Reference [3] reports the PhD contribution in [2] for an analysis of the pull-out failure strength.

In reference [4], Turvey reports independent resistance test results for the pull-out failure mode, which could not be used to verify Formula (12.33). A reason for this is that Turvey did not make available in [4] the characteristic value of the out-of-plane shear strength (xz plane) of the laminate material, $f_{xy,v,k}$.

The characteristic value of the out-of-plane shear strength (xz plane) of the laminate, $f_{xz,v,k}$, may be taken to be the characteristic interlaminar shear strength determined by the test method in standard EN ISO 14130 [5].

No commentary is required herein to introduce partial factor for a material or product property γ_m (defined in subclause 4.4.5 *Partial factors for materials* and corresponding to $f_{xz,v,k}$) and conversion factor, η_c (defined in subclause 4.4.7 *Nominal conversion factors*).

The following is taken from Background Report BR_4.4.6_PAR_3. Due to the lack of experimental data in the literature, it was not possible to apply the methodology described in background report BR_4.4.6_PAR_1 (used to determine the values of the partial factor associated with the uncertainty in a resistance model (γ_{Rd}) for profiles and laminates) to determine a specific value of γ_{Rd} for pull-out failure. Therefore, the value of γ_{Rd} = 1,5 for pull-out failure reported in Table 4.5 in 4.4.6(3) is based on the calibrated values of γ_{Rd} for the two failure modes of net-section and shear-out. Future research to characterise the pull-out failure mode in bolted connections of fibre-reinforced polymer composites is needed to confirm this hypothesis.

References

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

[2] Oppe, M. *Zur Bemessung geschraubter Verbindungen von pultrudierten faserverstärkten Polymerprofilen*. Schriftenreihe Stahlbau, Heft 66, Shaker-Verlag Aachen, 2009. (in German)

[3] Oppe, M., Knippers, J. Behaviour of bolted connections in GFRP subjected to tension loads. In: *Proceedings Fourth International Conference on Advanced Composites in Construction (ACIC 2009)*, Net Composites, Chesterfield, 495–506, 2009.

[4] Turvey, G.J. Experimental evaluation of bolt pull through in pultruded glass-fibre reinforced polymer plate. *Structures and Buildings*. 2011, **164**(5), 307–319. Available from: https://doi.org/10.1680/stbu.2011.164.5.307

[5] EN ISO 14130:1997. *Fibre-reinforced plastic composites – Determination of apparent interlaminar shear strength by short-beam method.*

REPORT NUMBER	BR_12.2.4.3_PAR_1
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	1.2.4.3 Bolted connections subjected to in- and out-of-plane forces
PARAGRAPH	(1)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023

CONTENT

(1) In presence of combined in-plane shear force and out-of-plane tensile force, the resistance at a single bolt should satisfy the linear interaction failure criterion given in Formula (12.35):

$$\frac{V_{\mathrm{b},i,\mathrm{Ed}}}{V_{\mathrm{br,Rd}}} + \frac{N_{\mathrm{z,Ed}}}{N_{\mathrm{z,Rd}}} \leq 1{,}0 \qquad (12.35)$$

where

$V_{\mathrm{b},i,\mathrm{Ed}}$ is the design value of the connection force per bolt (bearing force transferred per bolt) at the i^{th}-bolt row from Formula (12.2);
$V_{\mathrm{br,Rd}}$ is the design value of the pin-bearing resistance per bolt from 12.2.3.2 or from testing in accordance with the requirements of 12.2.3.2;
$N_{\mathrm{z,Ed}}$ is the design value of the out-of-plane tensile force transferred at the bolt (see Figures 12.8 and 12.9);
$N_{\mathrm{z,Rd}}$ is the design value for the resistance for the out-of-plane tension force from 12.2.4 or from testing.

NOTE: Guidance on design assisted by testing is provided in EN 1990:-, Annex D.

BOLTED CONNECTIONS SUBJECTED TO IN- AND OUT-OF-PLANE ACTIONS

Background

Paragraph 12.2.4.3(1) is for bolted connections and joints of fibre-polymer composite material components that satisfy the relevant requirements in subclauses 12.2.1 and 12.2.2 in CEN/TS 19101:2022. The linear-interaction Formula (12.37) for combining bearing force and out-of-plane tensile force was prepared specifically for this Eurocode project and is presented as Formula (8.8) in [1].

Reference

[1] 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.

REPORT NUMBER	BR_12.3.1_PAR_2
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.3.1 General
PARAGRAPH	(2)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023

CONTENT

(2) In beam-to-column bolted joints having negligible ultimate joint moments and adequate joint rotations, web cleat joints, consisting of a pair of leg-angles of composite material of constant thickness, shall be designed in accordance with 12.1, 12.2 and 12.3.

GENERAL FOR BOLTED JOINTS

Background

Paragraph 12.3.1(2) is specific to bolted joints having fibre-polymer composite components that are used to form a joint between fibre-polymer composite and/or other construction material components (say for beam and column members). References [1–4] give background and/or specific technical information from which this paragraph is prepared. The full-sized beam-to-column test results reported in references [3, 4] for the moment-rotation characteristics of web-cleated beam-to-column joints of pultruded components were conducted specifically to provide physical evidence for the joint rotation capacity at the onset of damage in fibre-polymer composite materials (cleats and/or members). The required (serviceability limit state) rotation, for a simply supported beam subjected to a uniformly distributed load, is 13 or 21 mrad for a mid-span deflection of span/250 or span/150, respectively. Sufficient rotation capacity is essential to having connection/joint details satisfying 12.3.1(2) and, as necessary, 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).

References

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

[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] Qureshi, J., Mottram, J.T. Response of beam-of-column web cleated joints for pultruded frames. *Journal of Composites for Construction*. 2014, **18**(2), 1–11. Available from: https://doi.org/10.1061/(ASCE)CC.1943-5614.0000392

[4] Qureshi, J., Mottram, J.T. Moment-rotation response of nominally pinned beam-to-column joints for frames of pultruded fiber reinforced polymer. *Construction and Building Materials*. 2015, **77**, 396–403. Available from: https://doi.org/10.1016/j.conbuildmat.2014.12.057

REPORT NUMBER	BR_12.3.3_PAR_1
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.3.3 Tying force failure of web cleat joints
PARAGRAPH	(1)
AUTHOR	J. Toby Mottram
REVIEWER(S)	Casper Kruger, Lee Canning
DATE	15 September 2023

CONTENT

(1) In web cleated beam-to-column joints of two leg-angles (see Figure 12.10) having constant thickness outstands, the design value of the tensile force or prying action, $N_{\text{ty,Ed}}$, for tying force failure should satisfy the condition given in Formula (12.39):

$$N_{\text{ty,Ed}} \leq N_{\text{ty,Rd}} \tag{12.39}$$

where

$N_{\text{ty,Rd}}$ is the design value of the tying force resistance of a web cleated beam-to-column joint of two leg-angles having constant thickness outstands, given by Formula (12.40),

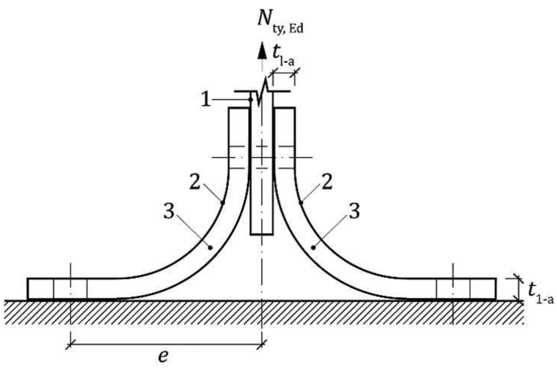
$$N_{\text{ty,Rd}} = \frac{h \cdot t_{1-a}^2 \cdot f_{\text{y,f,d}}}{3 \cdot e} \tag{12.40}$$

h is the depth of the leg-angle;
$t_{\text{1-a}}$ is the thickness of a leg-angle cleat, as shown in Figure 12.10;
e is the lever arm distance from the centre of the nearest line of bolt holes to the centre of the beam's web, as shown in Figure 12.10;
$f_{\text{y,f,d}}$ is the design value of the flexural strength of the laminate in the y direction, given by Formula (12.41),

$$f_{\text{y,f,d}} = \frac{\eta_{\text{c}}}{\gamma_{\text{m}} \cdot \gamma_{\text{Rd}}} \cdot f_{\text{y,f,k}} \tag{12.41}$$

where

γ_{m} is defined in 4.4.5 (to be selected for $f_{\text{y,f,k}}$);
γ_{Rd} is defined in 4.4.6 (Table 4.3, Material failure);
η_{c} is defined in 4.4.7 (to be selected for $f_{\text{y,f,k}}$);
$f_{\text{y,f,k}}$ is the characteristic value of the flexural strength of the laminate in the y direction.



Key:
(1) Beam web,
(2) Composite web cleat, and
(3) Delamination damage locations

FIGURE 12.10 Tying force failure mode for pair of composite web cleats.

TYING FORCE FAILURE

Background

Paragraph 12.3.3(1) with Figure 12.10 is for web-cleat joints of fibre-polymer composite materials that satisfy relevant requirements in subclauses 12.2.1 and 12.2.2 in CEN/TS 19101:2022. References [1, 2] give specific technical information when the cleats are of pultruded materials from which 12.3.3(1) was prepared. In reference [1], the tying capacity and failure modes of double pultruded web-cleat joints (as illustrated in Figure 12.10 above) are reported from static tests on two batches of specimens for six joints. The tensile-pulling load-displacement curves are found to be linear elastic up to 0,35 to 0,4 of the maximum (ultimate) tension forces and damage (in the cleats) was observed at 0,6 of the ultimate loads. Failure is identified to be owing to excessive delamination cracking emanating in the region of a cleat's fillet radius, as can be seen in Figure 1.

Figure 1 is a photo from one of the tying force tests presented in [1] that shows the form of damage at the end of the ultimate strength test. You are looking down, and at the bottom of the image is the flange of the column member and at the top is the top flange of the beam member. Between these frame members are the back-to-back web cleats (of pultruded leg-angle material) showing significant failure after the typing force test had been terminated. The failure mechanisms at ultimate failure are complex to describe and can be specific to the laminate material's properties and cleat geometry. What is known from the tension load-axial displacement plot, see example in Figure 2, and from visual observations of damage growth [1], is that delamination failures first occur for damage onset, this cracking grows and eventually contributes to the ultimate "flexural" strength failure of the joint as seen in Figure 1.

A model to predict tying resistance is proposed in reference [1], which is Formula (12.40), and which, in [1], is successfully calibrated against the reported test results reported in references [1, 2]. Furthermore, the contribution presented in [1] highlights the inadequacies of the two strength equations for the tying force in Section 5.10 (*Stresses in out-of-plane shear connections*) of [3]. The study in [1] is also important because it shows that a pair of 9,53 mm thick pultruded leg-angle web cleats can possess an adequate tying capacity when the cleat material is of fibre-polymer composite to design against disproportionate collapse.

Advanced computational analysis with ABAQUS® finite element software is presented in reference [4] to show that the test results for typing resistance presented in [1] can be reliably modelled and thereby be numerically predicted.

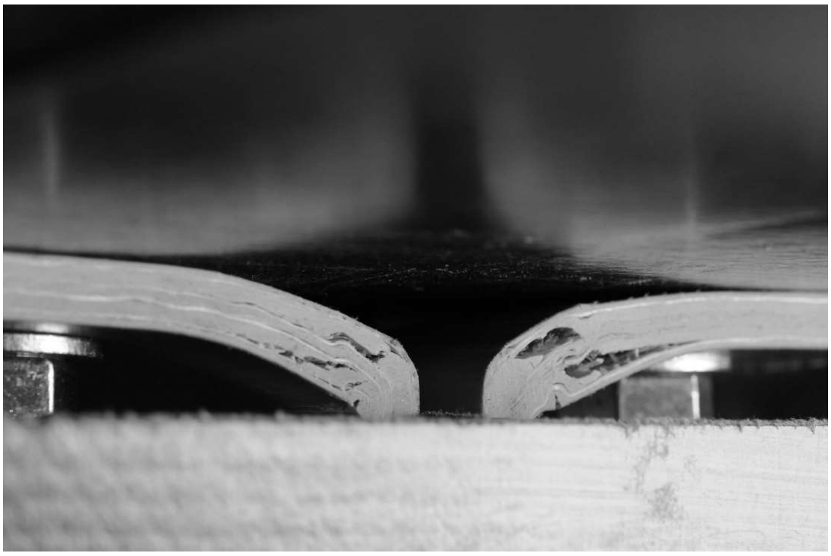


FIGURE 1 Typical failure pattern for pultruded material in a tying force test.

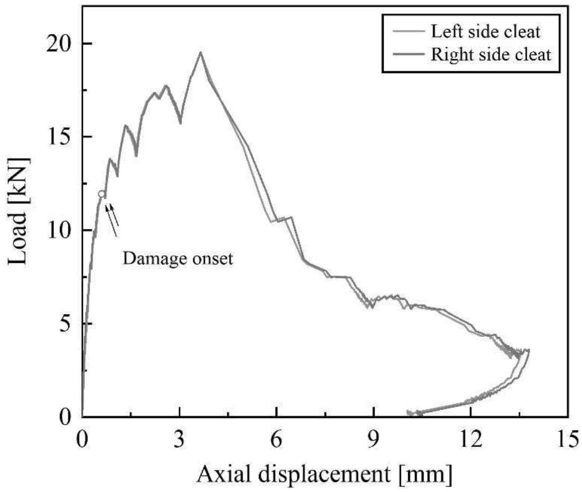


FIGURE 2 Tensile load-axial displacement for a back-to-back web cleat joint with typical ultimate failure patterns shown in Figure 1 (data from [1]).

The characteristic value of the flexural strength in the y direction, $f_{y,f,k}$, can be determined using test standard EN ISO 14125 [5]. No commentary is required herein to introduce a partial factor for a material or product property γ_m (defined in subclause 4.4.5 *Partial factors for materials* and corresponding to $f_{x,f,k}$) and conversion factor, η_c (defined in subclause 4.4.7 *Nominal conversion factors*).

Due to the lack of experimental data for relevant test results in the literature, it was not possible to apply the methodology described in Background Reports BR_4.4.6_PAR_1 (used to determine the values of the partial factor associated with the uncertainty in a resistance model (γ_{Rd}) for profiles and laminates) to determine a specific value of γ_{Rd} for tying force failure. Therefore, the value of γ_{Rd} for tying force failure equal to 1,4 has been specified as the value for material failure in Table 4.3 in 4.4.6(1) (which has been specified by the drafting team from engineering judgement). Future research is needed to confirm this hypothesis.

References

[1] Qureshi, J., Mottram, J.T., Zafari, B. Robustness of simple joints in pultruded frames. *Structures*. 2015, **3**, 120–129. Available from: https://doi.org/10.1016/j.istruc.2015.03.007

[2] Turvey, G.J., Wang, P. Failure of pultruded GRP angle leg junctions in tension. In: *Seventeenth International Conference on Composite Materials (ICCM-17)*, 27 - 31 July 2009, Edinburgh, Paper A1:1, p. 11, 2009.

[3] Bank, L.C. *Composites for Construction - Structural Design with FRP Materials*, John Wiley & Sons, New Jersey, 2006.

[4] Girão Coelho, A.M., Mottram, J.T., Matharu, N.S. Virtual characterization of delamination failures in pultruded GFRP composite angle cleats. *Composites Part B: Engineering*. 2016, **90**, 212–222. Available from: https://doi.org/10.1016/j.compositesb.2015.12.025

[5] EN ISO 14125:1988+A1:2011. *Fibre-reinforced plastic composites – Determination of flexural properties*.

REPORT NUMBER	BR_12.4.2_PAR_1
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.2 Design principles
PARAGRAPH	(1)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT (1) A composite structure comprising adhesive joints shall be designed as fail-safe, i.e. joint failure shall not result in failure of the structure or critical parts thereof.	

FAIL-SAFE DESIGN

Background

Failure of an adhesive connection may not be generally excluded throughout the entire design working life. Failure can occur due to, amongst other things, unnoticed defective execution (human error), local impact, elevated temperature/fire and fatigue. In [1], for instance, it is reported that an adhesive connection failed most probably due to a local impact, which produced tensile stresses transverse to the bond line. Furthermore, the resistance of adhesive connections exhibits greater uncertainty than that of the adherends and much less information about the long-term performance is available.

In prEN 1990:2020, 4.4 Robustness, it is specified that

"(1) A structure should be designed to have an adequate level of robustness so that, during its design service life it will not be damaged by adverse and unforeseen events, such as the failure or collapse of a component or part of a structure, to an extent disproportionate to the original cause.

NOTE 1 Progressive collapse is an example of a damage that is disproportionate to the original cause."

An adhesive connection in this sense is considered a component and its failure should therefore not lead to a progressive collapse, that is, the failure of the structure or large sections of the structure. An adhesive connection shall thus be considered a fail-safe component; see also Background Report. BR_12.4.2_PAR_2.

Reference

[1] Keller, T., Theodorou, N.A., Vassilopoulos, A.P., De Castro, J. Effect of natural weathering on durability of pultruded glass fiber-reinforced bridge and building structures. *Journal of Composites for Construction*. 2016, **20**(1). Available from: https://doi.org/10.1061/(ASCE)CC.1943-5614.0000589

REPORT NUMBER	BR_12.4.2_PAR_2
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.2 Design principles
PARAGRAPH	(2)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT (2) Failure of an adhesive joint shall be considered as an accidental situation in accordance with EN 1990.	

ACCIDENTAL SITUATION

Background

Adhesive connection failure is considered a local failure and shall thus be considered an accidental design situation according to prEN 1990:2020:

3.1.2.5 Accidental design situation:

"Design situation in which the structure is subjected to exceptional events or exposure.

Note 1 to entry: Caused by events such as fire, explosion, impact or local failure."

Furthermore, according to EN 1991-1-7:2006:

"Figure 3.1: Strategies for accidental design situations:

- design the structure to have sufficient minimum robustness,
- enhanced redundancy, e.g. alternative load paths."

The fail-safe provision in 12.4.2(1) is thus further justified by this paragraph.

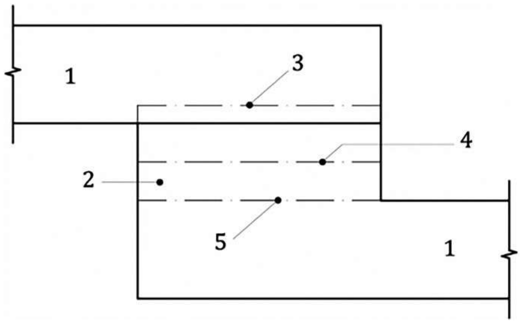
REPORT NUMBER	BR_12.4.2_PAR_3
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.2 Design principles
PARAGRAPH	(3)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023

CONTENT

(3) The failure modes of adhesive connections shall be either cohesive failure in the adhesive or fibre-tear failure in the adherend, defined in accordance with Figure 12.11.

NOTE 1: The environmental conditions can change the failure mode.

NOTE 2: Further details about failure modes in adhesive connections can be found in ASTM D5573.



Key:

(1) Adherend, (2) Adhesive layer, (3) Fibre-tear failure (inside composite adherend), (4) Cohesive failure (inside adhesive layer), and (5) Adhesive failure (in adherend-adhesive layer interface)

FIGURE 12.11 Failure modes in adhesive connections.

ADHESIVE FAILURE

Background

The failure modes of adhesive connections are defined according to ASTM D5573. Adhesive failure, that is, failure in the adherend-adhesive layer interface, is considered to be a consequence of material incompatibility and/or inappropriate surface preparation, see [1], 5.3.1.2(2). Both can be prevented by an appropriate material selection and surface preparation, including the use of primers if necessary, see 12.4.2(5).

Since it is often difficult to obtain "pure" failure modes, a maximum adhesive failure area of 10% is assumed to be acceptable, see 12.4.2(6).

Reference

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

REPORT NUMBER	BR_12.4.3_PAR_1
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.3 Joint and connection design
PARAGRAPH	(1)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023

CONTENT

(1) Adhesive joints should preferably be designed to be symmetrical with regard to the load axis and with minimized eccentricities; examples are shown in Figure 11.5.

NOTE 1: Tapering of the adherends and the addition of adhesive fillets can reduce stress peaks.

NOTE 2: The effectiveness of tapering of adherends and adding adhesive fillets to reduce stress peaks in lap-shear connections depends on the adhesive/adherend stiffness ratio and decreases with decreasing ratio.

NOTE 3: Size effects on strength can counteract the effect of reduced stress peaks on the connection resistance and thus limit the effectiveness of tapering and adhesive fillets in lap-shear connections. Reducing the stress peaks can however improve fatigue life.

SYMMETRICAL JOINT CONFIGURATION

Background

Eccentricities of the adherends in the adhesive connection induce bending moments and thus amplify through-thickness tensile (peeling) stresses, which often appear in the form of stress peaks at the joint edges. They can significantly affect the connection strength since these stresses act transversally to the fibres in the adherend.

Symmetric configurations, for example, double-lap connections, exhibit significantly lower through-thickness tensile stresses than corresponding asymmetric configurations, for example, single-lap connections (under the same load); symmetric configurations should thus be selected; also see [1], 5.3.1.3.

Reference

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

EFFECT OF REDUCING PEAK STRESSES ON JOINT STRENGTH

Background

Tapering (chamfering) of the adherends or the addition of adhesive fillets normally reduces stress peaks, depending on the adhesive/adherend stiffness ratio, for example, see the example in Eurocomp [1], Figure 5.29.

Several experimental works [2–4] have however shown that the effect of the reduction of the stress peaks may only have insignificant effects on the connection resistance because the reduced stresses act on a larger volume. The material strength is accordingly reduced due to a statistical (geometrical) size effect [5] and the connection resistance is not improved, see also Background Report BR_12.4.5.3_PAR_4.

References

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

[2] Vallée, T., Keller, T. Adhesively bonded lap joints from pultruded GFRP profiles, Part III: Effects of chamfers. *Composites Part B*. 2006, **37**(4–5), 328–336. Available from: https://doi.org/10.1016/j.compositesb.2005.11.002

[3] Vallée, T., Tannert, T., Murcia-Delso, J., Quinn, D.J. Influence of stress-reduction methods on the strength of adhesively bonded joints composed of orthotropic brittle adherends. *International Journal of Adhesion and Adhesives*. 2010, **30**(7), 583–594. Available from: https://doi.org/10.1016/j.ijadhadh.2010.05.007

[4] Vallée, T., Correia, J.R., Keller, T. Probabilistic strength prediction for double lap joints composed of pultruded GFRP profiles, Part I: Experimental and numerical investigations. *Composites Science and Technology*. 2006, **66**(13), 1903–1914. Available from: https://doi.org/10.1016/j.compscitech.2006.04.007

[5] Vallée, T., Correia, J.R., Keller, T. Probabilistic strength prediction for double lap joints composed of pultruded GFRP profiles, Part II: Strength prediction. *Composites Science and Technology*. 2006, **66**(13), 1915–1930. Available from: https://doi.org/10.1016/j.compscitech.2006.04.001

REPORT NUMBER	BR_12.4.3_PAR_2
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.3 Joint and connection design
PARAGRAPH	(2)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT	
(2) With regard to the connection dimensions, the adhesive layer thickness should be specified and verified with particular attention.	

ADHESIVE LAYER THICKNESS

Background

The adhesive layer thickness can significantly influence the connection resistance [1] and shall thus be specified and assured (e.g. by inserting spacers into the layer).

Reference

[1] Vallée, T., Correia, J.R., Keller, T. Optimum thickness of joints made of GFRP pultruded adherends and polyurethane adhesive. *Composite Structures*. 2010, **92**(9), 2102–2108. Available from: https://doi.org/10.1016/j.compstruct.2009.09.056

REPORT NUMBER	BR_12.4.4_PAR_2
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.4 Analysis
PARAGRAPH	(2)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT (2) The effect of the loading rate on the adhesive and connection responses should be taken into account in the adhesive connection design. NOTE: An increasing loading rate can result in a stiffer material and adhesive connection response, and an increased material strength and adhesive connection resistance, but also in a more brittle failure behaviour.	

EFFECT OF LOADING OR STRAIN RATE

Background

The loading or strain rate can significantly influence the stress-strain behaviour of the adhesive and the stress distribution and strength of the adhesive connection, for example, [1, 2].

References

[1] Angelidi, M., Keller, T. Ductile adhesively-bonded timber joints – Part 2: Strain rate effect. *Construction and Building Materials*. 2018, **179**, 704–713. Available from: https://doi.org/10.1016/j.conbuildmat.2018.05.213

[2] Pandey, P.C., Shankaragouda, H., Singh, A.K. Nonlinear analysis of adhesively bonded lap joints considering viscoplasticity in adhesives. *Computers & Structures*. 1999, **70**(4), 387–413. Available from: https://doi.org/10.1016/S0045-7949(98)00168-0

REPORT NUMBER	BR_12.4.4_PAR_3
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.4 Analysis
PARAGRAPH	(3)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT (3) The loading rate in the connection and in corresponding tests to obtain the material or connection properties should be in agreement, particularly in cases of (i) flexible adhesives, i.e. exhibiting a low adhesive/adherend stiffness ratio, or (ii) taking static resistances into account in fatigue *S–N* curves.	

LOADING RATE SENSITIVITY

Background

The adhesive properties are loading- or strain rate-dependent; see Background Report BR_12.4.4_PAR_2, particularly those of flexible adhesives [1].

For fatigue, on the other hand, the loading rate is normally high compared to the loading rates of standard static tests [2]. Static strength values, if included in the fitting of *S-N* curves, should thus result from tests conducted at the same high loading rate as applied in fatigue.

References

[1] Angelidi, M., Keller, T. Ductile adhesively-bonded timber joints – Part 2: Strain rate effect. *Construction and Building Materials*. 2018, **179**, 704–713. Available from: https://doi.org/10.1016/j.conbuildmat.2018.05.213

[2] Liu, L., Wang, X., Wu, Z., Keller, T. Tension-tension fatigue behavior of ductile adhesively-bonded FRP joints. *Composite Structures*, 2021. **268**. Available from: https://doi.org/10.1016/j.compstruct.2021.113925

REPORT NUMBER	BR_12.4.4_PAR_4
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.4 Analysis
PARAGRAPH	(4)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT	
(4) In the case of fatigue loading of an adhesive connection, the rules stipulated under Clause 10 shall be applied.	

FAIL-SAFE FATIGUE DESIGN

Background

According to 12.4.2(1), a composite structure comprising adhesive joints shall be designed as fail-safe. Therefore, fatigue failure of the connection shall not result in failure of the structure or critical parts thereof, also see Background Report BR_10.3_PAR_1.

REPORT NUMBER	BR_12.4.4_PAR_5
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.4 Analysis
PARAGRAPH	(5)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT	
(5) In the case of on-site bonding, the effect of low temperature on the adhesive curing process and associated delayed development of the T_g and mechanical properties should be taken into account.	

EFFECT OF LOW TEMPERATURE ON EARLY-AGE PHYSICAL AND MECHANICAL PROPERTIES

Background

The development of the physical (i.e. T_g) and mechanical properties of thermoset adhesives, at an early age and subjected to low temperature, that is 0–10°C, is significantly decelerated. At 0°C, curing can be inhibited or does not even initiate. At 5–10°C, curing can take place, but the process is significantly decelerated. Several days of curing can be required before higher curing degrees, for example, >80%, are reached [1, 2], see Figure 1.

Significant development of the mechanical properties begins only after the onset of material vitrification, see Figure 2. This is in contrast to the development of the glass transition temperature, which increases particularly before vitrification and levels off during vitrification, see Figure 3 [2]. An analytical model to estimate early-age mechanical properties as a function of low curing temperatures and time is shown in [2].

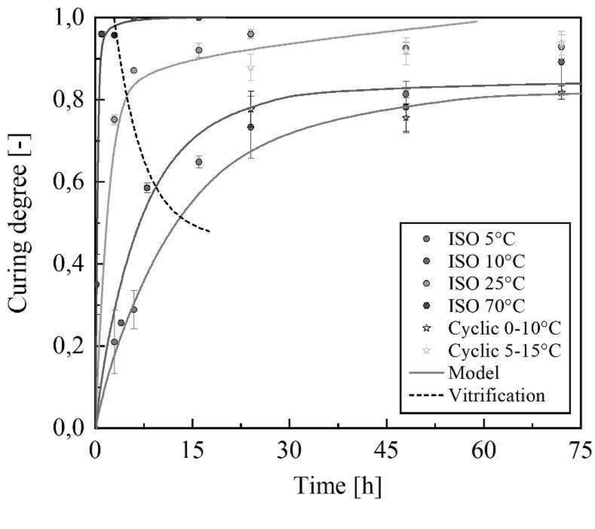


FIGURE 1 Curing degree *vs* curing time of partially cured epoxy samples at different isothermal and cyclic temperatures [2] (reprinted from International Journal of Adhesion and Adhesives, 35, Moussa *et al.*, Early-age tensile properties of structural epoxy adhesives subjected to low-temperature curing, 9-16, 2012, with permission from Elsevier).

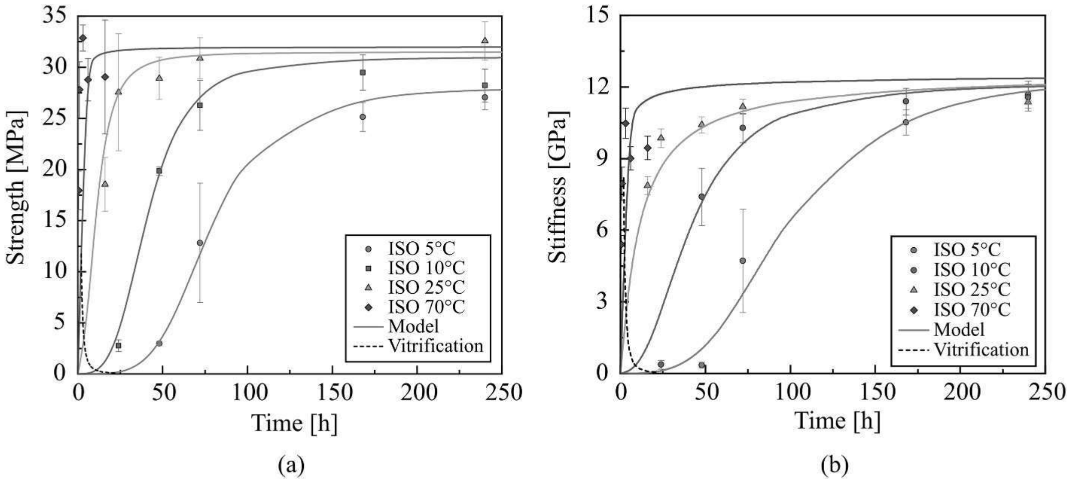


FIGURE 2 Mechanical property development of epoxy samples at different isothermal temperatures and early stages of curing: a) strength; b) stiffness [2] (reprinted from International Journal of Adhesion and Adhesives, 35, Moussa *et al.*, Early-age tensile properties of structural epoxy adhesives subjected to low-temperature curing, 9-16, 2012, with permission from Elsevier).

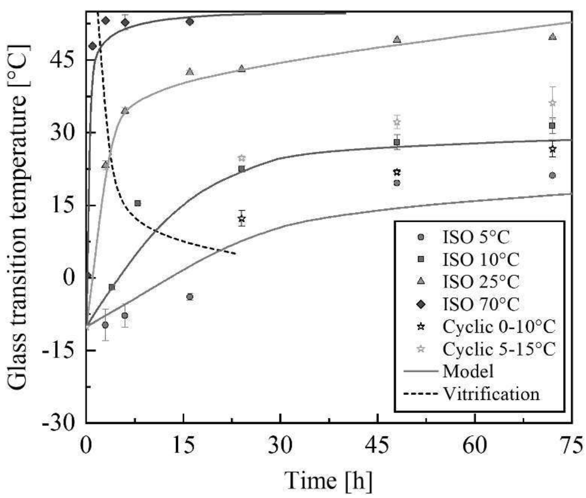


FIGURE 3 Glass transition temperature *vs* curing time of partially cured epoxy samples at different isothermal and cyclic temperatures [2] (reprinted from International Journal of Adhesion and Adhesives, 35, Moussa *et al.*, Early-age tensile properties of structural epoxy adhesives subjected to low-temperature curing, 9-16, 2012, with permission from Elsevier).

References

[1] Moussa, O., Vassilopoulos, A.P., Keller, T. Effects of low-temperature curing on physical behavior of cold-curing epoxy adhesives in bridge construction. *International Journal of Adhesion and Adhesives*. 2012, **32**, 15–22. Available from: https://doi.org/10.1016/j.ijadhadh.2011.09.001

[2] Moussa, O., Vassilopoulos, A.P., De Castro, J., Keller, T. Early-age tensile properties of structural epoxy adhesives subjected to low-temperature curing. *International Journal of Adhesion and Adhesives*. 2012, **35**, 9–16. Available from: https://doi.org/10.1016/j.ijadhadh.2012.01.023

REPORT NUMBER	BR_12.4.5.1_PAR_1
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.5.1 General
PARAGRAPH	(1)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023

CONTENT

(1) Adhesive connections should fulfil the condition in Formula (12.42):

$$E_{d} \leq R_{ac,Rd} \tag{12.42}$$

where

E_{d} is the design value of an action effect transmitted by the connection;
$R_{ac,Rd}$ is the design value of the corresponding adhesive connection resistance, given by Formula (12.43),

$$R_{ac,Rd} = \frac{\eta_{c}}{\gamma_{M,ac}} \cdot R_{ac,k} \tag{12.43}$$

where

$\gamma_{M,ac}$ is the partial factor for the adhesive connection resistance;
η_{c} is defined in 4.4.7 (corresponding to the material property which causes failure);
$R_{ac,k}$ is the characteristic value of the adhesive connection resistance.

TABLE 12.4
NDP belongs to Partial factors for adhesive connection resistance, $\gamma_{M,ac}$

Inspection and access	Fully controlled application	Partially controlled application
Connection subjected to periodic inspection and maintenance[a]; adhesive connection accessible	1,5	2,0
Connection subjected to periodic inspection and maintenance[a]; limited accessibility	1,7	2,2
Connection not subjected to periodic inspection and maintenance	2,0	2,5

[a] According to maintenance plan

NOTE 1: The values of the partial factor for the adhesive connection resistance, $\gamma_{M,ac}$, are given in Table 12.4 (NDP), unless the National Annex gives different values.

NOTE 2: The partial factor for the connection resistance depends on (i) the type of inspection and maintenance and accessibility of the adhesive connection, and (ii) the application conditions, either with fully controlled, i.e. reproducible process parameters, or with only partially controlled parameters.

ADHESIVE CONNECTION VERIFICATION FORMAT

Background

The partial factor for the adhesive connection resistance, $\gamma_{M,ac}$, includes the uncertainties of the material properties and resistance models. Since, due to the lack of data, it is not possible to define partial factors for resistance models, γ_{Rd}, only a single partial factor is provided, according to Formula (4.3) in 4.4.4(3).

Similarly to the partial factors for fatigue resistance, see Background Report BR_10.3_PAR_1, the partial factors for the adhesive connection resistance depend on the type of inspection and maintenance and accessibility of the adhesive connection. The partial factors are however not graded according to the Consequence Classes, since the fail-safe provision already fulfils the requirements of the highest classes.

The factors depend however on the application conditions, either with fully controlled, that is, reproducible, process parameters, or with only partially controlled parameters, as also taken into account in Eurocomp [1] by partial factor $\gamma_{m,2}$, see below. In-factory-made connections normally fulfil the first condition, while on-site connections normally fulfil the second condition.

The range of values (from 1.5 to 2.5) was adopted from Eurocomp [1], 5.1.10, P(4), that is, from the products of the partial factors ($\gamma_{m,1} \cdot \gamma_{m,2}$), listed in Tables 1 and 2.

The background of these Eurocomp values could however not be retraced and they thus require further validation.

Conversion factors for temperature, η_{ct}, for epoxy adhesives are provided in 4.4.7.2(3). In the case of fibre-tear failure, the values for composite adherends according to 4.4.7.2(1), matrix-dominated properties, should be used. Conversion factors for moisture, η_{cm}, for both epoxy adhesives and composite adherends are provided in Table 4.6.

TABLE 1
Partial factors $\gamma_{m,1}$ provided in Eurocomp [1]

Source of adhesive properties	$\gamma_{m,1}$
Typical or textbook values (for appropriate adherends)	1,5
Values obtained by testing	1,25

TABLE 2
Partial factors $\gamma_{m,2}$ provided in Eurocomp [1]

Method of adhesive application	$\gamma_{m,2}$
Manual application, no adhesive thickness control	1,5
Manual application, adhesive thickness control	1,25
Established application procedure with repeatable and controlled process parameters	1,0

Reference

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

REPORT NUMBER	BR_12.4.5.3_PAR_2
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.5.3 Design based on stress analysis
PARAGRAPH	(2)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT (2) For composite adherends, homogenized material properties may be used in FEM and material orthotropy should be taken into account.	

HOMOGENIZED ADHEREND PROPERTIES

Background

See Background Report BR_7.4.3.4_PAR_2. The precondition of this provision is that the fibre architecture of the adherends is symmetric and balanced.

REPORT NUMBER	BR_12.4.5.3_PAR_3
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.5.3 Design based on stress analysis
PARAGRAPH	(3)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023

CONTENT

(3) An appropriate failure criterion should be applied in the failure plane to estimate the connection resistance. In lap-shear connections exhibiting fibre-tear failure, the failure criterion may be defined as in Formula (12.44):

$$\left(\frac{\sigma_{z,t,Ed}}{f_{z,t,d}}\right)^2 + \left(\frac{\tau_{xy,Ed}}{f_{xy,v,d}}\right)^2 \leq 1{,}0 \tag{12.44}$$

where

$\sigma_{z,t,Ed}$ is the design value of the out-of-plane tensile (peeling) stress;
$\tau_{xy,Ed}$ is the design value of the in-plane shear stress;
$f_{z,t,d}$ is the design value of the out-of-plane tensile (peeling) strength, givenby Formula (12.45),

$$f_{z,t,d} = \frac{\eta_c}{\gamma_{M,ac}} \cdot f_{z,t,k} \tag{12.45}$$

$f_{xy,v,d}$ is the design value of the in-plane shear strength, given by Formula (12.46),

$$f_{xy,v,d} = \frac{\eta_c}{\gamma_{M,ac}} \cdot f_{xy,v,k} \tag{12.46}$$

where

$\gamma_{M,ac}$ is defined in Table 12.4 (NDP);
η_c is defined in 4.4.7 (corresponding to matrix-dominated composite properties (fibre-tear failure));
$f_{z,t,k}$ is the characteristic value of the out-of-plane tensile (peeling) strength;
$f_{xy,v,k}$ is the characteristic value of the in-plane shear strength.

FAILURE CRITERION TO ESTIMATE THE STATIC CONNECTION RESISTANCE

Background

The failure criterion (12.44) was derived in [1] and further discussed in [2]. The strength values $f_{z,t,k}$ and $f_{xy,v,k}$ can be influenced by a statistical (geometrical) size effect if significant stress peaks occur in the connection; see 12.4.5.3(4) and the corresponding Background Report BR_12.4.5.3_PAR_4.

References

[1] Keller, T., Vallée, T. Adhesively bonded lap joints from pultruded GFRP profiles. Part II: joint strength prediction. *Composites Part B*. 2005, **36**(4), 341–350. Available from: https://doi.org/10.1016/j.compositesb.2004.11.002
[2] Vallée, T., Correia, J.R., Keller, T. Probabilistic strength prediction for double lap joints composed of pultruded GFRP profiles, Part II: Strength prediction. *Composites Science and Technology*. 2006, **66**(13), 1896–1902. Available from: https://doi.org/10.1016/j.compscitech.2006.04.001

REPORT NUMBER	BR_12.4.5.3_PAR_4
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.5.3 Design based on stress analysis
PARAGRAPH	(4)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023

CONTENT

(4) The strength values indicated in failure criterion (12.43) should take into account the statistical size effect resulting from the type of stress distribution in the failure plane.

NOTE 1: The strength depends on the stressed material volume, i.e. stress peaks increase and uniform stress distributions lower the strength.

NOTE 2: In preliminary design and in the case of fibre-tear failure, the matrix strength can be assumed in the out-of-plane direction.

SIZE EFFECT ON STRENGTH, PROBABILISTIC DESIGN METHOD

Background

The failure criterion shown in 12.4.5.3(3), Formula (12.44), was adopted in this TS. The criterion is based on experimental investigations of adhesively bonded double-lap joints composed of pultruded glass-composite adherends and a stiff epoxy adhesive, published in [1, 2]. From these investigations and the application of the criterion, it was concluded in [3, 4] that a significant statistical size effect on strength occurred in these cases, which has to be taken into account in the strength values of the failure criterion in order to avoid a significant underestimation of the joint strength. The higher and narrower the stress peaks, the more the criterion would underestimate the joint strength without taking the size effect into account. In the case of soft adhesives, however, that is, almost uniform stress distributions in the joint without significant peaks, no size effect occurs.

A probabilistic method for the strength prediction of adhesively bonded double-lap joints composed of pultruded glass-composite adherends and exhibiting brittle material (fibre-tear) failure was developed in [4]. The method is based on the experimentally determined material strengths and their statistical distribution. It takes into account the scale sensitivity of the strength, modelled using Weibull statistics, and thus considers not only the magnitude of the stresses but also the volume within which stress peaks occur, that is, the increased resistance of local material zones to high and narrow stress peaks, which would normally cause failure of the bulk material. A comparison of joint strength results with those from Formula (12.44) without taking the size effect into account, revealed a statistical size effect with respect to joint strength in the order of 10–25%. The probabilistic method provides fairly precise results for brittle joint failure, but it cannot be used to predict joint strength of quasi-brittle or pseudo-ductile joint failures, which exhibit minor statistical scale sensitivity.

The predicted joint strengths in [4] were still slightly underestimated compared to the experimental results due to inaccurate modelling of the upper tail of the material strength by the Weibull statistical distribution. Alternative models for the upper tail are discussed in [5].

Indicative correction factors k_σ and k_τ were introduced in [3, 6] to adjust the out-of-plane tensile and in-plane shear strengths as follows:

$$\left(\frac{\sigma_{z,t,Ed}}{k_\sigma \cdot f_{z,t,d}}\right)^2 + \left(\frac{\tau_{xy,Ed}}{k_\tau \cdot f_{xy,v,d}}\right)^2 \leq 1{,}0 \tag{1}$$

Values for these correction factors were derived in two references for the corresponding joint configurations:

1) Glass-composite-epoxy double-lap joints with sharp stress peaks [3, 6]: k_σ = 4,0 and k_τ according to Table 1:

TABLE 1
Correction factors k_τ as a function of overlap length

Overlap length [mm]	50	75	100	200
k_τ	1.0	1.5	2.0	4.0

2) Glass-composite double-lap joints comprising a 100-mm overlap length and different adhesives [7]:

Correction factors were attributed to different stress distributions, according to Figure 1, for EP = epoxy, PU = polyurethane, and ADP = acrylic adhesives:

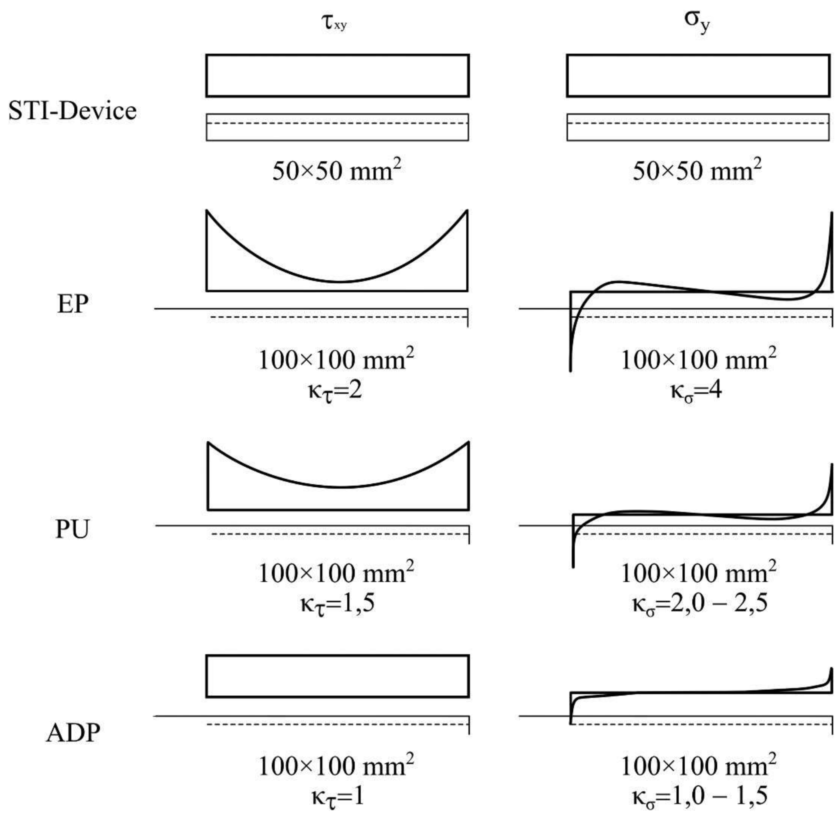


FIGURE 1 Stress distributions and associated correction factors.

These results demonstrate that for almost uniform stress distributions, as was the case with the soft acrylic adhesive, the size effect almost disappears, that is, the correction factors approach 1,0. For stress distributions exhibiting sharp peaks, however, in the epoxy case, the size effect is significant, that is, the strengths and corresponding correction factors are significantly increased.

References

[1] Keller, T., Vallée, T. Adhesively bonded lap joints from pultruded GFRP profiles. Part I: Stress-strain analysis and failure modes. *Composites Part B*. 2005, **36**(4), 331–340. Available from: https://doi.org/10.1016/j.compositesb.2004.11.001

[2] Vallée, T., Correia, J.R., Keller, T. Probabilistic strength prediction for double lap joints composed of pultruded GFRP profiles, Part I: Experimental and numerical investigations. *Composites Science and Technology*. 2006, **66**(13), 1889–1895. Available from: https://doi.org/10.1016/j.compscitech.2006.04.007

[3] Keller, T., Vallée, T. Adhesively bonded lap joints from pultruded GFRP profiles. Part II: joint strength prediction. *Composites Part B*. 2005, **36**(4), 341–350. Available from: https://doi.org/10.1016/j.compositesb.2004.11.002

[4] Vallée, T., Correia, J.R., Keller, T. Probabilistic strength prediction for double lap joints composed of pultruded GFRP profiles, Part II: Strength prediction. *Composites Science and Technology*. 2006, **66**(13), 1896–1902. Available from: https://doi.org/10.1016/j.compscitech.2006.04.001

[5] Vallée, T., Keller. T., Fourestey, G., Fournier, B., Correia, J.R. Adhesively bonded joints composed of pultruded adherends: considerations at the upper tail of material strength statistical distribution. *Probabilistic Engineering Mechanics*. 2009, **24**(3), 358–366. Available from: https://doi.org/10.1016/j.probengmech.2008.10.001

[6] Vallée, T. *Adhesively bonded lap joints of pultruded GFRP shapes*. PhD Thesis. École Polytechnique Fédérale de Lausanne, Lausanne, 2004. Available from: https://infoscience.epfl.ch/record/33437

[7] De Castro, J., Keller, T. Ductile double-lap joints from brittle GFRP laminates and ductile adhesives Part II: Numerical investigation and joint strength prediction. *Composites Part B*. 2008, **39**(2), 282–291. Available from: https://doi.org/10.1016/j.compositesb.2007.02.016

PRELIMINARY DESIGN

Background

Since the out-of-plane tensile (peeling) strength is often not yet known in preliminary design (prior to testing), in the case of fibre-tear failure, the tensile strength of the matrix can be assumed in a first approximation.

REPORT NUMBER	BR_12.4.5.3_PAR_6
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.5.3 Design based on stress analysis
PARAGRAPH	(6)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT (6) Results obtained from stress analysis shall be validated by tests. The failure mode obtained from tests and stress analysis, in particular, i.e. the depth of the failure plane and the adjacent materials, shall be identical.	

VALIDATION OF STRESS ANALYSIS RESULTS

Background

The in-plane shear and out-of-plane tensile stresses and the results of the failure criterion vary significantly across the joint thickness [1, 2]. It is thus essential that the predicted and experimentally obtained depths of the failure plane be identical and that the latter be located between the same materials.

References

[1] De Castro, J., Keller, T. Ductile double-lap joints from brittle GFRP laminates and ductile adhesives Part II: Numerical investigation and joint strength prediction. *Composites Part B*. 2008, **39**(2), 282–291. Available from: https://doi.org/10.1016/j.compositesb.2007.02.016

[2] Vallée, T., Correia, J.R., Keller, T. Probabilistic strength prediction for double lap joints composed of pultruded GFRP profiles, Part II: Strength prediction. *Composites Science and Technology*. 2006, **66**(13), 1896–1902. Available from: https://doi.org/10.1016/j.compscitech.2006.04.001

REPORT NUMBER	BR_12.4.5.4_PAR_1
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.5.4 Design based on fracture mechanics
PARAGRAPH	(1)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023

CONTENT

(1) A design based on fracture mechanics should be applied for crack initiation and may be based on the in Formula (12.47):

$$\left(\frac{G_{\mathrm{I,Ed}}}{G_{\mathrm{Ic,Rd}}}\right)^{m}+\left(\frac{G_{\mathrm{II,Ed}}}{G_{\mathrm{II}c,\mathrm{Rd}}}\right)^{n}\leq 1{,}0 \qquad (12.47)$$

where

$G_{\mathrm{I,Ed}}$, $G_{\mathrm{II,Ed}}$ are the design values of the strain energy release rate for crack initiation in Mode I and Mode II respectively, obtained from FEM;

m, n are exponents that depend on the actual connection configuration and are obtained from the fitting of theoretical and experimental results based on criterion (12.48) for crack initiation;

$G_{\mathrm{Ic,Rd}}$, $G_{\mathrm{IIc,Rd}}$ are the design values of the critical strain energy release rate for crack initiation in Mode I and Mode II respectively, given by Formula (12.48),

$$G_{ic,\mathrm{Rd}}=\frac{\eta_{\mathrm{c}}}{\gamma_{\mathrm{M,ac}}}\cdot G_{\mathrm{ic},k} \qquad (12.48)$$

where

i is Mode I or Mode II;

$\gamma_{\mathrm{M,ac}}$ is defined in Table 12.4 (NDP);

η_{c} is defined in 4.4.7 (corresponding to matrix-dominated composite properties (fibre-tear failure) or adhesive material, depending on the location of the failure plane);

$G_{ic,\mathrm{k}}$ are the characteristic values of the critical strain energy release rate for crack initiation, obtained from Mode I and Mode II standard fracture mechanics tests respectively, e.g. double cantilever beam (DCB, Mode I, ASTM D5528) and end-notched flexure specimen (ENF, Mode II, ASTM D7905/D7905M) can be used.

FRACTURE MECHANICS-BASED FAILURE CRITERION

Background

Fracture in adhesive joints and connections occurs in most cases under mixed-mode conditions, that is, under Mode I opening and Mode II shear loads.

An overview of different fracture mechanics-based mixed-mode failure criteria and further references are given in [1, 2]. The selection of the criterion, in a specific case, should be based on the best fit of the experimental data.

The simple power-law criterion shown in Formula 12.47 was applied in [2] for crack initiation and propagation (including fibre-bridging) and showed a good fit with the experimental results. It may thus be applied for adhesive joints and connections, particularly if they are composed of glass-composite pultruded adherends and epoxy adhesives and exhibit fibre-tear failure. The exponents