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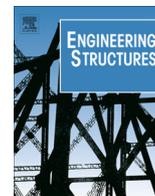
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Plain and threaded bearing strengths for the design of bolted connections with pultruded FRP material



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ABSTRACT

Presented are results from testing 28 batches of 5 or 10 nominally identical specimens to characterise the laterally unrestrained pin-bearing strength when bolting is with and without thread. For the test series flange material is taken from a 254x254x9.53 mm Pultex[®] SuperStructural 1525 series shape. Strengths are measured with the Fibre Reinforced Polymer (FRP) material oriented at either 0° or 90° to the direction of pultrusion. Four steel bolt sizes of M10, M12, M16 and M20 are used, and when threaded there are different standard teeth (pitch) geometries. To remove this variable in a comparison with plain pin strengths a unique test series of 12 batches was carried out with three non-standard thread profiles. The effect on pin-bearing strength of having a threaded bolt is evaluated using mean and characteristic strengths, the latter determined in accordance with EN 1990. A key finding is that the proposed reduction factor of 0.6 in a forthcoming American LRFD standard to calculate a thread characteristic strength from the plain value is acceptable. Other findings are important to the determination of pin-bearing strength, and to us having knowledge and understanding to prepare a universal design procedure for resistances in bolted connections when the mode of failure is bearing.

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1. Introduction

Pultrusion is a composite material processing method that produces continuous thin-walled sections of Fibre Reinforced Polymer (FRP) material [1,2]. Standard structural shapes mimic steel sections (I, H, box, leg-angle, etc.), and are used in civil engineering works to construct, for example, non-sway braced frame structures [3]. Members can be connected together by conventional stainless steel bolting [1–6]. These connections provide ease of assembly and low long-term maintenance, as well as being immediately capable of transferring the actions experienced in primary load bearing joints. Safe and reliable design of bolted connections with Pultruded FRP (PFRP) is critical to ensuring sound structural performance, and will involve a fundamental understanding of failure modes [6,7]. Due to the orthotropic and layered nature of PFRP laminates these failure modes can vary significantly [7]. Both damage and mode of failure at ultimate failure (for Ultimate Limit State design [6]) are dependent on connection detailing [6], material and fastener specifications, such as geometry, fibre reinforcement architecture, bolt type, clearance hole size, bolt loading, bolt

tightening, etc. It is known [7] that bearing failure (for localised compression failure in the laminate adjacent to the bearing steel bolt), is one of the distinct failure modes observed in failed PFRP bolted connections [6,7]. This failure mechanism is preferred in design owing to its potential to give a progressive pseudo-ductile response [8]. Other distinct failure modes, including net-tension, cleavage and shear-out, are avoided, if practical, since they will be more likely to yield catastrophically without a level of beneficial damage tolerance [8]. Beneficial damage tolerance is when the FRP experiences noticeable material failure without ultimate failure. The bolted connection continues to have an acceptable resistance to what the strength was prior to material damage being present.

Design and verification of details for bolted connections in PFRP frames is a complex exercise that had, in 2009, considerable gaps in knowledge [9]. One key knowledge gap is that designers/fabricators in America [1,2] will allow bolt thread to be in bearing. The effect this design detail has on bearing strength of bolted connection with PFRP structural shapes, if any, is unknown. Furthermore, any relationship between the pin-bearing value, when there is a smooth bolt shank in bearing, and a threaded bearing value has yet to be established. By definition the pin-bearing strength is for the condition where there is no lateral restraint

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due to tightening of the bolting. Although the term ‘pin-bearing’ should be limited to the situation of a smooth bolt shank in bearing, it will also be used in this paper for the threaded situation since measurement of this bearing strength is made without lateral restraint.

Previous studies using double lap-joints or coupon specimens have reported pin-bearing strengths for as-received materials when testing with a plain smooth steel pin [10–15]. The specific topic for this new contribution to knowledge and understanding is to make a comparison between measured pin-bearing strengths with [6] and without [12,14] bolt thread present.

2. Pin-bearing strength

Laterally unrestrained pin-bearing failure involves the onset of delamination fractures and crushing of the PFRP material directly beneath the contacting bolt. Empirical studies [7,8] have shown that the strength and response of bolted connections failing in bearing (pin or otherwise) are sensitive to bolt diameter, material thickness, fibre orientation and architecture, clearance hole size and environmental conditioning. In addition, when lateral restraint is applied through bolt torque, a significantly higher bearing strength is found [6,10]. This is due to a stiffness restraint that opposes inherent through-thickness deformation from the Poisson’s ratio effect. It is the localised ‘bulging’ form of deformations that creates a localised tensile through-thickness stress field that eventually initiate delamination fractures between the PFRP layers, which is for ultimate failure [16]. It can be difficult to fully account for all practical influences on bearing strength in assembled bolted connections, especially since viscoelastic (creep) relaxation [14] will significantly reduce bolt tension over the design working life, which may be 50 years, if not higher.

In preparing an American Load and Resistance Factor Design (LRFD) pre-standard [6] for the design of frames with PFRP structural shapes, it was agreed by the drafting team that the (plain) pin-bearing strength (where there is no lateral restraint or clamping force) was to be the mandatory bearing strength per bolt in design calculations for the bearing resistance (R_{br}) [6]. The strength formulae for this distinct failure mode is

$$R_{br} = tdF_{\theta}^{br} \quad (1)$$

Eq. (1) requires the specific pin-bearing strength (F_{θ}^{br}) that is measured with respect to the direction of pultrusion. The orientation θ is 0° (for longitudinal or lengthwise) when the connection force is parallel to the direction of pultrusion and it is 90° (for transverse or cross-wise) when orthogonal. The projected area for bearing is given by the thickness of the material (t) multiplied by the diameter of the bolt or pin (d). To use Eq. (1) requires its own ‘unique’ strength property (F_{θ}^{br}), and strength characterisation is acquired through back-calculation using test results obtained from having used, for example, the test methodology presented in Section 3 [10–15]. Ref. [6] provides guidance on how to determine F_{θ}^{br} by applying American Society of Testing and Materials (ASTM) standards. The 0° pin-bearing strength (F_{0}^{br}) is to be used in Eq. (1) for a connection force having an orientation of between 0° and 5° relative to the direction of pultrusion. For all other resultant orientations of the bolt bearing force from $>5^{\circ}$ to 90° the 90° pin-bearing strength (F_{90}^{br}) is chosen in design calculations [6]. To use Eq. (1) to calculate the connection strength for the bearing failure mode when thread is present the LRFD standard will specify a reduction factor to the characteristic value of F_{θ}^{br} , which is for the situation of a plain bolt. No reduction factor is given in the pre-standard [6] because the clause for pin-bearing strength was drafted for designing without thread in bearing.

3. Experimental programme

The results reported in this paper are from a comprehensive programme of testing for pin-bearing strength determination that is detailed in the PhD thesis by the first author [17]. The specimen used, shown in Fig. 1, has nominal dimensions of 80 mm square by 9.53 mm thick. Specimens were taken from the flange outstands of the Pultex® SuperStructural 1525 series Wide Flange (WF) shape of size $254 \times 254 \times 9.53$ mm, pultruded by Creative Pultrusions Inc. (CP), Alum Bank, Pennsylvania [1]. The PFRP has a thermoset polyester (Class FR1) matrix with glass fibre reinforcement in the form of alternative layers of UniDirectional (UD) rovings and an $+45^{\circ}/90^{\circ}/-45^{\circ}$ /random chopped strand four-layered mat, which is product E-TTXM 4008 from Vectorply® corporation. The PFRP fibre architecture consists of mat layers interspersed with non-constant thickness layers of UD and covered with an outer surface polyester veil (non-structural).

Mechanical properties for flange material, as tabulated in CP’s Design Manual [1], in the lengthwise (0°) direction are: compressive modulus (D695) is 26.5 kN/mm^2 ; compressive strength (D695) is 316 N/mm^2 ; maximum bearing strength (D953) is 227 N/mm^2 . Similarly, for the crosswise direction (90°): compressive modulus (D695) is 13.1 kN/mm^2 ; compressive strength (D695) is 122 N/mm^2 ; maximum bearing strength (D953) is 158 N/mm^2 . The identifier in brackets indicates the ASTM standard test used and this tabulated data [1] are stated to be ‘average’ values based on random sampling and testing of production lots.

Preparation of specimens required cutting material, using a diamond edged circular saw with water coolant to minimise machining-induced damage, into the 100×80 mm blanks. A schematic of the principal dimensions of the final semi-notched specimen are shown in Fig. 1. The hole centre is located centrally within the width (w) for a 40 mm side distance (e_2). The end distance (e_1) is constant at 80 mm, and is of sufficient length that the end bearing bottom surface will not adversely affect the localised deformations causing failure due to the bearing force. The drilling process, firstly, used a solid carbide 10 mm stub drill bit with the hole finished using a solid carbide 10 mm or 16 mm four flute end mills for

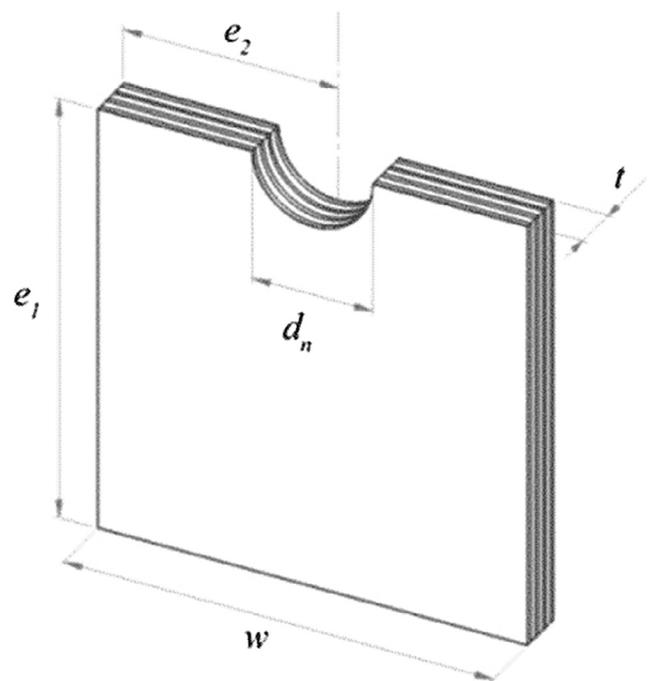


Fig. 1. Schematic of pin-bearing test specimen geometry.

having hole clearance diameters ($d_n > d$) of 12.2 (M10), 13.4 (M12), 18.4 (M16) and 22.4 mm (M20). Because bearing strength reduces with increasing hole diameter the maximum clearance was required, and this is given by the nominal hole clearance of 1/16 in. (1.6 mm) [1,2,6,17], plus maximum fabrication tolerance [18] of 0.6 mm for M10 or 0.8 mm for other bolt diameters.

Support is given at the tool exit side to minimise surface rupture and unwanted delamination damage, as well as the use of soluble oil to reduce excessive tool wear. The drilling method of circle-interpolation (or orbital drilling) is used, at 1800 rpm and a feed rate of 100 mm/min, which minimises thrust force, a known key factor creating drilling induced delamination in composite laminates [19]. Post-drilling, a specimen having the semi-circular notched was completed by a plane cut to obtain a specimen height of 80 mm (e_1 in Fig. 1). The fabrication procedure ensured a repeatable geometry precision and no delamination damage. This was confirmed by inspection and hole dimension measurements with an inside micrometre prior to the final plane cutting operation. The largest variation was for an under-size to the clearance hole by 0.02 mm. The thickness of every flange specimen was measured using an outside micrometre to the nearest 0.01 mm and ranged from 9.54 to 10.26 mm; the nominal thickness is 9.53 mm (for 3/8 in.). The batch means of thicknesses are reported in column (2) in Tables 1–4.

To compare the influence of plain and threaded pins a total of 16 batches of 10 specimens per batch were tested. Loading pins were cut from standard A4 (3 1 4) stainless steel bolts and for the standard 'off-the-shelf' threads the (coarse) pitches are 1.5 (M10), 1.75 (M12), 2.0 (M16) and 2.5 mm (M20). It is observed that the four standard thread pitches are not constant and this additional variable might have an impact on characterizing pin-

bearing strengths. Because the contribution of the thread pitch is unknown, a unique study with 12 batches of 5 specimens was carried out with non-standard thread pitches. The basic thread form for an ISO Metric (M) bolt is similar to the (American) Unified Coarse (UNC) designated bolts, which use threads per inch (TPI) instead of thread pitch. The various major dimensions associated with the bolt thread are defined in Fig. 2. The four thread pitches, P , in the parametric study are 1.5, 1.75, 2 and 2.5 mm. The standard sized pitch was not retested, and these are identified by the row entries in Tables 3 and 4 in bold font. In order to directly compare with the test results in Tables 1 and 2 the hole clearance sizes (i.e. d_n is constant) were unchanged. Non-standard threaded pins were prepared in-house. They were cut from A4 (3 1 4) stainless steel bar using thread cutting apparatus on a metal turning lathe; the precision of a profile was confirmed using a thread pitch gauge. Thread profiles on standard bolts is often formed using a rolled thread process instead of cutting threads with the difference being that the rolled thread can be stiffer than the cut thread method owing to steel being displaced into shape instead of being removed. The same basic thread template as shown in Fig. 2 was used to give an ISO metric profile. It is not believed that the difference in processing for standard and non-standard thread had any effect on the pin-bearing strength measurements presented in Section 4. Mean pin diameter measurements to the nearest 0.01 mm are recorded in column (1) in Tables 1–4.

Each static test was performed using the compression die-set with specimen fixtures shown in Fig. 3, and a DARTEC 9500 servo-hydraulic testing machine having a 250 kN load cell. The advantages of this testing configuration for measuring pin-bearing strength are discussed in detail in [14], or [17]. One potential weakness in previous test series [12,14] using the compression

Table 1
Plain pin-bearing strength test results.

| Pin diameter, d (mm) | Mean thickness, t (mm) | Mean max. failure load, $R_{br,mn}$ (kN) | Mean pin-bearing strength, F_{θ}^{br} (N/mm ²) | Standard deviation, (SD) (N/mm ²) | Coefficient of variation, (CV) (%) | Characteristic strength, $F_{k,\theta}^{br}$ (N/mm ²) |
|--------------------------|--------------------------|--|---|---|------------------------------------|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| <i>Longitudinal (0°)</i> | | | | | | |
| 9.81 (M10) | 9.77 | 20.1 | 210 | 19.9 | 9.5 | 176 |
| 11.8 (M12) | 9.77 | 21.5 | 186 | 21.5 | 11.6 | 149 |
| 15.8 (M16) | 10.0 | 32.7 | 205 | 13.1 | 6.4 | 182 |
| 19.8 (M20) | 9.66 | 37.9 | 198 | 17.6 | 8.9 | 168 |
| <i>Transverse (90°)</i> | | | | | | |
| 9.81 | 9.96 | 13.9 | 142 | 5.31 | 3.8 | 133 |
| 11.8 | 9.81 | 14.4 | 125 | 5.59 | 4.5 | 115 |
| 15.9 | 10.3 | 18.2 | 111 | 4.15 | 3.7 | 104 |
| 19.8 | 9.61 | 17.6 | 92 | 3.01 | 3.3 | 87 |

Table 2
Threaded bearing strength test results.

| Pin diameter, d (mm) | Mean thickness, t (mm) | Mean max. failure load, $R_{br,mn}$ (kN) | Mean pin-bearing strength, F_{θ}^{br} (N/mm ²) | Standard deviation, (SD) (N/mm ²) | Coefficient of variation, (CV) (%) | Characteristic strength, $F_{k,\theta}^{br}$ (N/mm ²) |
|--------------------------|--------------------------|--|---|---|------------------------------------|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| <i>Longitudinal (0°)</i> | | | | | | |
| 9.81 (M10) | 9.76 | 18.7 | 195 | 12.5 | 6.4 | 174 |
| 11.8 (M12) | 9.70 | 21.0 | 184 | 15.2 | 8.3 | 158 |
| 15.8 (M16) | 9.78 | 24.9 | 161 | 12.6 | 7.8 | 139 |
| 19.8 (M20) | 9.64 | 27.0 | 141 | 6.2 | 4.5 | 130 |
| <i>Transverse (90°)</i> | | | | | | |
| 9.81 | 9.96 | 15.4 | 158 | 7.3 | 4.6 | 146 |
| 11.8 | 9.82 | 16.5 | 143 | 9.5 | 6.6 | 127 |
| 15.8 | 9.65 | 18.8 | 123 | 7.7 | 6.2 | 110 |
| 19.8 | 10.3 | 20.4 | 100 | 3.3 | 3.3 | 94 |

Table 3
Thread pitch study with 0° flange material.

| Diameter of pin, <i>d</i> (mm) | Material thickness, <i>t</i> , (mm) | Thread pitch, <i>P</i> (mm) | Mean max. failure load, <i>R</i> _{br,mn} (kN) | Mean pin-bearing strength, <i>F</i> _{o^{br}} (N/mm ²) | Standard deviation (SD) (N/mm ²) | Coefficient of variation (CV) (%) | Characteristic strength, <i>F</i> _{k,o^{br}} (N/mm ²) |
|--------------------------------|-------------------------------------|-----------------------------|--|--|--|-----------------------------------|--|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| 9.81 (M10) | 9.70 | 1.50 | 18.7 | 195 | 12.5 | 6.4 | 174 |
| | 9.84 | 1.75 | 18.5 | 189 | 18.4 | 9.7 | 157 |
| | 9.54 | 2.00 | 17.7 | 186 | 5.6 | 3.0 | 176 |
| | 9.94 | 2.50 | 17.9 | 181 | 7.3 | 4.0 | 168 |
| 11.8 (M12) | 9.62 | 1.50 | 21.2 | 184 | 13.7 | 7.4 | 160 |
| | 9.70 | 1.75 | 21.0 | 184 | 15.2 | 8.3 | 158 |
| | 9.71 | 2.00 | 20.5 | 177 | 8.3 | 4.7 | 163 |
| 15.8 (M16) | 9.69 | 2.50 | 20.2 | 174 | 1.9 | 1.1 | 171 |
| | 9.81 | 1.50 | 26.3 | 168 | 9.47 | 5.6 | 152 |
| | 9.94 | 1.75 | 26.9 | 169 | 9.8 | 5.8 | 153 |
| | 9.78 | 2.00 | 24.9 | 161 | 12.6 | 7.8 | 139 |
| 19.8 (M20) | 9.86 | 2.50 | 24.1 | 153 | 15.2 | 9.9 | 127 |
| | 9.84 | 1.50 | 28.6 | 149 | 11.5 | 7.6 | 129 |
| | 9.83 | 1.75 | 28.9 | 147 | 9.4 | 6.4 | 131 |
| | 9.80 | 2.00 | 28.1 | 144 | 6.4 | 4.3 | 133 |
| | 9.64 | 2.50 | 27.0 | 141 | 6.2 | 4.4 | 130 |

Table 4
Summary of thread pitch study with 90° flange material.

| Diameter of pin, <i>d</i> (mm) | Material thickness, <i>t</i> , (mm) | Thread pitch, <i>P</i> (mm) | Mean max. failure load, <i>R</i> _{br,mn} (kN) | Mean pin-bearing strength, <i>F</i> _{o^{br}} (N/mm ²) | Standard deviation (SD) (N/mm ²) | Coefficient of variation (CV) (%) | Characteristic strength, <i>F</i> _{k,o^{br}} (N/mm ²) |
|--------------------------------|-------------------------------------|-----------------------------|--|--|--|-----------------------------------|--|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| 9.81 | 9.96 | 1.50 | 15.4 | 158 | 7.3 | 4.6 | 146 |
| | 9.85 | 1.75 | 15.3 | 156 | 6.2 | 4.0 | 145 |
| | 9.79 | 2.00 | 14.2 | 145 | 12.5 | 8.6 | 123 |
| | 9.78 | 2.50 | 13.5 | 141 | 9.6 | 6.8 | 125 |
| 11.8 | 9.67 | 1.50 | 15.3 | 132 | 5.2 | 3.9 | 123 |
| | 9.82 | 1.75 | 16.5 | 143 | 9.4 | 6.6 | 126 |
| | 9.59 | 2.00 | 14.9 | 130 | 4.9 | 3.8 | 122 |
| 15.8 | 9.58 | 2.50 | 14.5 | 127 | 5.8 | 4.6 | 117 |
| | 9.69 | 1.50 | 18.9 | 122 | 9.0 | 7.4 | 107 |
| | 9.73 | 1.75 | 18.0 | 116 | 7.4 | 6.4 | 103 |
| | 9.65 | 2.00 | 18.8 | 123 | 7.7 | 6.2 | 110 |
| 19.8 | 9.56 | 2.50 | 17.3 | 114 | 7.0 | 6.2 | 102 |
| | 9.92 | 1.50 | 20.4 | 105 | 5.5 | 5.2 | 96 |
| | 9.83 | 1.75 | 18.5 | 94 | 4.9 | 5.2 | 86 |
| | 9.82 | 2.00 | 18.6 | 95 | 7.4 | 7.7 | 83 |
| | 10.3 | 2.50 | 20.4 | 100 | 3.3 | 3.3 | 94 |

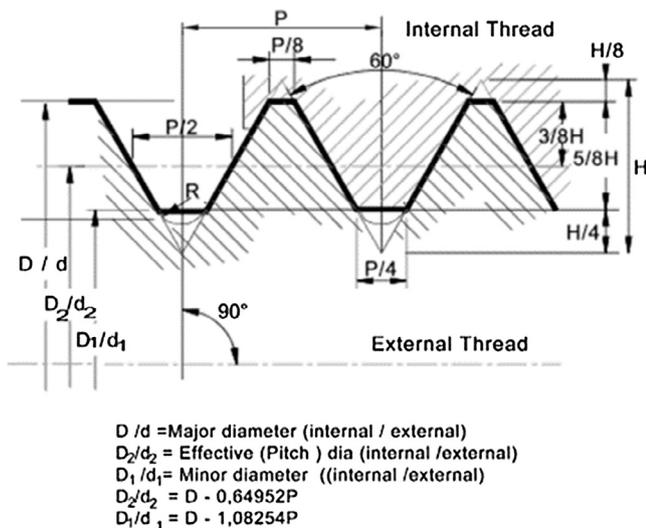


Fig. 2. Basic profile for an ISO metric coarse thread (http://www.roytech.co.uk/Useful_Tables/Screws/Thread_tol.html).

die-set with specimen fixtures was that the centre of the hole might not be directly aligned with the pin's centroid axis. Fig. 3 shows a fixture arrangement of a spring (left-side), a micrometer (right-side) and specimen holder (middle) that was introduced [17] to be able to centre the holder with its specimen. In addition, to accommodate the threaded pins (so as to reduce damage to the die set), a new V-notch top fixture (see Fig. 3) made of tool steel (gauge plate) was introduced. Testing [17] also required fabrication of a spacing-block to accommodate the smaller specimen size (compared to previous specimen size of 96 × 73 mm [14]), and re-milling of the anti-buckling side plates in the specimen holder to hold a thicker PFRP material.

Load is transferred into the notched specimen completely in-plane to ensure pure bearing damage can occur. Compression is applied under a constant stroke rate of 0.01 mm/s, and load and stroke are recorded once every second by National Instruments data acquisition equipment. Failure load, for *R*_{br} in Eq. (1) is defined as the maximum test load and the justification for this choice is discussed in [14]. The maximum compressive force includes the dead weight at 0.321 kN for the top plate and rocker fixture, partially seen at the top of the photograph in Fig. 3.

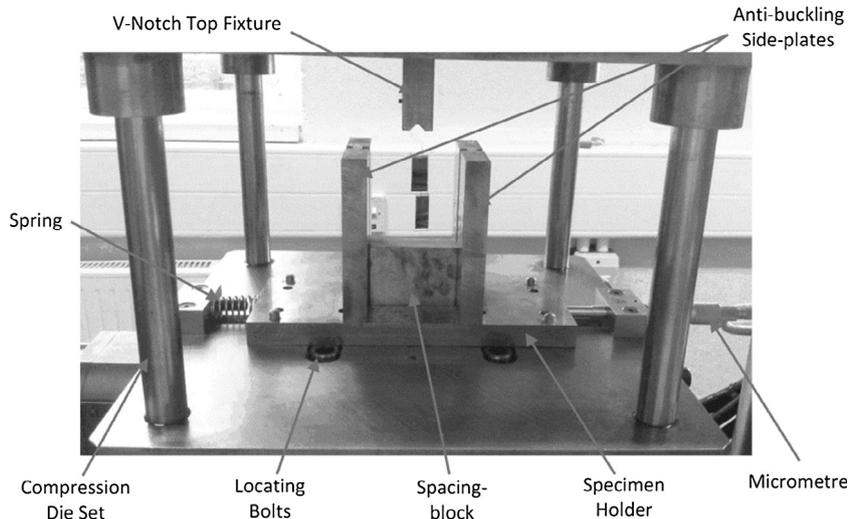


Fig. 3. Compression die-set with specimen fixtures for pin-bearing strength testing.

4. Results and discussion

Mean batch test results are reported in Tables 1–4. Columns (1) and (2) are for pin diameter, d , and mean flange thickness, t . In Tables 1 (plain) and 2 (threaded) column (3) reports the mean maximum load $R_{br,mn}$ from the 10 batch results. These two tables have entries for both the 0° and 90° material orientations. Using Eq. (1) the mean pin-bearing strength (F_0^{br}) is presented in column (4). The strength population is assumed to fit a Gaussian distribution [20], from which the Standard Deviation (SD) and Coefficient of Variation (CV) are reported in columns (5) and (6). The characteristic strength ($F_{k,0}^{br}$) in column (7) is determined, in accordance with Annex D of Eurocode 0, assuming the CV is a known property [20]. Because previous results using the same pin-bearing strength test method [12,14] gave batch CVs $\leq 10\%$ it is deemed acceptable to determine the characteristic value from (mean $- 1.72 \times SD$) [20]. This strength value in Eq. (1) is before the resistance factor in [6] would be applied, when calculating the design strength of an PFRP bolted connection.

Tables 3 and 4 are for the unique thread pitch study with material orientations of 0° and 90° , respectively. Columns (1) and (2) are unchanged in these two tables. Column (3) is for the thread pitch, P , with the three non-standard pitches reported using a non-bold font. P , as defined in Fig. 2, correlates to an TPI calculated as (P (mm) divided by 25.4 mm (1 in.)), giving 16.9, 14.5, 12.7 and 10.2 for pitches of 1.5, 1.75, 2.0 and 2.5 mm. The other columns (4) to (8) are for the same data as in columns (3) to (7) in Tables 1 and 2, except with the lower batch size of five specimens the characteristic strength now is given by (mean $- 1.80 \times SD$) [20].

Inspection of the results in Tables 1–4 show that the CVs (column (6) or (7)) are in the range of 1.1 (threaded) to 11.6% (plain), with only one of the 28 batches having an CV $> 10\%$. The highest group of CVs, for a mean of 9.1%, are with the plain pins and 0° orientation. For threaded pins the 16 CVs have a lower mean CV at 6.0%. When the flange material is at 90° the equivalent CVs are lower still, at 3.8 and 5.7%, respectively. Determining the characteristic strengths in Tables 1–4 by assuming the CV is a known value [20] is found from the test results to be appropriate.

Using the same axis scales, Fig. 4(a)–(d) show typical load-stroke responses for the two material orientations of 0 and 90° without thread ((a) and (c)), and with thread ((b) and (d)). For the four bolt diameters (M10–M20) the shape of the curves in Fig. 4(a) and (c) for the smooth shank contact show an initial 'bed-

ding in' stage, after which there is a nearly linear (elastic) load increase to the maximum load, when bearing failure occurs, and with 0° orientation there is sudden noticeable load loss. Comparing with the plots in Fig. 4(b) and (d) it can be seen that specimen stiffness is lower, this being due to thread embedment. For post-bearing failure there is a small, if any, loss in bearing capacity, even for the 0° material. The magnitude of the measured stroke at failure is predominately controlled by the localised bearing deformations owing to the relatively higher axial stiffness of the steel testing machine frame, test fixtures and pins (see Fig. 3).

Fig. 5(a) is a photograph showing the typical failure with a plain pin, when viewed normal to the bearing area. The image in Fig. 5(b) is for the threaded situation. The specimens in these figures had testing terminated after there was a loss in compression force that signals onset of bearing failure. Fig. 5(b) reveals that by having thread in bearing there is greater peripheral cracking at the top of the specimen, thereby suggesting there is a different internal fracturing morphology caused by the embedment of the thread profile. The nature of the mechanisms for failure was not within the scope of the PhD study with the first author [17].

Fig. 6(a) and (b) present bar charts for 16 mean pin-bearing strengths and standard deviation error bars with plain (unfilled) and threaded (filled) batches adjacent to each other. The general trend seen from this presentation for 0° in Fig. 6(a) and 90° in Fig. 6(b) is that as the pin diameter increases the strength decreases. Intuitively, this relationship would seem paradoxical. It's to be noted that pin-bearing strength is a function of both pin diameter and material thickness (the projected bearing area being dt), and so the bearing resistance ($R_{br,mn}$ in column (3) or (4) in Tables 1–4) is actually increasing with increasing bolt diameter. When the orientation is 0° the plain pin strength (F_0^{br}) in Fig. 6(a) is lower for the threaded situation and the reverse situation for F_{90}^{br} is seen in Fig. 6(b) for loading in the orthogonal direction. This finding is for an emerging proposition that changes in failure mechanism with thread bearing are affected differently by the material orientation angle θ .

Using the characteristic strengths presented in Tables 1 and 2, Fig. 7(a) and (b) are plots for $F_{k,0}^{br}$ and $F_{k,90}^{br}$ variations with ratio d/t ; t for the ratios is the nominal flange thickness of 9.53 mm. Subscript 'k' is for the characteristic strength. Part (a) is for plain pin and part (b) for the threaded bolt. Except for $F_{k,0}^{br}$ plain in Fig. 7(a), the other three sets of test results show a fairly linear decreasing strength trend with increasing d/t ratio. This is the expected

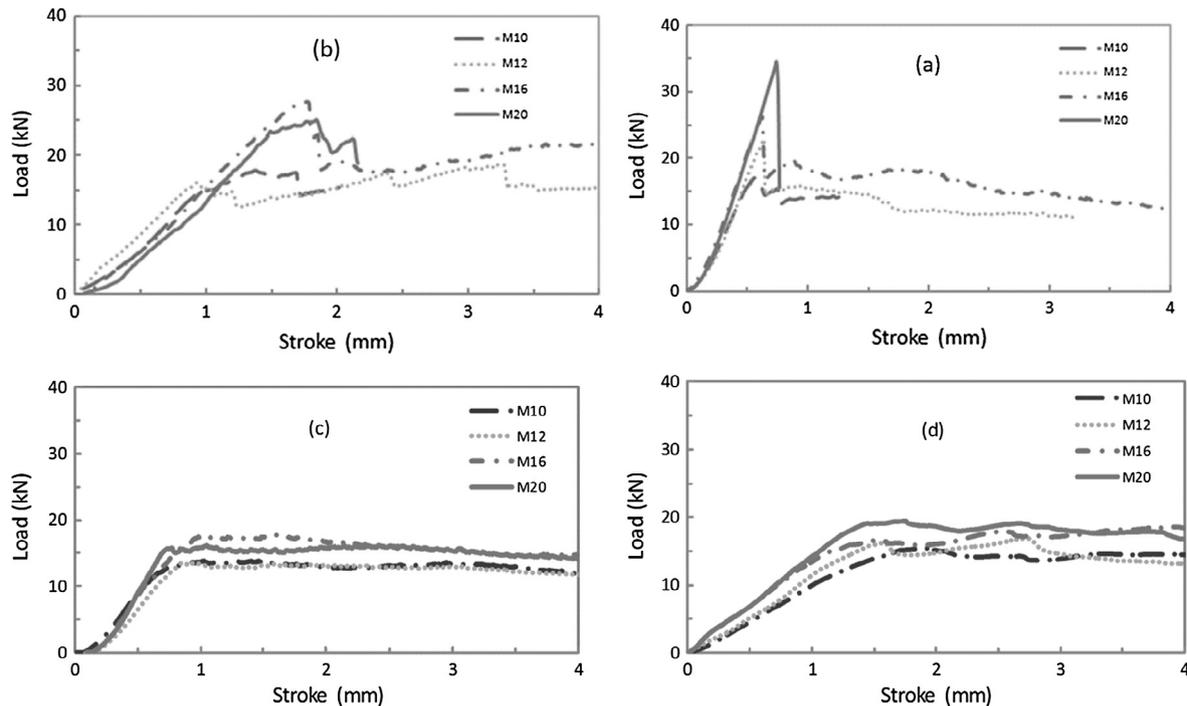


Fig. 4. Typical load-stroke plots for plain and threaded pins: (a) plain and 0°; (b) threaded and 0°; (c) plain and 90°; (d) threaded and 90°.

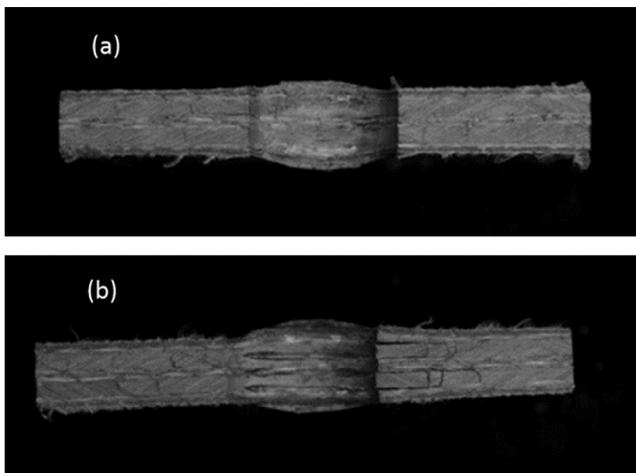


Fig. 5. Observed failure of pin-bearing specimen with bearing pin: (a) plain; (b) threaded.

result from the information reported in previous test studies on pin-bearing strength [10–15]. In both parts (a) and (b) it can be seen that when there is thread in bearing the relationship between the strength and d/t is virtually linear, this is confirmed by a straight-line R^2 correlations of 0.96 and 0.98, respectively.

The one obvious irregularity within the data points plotted in Fig. 7(a), which doesn't follow the expected decreasing linear trend, is $F_{k,0}^{br}$ with the M12 plain pin. This characteristic strength at 149 N/mm^2 is seen to be approximately 10% lower than what would be expected had it followed the linear relationship with d/t . This unexpected finding was initially investigated by conducting five more nominally identical tests to find out if it was due to having a batch size of 10. Results from an additional 5 specimens gave $F_{k,0}^{br}$ (in N/mm^2) for 5, 10 and 15 specimens of 143 (mean – $1.80 \times \text{SD}$), 149 (mean – $1.72 \times \text{SD}$) and 146 (mean – $1.70 \times \text{SD}$).

From a 2 to 4% batch variation it is observed that there is no significant difference. It can be speculated that a plausible explanation for why there is a relatively too low strength for this set of test parameters is for an unknown relationship between the UD fibre roving bundle geometry and pin size. This proposition needs to be investigated, and to do so will require a detailed study on the fundamentals of the failure mechanisms (see Fig. 5). Inspection of the plain pin results in Fig. 7(a) indicates that the M10 characteristic strength is probably on the low side of what is predicted on accepting the M16 and M20 values.

Presented in Fig. 8 are plots of mean threaded pin-bearing strength against Threads Per Inch (TPI) for the four bolt sizes. Linear trend lines have been included to highlight a common change. Part (a) is for 0° material and part (b) for the 90° orientation. The straight lines joining the four data points do not necessarily reflect the actual trend with change of TPI. It can clearly be seen from the results in Fig. 8 that as TPI increases (or as thread pitch decreases) for a finer thread the strength increases as well, and for the largest pin (M20) and 0° material (symbols X) it can be seen in Fig. 8(a) that a virtually linear trend exists. This strength trend is less apparent when material is oriented at 90°. Using the mean results in Tables 3 and 4, and involving the trends in Fig. 8, it can be calculated that a 1.0 mm increase in thread pitch results in an average decrease in the pin-bearing strength of between 4 and 8%. This indicates that the likely contribution of pitch geometry is insignificant in establishing the reduction factor for calculating the characteristic thread pin-bearing strength from the plain value.

Considering that a measured pin-bearing strength for Eq. (1) is for the compressive force exerted upon a semi-circular notch by a plain pin, it is not unreasonable that a comparison be drawn between the average compressive strength tabulated in the Design Manual of the pultruder CP [1], and the mean pin-bearing strength. There is anecdotal evidence that practitioners choose the compression strength, because it is available to them [1,2] when the plain pin-bearing strength is not. Strongwell [2], another American pultruder, recommends for bolted connection design an admissible safety factor of 4 for a pragmatic stress allowable design approach.

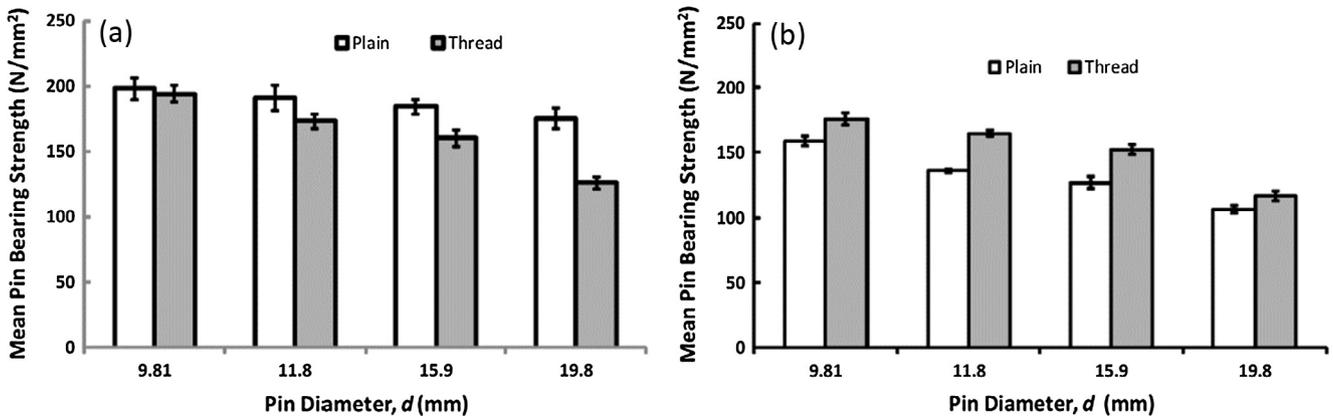


Fig. 6. Bar charts for mean pin-bearing flange strengths with (filled) and without (unfilled) thread for: (a) 0°; (b) 90°.

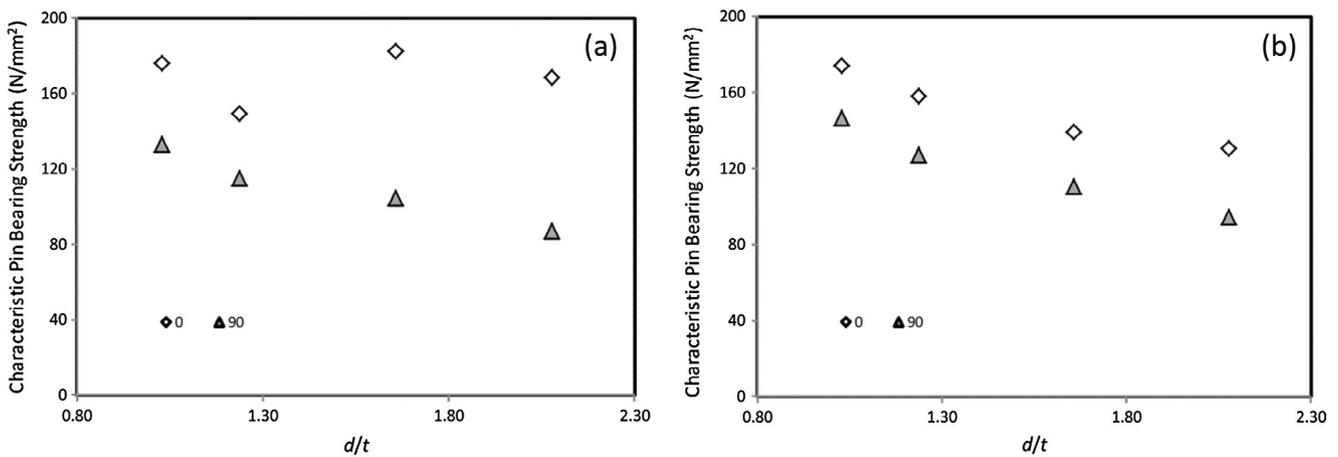


Fig. 7. Plain and threaded pin-bearing characteristic strengths for flange material with pin diameter: (a) $F_{k,\delta}^{\circ}$; (b) $F_{k,90}$.

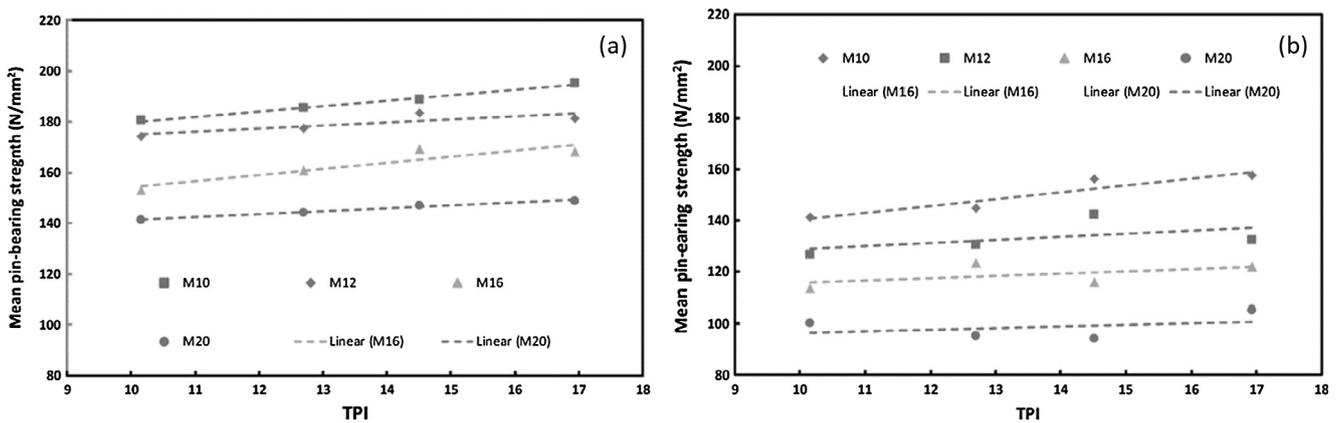


Fig. 8. Thread pitch study results with mean flange pin-bearing strength plotted against Threads Per Inch (TPI) for: (a) 0°; (b) 90°.

The 0° compression characteristic strength measured by the first author [17] for the flange material is 270 (3 1 6) N/mm². The bracketed value is the average taken from CP's Design Manual [1]. The higher of the two compression strengths gives an admissible bearing strength of 79 N/mm² (from 316/4). Comparing this 0° 'bearing' strength with the lowest equivalent measured mean of 149 N/mm² (for M12 pin in Tables 1), it is found that there is a significant difference of ≈47%. A positive finding is that the American pultruders' design approach is likely to be reliable since the admis-

sible strength used in design calculations should be on the low side of the actual 'design' pin-bearing strength obtained from testing.

To complicate what information the designer has from CP for Pultex® SuperStructural 1525 series materials, the Design Manual [1] has tabulated maximum bearing strengths that are said to be 'average' values based on random sampling and testing of production lots. Using the standard method in ASTM D953, testing has a single pin of 6.35 mm (1/4 in.) diameter and no clearance hole. For flange material the average maximum bearing strengths tabu-

lated are 227 (0°) and 158 (90°) N/mm². The specified test parameters give the relatively low d/t ratio of 0.67, and this is one technical reason why the M10 to M20 mean plain pin strengths (Table 1) of 186–210 N/mm² for 0° and of 92–142 N/mm² for 90° are lower. Note that the same outcome is obtained if the threaded test results in Table 2 are used in the comparison.

Given that increasing ratio d/t (and increasing hole clearance to the maximum allowed [6,17]) always lowers a pin-bearing strength it is recommended that the most severe design parameters to be found on-site are present when determining F_0^{br} in Eq. (1) by testing.

It is noteworthy to have a cursory discussion on the contribution of the fibre reinforcement in the SuperStructural[®] flange material. It is observed that there is a thicker UD layer on the top most side of the flange (see Fig. 5) in the 254 × 254 × 9.53 mm shape, which is present to increase flexural rigidity of the WF section under bending action. This asymmetrical layering in the flange could have an influence on the variation in pin-bearing strength results. In particular, the through-thickness stress field could be more localised and more non-uniform across the thickness than would be the case with the more common symmetrical lay-up found in earlier CP pultruded shapes [2,3,12,14]. This symmetry in lay-up is the situation for the web material in the same WF shape. In [21] Matharu and Mottram present web test results to show that plain and threaded pin-bearing strengths are similarly and vary similarly to what has been reported by the flange study reported in Tables 1 and 2.

One important objective for carrying out a comprehensive series of tests [17] was to establish whether or not a reduction factor is required to determine the threaded characteristic strength from the equivalent known pin-bearing plain pin value. Presented in Table 5 are the normalised mean and characteristic strength reduction factors between plain and threaded situations. Column (1) is for pin diameters and columns (2) and (3) for mean and characteristic reductions obtained by dividing the two means taken from Tables 1–4. The results show there is no reduction when the material orientation is 90°, in fact there is an increase of 5–14%. The maximum reduction is with M20 and 0° and it is either 29% or 22% using mean or characteristic strength results. From an independent series of tests, performed by Troutman and Mostoller of CP [13], in the spirit of ASTM D953, the mean reduction was found to be 30%; having a peak at 37%.

Results plotted in Fig. 8 give a clear trend that an increase in TPI corresponds to a higher pin-bearing strength. A plain pin can be thought of as a threaded pin with an infinitely high TPI. It is to be noted that Troutman and Mostoller [13] found the largest strength reduction with a 15.9 mm diameter plain pin and 12.7 mm thick 0° material. For the smaller diameter of 12.7 mm the reduction was lower at 28%. This finding may suggest that

the d/t ratio does play a significant role in the amount of strength reduction from the 0° plain pin value.

It has been proposed for an American LRFD standard that, for a threaded bolt in bearing, the characteristic pin-bearing strength in Eq. (1) shall be determined by applying a reduction factor of 0.6 to the characteristic plain pin-bearing strength, the latter to be determined using the guidance for testing in the pre-standard's commentary [6]. Note that in the pre-standard [6] the clause for bearing strength is without thread allowed. American practitioners said that this mandatory provision was too restrictive and this requirement led to a revision during the committee stage to prepare the standard. The reduction factors in Table 5 for 'as received' flange material do not provide evidence to question the reliability for the 0.6 reduction factor to be specified in the LRFD standard (which is under preparation).

The existence of a reverse in the reduction factor with 90° oriented PFRP is contradictory to the previously held viewpoint that having thread in bearing would only adversely lower a pin-bearing strength. Although, the threaded strength is higher, the maximum load is specified by satisfying the maximum load criterion used to calculate strength using Eq. (1). For the 90° case there can be significant damage as progressive failures develop and the maximum load occurs at significantly higher load and stroke than for damage onset. This softening effect from thread embedment is seen in the load-stroke plots in Fig. 4(b) and (d). A prominent feature is a knee in many of the load-stroke curves, which is thought [17] to be the state at which there is full embedment of the thread profile. This contrasts with the load-stroke curves in Fig. 4(a) for the plain cases that, after small initial lower stiffness (bedding-in) stage, are mostly linear up to maximum load. This suggests that, perhaps, for a threaded bolt the criterion for selecting the bearing failure load for Eq. (1) should not be the maximum load. This observation opposes the recommendation made by Mottram and Zafari [14] that the maximum load is the only practical test load to take when characterising an PFRP material. It is noteworthy that this recommendation was made with the important assumption that the bolt shaft is plain (not threaded) and the mat reinforcement in the PFRP material is of continuous filaments [2,6,12,14].

The pin-bearing strength results presented above are for an PFRP material from the American pultruder Creative Pultrusions Inc. with the mat reinforcement of the tri-axial mat Vectorply E-TTXM 4008. Other pultruders produce 'standard' PFRP shapes with a mat reinforcement that is of continuous filaments in a random distribution. For this material no characterisation work has been carried out to compare the characteristic strengths of plain and threaded bolts, and as such no quantification has been made for the reduction factor. No verification can be made today to verify that the LRFD factor of 0.6 is appropriate. What we do have are characteristic pin-bearing strengths for the non-aged web material of CP standard shapes (pultruded in the 1990 s) [12,14], and numerical predictions in [16] for the mean strength for both standard and Pultex[®] SuperStructural materials. Physical test results for plain pin-bearing strengths reported in Tables 2 (0°) and 4 (90°) in [14] do not suggest a significant difference in strength between having the mat reinforcement as either continuous filament mat or the tri-axial mat (see Table 1). The Abaqus simulation outputs [16] show that there is no benefit to increasing the plain pin-bearing strength on having replaced continuous filament mat with the tri-axial mat. It is the authors' understanding that the results presented in this paper are going to be acceptable in providing evidence for the pin-bearing strengths of standard PFRP material when the laterally unrestrained steel bolt is with or without thread in bearing.

The discussion in this paper is highlighting that thread in bearing has significant influence on the: pin-bearing strength; load-

Table 5
Thread reduction for mean and characteristic strengths.

| Pin diameter (mm) | Reduction in mean bearing strength (%) | Reduction in characteristic strength (%) |
|--------------------------|--|--|
| 1 | 2 | 3 |
| <i>Longitudinal (0°)</i> | | |
| 9.81 (M10) | 0.93 | 0.99 |
| 11.8 (M12) | 0.99 | 1.06 |
| 15.8 (M16) | 0.79 | 0.76 |
| 19.8 (M20) | 0.71 | 0.78 |
| <i>Transverse (90°)</i> | | |
| 9.81 | 1.11 | 1.10 |
| 11.8 | 1.14 | 1.10 |
| 15.8 | 1.11 | 1.06 |
| 19.8 | 1.09 | 1.09 |

stroke behaviour; bearing failure mechanisms. Regardless of the geometry of the thread profile it has to be recognised that with this type of bolted connection being exposed to an aggressive environment, over its service life, thread embedment is likely to impair the long-term durability of the joint [17]. This observation offers an engineering justification to why it might be counterproductive in practice to expect say, a design working life of 50 years, from an PFRP bolted structure when there is thread in bearing.

5. Concluding remarks

The key finding from the experimental based study to determine the pin-bearing strengths of a Pultruded Fibre Reinforced Polymer (PFRP) material having steel bolting with or without thread is that the reduction factor of 0.6 in a forthcoming American LRFD standard, based on a 2010 pre-standard [6], is acceptable and safe. This factor is required to calculate the thread characteristic strength from the equivalent measured plain value. There is evidence from the results and discussion presented to question the criterion, for the threaded situation, of selecting the maximum failure load when testing is used to determine the pin-bearing strength for designing with Eq. (1). It is important to recognize that this recommendation was made by Zafari and Mottram [14] with the important assumption that the bolt shaft is always plain (no thread), and the mat reinforcement is of continuous filaments.

Other findings from the evaluation of test results presented are:

- Because the coefficient of variation for 27 of the 28 batches is <10% the characteristic strength can be determined using the Eurocode 0 approach for a known coefficient of variation.
- When thread is present the load-stroke curve shows a softening stage that is due to thread embedment. The stroke at maximum load can be much higher than when the steel bolt has a smooth shank in bearing.
- For specimens loaded in the direction of pultrusion the pin-bearing strength is found to be lower for the threaded than plain situation and the reverse strength variation is found when the bearing force is applied in the orthogonal direction. This finding is for an emerging proposition that changes in failure mechanism with thread bearing are affected differently by the material orientation.
- The influence of the pin diameter to material thickness ratio is known to be strong, and the results reported using a different PFRP material and four bolts sizes (M10, M12, M16 and M20) confirming the relationship. The effect of this geometrical ratio on lowering pin-bearing strength is found to hold for the same test conditions with and without thread in bearing, with an almost linear relationship when thread is present.
- There is a single batch data point (M12 and plain pin) that appears to possess a low strength compared to the strength trend from the three other bolt sizes of M10, M16 and M20, and it is speculated that as a plausible explanation for this relatively low strength might be an unknown relationship between the unidirectional fibre roving bundle geometry and pin diameter.
- The characteristic pin-bearing strength for flange material from the Pultex® SuperStructural 1525 series of shapes is not constant and depends on bolt diameter. It has its lowest value for the M20 bolt size. For a bearing force aligned with the direction of pultrusion the lowest characteristic strength is 168 N/mm² with a plain bolt shank and 130 N/mm² for the standard threaded bolt. When the direction of pultrusion is orthogonal to the direction of bearing force the characteristic strength is considerably lower with plain bolt at 87 N/mm² and threaded at 94 N/mm².

- The unique study presented, in which the variation in threaded pin-bearing strength is characterized by way of a standard and three non-standard thread pitches for the four bolt sizes (M10 to M20) provides new strength results that shows there is no significance on a likely contribution from pitch geometry to establishing a reduction factor for the threaded situation (it is to be 0.6 in the forthcoming LRFD standard).
- It is shown that a design approach for bolted connections that can be formulated by taking the material compression strength with an admissible safety factor of 4 from the American pultruders' design manuals is likely to be reliable since the admissible bearing strength obtained should be on the low side of the actual design pin-bearing strength.
- Knowing that increasing the pin diameter to material thickness ratio (and increasing hole clearance to maximum allowed) lowers the pin-bearing strength, it is recommended that the most severe connection parameters used on-site be present when determining a characteristic pin-bearing strength by testing.
- Finally, the discussion emphasises that thread in bearing does have a significant influence on the: pin-bearing strength; load-stroke behaviour; bearing failure mechanisms. Regardless of the geometry of the thread profile, should this form of bolted connection be exposed, over years, even decades, to environmental aging the thread embedment will undoubtedly cause the PFRP material to deteriorate at a quicker rate. This observation on a durability concern provides us with a strong engineering argument to why it might be counterproductive in practice to expect a design working life of, say 50 years, from an PFRP bolted frame structure when there is thread in bearing.

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References

- [1] Creative Pultrusions. The new and improved Pultex® pultrusion design manual of standard and custom fiber reinforced polymer structural Profiles. Imperial Version vol. 5 Rev. 3. Alum bank, PA, USA: Creative Pultrusions Inc.; 2017. (<http://www.creativepultrusions.com/index.cfm/products-solutions/fabrication-capabilities/pultexc2ae-pultrusion-design-manual1/>) (16/02/17).
- [2] Strongwell. Strongwell design manual. Bristol, VA: Strongwell; 2017. (<http://www.strongwell.com/>) (16/02/17).
- [3] Bank LC. Composites for construction – structural design with FRP materials. New Jersey: John Wiley and Sons; 2006.
- [4] Turvey GJ. Bolted connections in PFRP structures. *Prog Struct Eng Mater* 2000;2(2):146–56.
- [5] Mottram JT. Does performance based design with fibre reinforced polymer components and structures provide any new benefits and challenges? *Struct Eng* 2011;89(6):23–7.
- [6] ASCE. Pre-standard for load and resistance factor design (LRFD) of pultruded fiber reinforced polymer (FRP) structures. American Society of Civil Engineers; 2010.
- [7] Mottram JT, Turvey GJ. Physical test data for the appraisal of design procedures for bolted joints in pultruded FRP structural shapes and systems. *Prog Struct Eng Mater* 2003;5(4):195–222.
- [8] Thoppul SD, Finegan J, Gibson RF. Mechanics of mechanically fastened joints in polymer-matrix composites – a review. *Compos Sci Tech* 2009;69(3–4):301–29.
- [9] Mottram JT. Design guidance for bolted connections in structures of pultruded shapes: Gaps in knowledge. In: Seventieth international conference on composite materials (ICCM-17); 2009. Paper A1.6. pp. 12.
- [10] Turvey GJ. Single-bolt tension joint tests on pultruded GRP plate – effects of tension direction relative to pultrusion direction. *Compos Struct* 1998;42(4):341–51.

- [11] Wang YJ. Bearing behavior of joints in pultruded composites. *Compos Mater* 2002;36(18):2199–216.
- [12] Mottram JT. Determination of pin bearing strength for the design of bolted connections with standard pultruded profiles. In: Fourth international conference on advanced composites in construction (ACIC 2009) Chesterfield: NetComposites Ltd.; 2009. pp. 483–495.
- [13] Troutman D, Mostoller J. An investigation of pin bearing strength on composite materials. In: Proceeding of 2010 CTI (Cooling Tower Institute) annual conference. Paper No: TP10-24. Houston Texas 77056; 2010. pp. 8.
- [14] Mottram JT, Zafari B. Pin-bearing strengths for bolted connections in fibre-reinforced polymer structures. *P I Civil Eng-Str* 2011;B164(SB5):291–305.
- [15] Lee Y, Park S, Park J, Nam J, An D, Yoon S. Structural behavior of PFRP connection with single bolt. In: Eighteenth international conference on composite materials. The Korean Society for Composite Materials; 2011. pp. 5.
- [16] Girão Coelho AM, Mottram JT. Numerical evaluation of pin-bearing strength for the design of bolted connections of pultruded FRP material. *J Compos Construct* 2017;21(5):13.
- [17] Matharu NS. Aspects of bolted connections for fibre reinforced polymer structures [PhD Thesis]. UK: University of Warwick; 2014.
- [18] ACMA. Code of standard practice for fabrication and installation of pultruded FRP structures. ANSI standard. 1st ed. American Composites Manufacturers Association: Arlington, VA; 2012.
- [19] Khasabu UA, El-Sonbaty IA, Selmy AI, Megahed AA. Machinability analysis in drilling woven GFR/epoxy composites: Part I – effect of machining parameters. *Compos Part A* 2010;41(3):391–400.
- [20] BS EN1990:2002. Eurocode 0 – Basis of Structural Design. United Kingdom: British Standards Institute; 2002.
- [21] Matharu NS, Mottram JT. Laterally unrestrained bolt bearing strength: Plain pin and threaded values. In: Sixth international conference on FRP composites in civil engineering (CICE 2012). Rome; 2012. Section 14: Codes and Design Guidelines Paper 311. pp. 8.