Abstract

This paper presents test results to examine the effect of load orientation on the pin-bearing strength of a pultruded fibre reinforced polymer material. Using a non-standard test method a series of tests have been conducted to characterize material cut from the web of a 203 × 203 × 9.53 mm wide flange standard shape. Presented are prominent results for pin-bearing strengths when load is oriented at 5, 10, and 20° to the direction of pultrusion and there is a clearance hole of at least 1.6 mm. For the test matrix there are four sizes of pin diameter from 9.7 mm to 25.4 mm. Combining with previous results for the three orientations of 0, 45 and 90° an evaluation of the data, with varying pin diameter-to-thickness ratio, is made with the aim of establishing how we can specified strength with material orientation for the safe and reliable design of bolted connections.

Keywords: Pultruded structures, bolted connections, pin-bearing strength, material orientation, codes and guidelines.

1. INTRODUCTION

Design of connections and joints is one of the most critical aspects when establishing that a primary load bearing structure, of any construction material, is safe and reliable. Steel bolting is the preferred method of connection in the pultrusion industry [1, 2] because of the advantages of historical precedence, low cost, easy fabrication, readily dismantling, straightforward inspection procedures and manageable quality control. The main class of construction to be designed when using the American pre-standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber-Reinforced Polymer Structures [3] is non-sway braced frames that have simple shear joints between members (cross-section shapes mimic conventional steel sections) and bracing to transfer lateral loads to the ground. Bank [4] shows applications of steel bolted connections in such pultruded frame structures.

Considered in this paper is the strength of plate-to-plate connections when its strength is to be determined by the distinct mode of failure known as bearing. We further restrict the discussion to plate-to-plate connections having the double lap-shear single bolted configuration, and with in-plane loading [5]. It is well-known that such bolted connections of pultruded material can fail ultimately in one of a number of failure modes. Figures 1(a) to 1(d) show the distinct modes of failure to be bearing, shear-out, net-tension and cleavage. It is standard practice that the chosen size (diameter) of the steel bolting is such that failure either by bolt rupture or by bolt pull-through will not occur [5]. There is a strength formula in the LRFD pre-standard [3] for each of the four failure modes illustrated. These depend on
geometry values \((d_n, e_1\) and \(e_2)\) and material failure strengths and the lowest value calculated using the formulae may be taken as the single bolted connection’s strength.

![Diagram of distinct modes of failure](image)

**Figure 1.** Plate-to-plate distinct modes of failure with a single steel bolt; (a) bearing, (b) net-tension, (c) shear-out, (d) cleavage.

It should be understood that mixed modes (e.g. when the connection force is off-axis with respect to the direction of pultrusion) are possible with the single bolt situation, and block-shear is a new mode when there are multiple rows of bolts [5].

If we consider the connection detail in Figure 1 the plate is of constant thickness \(t\) and constant width \(w\). Because the bolt is centrally placed the width is twice the edge (or side) distance \(e_2\). Other relevant geometric parameters in establishing connection strength are the hole diameter \(d_n\), and the bolt diameter \(d\), which due to a hole clearance is less than \(d_n\). Mottram and Turvey [5] used the results from series of single-bolted double lap-shear tests to observe that the mode of failure can be made to change by varying the geometric ratios \(e_1/d\) (or \(e_1/d_n\)) and \(w/d\) (or \(w/d_n\)), with \(w = 2e_2\). To make bearing failure the most likely mode, at room temperature, these two ratios need to be four or higher when the fibre reinforced polymer material is pultruded.

Bearing is the distinct mode of failure with a strength formula [4] having its specific ‘material’ strength \(F_{br}\), and the formula is

\[
R_{br} = t d \ F_{br}.
\]

This is the specified strength formula in Chapter 8 of the LRFD pre-standard [3]. It is important to recognize that \(F_{br}^{0}\) is a directional (characteristic) strength, specific to the bearing load situation, and depending on the orientation \((\theta)\) of the connection force with respect to the direction of pultrusion. By definition \(F_{br}^{90}\) is the mean stress over the projected bearing surface (i.e. area \(dt\)) when failure is that of bearing. Its pin-bearing value is the lower bound strength because there is no through-thickness constraint that is known [5] to increase the connection force prior to bearing failure. It is further assumed that there is no thread in bearing for this strength measurement. Following the reasoning given in Mottram and Zafari [6] the load taken from the strength test, to determine the pin-bearing strength, is the maximum attained.

For the purpose of design calculations Eq. (1) requires the characteristic value of \(F_{br}^{0}\) per bolt. When the connection force is aligned with the longitudinal direction of pultrusion we have \(\theta = 0^\circ\), and \(F_{br}^{0}\) is the highest pin-bearing strength. If \(\theta = 90^\circ\) the force is parallel to the transverse direction of pultrusion and \(F_{br}^{90}\) is the lowest pin-bearing strength. It has been
recommended in the LRFD pre-standard that for $\theta$ between $0^\circ$ and $90^\circ$ the pin-bearing strength be the $0^\circ$ ($F_{0}^{br}$) value when $0^\circ < \theta < 5^\circ$, and it is the $90^\circ$ ($F_{90}^{br}$) value for $\theta > 5^\circ$.

To verify this mandatory guidance we need to have characteristic strengths for different orientations that can allow the strength variation from $0$ to $90^\circ$ to be obtained from curve fitting. In a previous paper Mottram and Zafari [6] determined the characteristic pin-bearing strengths of the same web material at the three orientations of $0$, $45$ and $90^\circ$.

In this paper new test results will be presented when loading is oriented at $5$, $10$, and $20^\circ$ to the direction of pultrusion using the same pultruded material, same test matrix (for other variables) and same test method. To enable the strength variation with $\theta$ to be established these three orientations were chosen because the authors’ previous test results [6] showed that there is a relatively small strength reduction between the orientations of $45$ and $90^\circ$.

2. MATERIAL AND TEST PROCEDURE

Specimens are cut from a $203 \times 203 \times 9.53$ mm wide flange shape having a web depth of $180$ mm. The Creative Pultrusions Inc. [1] product is from the 1525 series having a filled isophthalic polyester polymer, and the sections had been pultruded in the 1990s. E-glass reinforcement is in the form of alternative layers, but not necessarily continuous or of constant thickness, of unidirectional (UD) rovings and continuous strand mats [2, 4].

Testing is performed with four pin diameters ($9.7$, $12.2$ $18.8$ and $25.4$ mm) that are permitted in practice. These pin represented the smooth shafts of steel bolts of diameters $3/8$ in., $1/2$ in., $3/4$ in. and $1$ in., respectively. The diameter of the hole is larger than the pin diameter, giving a clearance hole in excess of the minimum of $1.6$ mm ($1/16$th in.) specified in the LRFD pre-standard (taken from the pultruders’ design manuals [1, 2]). Strength testing is carried out under ambient laboratory conditions (about $20^\circ$C).

Figure 2 shows an in-house compression die set with fixtures to apply compressive loading. The specimen in the figure has material orientation of $45^\circ$ to the bearing load [6]. The maximum force for bearing failure is defined by notation $R_{br, test}$ in the figure and its value is back substituted into Eq. (1) to determine $F_{0}^{br}$. In Figure 2 the pin, cut from the smooth shank of a black steel bolt (Grade 8.8), has diameter of $25.4$ mm ($1$ in.). The specimen holder accommodates the nominal specimen thickness of $9.53$ mm and is required to maintain the specimen vertical, and to provide it with a degree of lateral restraint against out-of-plane flexural deformation. The width of the specimen is constant at $100$ mm. The height of the specimen can be varied and is set at $100$ mm because experience has shown that this height ($e_1$), which is four times $25$ mm, does not affect the maximum load for bearing failure.

For each of the three orientations of $5$, $10$ and $20^\circ$ there are four batches, comprising the following pairs of nominal hole diameters ($d_n$) and pin diameters ($d$): $12$ mm and $9.7$ mm; $15$ mm and $12.2$ mm; $21$ mm and $18.8$ mm and $28$ mm and $25.4$ mm. Web thickness per specimen was measured to the nearest $0.05$ mm with an outside micrometer, and $t$ is found to have a mean in the range of $9.18$ to $9.24$ mm. The mean thicknesses per batch are given in the first row in Tables 1 to 3 and the mean measured diameters ($d$ and $d_n$) and mean hole clearance ($d_n - d$) are given in rows two to four. Number of nominally identical specimens per batch is from $10$ to $13$ and this batch property is reported in the fifth row of the tables.

Compression load is applied under a constant stroke rate of $-0.01$ mm/s using a DARTEC 9500 hydraulic testing machine with a $250$ kN load cell. To establish the maximum compressive force at failure, $0.338$ kN is added to the maximum machine reading to allow for the dead weight of the top plate and rocker transfer fixture.
A National Instrument data acquisition system is used to monitor the load and stroke in real time. To reach the failure load the duration of testing can be 120 seconds.

![Figure 2. Warwick University (WU) pin-bearing strength test rig with specimen.](image)

### 3. TEST RESULTS AND DISCUSSION

Tables 1 and 3 present the test results, with the ordering for orientations of 5, 10 and 20°. Strengths are given in units of N/mm² (MPa) and specimen results have been determined by Eq. (1) with maximum test load $R_{br, test}$ and measured $d$ and $t$. For each batch the mean, standard deviation and Coefficient of Variation (CV) are given in rows six to eight on the assumption that the strength population fits the Gaussian distribution. Characteristic values in row nine are determined using the guidance in Annex D7 (General principles for statistical evaluation) of Eurocode 0 (BS EN 1990:2002 [7]), and they maybe associated with a pin-bearing strength when using Eq. (1) to design a bolted connection. The CV is typically between 5 and 10% which implies it is known. The tenth and final row entries in the tables give the mean pin diameter-to-material thickness ratios ($d/t$).

Comparing the pin-bearing strength for 0° material [6] with test results of 5, 10 and 20° it is found that the strength has reduced by about 2.5%, 6% and 10%, respectively, if we take the mean of the characteristic strengths for the four different pin diameters. The small reduction of strength value at 5° gives evidence to what is currently proposed in the LRFD pre-standard [3]. This is to accept the pin-bearing strength as the $F_0^{br}$ when $0° < θ < 5°$. These results also show that for orientations of 20° and 45° the percent of strength reduction is still < 10% so there is a penalty, on the safe side, for taking the 90° strength for all orientations > 5°.

Plotted in Figure 3 are typical specimen stress-stroke curves for 20° and for each of the four pin diameters. It can be seen that the stress-stroke curves are virtually linear until the maximum load is attained. The sudden load reduction that occurs signifies the start of the delamination damage for bearing failure, and the degree of reduction reduces in magnitude with increase of pin diameter ($d$). This sudden reduction in load, at onset of bearing failure, is found to be less at 20° than for the specimens with orientations of 0, 5 and 10°; this is an expected finding as the unidirectional fibre reinforcement is becoming less dominant. Figure 3 shows that when the pin diameter is 25.4 mm its curve is also fairly linear to the maximum load. This is also true for the four hole diameters when the orientation is 5° and with pins of 18.8 and 25.4 mm diameter at 10°. In Figure 3 the shape of the curves with pin diameters of 9.7, 12.2 and 18.8 mm show a form of ‘ductility’. Also the maximum load for the two larger pins is slightly higher than at first peak (for initiation of bearing failure). For the case of the
smallest pin diameter the stress-stoke plot shows that the maximum load is, actually, significantly higher and this might have an influence on the statistical strengths calculated.

Table 1. Statistical test results for 5° pin-bearing strengths using the WU test approach with web material from a 203 × 203 × 9.53 mm wide flange shape.

<table>
<thead>
<tr>
<th>PIN ORIENTATION</th>
<th>WEB MATERIAL</th>
<th>MEAN WEB THICKNESS, t (mm)</th>
<th>MEAN NOTCH DIAMETER, dₙ (mm)</th>
<th>MEAN PIN DIAMETER, d (mm)</th>
<th>MEAN CLEARANCE, dₙ - d (mm)</th>
<th>NUMBER OF NOMINALLY IDENTICAL SPECIMENS</th>
<th>MEAN PIN-BEARING STRENGTH, F₅br (N/mm²)</th>
<th>SD (N/mm²)</th>
<th>CV (%)</th>
<th>CHARACTERISTIC VALUE* (N/mm²)</th>
<th>MEAN d/t RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>5°</td>
<td>5° web material</td>
<td>9.18</td>
<td>12.0</td>
<td>9.7</td>
<td>2.3</td>
<td>10</td>
<td>179</td>
<td>7.4</td>
<td>4.1</td>
<td>166</td>
<td>1.06</td>
</tr>
<tr>
<td>10°</td>
<td>10° web material</td>
<td>9.20</td>
<td>14.9</td>
<td>12.2</td>
<td>2.7</td>
<td>11</td>
<td>178</td>
<td>11.6</td>
<td>6.5</td>
<td>158</td>
<td>1.06</td>
</tr>
<tr>
<td>20°</td>
<td>20° web material</td>
<td>9.24</td>
<td>21.1</td>
<td>18.8</td>
<td>2.3</td>
<td>11</td>
<td>175</td>
<td>12.4</td>
<td>7.1</td>
<td>154</td>
<td>1.05</td>
</tr>
</tbody>
</table>

* Mean – 1.72SD

Table 2. Statistical test results for 10° pin-bearing strengths using the WU test approach with web material from a 203 × 203 × 9.53 mm wide flange shape.

<table>
<thead>
<tr>
<th>PIN ORIENTATION</th>
<th>WEB MATERIAL</th>
<th>MEAN WEB THICKNESS, t (mm)</th>
<th>MEAN NOTCH DIAMETER, dₙ (mm)</th>
<th>MEAN PIN DIAMETER, d (mm)</th>
<th>MEAN CLEARANCE, dₙ - d (mm)</th>
<th>NUMBER OF NOMINALLY IDENTICAL SPECIMENS</th>
<th>MEAN PIN-BEARING STRENGTH, F₁₀br (N/mm²)</th>
<th>SD (N/mm²)</th>
<th>CV (%)</th>
<th>CHARACTERISTIC VALUE* (N/mm²)</th>
<th>MEAN d/t RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>5°</td>
<td>5° web material</td>
<td>9.18</td>
<td>12.0</td>
<td>9.7</td>
<td>2.3</td>
<td>10</td>
<td>179</td>
<td>7.4</td>
<td>4.1</td>
<td>166</td>
<td>1.06</td>
</tr>
<tr>
<td>10°</td>
<td>10° web material</td>
<td>9.20</td>
<td>14.9</td>
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<td>2.7</td>
<td>11</td>
<td>178</td>
<td>11.6</td>
<td>6.5</td>
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<tr>
<td>20°</td>
<td>20° web material</td>
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<td>2.3</td>
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<td>175</td>
<td>12.4</td>
<td>7.1</td>
<td>154</td>
<td>1.05</td>
</tr>
</tbody>
</table>

* Mean – 1.72SD

Table 3. Statistical test results 20° pin-bearing strengths using the WU test approach with web material from a 203 × 203 × 9.53 mm wide flange shape.

<table>
<thead>
<tr>
<th>PIN ORIENTATION</th>
<th>WEB MATERIAL</th>
<th>MEAN WEB THICKNESS, t (mm)</th>
<th>MEAN NOTCH DIAMETER, dₙ (mm)</th>
<th>MEAN PIN DIAMETER, d (mm)</th>
<th>MEAN CLEARANCE, dₙ - d (mm)</th>
<th>NUMBER OF NOMINALLY IDENTICAL SPECIMENS</th>
<th>MEAN PIN-BEARING STRENGTH, F₂₀br (N/mm²)</th>
<th>SD (N/mm²)</th>
<th>CV (%)</th>
<th>CHARACTERISTIC VALUE* (N/mm²)</th>
<th>MEAN d/t RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>5°</td>
<td>5° web material</td>
<td>9.18</td>
<td>12.0</td>
<td>9.7</td>
<td>2.3</td>
<td>10</td>
<td>179</td>
<td>7.4</td>
<td>4.1</td>
<td>166</td>
<td>1.06</td>
</tr>
<tr>
<td>10°</td>
<td>10° web material</td>
<td>9.20</td>
<td>14.9</td>
<td>12.2</td>
<td>2.7</td>
<td>11</td>
<td>178</td>
<td>11.6</td>
<td>6.5</td>
<td>158</td>
<td>1.06</td>
</tr>
<tr>
<td>20°</td>
<td>20° web material</td>
<td>9.24</td>
<td>21.1</td>
<td>18.8</td>
<td>2.3</td>
<td>11</td>
<td>175</td>
<td>12.4</td>
<td>7.1</td>
<td>154</td>
<td>1.05</td>
</tr>
</tbody>
</table>

* Mean – 1.72SD

In Figure 4 the characteristic strengths from Tables 1 to 3 are plotted against the mean bolt diameter-to-material thickness ratio (d/t). It is assumed that there is a linear variation between the data points. The legend defines the plots that are for 5, 10 and 20° orientations with solid lines and for the 0, 45 and 90° orientations, taken from [6], with coloured dashed lines. As the d/t ratio increases from 1.05 to 2.76 the pin-bearing strength is seen to reduce. The trend of the strength reduction, for all six orientations, might be modelled as linear, but confirmation
does require more test results. The trends also highlight that there is a relatively small change between 5 and 0° and that their curves have a tendency to coincide for the highest d/t ratios. It is seen that the two curves for characteristic strength at 20 and 45° cross each other.

Figure 3. Pin-bearing stress with stroke curves for web material at 20° material orientation and four pin diameters in mm.

Figure 4. Characteristic pin-bearing strengths (in N/mm²) of web material with d/t ratio and hole clearance of 2.2 mm or larger.

Figure 5 shows five plots for a normalised mean pin-bearing strength against material orientation. The normalisation is calculated using the 0° mean value. There are two experimental curves for using \( F_{0}^{br} \) measurements from Tables 1 to 3 and reference [6], after the occasional specimen outlier had been removed from a batch. The means at the six orientations are given by square markers. The two dashed curves with the same 0 and 90° values, from the test results [6], are plotted for pin diameters of 9.7 and 18.8 mm using the Hankinson’s formula [8]. The normalised form of this formula is

\[
\frac{F_{0}^{br}}{F_{0}^{br}} = \frac{F_{90}^{br}}{F_{0}^{br}} \left( \sin^{2}\theta + \frac{F_{90}^{br}}{F_{0}^{br}} \cos^{2}\theta \right).
\]  (2)
Eq. (2) is a mathematical relationship that has successfully been used to predict the off-axis dowel or pin-bearing strength of timber. It is for this reason that Eq. (2) is given for the dowel strength in the American design standard (ASCE-16-95) for engineered wood construction [9]. Its existence might suggest an application with fibre reinforced polymer materials. The curve with the lowest normalized strength, at all orientations, has been plotted using the test results of Ascione, Feo and Maceri [10] for a glass fibre/epoxy plate laminate of 10 mm thickness. Their FRP plate was made using a vacuum moulding process; it is not a pultruded material. In this independent testing for the variation of pin-bearing strength with material orientation the nominal hole and pin diameters are 21 and 20 mm, respectively. Ascione et al. employed their own test method as described in their paper, and measurements were made at the 16 material orientations of 0, 1, 3, 5, 7, 10, 15, 20, 25, 30, 35, 40, 45, 60, 75 and 90°.

![Figure 5. A comparison for Hankinson formula [8] with Warwick University (WU) and Ascione et al. [10] normalised pin-bearing strengths with material orientation from 0 to 90 degrees.](image)

The shape of the curves generated from the Ascione et al. and WU test results in Figure 5 show a similarity that cannot be determined using the Hankinson equation. Whereas Eq. (2) predicts a very gradual fall-off in strength with orientation, the three experimentally derived curves show that it falls away much more rapidly before levelling off at higher orientations (>45°). Perhaps, because of too few data points, the WU generated curves show a ‘wavy’ profile on curve fitting. It can be seen that the Ascione et al. data, with 16 points, gives a smooth and continuous profile from \( F_0^{br} \) to \( F_{90}^{br} \). It can be shown that to establish a curve fit, having an acceptable correlation coefficient, requires a polynomial of order six. This order would not be suitable as for the pin-bearing strength formula in a standard for routine design calculations.

4 CONCLUDING REMARKS

Reported are characteristic values for pin-bearing strengths of a pultruded material at the three orientations of 5, 10 and 20° for four pin diameter-to-material thickness ratios in the range of 1.05 to 2.76. To represent site application a clearance hole (>1.6 mm) is present. By plotting characteristic values it is found that strength decreases with increase of this ratio. The trend might be linear, but confirmation requires more test results. The mean test results show an insignificant reduction in strength in going from 0 and 5° and that, at the highest \( d/t \) ratios,
there is a tendency for their means to coincide. This finding does not contradict the current proposed design guidance in an American pre-standard [3] to use the 0° characteristic value for orientations between 0 and 5° and the 90° strength for all other orientations.

In America, the engineered wood construction standard [9] offers the Hankinson strength formula to calculate dowel strength with orientation of the connection force to the grain of timber. By using normalized plots it is shown that the variation of pin-bearing strength of the pultruded material cannot be predicted by this simple formula, which requires only the 0 and 90° strengths to be determined by a standard test method. Moreover, the same poor correlation is found on comparing the Hankinson curve with independent results for a different fibre reinforced polymer material that had pin-bearing strength measured by a different test method. To establish a curve fit to the strength variation with orientation of fibre reinforced polymer material requires a polynomial of order six. This high-order of expression would not be suitable for a strength formula in a standard.

5 ACKNOWLEDGMENTS

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6 REFERENCES