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

m and n are fitted to the experimental results; depending on their values, the criterion is either convex ($m = n < 1{,}0$), linear ($m = n = 1{,}0$) or concave ($m = n > 1{,}0$), as shown in Figure 1, where $\alpha = m$ and $\beta = n$ [1]:

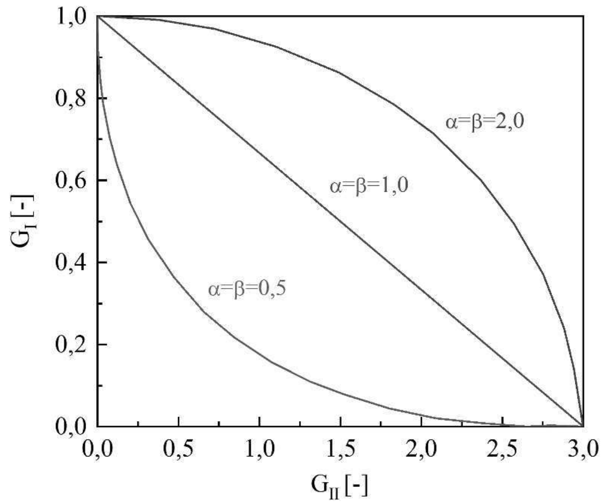

FIGURE 1 Mixed-mode failure criteria according to [1].

Further fracture mechanics-based failure criteria are applied in [2] (quadratic polynomial, Benzeggagh and Kenane, piecewise-linear) and compared to the power-law criterion. Figure 2 compares the polynomial and power-law criteria for crack initiation, G_{tip}, and propagation, G_{br}, the latter including fibre-bridging; the criteria compare well, and they are convex [2].

In addition, a polynomial failure criterion is used in [3] within a progressive damage model for adhesively bonded fibre-reinforced polymer joints.

The failure criterion of Formula 12.47 can be applied for crack initiation and crack propagation, including fibre-bridging contributions in the latter case; see Background Report BR_12.4.5.4_PAR_2.

The design values of the strain energy release rate for crack initiation in Mode I, $G_{I,Ed}$, and Mode II, $G_{II,Ed}$, can be obtained from FEM, see Background Report BR_12.4.5.4_PAR_3.

The characteristic values of the critical strain energy release rates under Mode I, $G_{Ic,k}$, and Mode II, $G_{IIc,k}$, loading can be obtained from standard fracture mechanics tests, for example, double

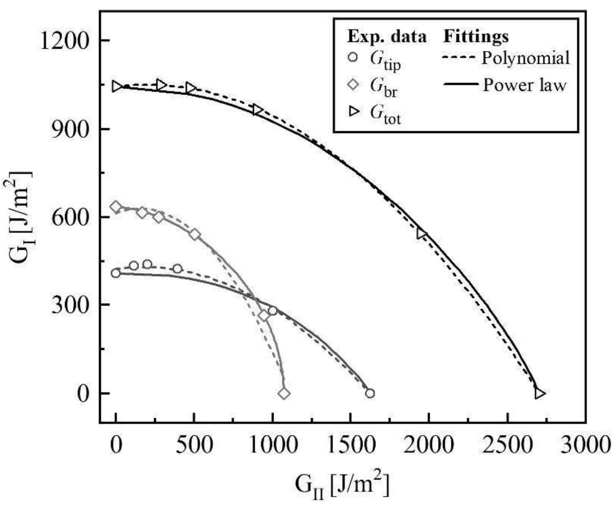

FIGURE 2 Separation of failure criterion into G_{tip} and G_{br} for crack propagation along Path II (data from [2]).

cantilever beam tests (DCB, Mode I, ASTM D5528-01), and end-notched flexure specimen tests (ENF, Mode II, ASTM D7905/D7905M-14); examples are given in [2]. The condition specified in 12.4.5.4(4) must however be fulfilled, see Background Report BR_12.4.5.4_PAR_4.

References

[1] Reeder, J.R. *An evaluation of mixed-mode delamination failure criteria*. NASA Technical Memorandum 104210, February, 1992. Available from: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19920009705.pdf

[2] Shahverdi, M., Vassilopoulos, A.P., Keller, T. Mixed-mode quasi-static failure criteria for adhesively-bonded pultruded GFRP joints. *Composites Part A*. 2014, **59**, 45–56. Available from: https://doi.org/10.1016/j.compositesa.2013.12.007

[3] Cameselle-Molares, A., Sarfaraz, R., Shahverdi, M., Keller, T., Vassilopoulos, A.P. Fracture mechanics-based progressive damage modeling of adhesively-bonded FRP joints. *Fatigue & Fracture of Engineering Materials & Structures*. 2017, **40**(12), 2183–2193. Available from: https://doi.org/10.1111/ffe.12647

REPORT NUMBER	BR_12.4.5.4_PAR_2
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.5.4 Design based on fracture mechanics
PARAGRAPH	(2)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023

CONTENT

(2) Formula (12.47) should be applied for crack initiation. In justified cases, it may also be applicable for stable crack propagation within a damage-tolerant design, e.g. to take the positive contribution of fibre-bridging into account. $G_{\mathrm{Ic,Rd}}$ and $G_{\mathrm{IIc,Rd}}$ are then the critical strain energy release rates for crack propagation.

NOTE: While the critical strain energy release rate for crack initiation can be considered as a material parameter, the critical strain energy release rate for crack propagation, i.e. the contribution of fibre-bridging, depends on the joint geometry and the stiffnesses of the adherends.

CRACK INITIATION VS. PROPAGATION

Background

In order to prevent crack initiation in the joint or connection, Formula (12.47) should be fulfilled for crack initiation. Crack initiation normally occurs below the peak load and the joint or connection resistance is thus underestimated in one-dimensional crack propagation [1]. In the case of two-dimensional crack propagation, however, the resistance can be largely underestimated if based on one-dimensional analysis [2].

In a damage-tolerant design, if stable crack propagation occurs (mostly in the post-peak phase), the possible beneficial contribution of fibre-bridging to the strain energy release rate can be considered, up to the critical strain energy release rate for crack propagation [1].

The critical strain energy release rate for crack initiation represents the energy released at the crack tip and can therefore be considered as a material parameter. The critical strain energy release rate for crack propagation includes, in addition to the initiation value, the energy released by fibre-bridging behind the crack tip. The latter, however, depends on the joint geometry and stiffness of the adherends, which influence the fibre-bridging length, through the crack opening angle and the curvature of the adherends [2, 3].

References

[1] Shahverdi, M., Vassilopoulos, A.P., Keller, T. Mixed-Mode I/II fracture behavior of asymmetric adhesively-bonded pultruded composite joints. *Engineering Fracture Mechanics*. 2014, **115**, 43–59. Available from: https://doi.org/10.1016/j.engfracmech.2013.11.014

[2] Cameselle-Molares, A., Vassilopoulos, A.P., Renart, J., Turon, A., Keller, T. Numerical simulation of two-dimensional in-plane crack propagation in FRP laminates. *Composite Structures*. 2018, **200**, 396–407. Available from: https://doi.org/10.1016/j.compstruct.2018.05.136

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REPORT NUMBER	BR_12.4.5.4_PAR_3
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.5.4 Design based on fracture mechanics
PARAGRAPH	(3)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT (3) To obtain $G_{I,Ed}$ and $G_{II,Rd}$ from FEM, the virtual crack closure technique (VCCT) or cohesive zone modelling (CZM) can be applied, the former for crack initiation and the latter for both crack initiation and propagation. NOTE: VCCT does not take fibre-bridging into account and its application is limited to linear-elastic fracture mechanics.	

DESIGN VALUES OF STRAIN ENERGY RELEASE RATE

Background

The virtual crack closure technique (VCCT) provides the fracture parameters at the crack tip, for example, the strain energy release rate, G_{tip}, also referred to as strain energy release rate at crack initiation, G_{ini}. The latter normally remains constant with increasing crack length [1] and cannot take into account the strain energy release rate contribution of fibre-bridging during crack propagation, G_{br}, for example, [1]. The use of the VCCT is limited to LEFM (linear-elastic fracture mechanics).

Cohesive zone modelling (CZM), however, can capture both the strain energy release rate at the crack tip, G_{tip} [2] and the strain energy release rate contribution of fibre-bridging during crack propagation, G_{br}, and thus the total strain energy release rate, $G_{tot} = G_{tip} + G_{br}$ [1, 2].

Summaries of these theories are provided in [1, 2], in addition to further references where more details can be found.

References

[1] Shahverdi, M., Vassilopoulos A.P., Keller, T. Modeling effects of asymmetry and fiber bridging on Mode I fracture behavior of bonded pultruded composite joints. *Engineering Fracture Mechanics*. 2013, **99**, 335–348. Available from: https://doi.org/10.1016/j.engfracmech.2013.02.001

[2] Cameselle-Molares, A., Vassilopoulos, A.P., Renart, J., Turon, A., Keller, T. Numerical simulation of two-dimensional in-plane crack propagation in FRP laminates. *Composite Structures*. 2018, **200**, 396–407. Available from: https://doi.org/10.1016/j.compstruct.2018.05.136

REPORT NUMBER	BR_12.4.5.4_PAR_4
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.4.5.4 Design based on fracture mechanics
PARAGRAPH	(4)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT	
(4) The failure modes of the actual connection and the fracture mechanics specimens shall be identical and verified by testing, i.e. the failure plane shall be located between or within the same materials.	

CONDITIONS CONCERNING FAILURE MODES

Background

The strain energy release rate depends on the material in which the crack propagates [1–3]. It is thus essential that the failure modes of the actual joint or connection and the fracture mechanics specimens are identical, that is, the failure planes are in, or between, the same materials and the fracture surfaces are similar.

References

[1] Shahverdi, M., Vassilopoulos, A.P., Keller, T. A phenomenological analysis of Mode I fracture of adhesively-bonded pultruded GFRP joints. *Engineering Fracture Mechanics*. 2011, **78**(10), 2161–2173. Available from: https://doi.org/10.1016/j.engfracmech.2011.04.007

[2] Shahverdi, M., Vassilopoulos, A.P., Keller, T. Modeling effects of asymmetry and fiber bridging on Mode I fracture behavior of bonded pultruded composite joints. *Engineering Fracture Mechanics*. 2013, **99**, 335–348. Available from: https://doi.org/10.1016/j.engfracmech.2013.02.001

[3] Shahverdi, M., Vassilopoulos, A.P., Keller, T. Mixed-mode quasi-static failure criteria for adhesively-bonded pultruded GFRP joints. *Composites Part A*. 2014, **59**, 45–56. Available from: https://doi.org/10.1016/j.compositesa.2013.12.007

REPORT NUMBER	BR_12.5.1_PAR_1-2
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.5.1 General
PARAGRAPH	(1)-(2)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT (1) The resistances of the adhesive bond and bolting should not be summed in hybrid, i.e. combined, adhesive-bolted joints and connections. (2) In the case of flexible adhesives, the resistances of the adhesive bond and bolting may be summed, if confirmed by testing.	

RESISTANCE OF HYBRID JOINTS

Background

The high stiffness of the adhesive bond does not normally allow the bearing mechanism of the bolts to be significantly activated unless flexible adhesives are used and the bolt clearance is reduced to a minimum [1, 2].

Figure 1 (left) shows the behaviour of a hybrid basalt-composite double-lap joint comprising a stiff epoxy adhesive (H), compared to the corresponding bolted (B) and adhesive (A) joints of the same geometries and materials [2]. The hybrid and adhesive joints failed before the clearance of the bolted joint was compensated. After the adhesive bond failure in the hybrid joint, its bolted connection was activated and it exhibited a similar response to that of the bolted joint. The resistances of the bolted and adhesive connections cannot therefore be summed in the hybrid joint if a stiff adhesive is used.

Figure 1 (right) shows the same three joint configurations, this time in the case of a flexible acrylic adhesive. The ultimate deformation capacity of the bonded joint was much larger than the

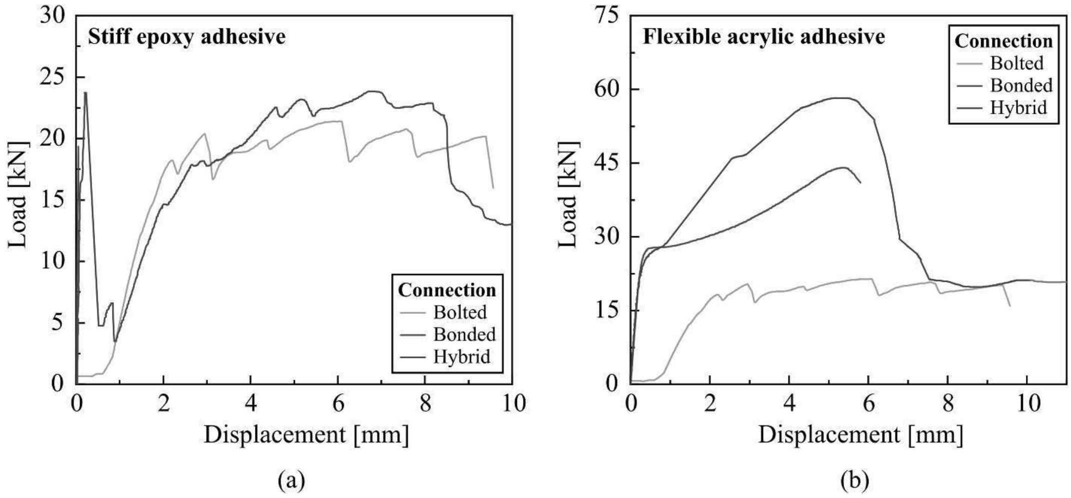

FIGURE 1 Load-displacement responses of bolted (B), bonded (A) and hybrid (H) joints with stiff (left) and flexible (right) adhesive, in [2]

clearance of the bolted joint. Accordingly, the hybrid joint resistance increased significantly and, on average, corresponded to the sum of the bolted and bonded joint resistances. The resistances of the bolted and adhesive connections can therefore be summed in hybrid joints if a sufficiently flexible adhesive is used [2].

References

[1] Hart-Smith, L.J. Bonded-bolted composite joints. *Journal of Aircraft*. 1985, **22**(11), 993–1000. Available from: https://doi.org/10.2514/3.45237
[2] Liu, L., Wang, X., Wu, Z., Keller, T. Resistance and ductility of FRP composite hybrid joints. *Composite Structures*. 2020, **255**. Available from: https://doi.org/10.1016/j.compstruct.2020.113001

REPORT NUMBER	BR_12.5.1_PAR_3
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.5.1 General
PARAGRAPH	(3)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT (3) The possible positive effect of pre-tensioned bolting on the stress distribution in the adhesive layer shall not be considered in the design of hybrid joints and connections.	

EFFECTS OF PRE-TENSIONED BOLTS

Background

The positive effect of bolt pre-tensioning, that is, the suppression of through-thickness tensile (peeling) stresses and the associated increase of the joint or connection resistance, is normally lost through creep of the adherends' matrix, after a relatively short time period. The positive effect of bolt pre-tensioning shall thus not be considered in the design of permanent composite structures.

REPORT NUMBER	BR_12.5.1_PAR_4
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.5.1 General
PARAGRAPH	(4)
AUTHOR(S)	Thomas Keller
REVIEWER(S)	Reza Haghani Dogaheh, Marko Pavlović, José Sena-Cruz
DATE	15 September 2023
CONTENT (4) Bolting may be used as a back-up system in adhesive joints and connections to maintain the fail-safe condition.	

BOLTS AS BACK-UP SYSTEM

Background

To fulfil the fail-safe condition of 12.4.2(1), back-up bolts may be used to prevent structural collapse in the case of adhesive connection failure [1]; an example is shown in [2].

References

[1] Liu, L., Wang, X., Wu, Z., Keller, T. Resistance and ductility of FRP composite hybrid joints. *Composite Structures*. 2020, **255**. Available from: https://doi.org/10.1016/j.compstruct.2020.113001

[2] Keller, T., Theodorou, N.A., Vassilopoulos, A.P., De Castro, J. Efefect 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_12.5.1_PAR_5
CLAUSE / ANNEX	12. CONNECTIONS AND JOINTS
SUBCLAUSE	12.5.1 General
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 a sudden adhesive bond failure, the possible dynamic amplification of the static action should be considered in the design of a bolted back-up system. The dynamic amplification effect can be determined by testing.	

DYNAMIC AMPLIFICATION IN CASE OF SUDDEN BOND FAILURE

Background

The static load transferred by the adhesive bond may be significantly increased by dynamic effects in the case of sudden and brittle adhesive bond failure. Since there are as yet no models to capture this effect, the design should be based on testing.