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Preparation of a Resistance Formula for Net-Tension Failure of Single and Multi-rowed Bolted Connections of Fibre-Polymer Composite

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ABSTRACT

Presented in this paper is a semi-empirical formula to determine net-tension strengths of single and multi-rowed bolted connections of fibre-polymer composite laminates, when 'double-lap shear joints' are subjected to tension action. This formula, with two tables of stress concentrations for nine different bolted connection configurations and two material orientations are in provisions for the design of net-tension failure in FprCEN/TS 19101, which is the CEN Technical Specification (TS) for the *Design of Fibre-Polymer Composite Structures*. A TS is the output from Stage 2 of 3 to having a structural Eurocode. The scope of bolted configurations in the TS is from a single bolt or single row of bolts to a maximum of four bolt rows having four bolts per row. To develop how the formula is used this paper reproduces a net-tension failure paragraph from the TS (is Appendix I) and presents the analysis of test results that establishes 'stress concentration factors' for different single and multi-rowed bolted configurations having pultruded laminates oriented in the x direction to the tension load. Several features from the net-tension failure provisions in the TS are introduced to emphasis the design approach when materials are of fibre-polymer composites.

INTRODUCTION

To have knowledge and understanding on why fibre-polymer composites are or should be considered as conventional structural materials you are directed to consult the guidance in [1], with particular emphasis to reading Chapters 1 to 3 on bridge engineering, and Chapter 8 on sustainability (for why these structures offer 'positive-choices' in whole life cycle analyses). We have, since the 1990s referred to laminated composites with a polymer-based matrix by the abbreviation 'FRP', for 'Fibre Reinforced Polymer'. During the drafting of the European Technical Specification (TS) [2] a decision was made by the Project Team neither to use the terminology 'Fibre Reinforced Polymer' nor its abbreviation, and instead, in [2], these structural materials are referred to as 'fibre-polymer composites'. The author is a member of both CEN/TC 250 Working Group 4 (*Fibre-reinforced Polymer Structures*), and of the WG4 Project Team (WG4.T2) that together prepared the TS for the *Design of Fibre-Polymer Composite Structures*. In this paper TS is used as the abbreviation for FprCEN/TS 19101 [2], the version before the Fromal Vote in 2022. The TS is the deliverable of Stage 2 of 3 towards us having a structural Eurocode, and it should be published by February 2023. This important milestone, together with '300' pages for a collection of 17 worked examples and '1000' pages for a Commentary [3], will enable stakeholders to practice designs for both permanent and temporary structures of fibre-polymer composites. Later, after a consultation period and by way of a critical evaluation of these activities, the Stage 3 work will be to prepare the Eurocode part itself. This paper is offering a taster to the TS and its background commentary, that is further supported by the worked examples.

To provide a sound background to the design approach developed herein we start by introducing how the Stage 1 report [4] (which is known as '*The Prospect*'), scopes the determination of resistances of bolted connections when the failure mode is net-tension across the width of fibre-polymer composite materials. Fig. 1 is for two images of pultruded flat plates from testing double-lap shear (plate-to-plate) joints having two rows of two M10 steel bolts. In the images it is observed by the fracture paths that these joints had their resistances governed by the net-tension mode of failure. The testing arrangement used by Lutz [5] is of double lap-shear (see Fig. 2) with the pultruded material sandwiched between two steel plates; there was no clearance hole with M10 steel bolting and bolt tightening was relatively low.

A design procedure for resistance when the mode of failure is net-tension is required in design situations where a thin-walled plate (of fibre-polymer composite) is connected by bolting to another component or two components, such that we have the ‘double-lap shear’ joint arrangement. By this we mean that there is a relatively low moment within the plate (with the bolting) owing to the inherent eccentricity in the load path of the joint’s connection force, which is tensile. The other component or components can be of any structural material, providing their flexural stiffness(es) is(are) adequate to resist bending deformations owing to the moment generated by inherent load eccentricity. Note that if the bolted joint comprises of two thin-walled plate components then this is for the ‘single-lap shear’ joint configuration [1], and the net-tension design procedure requires a reduction factor to account for the reduced connection resistance owing to the presence of a relatively higher moment in the bolted connection/joint. Examples in practice of where double- and single-lap shear bolted connections/joints are found are in gusset plates, splice connections and bracing connections. In fact, all bolted connections that are to resist a tensile force will need to be checked by a design procedure for the net-tension mode of failure. Although plate widths in practice are not necessarily constant the design procedure is valid because we know the width dimension at the level of the first row of bolts, where net-tension failure occurs.

For single bolted, multi-bolted (single row) and multi-rowed bolted joints the design value of the net-tension strength, $N_{\mathrm{nt,Rd}}$, can be defined by the formula (refer to Formula (12.4) in **Appendix I**):

$$N_{\mathrm{nt,Rd}} = \frac{1}{k_{\mathrm{tc}}}\left(w - n_{\mathrm{b,1}} \times d_0\right) \times t \times f_{\mathrm{t,d}} \qquad (1)$$

where: w is the width of the plate (of constant thickness); $n_{\mathrm{b,1}}$ is the number of bolts across the first bolt row (maximum is four) where the net-tension failure mode occurs (see Fig. 1); d_0 is the nominal bolt hole diameter (*not bolt diameter*); t is the laminate thickness; and $f_{\mathrm{t,d}}$ is the appropriate design value of the tensile strength of the material (i.e. the fibre-polymer composite), which is $f_{\mathrm{t,x,d}}$ when the laminate orientation is for the x direction.

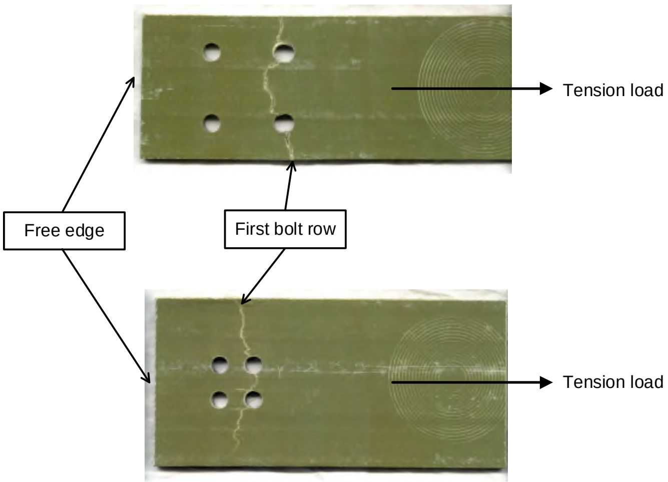

Figure 1. Two examples of 2x2 bolted connections that failed in net-tension at the first bolt row; test results from [4] (*note that the lower configuration has bolt spacings that are not permitted by the provisions in TS* [2]).

Equ. (1) is also Formula (8.3a) in ‘*The Prospect*’ [4] for x direction laminates. Variable k_{tc} in the formula is the ‘stress concentration factor’, which in [4] is assumed to be a constant equal to 3,75 (*as per Eurocode convention a comma is used for decimal place*). This ‘stress concentration factor’ variable is not for the peak stress in the tensile stress profile across the width of the plate that passes through the centre of the bolting at the first row. Rather it represents the differences in tensile strengths between material strengths of the net cross-sectional area and the actual strengths of bolted connections that fail with the net-tension mode of failure. It is observed that the term $(w - n_{\mathrm{b,1}} \cdot d_0) \cdot t$ in Equ. (1) is for the net cross-sectional area of the plate, accounting for a reduction in cross-sectional area owing to bolt holes (and for the examples in Fig. 1 integer variable $n_{\mathrm{b,1}} = 2$). Although ‘*The Prospect*’ design procedure is simple and pragmatic [4] the WG4 Project Team recognises that its weakness is having a constant k_{tc} equal to 3,75, which is for an overall reduction factor on strength of around five. This means that for every bolted connection configuration the initial (unfactored) strength is around 20% of the design value of the material’s tensile strength based on net cross-sectional area. How $N_{\mathrm{nt,Rd}}$, in Equ. (1) is also established to account for material uncertainties and long-term (durability) effects will be introduced later when the procedure for specifying $f_{t,d}$ is presented.

NET-TENSION FAILURE IN THE TECHNICAL SPECIFICATION [2]

Section 12 of the TS is for *Connections and Joints,* and sub-clause 12.2.3.1 *Net-tension failure* is to determine the net-tension resistances for bolted connections/joints of laminates that satisfy relevant requirements, several of which are not presented herein because of the limited space. Two of these requirements are that the steel bolts are to be of a constant diameter, d, and that there cannot be more than four bolt rows. **Appendix I** in this paper reproduces paragraph 12.2.3.1(1) that is to determine net-tension resistances when the tension force, N_{Ed}, (see Fig. 2) is oriented between 0 and 5^{o} to the x direction of fibre-polymer composite plates [1-3]. Note that all references herein to formulae, figures and tables prefixed with the number 12 are to be found in **Appendix I**. A multi-bolted situation having two rows and two columns (for a 2x2 configuration) is drawn in Fig. 12.3, with actual net-tension fractures shown in Fig. 1. For the multi-row case the first row of bolts is the furthest in distance from the free edge perpendicular to the direction of N_{Ed}. For design strengths determined by 12.2.3.1(1) to be valid the bolted connection configurations must be: of pultruded laminates with glass fibre reinforcement; of constant thickness; and with symmetry of the bolted connection geometry in the in-plane geometry.

References [4-11] give specific technical information and/or physical test results from which 12.2.3.1(1) was prepared. Figs. 12.2 and 12.3 (see **Appendix I**) illustrate two situations for net-tension failure at the first row of bolting. The situation of a single bolt row (illustrated by the single bolt configuration) is shown in Fig. 12.2. In this figure the orientation of the principal direction of the laminate is defined in terms of the angle θ to the direction of loading. For net-tension strengths to be based on the design value of the tensile strength of material in the x direction, which is $f_{t,d}$ in Equ. (1) or $f_{x,t,d}$ in Equ. (12.4) of **Appendix I**, the direction of the loading must be oriented within 5^{o} of the pultrusion's x (or longitudinal) direction [1]. It is observed that Equ. (12.4) is a specific case of Equ. (1) for x direction material, and that in the TS [2] the key revision and maturity from sub-clause in the '*The Prospect*' [4] is to have lower values of k_{tc} for different bolted connection configurations. The following presentation is for how Table 12.2 was established using a semi-empirical methodology. It lists k_{tc}s for nine bolted connection configurations, with staggered bolt arrangements permitted. Fig. 2 illustrates a double-lap bolted joint with symbols for staggered bolts. Table 1 reports experimental-derived stress concentration factors (for k_{tc}) from joint testing (often with only one (the middle) of the three plates in the double-lap shear joint specimens of pultruded material; the other two are of steel). The table scopes nine different single-bolted and multi-bolted connection configurations. Tabulated results in the evaluation for k_{tc}s are for configurations that closely satisfy the connection geometries specified in Table 11.1 (with symbols in Fig. 2) of 11.4(2) in the TS [2], and for completeness Table 11.1 is reproduced below. This restriction on valid geometries means that several test results from several of the sources [5] to [11] reporting net-tension strengths of bolted connections had to be ignored.

Table 1. Determination of the range of stress concentration factors from physical testing of plate-to-plate bolted connections with pultruded material with x direction orientation.

Bolt configuration	Rosner [6][1] or Hassan [7][1]	Lutz [5][1] or Wang [8] or Turvey [9]	Prabhakaran Razzaq & Devara [10]	Matharu [11]	k_{tc} in Formula (12.4)
(1)	(2)	(3)	(4)	(5)	(6)
Single	1,0-1,6	1,5-1,6[1]; 1,5			2,0
1x2 (single row)	0,9-2,0	1,3-2,3; 1,6-2,2		1,5-1,8	2,5
2x1 (single column)	1,0-1,9	1,3-2,2	1,7	1,7	2,5
1x3	1,1-2,0				2,5
3x1	1,4-2,4				2,5
2x2	1,0-1,6	1,3-1,9; 1,4-2,1	1,8	1,2-1,3	2,0
3x3		1,2-1,4			1,5
1x1 (staggered)				1,9	2,0
2x2 (staggered)			2,1; 1,8; 2,1		2,0

Notes: 1. Width only $3d$ when geometry requirements specify minimum of $4d$.

In Table 1 the stress concentration factors (k_{tc}s) were established as followed. Determined in Step 1 is the tensile strength using Formula (12.4) with x direction material strength after setting k_{tc} = 1,0. The 'mean' x direction tensile strength of the pultruded material is taken from the sources ([5] to [11]). This calculation is for material strength based on net cross-sectional area of the joint. To calculate k_{tc} in Step 2 we divide the tensile strength calculated in Step 1 by the mean test net-tension strength taken directly from the source (which is a value determined from test results for one to five nominally identical specimens per batch).

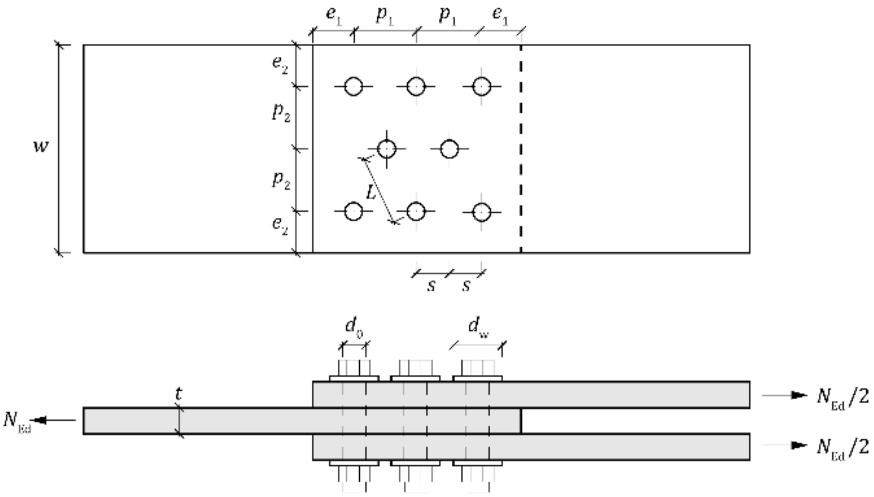

Figure 2. Double-lap bolted joint with symbols for staggered bolts (is Figure 11.3 in *TS* [2]).

Table 11.1. Minimum requirements for bolted connection geometries (reproduced from [2]).

Nominal bolt diameter (d) (recommended range)	$d \geq t_{min}$ ($t_{min} \leq d \leq 1,5\ t_{min}$)
Nominal bolt hole clearance	$d_0 - d \geq 1$ mm
Distances between holes without staggered bolts	$p_1 \geq 4d$; $p_2 \geq 4d$
Distances between holes with staggered bolts	$p_1 \geq 4d$; $p_2 \geq 2d$; $L \geq 2,8d$
Distances from edges single row multi-rows	side $e_2 \geq 2d$ end $e_1 \geq 2,5d$ or ≥ 30mm end $e_1 \geq 2d$

Column (1) in Table 1 gives the bolted connection configurations that have been scoped by one or more of the sources ([5] to [11]) offering relevant net-tension strength test results and material tensile strengths (as mean values). There can be one or more of the geometrical variables in a test programme that are not exactly aligned to what is specified in sub-clause 11.4 (and Table 11.1) or Section 12 of the TS. Engineering judgement was employed by the WG4 Project Team to decide which test results are valid and reliable. Columns (2) to (5) in Table 1 reports the range of k_{tc}s obtained from using the test results. Using the data in Columns (2) to (5) leads to specifying in Column (6) a limited number of different k_{tc}s that are used to prepare Table 12.2, which accompanies resistance Formula (12.4) in paragraph 12.2.3.1(1). These k_{tc}s are << 3,75, and are in increments of 0,5, with the lowest at 1,5 and the highest at 2,5. It is observed that the k_{tc} in Column (6) is often higher than the tabulated maxima in the same row in Columns 2 to 5. These observations on the semi-empirical values for k_{tc} presented in Table 1 support the WG4 Project Team proposing that for other bolted connection configurations where there are no test results, such as, for example, 4x4 bolting, k_{tc} can be constant and equal to 3,0 (< 3,75). This is for the maximum k_{tc} used in Formula (12.4) and is for the minimum reduction in the stress concentration factor of 20% had the constant value of 3,75 from '*The Prospect*' [4] continued as k_{tc} into the TS provisions for the net-tension mode of failure [2].

Formula (12.5) in **Appendix I** is used to establish the design value of the tensile strength of the material, $f_{x,t,d}$, and is for tension loading in the x direction of the pultruded laminates. It is founded on the characteristic value of the tensile strength of the material, $f_{x,t,k}$, which can be determined using test standard EN ISO 527 [12] and the data reduction procedure in prEN 1990, Annex D [13]. To calculate $f_{x,t,d}$ the characteristic strength, $f_{x,t,k}$, is factored by multiplying its value by a conversion factor η_c (≤ 1,0) and dividing it by the product of a partial factor for a material, γ_m, (probably < 1,30) and a partial factor for resistance model, γ_{Rd}. To account for durability effects η_c is the product of a conversion factor for temperature and a conversion factor for moisture, with provisions in sub-clause 4.4.7 of the TS. Provisions for the two partial factors γ_m and γ_{Rd} are given in sub-clauses 4.4.5 and 4.4.6 of the TS.

Because the test results from references [6], [7] and [11] were considered complete and the most reliable they were used to calibrate partial factors of resistance for the net-tension mode of failure. γ_{Rd} = 1,5 in Formula (12.4) was obtained from a calibration exercise using the methodology in ISO 2394, Annex C, Section C.6 and prEN 1990, Annex D [12]. To determine the partial factor for resistance model the procedure employed by the WG4 Project Team is presented in references [14] and [15] for the failure mode of global buckling of pultruded thin-walled profiles. For the specific case of net-tension failure there is commentary on the equivalent procedure in background report BR_4.4.6_PAR_3 (in [3]) to why the preliminary adopted value for γ_{Rd} is 1,5 (for x direction pultruded material the calibrated γ_{Rd} is 1,42 using 145 data points). Future characterization work will determine material strengths and strengths of bolted connections failing in net-tension, and new validation/calibration exercises with more test results in the reliability analyses [12, 14, 15] will either confirm γ_{Rd} = 1,5 or update its value.

Using a different approach in [16], to establish the variation in k_{tc} that is required to determine the net-tension resistances in multi-bolted and multi-rowed bolted connections the author finds that a value of k_{tc} = 3,75 in Formula (12.4) will be very acceptable for every conceivable bolted connection configuration that satisfies the design requirements in the TS [2]. This observation for pultruded laminates provides the designer with the most conservative design approach should they prefer to use a single '*upper-limit*' constant for k_{tc} (equal to 3,75) in Formula (12.4) of sub-clause 12.2.3.1.

12.2.3.1 comprises five paragraphs with paragraph 12.2.3.1(2) for when the net-tension force is oriented at angles $\pm 5^o < \theta \leq \pm 90^o$ to the x direction. The changes to Formula (12.4) are to have different k_{tc}s (now in Table 12.3) for the same nine bolted connection configurations as in Table 12.2, and the design value of tensile strength of material is in the y direction, $f_{y,t,d}$. γ_{Rd} is again taken to be 1,5, with the calibrated value at 1,54, using 93 data points (see BR_4.4.6_PAR_3 in [3])). Note that the higher x direction (or 0^o) design tensile strength of material, $f_{x,t,d}$, only governs for a 10^o arc of N_{Ed} orientations in 180^o. Paragraph 12.2.3.1(3) extends the provisions to fibre-polymer composites having balanced symmetrical laminations and glass fibre reinforcements. Testing or numerical modelling is recommended in 12.2.3.1(4) for laminates having fibres that are not glass (can be of carbon, aramid and basalt), and 12.3.2.1(5) accommodates situations when a plate is not of constant thickness across the width, *w*, and has, for example, a plate element of the same fibre-polymer composite that is perpendicular to the plane of the plate with the bolting (as can be found when using a leg-angle section for a bracing element). Because of space limitation paragraphs 12.2.3.1(2)-(5) are not reproduced in **Appendix I**.

CONCLUDING REMARKS

A semi-empirical formula can be employed to determine the design values for net-tension failure strengths of bolted connections of fibre-polymer composites. In its simplest form this formula has a constant 'stress concentration factor' (can be 3,75) to account for the strength reduction with bolting from the material's tension strength of the net cross-sectional area (without bolting) of the plate component. This pragmatic approach was proposed in '*The Prospect'*, which is the Stage 1 of 3 outcome towards us having a structural Eurocode for the *Design of Fibre-Polymer Composite Structures*. For Stage 2 the Technical Specification FprCEN/TS 19101 has been drafted, and the project work for this deliverable required the provisions in '*The Prospect*' to be critically evaluated, revised and/or matured. One important revision, which is presented in this paper, has been to replace in the resistance formula the constant, and relatively high 'stress concentration factor' value of 3,75 with lower values of 1,5, 2,0 or 2,5 and 3,0 that scope different bolted connection configurations. This maturity makes the design procedure more applicable, not least because it can save on fibre-polymer composite weight in joint details. This paper provides a taster on how a design provision in the Technical Specification is set-out and how the design value of tensile strength of the material is established from the characteristic tensile strength, a conversion factor linked to durability (for temperature and moisture effects), and two partial factors for a material and resistance due to the net-tension mode of failure.

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APPENDIX I. PARAGRAPH 12.2.3.1(1) NET-TENSION FAILURE

1) When the net-tension force is oriented at an angle $0^{o} \leq \theta \leq \pm 5^{o}$ to the x direction of pultruded profiles or pultruded flat laminates of constant thickness (see Figures 12.2 and 12.3), its design value, N_{Ed}, for net-tension failure should satisfy the condition in Formula (12.3):

$$N_{\mathrm{Ed}} \leq N_{\mathrm{x,nt,RD}} \qquad (12.3)$$

where

$N_{\mathrm{x,nt,Rd}}$ is the design value of the net-tension resistance in the x direction, given by Formula (12.4),

$$N_{\mathrm{nt,Rd}} = \frac{1}{k_{\mathrm{tc}}}\left(w - n_{\mathrm{b,1}} \times d_0\right) \times t \times f_{\mathrm{x,t,d}} \qquad (12.4)$$

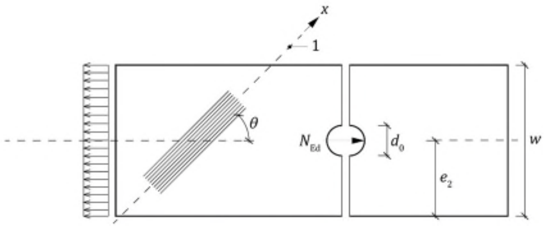
where

w	is the width of the component ($w \geq 4\ d$, from Table 11.1), see also 12.2.3.1(5);
$n_{\mathrm{b,1}}$	is the number of bolts across the first bolt row (Row 1) where the net-tension failure mode occurs (see Figures 12.2 and 12.3);
d_0	is the nominal bolt hole diameter;
t	is the laminate thickness;
k_{tc}	is a stress concentration factor that should be taken from Table 12.2 for specified bolted connection configurations that satisfy the geometry requirements in Table 11.1; for other bolted connection configurations, k_{tc} should be taken equal to 3,0;
$f_{\mathrm{x,t,d}}$	is the design value of the tensile strength of the pultruded laminate in the x direction, given by Formula (12.5),

$$f_{\mathrm{x,t,d}} = \frac{\eta_{\mathrm{c}}}{\gamma_{\mathrm{m}} \cdot \gamma_{\mathrm{Rd}}} f_{\mathrm{x,t,k}} \qquad (12.5)$$

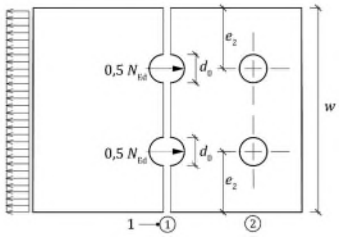
where

γ_{m}	is defined in 4.4.5 (corresponding to $f_{\mathrm{x,t,k}}$);
γ_{Rd}	is defined in 4.4.6 (Table 4.5, Net-tension failure);
η_{c}	is defined in 4.4.7 (corresponding to $f_{\mathrm{x,t,k}}$);
$f_{\mathrm{x,t,k}}$	is the characteristic value of the tensile strength of the pultruded laminate material in the x direction.



Key
1 Principal direction of laminate or direction of pultrusion

Figure 12.2 – Net-tension failure mode illustrated with a single bolt, $n_{\mathrm{b,1}} = 1$



Key
1 Row No. (*i*)

Figure 12.3 – Net-tension failure mode illustrated with a 2×2 multi-bolted connection, $n_{\mathrm{b,1}} = 2$

Table 12.2 — Values of stress concentration factor k_{tc} for specified bolted connection configurations when N_{Ed} is oriented with an angle $0^{\circ} \leq \theta \leq \pm 5^{\circ}$ to the major principal axis (x direction) of pultruded laminates with glass fibre reinforcement

Bolted connection configuration	k_{tc}
Single	2,0
1×2 (single row)	2,5
2×1 (single column)	2,5
1×3	2,5
3×1	2,5
2×2	2,0
3×3	1,5
1×1 (staggered)	2,0
2×2 (staggered)	2,0

NOTE: For staggered bolted configurations there is one bolt per bolt row. Configuration 1×1 (staggered) means there is a total of two bolts and two bolt rows, with distance between holes $L > 2{,}8$.