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Pin-bearing Strengths for Bolted Connections in FRP Structures

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Summary

Presented in this paper are pin-bearing strengths for pultruded fibre reinforced polymer materials that are required to check for the bearing resistance when designing bolted connections. For steel pin diameters up to 16 mm equivalent test results, at room temperature, using the European standard test method BS EN 13706-2 and a test method (like ASTM D 5764) are shown not to be significantly different. Because the latter method uses much smaller specimen blanks new pin-bearing strengths can be determined for the web material in a 203 x 203 x 9.5 Wide Flange shape, with the connection force at 0^{o}, 45^{o} or 90^{o} to the direction of pultrusion. An evaluation is made of the test results and recommendations given on how pin-bearing strengths are to be determined so that they will match the geometries of bolted connections and connection forces found in practice.

Keywords: Codes of practice & standards, FRP composite structures, Strength and testing of material.

Notation

d	Bolt diameter, mm
d_n	Hole diameter, mm
e_1	End distance, mm
e_2	Side distance, mm
t	Constant thickness of FRP material, mm
w	Constant plate width for single bolted connection with $e_2 = w/2$, mm
F_{θ}^{br}	Pin-bearing strength for the orientation of the resultant force at the bolt/FRP contact with respect to the direction of pultrusion, MPa
F_{0}^{br}	Pin-bearing strength in the longitudinal (0^{o}) direction of pultrusion, MPa
F_{45}^{br}	Pin-bearing strength for 45^{o} to the direction of pultrusion, MPa

F_{90}^{br}	Pin-bearing strength in the transverse (90^{o}) direction of pultrusion, MPa
R_{br}	Pin-bearing strength (resistance) per bolt, kN
$R_{br,test}$	Compressive force using the Warwick University test arrangement, kN
R_{n}	Nominal (design) strength (resistance) for bolted connection, kN

Introduction

In 2007 the American Society of Civil Engineers (ASCE) and the American Composites Manufacturers Association (ACMA) signed a three-year agreement to develop a pre-standard for the *Load and Resistance Factor Design (LRFD) of Pultruded Fiber-Reinforced Polymer (FRP) Structures*. When published this LRFD standard is expected to help structural engineers and architects use pultruded FRP composites (standard shapes) in building and transportation designs and bring benefits, such as its strength-to-weight ratio, resistance to corrosion, low maintenance and long life cycle, to US infrastructure (Anonymous, 2007).

Pultruded standard shapes consist of a number of thin-walled panels of glass fibre reinforced polymer matrix connected to form open or closed cross-sections. I, Wide Flange (i.e., an H cross-section), channel, leg-angle shapes (or profiles) mimic steel sections, and so it is natural that construction follows what is seen in conventional steelwork (Turvey, 2000; Bank, 2006; Anonymous 2011a,b). Being lightweight and resistant to corrosion pultruded shapes and structures are increasingly used where these attributes meet the clients' requirements.

Standard shapes (Turvey, 2000; Bank, 2006; Anonymous, 2011a,b) are reinforced with E-glass fibres and possess a matrix often based on a polyester or vinyl ester thermoset resin with fillers and additives. Each panel has an outermost layer of a thin protective veil, which does not provide reinforcement. The first reinforcement layer is often of Continuous Filament (or Strand) Mat (abbreviation CFM (or CSM)). This is followed by alternate layers of unidirectional (UD) rovings and CFM forming the material's core. Because each profile has its own layered construction the directional elastic constants and material strengths of the orthotropic fibre reinforced material will change accordingly (Bank, 2006; Anonymous, 2011a,b), and this poses a challenge when mean or characteristic properties are required for the preparation and application of design formulae in the LRFD pre-standard (Anonymous, 2011c).

The main class of construction that will be designed by the LRFD pre-standard is for non-sway braced frames that have simple shear joints between main members and bracing to transfer lateral loads to the ground. A simple joint can be assumed not to transmit bending moments. The method of connection is by steel bolting (there is no adhesive bonding), and so the types of connections scoped will correspond to the engineering drawings in in-house design manuals (see, e.g. Figure 1), independently prepared by American pultruders (Anonymous, 2011a,b). Bank (2006) and Turvey (2000) show applications of such bolted connections in frame structures of pultruded shapes. Chapter 8 in the pre-standard (Anonymous, 2011c) is therefore for the design of such bolted connections, and the first author was a member of the drafting team.

To scope the types of connections and joints the bolted connection chapter combines the need to design for frame joints, such as the web-cleated type shown in Figure 1 (will classify as simple), with the design of plate-to-plate connections, such as there is for the beam's web and in each of the two legs for the web cleat shown in the figure. The beam shape in Figure 1 can be used to define the orientations of the material with the 0^o (or longitudinal) direction coincident with the direction of pultrusion of the beam. The 90^o (or transverse) direction is normal to the pultrusion direction, within the plane of the panels forming the thin-walled shape. An orientation of 45^o is for the angle half way between the 0^o to 90^o directions. For a pultruded web-cleat in Figure 1 the orientations for the 0^o and 90^o directions will be rotated through ninety degrees relative to their directions in the beam shape.

In this paper, we shall consider the connection building block for joints, which comprises bolting and two or more thicknesses of material. We shall restrict the discussion to plate-to-plate connections having the double lap-shear configuration, and with in-plane loading. It is well-known that such bolted connections of pultruded material fail ultimately in one of a number of failure modes (e.g. bearing, shear-out, cleavage, net-tension and block shear). In design, the size of the steel bolting is chosen such that failure, either by bolt rupture or bolt pull-through, should not occur (Mottram and Turvey, 2003). The sketches in Figure 2 show the simplified stress distributions and fracture paths for these distinct plate-to-plate modes of failure (for tension loading). Mix modes (e.g. when the connection force is off-axis with respect to the direction of pultrusion) are possible and block-shear is a mode when there are multiple rows of bolts (Mottram and Turvey, 2003).

For the basic connection building block of a single-bolted situation the plate is of constant thickness t and constant width w, which is twice the edge (or side) distance e_2 because the bolt is centrally placed. Other relevant geometric parameters 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 (2003) used the results from series of tests to observe that the mode of failure will change on varying the geometric ratios e_1/d (or e_1/d_n) and w/d (or w/d_n), with $w = 2e_2$. To promote failure of the single bolted connection in the bearing mode these two geometric ratios need to be four or higher when the FRP material is pultruded.

Bearing (mode in Figure 2(a)) is the only one of the 'distinct' modes that does not always give a brittle failure response, and can be used to provide the bolted connection with a degree of damage tolerance; this is desirable in design because it imparts structural integrity into the design (Mottram and Turvey, 2003; Thoppul *et al*., 2009). It is also the mode of failure with a strength formula (Bank, 2006) that requires its 'own' material strength property (F_{θ}^{br}), and the formula per bolt is

$$R_{\mathrm{br}} = t\,d\,F_{\theta}^{\mathrm{br}}\,. \tag{1}$$

Using LRFD standard language the pin-bearing strength (R_{br}) by Equation (1) is given by the projected area of bolt bearing multiplied by the characteristic pin-bearing strength (F_{θ}^{br}) for the orientation (θ) of the resultant force at the bolt/FRP contact with respect to the direction of pultrusion. When designing a bolted connection, such as shown in Figure 1, bearing strength (in kN) is to be the sum of the appropriate R_{br}s calculated using Equation (1) multiplied by the number of bolts for each of the different pin-bearing strengths per bolt. Clearly, if the bolt and hole sizes are constant then only a single R_{br} is to be calculated.

When the connection force is aligned with the longitudinal direction of pultrusion we have $\theta = 0^{\mathrm{o}}$, and F_{0}^{br} is the highest pin-bearing strength. If $\theta = 90^{\mathrm{o}}$ the force is coincident with the transverse direction and F_{90}^{br} is the lowest pin-bearing strength. In the pultruders' manuals (Anonymous, 2011a,b) the 0^{o} direction is referred to as LengthWise (LW) and the 90^{o} direction as CrossWise (CW). For the web connection in Figure 1 the nominal pin-bearing strength (resistance) is $2R_{br}$, with the terms in Equation (1) to be $F_{\theta}^{br} = F_{90}^{br}$, t = 9.53 mm (3/8 in.) and d = 9.53 mm (3/8 in.), or 12.7 (1/2 in.) or 15.85 mm (5/8 in.).

By definition the pin-bearing strength (F_{θ}^{br}) is the mean stress over the bearing area at bearing failure (however the failure load is defined, and there are several choices (Johnson and Matthews, 1979), as shown in Figure 3), when there is no lateral restraint. It is further assumed that when measuring F_{θ}^{br} there is no bolt thread bearing against the FRP material. It is important to emphasize that for the bearing strength to be the pin value there must be no tightening of the bolting. It is well-known that bearing strength increases significantly on tightening, because a torqued steel bolt provides stiffness to oppose the 'free' through-thickness deformation (Cooper and Turvey, 1995; Mottram, 2004). Other factors not already mentioned that influence the bearing strength are; the fibre reinforcement architecture, material thickness and orientation, the bolt-flexibility, the presence of thread in contact with the bearing surface, the bolt diameter-to-thickness (d/t) ratio, the size of the clearance hole and environmental conditioning.

The strength equations for the other distinct failure modes shown in Figure 2 require one or two material strengths (such as those tabulated in Anonymous (2011a) and Anonymous (2011b)), and appropriate values may be determined by using, for example, an ASTM standard test method.

Historical Review of Test Methods for Pin-bearing Strength

A historical review of standard test methods will be used to show that there is a lack of consistency in how pin-bearing strengths of pultruded materials have been measured. Prior to giving the review, it is appropriate first to summarise the likely scope of bolted connections by way of the LRFD pre-standard chapter. Material thicknesses are to be in the range from 6.35 mm (1/4 in.) up to, and, perhaps, including 25.4 mm (1 in.). Standard pultruded shapes (Bank, 2006, Anonymous, 2011a,b) are to be either of flat sheets or structural cross-sections (I, H, leg-angles, etc.); with the structural shapes having the higher volume fraction of UD rovings. This unidirectional E-glass reinforcement is aligned with the longitudinal (0^{o} or LW) direction. Although not completely excluded in practice, it will be assumed in this presentation that there is no or little of the bolt thread in bearing. Bolts and nuts will be to ASTM standards A193, A304, A307 and A316 and the range of bolt diameters, d, is from 9.53 mm (3/8 in.) up to, and including 25.4 mm (1 in.). Hardened flat circular washers are to have an outer diameter at least twice the nominal bolt diameter, and at least one washer is to be used at the head of the bolt and at the nut. Bolts are to be torqued to the snug-tightened condition. Guidance for setting this bolt tensioning is not specified in the LRFD pre-standard. The nominal hole diameter, d_n, is to be a minimum of 1.6 mm (1/16 in.) larger than the nominal bolt diameter, d, and holes are to be drilled or reamed. The hole clearance is therefore in the range $0.06d_n$ to $0.14d_n$ as the bolt diameter reduces from 25.4 to 9.53 mm.

With such a wide scope in connection details permitted by the pre-standard chapter we need confidence in published pin-bearing strengths to be used with Equation (1). So why did the writers of Chapter 8 (Bolted connections) specify a pin-bearing strength in Equation (1) when the LRFD pre-standard specifies that the bolting is to be snug-fit? The beneficial effect of bolt tightening on bearing strength (Cooper and Turvey, 1995) has to be off-set by its long-term reduction due to creep relaxation (Thoppul *et al*., 2009; Mottram, 2004) and from other possible influences to durability over the intended service life of pultruded structures, which will be in tens of years. To ensure that a bolted connection should not fail prematurely it was deemed prudent by the pre-standard writers for the bearing strength per bolt to be calculated using Equation (1) with the 'lowest' characteristic strength that can exist in practice, and this is the pin-bearing strength that accounts for all detrimental affects.

Although historical bearing strengths are reported (Wang, 2004; Lutz, 2005, Anonymous, 2011a,b) their provenance is not always in the public domain and significant differences in values may be partially explained by differences in materials and test methods. Another reason for observed differences is the seven possible ways of defining failure load from the load-stroke plot, which can be recorded during the bearing strength test. Figure 3 shows a typical bearing load against measured extension (stroke) plot based on 1970s research by Johnson and Matthews (1979). Consideration of this curve suggests that there are seven ways of defining failure load, and these are:

(a) The maximum load. Usually considerable damage may have occurred in reaching this load.

(b) The first peak in the load/extension plot. Damage sustained up to this load is not insignificant.

(c) The load corresponding to a specified amount of hole elongation; which has been specified at various percentages up to 4% (ASTM D 953-02, 2002; MIL-HDBK-17-3F, 2002; ASTM D5961-05, 2005; Thopull *et at*., 2009)

(d) The load at which the load/extension curve first deviates from linearity. The point at which this occurs is usually difficult to establish.

(e) The load at which cracking first becomes audible. Specimens examined at this point would show visible cracks around the loaded side of the bolt hole.

(f) The load at which cracking is initiated. This load is probably quite low and very difficult to determine.

(g) The load at which cracks become visible outside the washers.

Towards the end of the review we will return to the question of which failure load is to be used when determining a pin-bearing strength for Equation (1).

The Pultrusion Industry Council (PIC) of ACMA recommends that bearing strengths be determined in accordance with D 953–02 (2002). This ASTM (American) standard was first published in 1948, and its previous edition was published in 1995. Introduced next are the specific features to the D 953 test method that deviate from the bolted connection details permitted by the LRFD pre-standard chapter. Its scope is actually for rigid plastics, in either sheet or moulded form. In other words, the 2002 edition is not necessarily suitable for the testing of pultruded materials. This test method, and its tensile Procedure A (fixture for the double lap-shear loading is shown in Figure 4), uses a hardened steel pin (no lateral constraint) of nominal diameter 6.325 mm (d) and a maximum hole diameter of $d_n = 1.012d$. This geometry has a maximum hole clearance of only $0.012d_n$, many times smaller than the minimum of $0.06d_n$ permitted by the LRFD standard. Testing is conducted under stroke control at a displacement rate to make the loading static. Test specimen (No. 6 in Figure 4) thickness is specified at 6.4 mm, the edge distance ratio is 3 (e_1/d) and side distance (e_2) is 1.85d. The length of material behind the hole with the bearing pin (No. 5 in Figure 4) is 100 mm (part of this length is used for load transfer gripping). The extensometer span (No. 4 in Figure 4) is the length of the straight-sided coupon used to measure the deformation that gives the load for the pin-bearing strength when the hole is deformed by 4% of its diameter (see Figure 3). This strength measure (Mottram and Turvey, 2003; Anonymous, 2011b; Thoppul *et al*., 2009) is for failure load (c) in Figure 3 and is known as the 4% hole deformation bearing strength. The LRFD writers have doubts about its reliability.

Back calculation using Equation (1) is the procedure employed to obtain a strength measurement; it is this procedure that the authors use to obtain pin-bearing strengths by testing. D 953 has been adopted by the American pultruders and its application provides the maximum bearing strengths reported in their design manuals (Anonymous, 2011a,b).

A second ASTM standard for bearing strength is D 5961-05 (2005), and as its title suggests it was written to be used with laminated FRP composites, commonly found in non-construction applications. It is not a coincidence therefore that it is consistent with the recommendations in MIL-HDBK-17 (2002), and that we find the test requirements correspond to how aircraft bolted connections are fabricated. It has provisions for coupon testing with both the double and single lap-shear configuration. Specified specimen geometry and fastener diameter are not too different from D 953-02, with $e_1/d = 3$, $w/d = 6$ and laminate thickness t between 3 and 5 mm. Bearing load is normally applied through a close-tolerance, lightly torqued (2.2-3.4 N.m (20-30 lbf-in.)) metallic fastener of diameter 6 mm. The ultimate bearing strength of the material is determined from the maximum load (point (a) in Figure 3); there is a provision also for determining an offset bearing strength (2% is used in D 5961). Because this test standard is to be used with materials for which the laminate is balanced and symmetric with respect to the load direction the bearing mode is most likely to occur with $e_1 = 3d$; it is noteworthy that for the bearing mode to govern with pultruded materials a bigger end distance ratio is usually required.

Since 2002 there has been a European EN in three parts for *Reinforced Plastics Composites - Specification of Pultruded Profiles*, with Annex E in Part 2 (BS EN 13706-2:2002) describing a tensile test procedure for pin-bearing strength. This double lap-shear test method (same as shown in Figure 4) does not define failure by a percentage of hole deformation, and requires only the determination of the maximum stress from the maximum load (this is similar to D 5961-05 and uses point (a) in Figure 3). BS EN 13709-2 requires a similar specimen to Procedure A in D 953-02, but with the geometrical ratio e_1/d_n doubled, at 6, and e_2/d_n increased to 3. Hole diameter is to be 6±0.2 mm; the diameter of pin (i.e. a bolt without any lateral constraint) is actually not specified, but is believed to have a nominal diameter of 6 mm, for a close fit. It is important to understand that the absence of a clearance hole from the standard test methods is a major deviation from what the LRFD pre-standard (Anonymous, 2011c) specifies for the design of bolted connections.

In Part 3 of BS EN13706-3:2002 there is a table to report minimum properties that are required, for two grades of pultruded material. From this table we are informed that the minimum pin-bearing strengths of F_0^{br} and F_{90}^{br} (in N/mm^2) are 150 and 70 for Grade 23, and 90 and 50 for Grade 17 (the material grade number gives the minimum longitudinal tensile modulus of elasticity or LengthWise tensile modulus). It may be assumed that the higher material grade is for structural shapes and that the lower is for flat sheets; although this association is not strong.

The two American standards and the single European standard recommend a sample size of five; which is not large when a statistical analysis (ASTM D 7290-06 (2006) requires a minimum of ten specimens per batch) is required to establish a characteristic strength. Because the three standard test methods were not written concurrently with the drafting of a structural standard for the design of pultruded FRP structures their specifications ensure that some required (pin) bearing strengths cannot be measured and when they can be, they may not be acceptable for F_θ^{br} in Equation (1). The reasons for this finding will further be developed and discussed in the rest of this paper.

Having reviewed what the three standard test methods offer a valid test method requires a relevant definition for the failure load. Earlier in the historical review the seven different failure load definitions from Johnson and Matthews (1979) are listed. Failure loads (d) to (g) have not been observed with pultruded materials when the test method is for the pin-bearing strength. Failure load (c) is dependent on the length of gauge used to measure hole elongation and at 4% (for D 953) the elongation can be too high for pultruded materials. Testing for F_0^{br} always gives load-stroke plot curves without a failure load (b), and so by virtue of elimination the pin-bearing strengths for Equation (1) in the LRFD pre-standard chapter should always be determined using failure load (a), the maximum load (it is usually the load for failures giving failure loads, (b), (e) and (f)). This complies with what is required by testing to ASTM D 5961-02 and BS EN 13706-2:2002.

A Test Method for Pultruded Structural Shapes

To be able to characterise the pin-bearing strength for the LRFD pre-standard it will be necessary to test with pin sizes up to the maximum permitted bolt diameter. Applying any of the three test methods introduced above it will be necessary, when the bolt diameter is 25.4 mm (1 in.), for the length of the double-lap specimen (see item 6 in Figure 4) to be 300 mm or higher. For this biggest bolt diameter the specimen width ought to be 150 mm (i.e. 6*d*). Such a specimen size (0.3 by 0.15 m) can readily be cut from 'off-the-shelf' flat sheets (Anonymous, 2011a,b) of 1.828 by 1.21 m (6 ft. by 4 ft.) to determine F_{θ}^{br} for any orientation required. This specimen size, however, cannot readily be accommodated in the longitudinal direction ($\theta = 0^{\mathrm{o}}$) with many structural shapes (see Figure 1 and examples in Turvey (2000), Bank (2006) and Anonymous, (2011a,b)), and definitely is far too big, and remains so, even with the smallest bolt diameter of 9.53 mm (3/8 in.), when the direction of loading is in the transverse direction (for $\theta = 90^{\mathrm{o}}$).

To overcome the tensile specimen dimension limitation when characterising orthotropic material from a structural shape (or profile in EN 13706) Clause 6 to the *Preparation of plates and test specimens* in Part 2 of EN 13706 gives "…a test plate can be used to simulate the pultrusion for the determination of the laminate properties for design…" To the authors' knowledge this approach is not practiced and so a test method is very desirable that has a reduced specimen size to remove the dimension limitation with the tensile specimen of the current standard test methods.

A preliminary study by Mottram (2009) presents a comparison for a longitudinal pin-bearing strength (F_0^{br}) determined using two test methods. One is in the spirit of EN 13706-2 (Figure 4) and the second, using the test arrangement shown in Figure 5, requiring a much smaller compression specimen is found to be in the spirit of the timber test method ASTM D 5764-97a (reapproved 2007). The load arrangement has previously been used by Wang *et al*., (1996) to characterise bearing strengths of laminated FRPs for the aerospace industry. The Warwick University test arrangement is shown in Figure 5. It is based on compressing a pin into a small rectangular specimen with a semi-circular notch held vertically by a specimen holder having uniform grooves in the side walls to accommodate the material thickness. This approach to apply the pin bearing force removes the tensile specimen size problem. Mottram (1994) gives a description of how the compression 'die set' in Figure 5 is used to subject a compression coupon to pure compression for determination of compression strength.

The material, of nominal thickness 6.35 mm (1/4 in.), was pultruded by Creative Pultrusions Inc. (Anonymous, 2011a) and is from the 1625 series of flat sheets. It consists of E-glass fibre reinforcement in a thermoset Vinyl Ester (Class 1 FR) based matrix. This series of flat sheets, with thicknesses from 3.18 mm (1/8 in.) to 25.4 mm (1 in.), have the following reported mechanical properties in the longitudinal (0° or LengthWise) direction: compression modulus (D 695) = 12.4 kN/mm^2; compression strength (D 695) = 165 N/mm^2; bearing strength (D 953) = 220 N/mm^2 (it is actually a pin-bearing value).

The number of nominally identical specimens per batch of specimens was six (Mottram, 2009). There were twelve batches, six for each of the two test arrangements, and with the six comprising of the three pin diameters (d) of 8, 12 and 16 mm, with and without a hole clearance of nominally 1 mm (which is 0.6 mm below the minimum value given in the LRFD pre-standard). The actual measured mean diameters (d) of the pins, cut from metric steel bolts (Grade 8.8), were 7.84, 11.84 and 15.8 mm. The six nominal hole diameters (d_n) were 8, 9, 12, 13, 16 and 17 mm and their mean measured values were (to nearest 0.05 mm) 7.75, 8.80, 11.80, 12.8, 15.7 and 16.8 mm, respectively. Note that tolerances in drilling mean the holes were undersized by up to 0.3 mm. In Mottram (2009) each batch was labelled, with WU09 for specimens having a 9 mm diameter hole, loaded with the Warwick University (WU) test arrangement of Figure 5, while EN17 is for the 17 mm hole diameter, loaded using the EN 13760 test arrangement (Figure 4). Specimen thicknesses were measured to the nearest 0.05 mm with an outside micrometer, and t was found to range between 6.10 and 6.60 mm.

Figure 5 shows the in-house compression 'die set' (Mottram, 1994) with fixtures and steel pin to apply compressive loading into a semi-circular notched rectangular specimen. The specimen holder for the 6.35 mm thick plate required a specimen width of 73 mm (Lutz, 2005). For this preliminary study, the height of a specimen was set at 6d, so that for the WU16 specimen shown in Figure 5 this dimension is 96 mm. Load was 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, 0.165 kN was added to the maximum machine reading to allow for the dead weight of the top plate and rocker transfer fixture (not shown in Figure 5). For the EN testing the tension loading to the double lap-shear specimen (like Figure 4) was applied using a constant stroke rate of 0.01 mm/s. The duration of each static strength test to failure load (a) (in Figure 3) was between 60 and 90 seconds.

Presented in Tables 1 and 2 is a summary of the F_0^{br} results from this first series of tests, with Table 1 for the WU batches and Table 2 for the equivalent EN batches. Batch mean, Standard Deviation (SD) and Coefficient of Variation (CV) are given on the assumption that the strength population fits the Gaussian distribution. Characteristic values for F_0^{br} are determined using the guidance in Annex D7 to Eurocode 0 (BS EN 1990:2002), and they may be associated with the characteristic strength for Equation (1) in the LRFD pre-standard (Anonymous, 2011c). Both BS EN 1990:2002 and the commentary by Gulvanessian *et al*. (2002) on Eurocode 0 give details on how characteristic properties are to be determined. The CV is typically between 5 and 10% and this justifies calculating the characteristic strength on the assumption that the coefficient of variation is know *a prio*ri. A full discussion on the findings from this series of tests is to be found in Mottram (2009).

To have the confidence to continue characterising pin-bearing strengths using the Warwick University test arrangement it is imperative to be confident that the two methods do not give significantly different strength measurements. In Figure 6 the characteristic values from Tables 1 and 2 are plotted against the bolt diameter-to-thickness ratio (*d*/*t*). For convenience it is assumed that there is a linear variation between the four data points. The legend defines the four plots, with the upper two for close-clearance and the lower two for the nominal 1 mm clearance situation. For the range of bolt diameters used the *d*/*t* ratio increases from 1.24 to 2.55 for the 6.35 mm flat sheet material. In the Warwick University test arrangement the compressed steel pin is fully restrained along its length and cannot undergo flexure deformation. It is therefore proposed in Mottram (2009) that the reason why the EN strengths in Figure 6 are slightly lower is because the EN test fixture (Figure 4) allows bolt flexure to occur and this causes the bearing pressure across the specimen to be less uniform and thereby higher at the free edges where delamination failure initiates.

When the clearance size is small (0.2 mm) it is seen in Figure 6 that pin-bearing strength decreases (linearly) by about 15% with increasing *d*/*t*. This is an important observation because it suggests that characteristic pin-bearing strengths for the LRFD pre-standard must be determined for the largest *d*/*t* ratio, and this is not what the current standard test methods provide for. Such a strength trend is not obvious from the plots in Figure 6 when the clearance is higher at 1 mm, and this observation indicates the need for further characterisation work. Of course the lower strength with clearance seen with the results plotted in Figure 6 ensures that testing without the specified clearance is not to be recommended when pin-bearing strength data for Equation (1) is being measured.

NEW TEST RESULTS AND DISCUSSION

Prior to reporting on the new test results it will be instructive to introduce a specific design example to show why we need a recognised test method for the reliable determination of pin-bearing strength of pultruded materials. Later we shall return to this example to examine it with the new strength data. Figure 1 shows a typical web cleat connection (Anonymous, 2011b) for a beam member of the Wide Flange shape of size 203 x 203 x 9.35 mm (8 x 8 x 3/8 in). This type of beam-to-column joint is covered by the design clauses in the bolted connection chapter to the LRFD pre-standard (Anonymous, 2011c). When checking the resistance of the web cleat connection it is assumed that the vertical shear force from the beam loading splits equally between the two bolts and the relevant pin-bearing strength is F_{90}^{br} . Page 8-14 of the Strongwell Design Manual (Anonymous, 2011b) has a load table for this standard structural shape when used as a simply supported beam having a uniformly distributed load. For a span of 4 m (i.e. 13 ft) and a maximum allowable central deflection of span/150 the end shear force is 8.85 kN. Assuming the two steel bolts take equal shear force and have the smallest diameter (*d*) of 9.53 mm (3/8 in.), the web has a mean thickness (*t*) of 9.1 mm (from Tables 3 to 5) the required design F_{90}^{br} is found to be 51 N/mm^2. This reduces to 32 N/mm^2 if the serviceability limit on linear elastic deflection is set to span/240. The design manual also allows for bolting with bolts of 12.7 mm (1/2 in.) or 15.8 mm (5/8 in.) sizes and the required pin-bearing strength will reduce. The required strength for the web cleats is significantly lower because, at each bolt level, the nominal cleat thickness is nearly 2.7 times greater than the thickness of the web. F_{0}^{br} is, however, to be the pin-bearing strength when checking the web cleats for bearing failure and when the designer calculates the tying force resistance for the beam's bolted connection.

Test results for 0°, 45° and 90° material orientations (Figure 1) are obtained from a series of pin-bearing strength tests using the WU test arrangement shown in Figure 7.

The test procedure is that given earlier and in Mottram (2009). This test method is required because the specimens are cut from the web of a 203 x 203 x 9.53 mm Wide Flange shape having a depth of 180 mm. The shape is from Creative Pultrusions Inc. (Anonymous, 2011a) and the standard 1525 series product range with a fire retardant matrix, comprising a filled isophthalic polyester polymer. The 1525 series shapes are coloured gray. The material has the following reported mechanical properties (Anonymous, 2011a):

- in the longitudinal (0^o or LengthWise) direction - compressive modulus (D695) = 20.7 kN/mm^2; compression strength (D 695) = 231 N/mm^2; maximum bearing strength (LW), F_0^{br} (D 953) = 206 N/mm^2.
- in the transverse (90^o or CrossWise) direction - compressive modulus (D695) = 7.0 kN/mm^2; compression strength (D 695) = 115 N/mm^2; maximum bearing strength (CW), F_{90}^{br} (D 953) = 124 N/mm^2.

These mechanical properties from the pultruder are averages based on random sampling and testing of production lots for the series range of shape. As a consequence of their provenance they cannot be linked directly to specific shapes, such as those shown in Figure 1. In the Design Manual (Anonymous, 2011a) the longitudinal pin-bearing strength F_0^{br} is defined as the Maximum Bearing Strength (LW). There are no accompanying notes to explain why the word 'Maximum' is used. D953 does define maximum bearing stress to be the maximum load in newtons (or pounds-force) sustained by the specimen, divided by the bearing area. This is not what D953 defines as bearing strength, which is the bearing stress at which the bearing hole is deformed 4% of its diameter. Because Creative Pultrusions Inc. used the standard test method ASTM D 953 the word 'Bearing' ought to be 'Pin-bearing'.

Such a casual choice of words in the Design Manual (Anonymous, 2011a) is not helpful to practitioners; it is an example of the numerous gaps in knowledge that led the PIC of ACMA to support the project for the preparation of the LRFD pre-standard (Anonymous, 2007, 2011a).

It is also of interest to observe that if we assume the material of the Wide Flange shape is classified as Grade 23, BS EN 13706-3:2002 says the minimum longitudinal (F_0^{br}) and transverse (F_{90}^{br}) pin-bearing strengths are 150 and 90 N/mm^2, respectively. The Creative Pultrusion Inc. values at 206 and 124 N/mm^2 are seen to 38% higher. They were obtained in-house in accordance with test method ASTM D 953 and a bearing failure load for a 4% hole elongation, which we have already exposed weaknesses in determining pin-bearing strength.

Micromechanical modelling can be used to estimate the elastic moduli of a pultruded material. Volume fractions of the constituents are obtained by using the resin burn-off method. Lane (2002) took the constituent properties for the E-glass and polyester matrix and used micromechanical modelling to estimate that the web material in the Wide Flange shape has a longitudinal modulus of elasticity of 17 kN/mm^2 and a transverse modulus of 10 kN/mm^2. This theoretically derived longitudinal modulus is significantly lower than the 24.3 kN/mm^2 measured by strain gauging (Lane, 2002) and the higher modulus, for the flange material in the same shape, of 26.0 kN/mm^2 using micromechanical modelling (Lane, 2002). This difference in longitudinal modulus of elasticity between flanges and web is because the web material has less UD rovings per unit area and to compensate a greater volume fraction of CSM reinforcement than in the flanges.

The test results are presented in Tables 3 and 5. In this series of tests the number of nominally identical specimens per batch is six when the loading is either at 45^o or 90^o to the direction of pultrusion. For the tests with the load at 0^o the batch size is bigger at 11. For each of the three material orientations there are four batches, comprising the following pairs of nominal hole diameters (d_n) and nominal pin diameters (d): 11.8 and 9.7 mm; 14.8 and 12.7 mm (1/2 in.); 20.9 and 18.8 mm (3/4 in.) and 27.9 and 25.4 mm (1 in.). The four pins were cut from standard steel (Grade 8.8) bolts. The mean measured diameters (d and d_n) and mean hole clearances ($d_n - d$) to nearest 0.1 mm are given in rows two to four in Tables 3 to 5. Because of available diameters of the drill bits it is to be noted that the minimum clearance of 1.9 mm is greater than the minimum 1.6 mm (1/16 in.) required by the LRFD pre-standard; we can therefore expect pin-bearing strength measurements to be on the lower side of their values that can be used with Equation (1).

Mean web thickness per specimen was measured to the nearest 0.05 mm with an outside micrometer, and t is found to have mean specimen values in the range of 9.07 to 9.18 mm. The mean thicknesses per batch of six or 11 specimens are given in the first row in Tables 3 to 5.

Figure 7 shows a second in-house compression 'die set' arrangement for testing that applies the pure compressive bearing load through a pin. The 'die set' and specimen holder are bigger than those for the same test arrangement shown in Figure 5, and the specimen holder (for nominally 9.53 mm thick material) requires a specimen with a width of 100 mm. By inspection of the surface texture of the specimen in Figure 7 it can be seen that the material orientation is 45^o. Because bearing failure is known to occur (Lutz, 2005; Wang, 2004) when the end distance (e_1) of the tensile specimen (Figure 4) is 4*d* or higher, the specimen height for all four pin diameters is set at 100 mm (i.e. 4 × 25 mm). To achieve this height the blanks cut from the web had to be 125 mm long to accommodate drilling for the 28 mm diameter hole. It is noteworthy that the 45~~90~~° blanks of 125 by 100 mm for the WU test method (Figure 7) can readily be cut from the 180 mm deep web of the Wide Flange shape.

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 (not shown in Figure 7). A Solartron SI 3531 data acquisition system is used to monitor the load and stroke in real time, at the rate of one pair of readings every two seconds. To reach the maximum load the duration of testing can be 110 seconds.

Tables 3 and 5 present a summary of test results, with, respectively, the table ordering for longitudinal (0°), 45° and transverse (90°) material orientations. The number of specimens per batch is given in row five. For each batch the mean, Standard Deviation (SD) 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 of the tables are determined using the guidance in Annex D of Eurocode 0 (Gulvanessian *et al.*, 2002), and they may be associated with a characteristic strength for Equation (1). Because CV typically lies between 5 and 10% it was acceptable to calculate the characteristic strength on the assumption that the coefficient of variation is known *a priori*. The final row entries in the tables give the pin diameter-to-material thickness ratios.

It is seen from the results in Table 1 that the minimum mean F_0^{br} of 136 N/mm^2 is below the BS EN 13706-3:2002 minimum required strength of 150 N/mm^2 (for Grade 23 material). An even less favourable finding is that the minimum characteristic value of 111 N/mm^2 is 26% below this EN minimum. For F_{90}^{br} the minimum mean and characteristic values of 110 N/mm^2 and 97 N/mm^2, respectively, are found to be well in excess of the EN 13706-3:2002 minimum of 70 N/mm^2.

Figures 8 to 10 presents pin-bearing stress (calculated using $R_{br,test}/td$, where $R_{br,test}$ is the test compressive force (see Figure 7)) against stroke plots. The stroke is that measured by the DARTEC 9500 testing machine and because of the much higher axial stiffness of test fixtures, steel pin, and testing machine this stroke is dominated by the compressive deformation of the (100 – d_n/2) mm high FRP specimen. When the compressive load is aligned with the pultrusion direction it has been previously found (Mottram, 2009) that the load-stroke curves are virtually linear to maximum load, and that there is a sudden load reduction as significant bearing failure occurs. This justifies the choice of failure load (a) in Figure 3, from Johnson and Matthews (1979), for calculating pin-bearing strength. The typical plots for stress against stroke in Figures 8 and 9 are therefore for the newer load cases when $R_{br,test}$ is acting transverse (90^o) or 45^o to the pultrusion direction. As expected, the sudden reduction in load at onset of bearing failure is less than when loading is in the 0^o material direction (Mottram, 2009). The curves in these two figures show that when the pin diameter is 18.8 or 25.4 mm the curves are also fairly linear to the maximum load. For the smaller pin diameter of 12.2 mm this is also found for the 45^o loading case. For this pin size and 90^o loading, and for the smallest pin diameter of 9.7 mm, with both 45^o and 90^o loading cases, the three curves show a form of ductility with the maximum load higher than at first peak. Figure 8 shows that the maximum load is more than just slightly higher for the specimen with the 9.7 mm pin. This is the only specimen out of 92 in the test series where the failure load could be defined by point (b) in Figure 3; the other 91 can be defined by the maximum load.

Plotted in Figure 10 are typical stress-stroke curves at the three material orientations of 0^o, 45^o and 90^o for a specimen with the 25.4 mm pin and 28 mm hole diameters. Their characteristics are similar with the maximum load occurring at a stroke of about 1.0 mm and in descending magnitude with increasing material orientation. After the initial embedding stage, the slope of the linear part of load-stroke curve should be proportional to the modulus of elasticity. The ratio of gradients (for stroke between 0.4 and 0.8 mm) for the 0 and 90^o tests is 1.72; very close to 1.7 given by the moduli for the web material reported from micromechanical modelling by Lane (2002). Using the gradient for the 45^o specimen in Figure 10 it is estimated that the 45^o modulus of elasticity is 11.2 kN/mm^2, which is 12% higher than in the transverse direction. For the pin-bearing strengths, not governed by the UD roving reinforcement, we find the ratio $F_{45}^{\mathrm{br}} / F_{90}^{\mathrm{br}}$ is 1.13 using the mean of the four characteristic strengths in Tables 4 and 5. This suggests that for orientations away from 0^o there might be a correlation between the modulus of elasticity and the pin-bearing strength.

In Figure 11 the characteristic strengths in Tables 3 to 5 are plotted against the 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 three plots for material orientations of 0^o, 45^o and 90^o. The *d*/*t* ratio increases from 1.06 to 2.80 (final row in the tables). Now, when there is a hole clearance present the pin-bearing strength, *c.f.* with equivalent curves in Figure 6, is seen to reduce with increase in *d*/*t*, thereby adding evidence (Mottram 2009) to the requirement that a characteristic strength for Equation (1) must be determined using the most severe design parameters found in practice. We find therefore that reliability in establishing R_{br} with Equation (1) cannot be assured when pin-bearing strength is determined by rigorously complying with the standard test methods of ASTM D 953-02 or BS EN 13706-2:2002. The trend of the strength decrease in Figure 11 might be linear, but confirmation of this useful observation for reducing the amount of testing to characterise the strength requires more results.

Yuan *et al*. (1996) conducted tests to show that by increasing hole clearance up to 50% of pin diameter (12.7 mm) the bearing strength was still reducing. For pin-bearing test results reported in Tables 3 to 5 the available drill bits meant the clearance sizes, as a percentage of pin diameter, were 20, 21, 11 and 10 for the bolt (pin) diameters of 9.7, 12.2, 18.8 and 25.4 mm. It is therefore likely that measurements for the two smaller bolt sizes are relatively lower than what has been measured for the two bigger bolt sizes. This observation suggests that to establish a trend, if, indeed, it exists, between pin-bearing strength and the *d*/*t* ratio, testing should be performed with a clearance size that is set at a constant percentage (say 10%) of the pin diameter, for all bolt sizes. When using the historical review to introduce what is permitted in the LRFD pre-standard (Anonymous, 2011c) the authors stated that the minimum clearance hole size is 1.6 mm (1/16th in.) for bolts from 9.53 (3/8 in.) to 25.4 mm (1 in.). On the assumption that the clearance remains constant the reduction in strength is therefore largest for the smallest bolt size and this influence is hidden as bolt diameter increases because the strength will decrease as *d*/*t* increases.

Returning to the design checks for the web in the beam of Figure 1 the required design pin-bearing strength (F_{90}^{br}) was earlier estimated to be 51 N/mm^2, for a central deflection of span/150. For the 9.7 mm bolt size the results in Table 5 say the characteristic F_{90}^{br} is 149 N/mm^2. Given that the required design value is about 1/3rd of what is available, this single design comparison does not immediately raise alarm bells over the reliability of the 'room temperature' load table for 203 x 203 x 9.53 mm shape in the Strongwell Design Manual (Anonymous, 2011b). The Strongwell Wide Flange shape will possess the same mechanical properties as the equivalent standard section from Creative Pultrusions Inc. It is noteworthy that should the minimum characteristic F_{90}^{br} of 97 N/mm^2 be used in design calculations the level of reliability will reduce significantly, and this is without any strength reduction due to service life affects (such as from cyclic loading and/or environmental degradation).

Another finding from this series of tests is that the maximum transverse pin-bearing strength of 124 N/mm^2 (D 953), taken from the Creative Pultrusion Inc. Design Manual (Anonymous, 2011a) is 30% higher than the lowest characteristic strength entry in Table 5.

As expected the highest strength is in the longitudinal direction and as seen in Figure 11 the decrease of F_0^{br} with *d*/*t* is the most dramatic. Whereas Creative Pultrusion Inc.

state that the maximum bearing strength (LW) for the Wide Flange shape is 206 N/mm^2, the characteristic results in Table 3 show it can be much lower (up to 46%) and this must be accounted for should bearing failure govern the tying force requirement of a beam's joint. A reason for the significant difference in strength when the bolt diameter is 25.4 mm is that the standard test method ASTM D 953 does not require a clearance hole and the *d*/*t* ratio is specified to be 1.0.

Because we do not have details on how the Creative Pultrusion Inc. Design Manual maximum bearing strengths were established the authors cannot provide an exact explanation for the difference with the new results. What can be said is that there are a number of differences in how the pin-bearing strengths were measured and that the test approach for F_0^{br} and F_{90}^{br} in this paper is the one that is representative of the geometry of bolted connections found in practice.

Depending on how orthotropic the pultruded material is, it was believed (Mottram, 2009) that the strength ratio $F_0^{\mathrm{br}} / F_{90}^{\mathrm{br}}$ lies within the range 1.2 to 1.5. From the characteristic strengths reported in Tables 3 and 5 the lowest value to the ratio $F_0^{\mathrm{br}} / F_{90}^{\mathrm{br}}$ is 1.13 (mean of the four values is 1.23), and this ratio is lower than the previously understood lower bound ratio of 1.2 (Mottram, 2009). Given that the ratio of the directional modulus of elasticity is 1.7 (Lane, 2002) it is observed that this pin-bearing strength ratio is not proportional to the modulus ratio. An explanation for this finding could be that the mechanism for the bearing mode of failure has changed with orientation, and this finding is the subject of new research.

CONCLUDING REMARKS

A historical review of the standard test methods (ASTM D 953-02 and EN 13706-2:2002) used to determine the bearing strength of pultruded fibre reinforced polymer materials in structural shapes has been used to expose their limitations in the context of obtaining reliable and relevant strengths for the design of bolted connections. It is observed that these standards do not require the strength to be determined when there is a clearance hole, and for the much larger material thicknesses and bigger bolt sizes found in practice. Another finding from the review of standard test methods is that the size of the tension specimens is too large for it to be cut from pultruded shapes. An alternative test arrangement, with a smaller specimen size, is therefore needed if all pin-bearing strengths required to design bolted connections are to be determined.

To account for all possible influences on lowering the bearing strength of the pultruded material, by the end of a structure's service life, the authors recommend that the pin-bearing strength (determined with no lateral restraint from tightening the nut and bolt) should be used in calculations for the strength of bolted connections.

A comparison is reported by Mottram (2009) for pin-bearing strengths determined using the larger tensile specimen with the test method EN 13706-2:2002 and the smaller compression specimen with the Warwick University test method, the latter loading approach is linked to ASTM D 5764-97a for evaluating dowel-bearing strength of wood and wood-based products. Building on this previous study, a new series of tests have been conducted to characterise the web material in a 203 x 203x 9.5 mm Wide Flange shape from the pultruder Creative Pultrusion Inc. Testing is performed on batches of specimens with the loading oriented at 0^o, 45^o or 90^o to the direction of pultrusion. If this characterisation had been constrained by the need to use a tensile specimen (for D 953 or EN 13706) the specimen size would have only allowed the longitudinal (0^{o}) pin-bearing strength to be determined.

Salient test results are presented and characteristic strengths are calculated in accordance with Eurocode 0. The bolt diameter-to-material thickness ratio is varied from 1.06 to 2.80, and the clearance hole is a minimum of 1.9 mm. Plots for the characteristic strength for the three orientations highlight its decrease as this ratio increases. The trend might be linear, but confirmation requires more test results (and with a minimum of 10 nominally identical specimens per batch). It is found that the minimum characteristic strengths are obtained with the biggest steel bolt diameter of 25.4 mm. The maximum (0^{o} or longitudinal) and minimum (90^{o} or transverse) characteristic strengths at 111 and 97 N/mm^2, respectively, cannot easily be compared with the maximum (pin) bearing strengths of 206 and 124 N/mm^2, respectively, tabulated in the Creative Pultrusion Inc. Design Manual (Anonymous, 2011a). What is known is that there are significant differences in how the pin-bearing strengths were measured by Creative Pultrusions Inc. and the authors, and that the test approach used in this paper is the one that represents the geometry of bolted connections found in practice.

The main finding from this study towards the determination of pin-bearing strength is that it is necessary to relax the requirements specified in the standard test methods (D 953 or EN 13706) currently used by pultruders and researchers. To be able to measure every characteristic strength used in design it will be necessary to apply a test methodology similar to that used by the authors, and to ensure that the test matrix involves material orientations and thicknesses, and pin and hole diameters found in practice. A recommended test matrix can be established by way of the scope permitted in the bolted connection chapter to the future LRFD standard (Anonymous, 2011c). It is further recommended that the minimum batch size be set at 10 and that characterisation must involve environmental conditioning that will encompass the likely forms of material degradation in the region of the bolt holes over the intended service lives of pultruded FRP structures.

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Table 1. Statistical test results for longitudinal pin-bearing strengths using the WU test approach with 6.35 mm thick flat sheet material.

F_0^{br}	Batches of six specimens					
	WU08	WU09	WU12	WU13	WU16	WU17
Mean (N/mm^2)	362	241	315	227	314	239
SD (N/mm^2)	21.6	25.2	10.0	24.5	31.0	17.0
CV (%)	6.0	10.5	3.2	10.8	9.9	7.1
Characteristic[1] (N/mm^2)	314	186	293	174	246	202
Mean *d*/*t* ratio	1.25	1.27	1.92	1.91	2.55	2.54

Table 2. Statistical test results for longitudinal pin-bearing strengths using BS EN 13706-2 test approach with 6.35 mm thick flat sheet material.

F_0^{br}	Batches of six specimens, except for EN09 with five					
	EN08	EN09	EN12	EN13	EN16	EN17
Mean (N/mm^2)	324	232	298	201	297	235
SD (N/mm^2)	10.4	17.6	19.5	7.6	22.2	19.6
CV (%)	3.2	7.6	6.6	3.8	7.5	8.4
Characteristic[1] (N/mm^2)	301	191	255	185	245	192
Mean *d*/*t* ratio	1.23	1.25	1.92	1.88	2.51	2.49

Note: 1. Mean – 2.18SD.

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

Longitudinal (0^o) web material				
Mean web thickness, t (mm)	9.16	9.14	9.12	9.14
Mean notch diameter, d_n (mm)	11.8	14.8	20.9	27.9
Mean pin diameter, d (mm)	9.7	12.2	18.8	25.4
Mean clearance, d_n - d (mm)	1.9	2.6	2.1	2.5
Number of nominally identical specimens	11	11	11	11
Mean pin-bearing strength F_0^{br} (N/mm^2)	188	170	154	136
SD (N/mm^2)	6.2	9.1	12.7	14.8
CV (%)	3.3	5.3	8.4	10.9
Characteristic[1] value of F_0^{br} (N/mm^2)	177	155	133	111
Mean d/t ratio	1.06	1.34	2.05	2.78

Note: 1. Mean – 1.72SD

Table 4. Statistical test results for 45^o pin-bearing strengths using the WU test approach with web material from a 203 x 203 x 9.53 mm wide flange shape.

45^o web material				
Mean Web thickness, t (mm)	9.14	9.10	9.11	9.07
Mean notch diameter, d_n (mm)	11.8	14.8	20.9	27.9
Mean pin diameter, d (mm)	9.7	12.2	18.8	25.4
Mean clearance, d_n - d (mm)	1.9	2.6	2.1	2.5
Number: nominally identical specimens	6	6	6	6
Mean pin-bearing strength F_{45}^{br} (N/mm^2)	174	158	134	118
SD (N/mm^2)	10.3	8.4	7.5	4.4
CV (%)	5.9	5.3	5.6	3.7
Characteristic[1] value of F_{45}^{br} (N/mm^2)	156	143	121	111
Mean d/t ratio	1.06	1.34	2.06	2.80

Note: 1. Mean – 1.77SD

Table 5. Statistical test results for transverse pin-bearing strengths using the WU test approach with web material from a 203 x 203 x 9.5 mm wide flange shape.

Transverse (90^o) web material				
Mean Web thickness, t (mm)	9.09	9.10	9.17	9.18
Mean notch diameter, d_n (mm)	11.8	14.8	20.9	27.9
Mean pin diameter, d (mm)	9.7	12.2	18.8	25.4
Mean clearance, d_n - d (mm)	1.9	2.6	2.1	2.5
Number: nominally identical specimens	6	6	6	6
Mean pin-bearing strength F_{90}^{br} (N/mm^2)	168	146	120	110
SD (N/mm^2)	10.5	13.7	10.1	7.2
CV (%)	6.2	9.3	8.5	6.6
Characteristic[1] value of F_{90}^{br} (N/mm^2)	149	122	102	97
Mean d/t ratio	1.07	1.34	2.05	2.77

Note: 1. Mean – 1.77SD

Figure Captions

Figure 1. Typical beam-to-column bolted joint for steel bolts of diameters 9.53 mm (3/8 in.) to 15.9 mm (5/8 in.) based on engineering drawing on Page 19-6 of the Strongwell Design Manual (Anonymous, 2011b).

Figure 2. Plate-to-plate distinct modes of failure with a single steel bolt; (a) bearing, (b) net-tension, (c) shear-out, (d) cleavage.

Figure 3. Bearing load with measured extension showing seven ways to define failure load, labelled (a) to (g), which can be used to determine a bearing strength (Johnson and Matthews, 1979).

Figure 4. Steel tension loading fixture and FRP test specimen for D 953-02: 1 – Hardened spacer plate; 2 – 6.35 mm steel bolts in reamed holes; 3 – Hardened side plate; 4 – Extensometer span; 5 – Hardened steel pin in reamed hole; 6 – Test specimen.

Figure 5. The smaller Warwick University (WU) pin-bearing strength test rig (from Lutz, 2005).

Figure 6. Characteristic pin-bearing strengths (in N/mm^2) of 6.35 mm series 1625 flat sheet (Anonymous, 2011a) with d/t ratio, and with and without a 1 mm hole clearance.

Figure 7. The larger Warwick University (WU) pin-bearing strength test rig (Mottram, 2009).

Figure 8. Pin-bearing stress (in N/mm^2) with stroke (in mm) curves for transverse orientation of the web material with four pin diameters from 9.7 to 25.4 mm.

Figure 9. Pin-bearing stress (in N/mm^2) with stroke (in mm) curves for web material oriented at 45^o to load direction with four pin diameters from 9.7 to 25.4 mm.

Figure 10. Pin-bearing stress (in N/mm^2) with stroke (in mm) curves for the web material at the three orientation of 0^o, 45^o and 90^o and pin diameter of 25.4 mm (giving $d/t = 2.78$).

Figure 11. Characteristic pin-bearing strengths (in N/mm^2) of 9.1 mm thick web material with d/t ratio and hole clearance of 1.9 mm or larger.

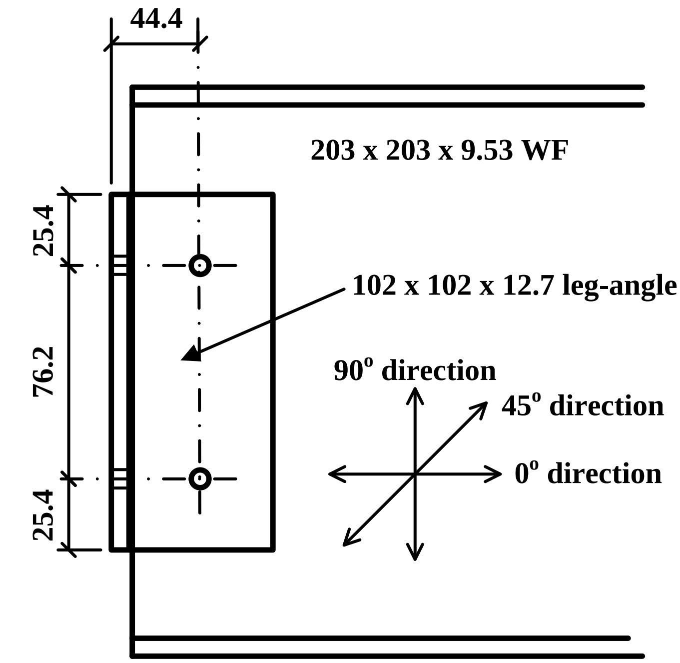

Fig. 1 JTM/BZ January 2011

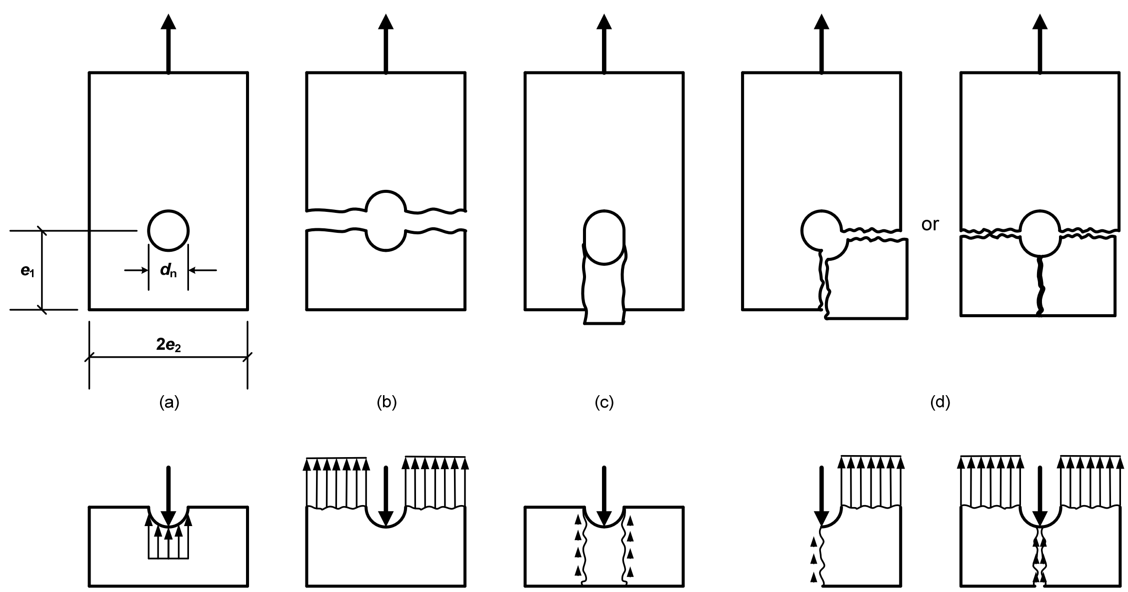

Fig. 2 JTM/BZ January 2011

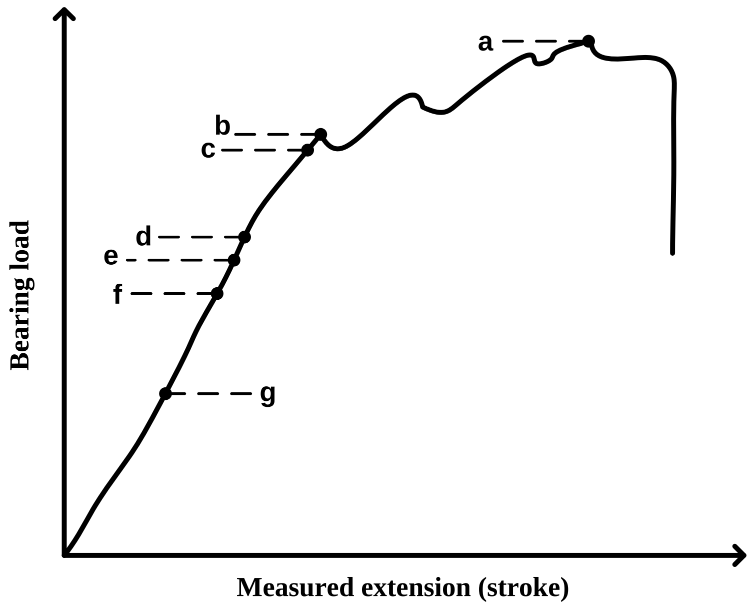

Fig. 3 JTM/BZ January 2011

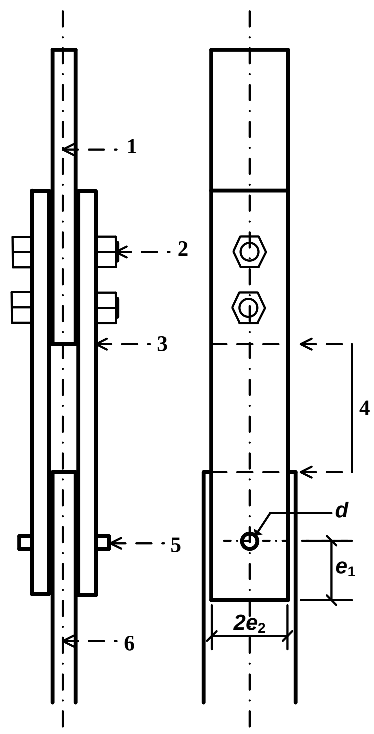

Fig. 4 JTM/BZ January 2011

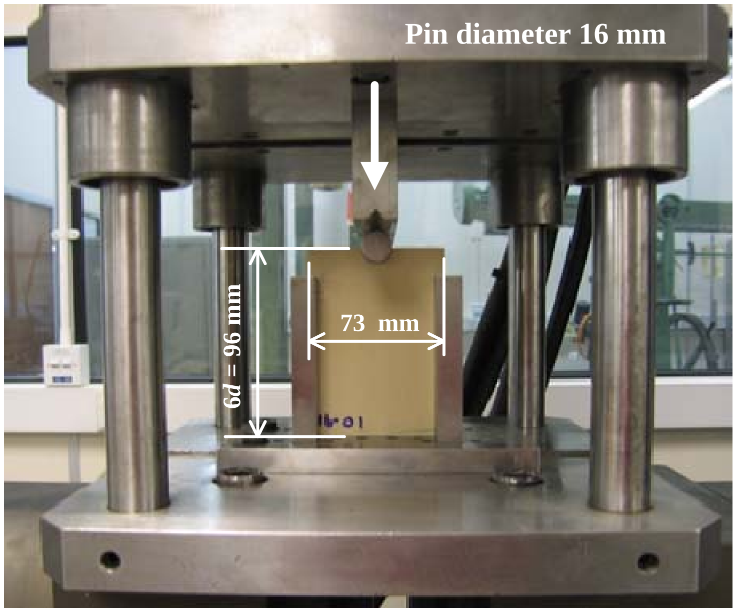

Fig. 5 JTM/BZ January 2011

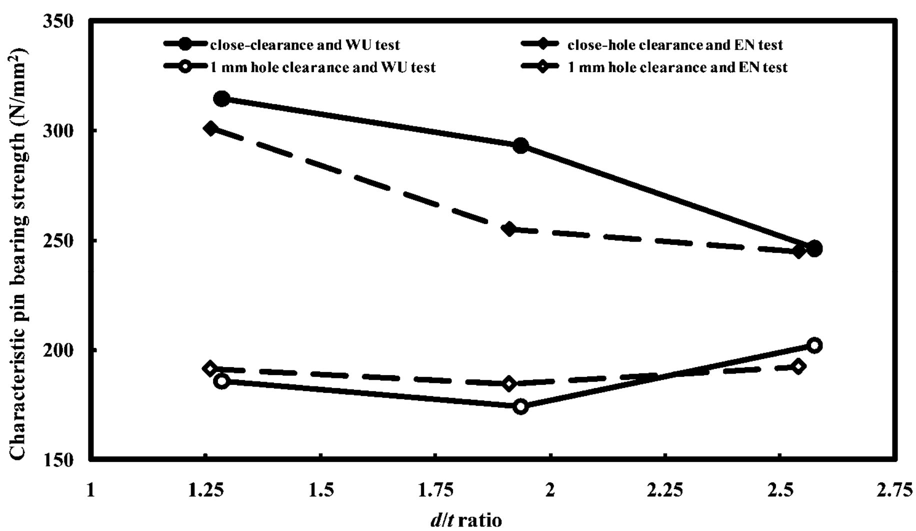

Fig. 6 JTM/BZ January 2011

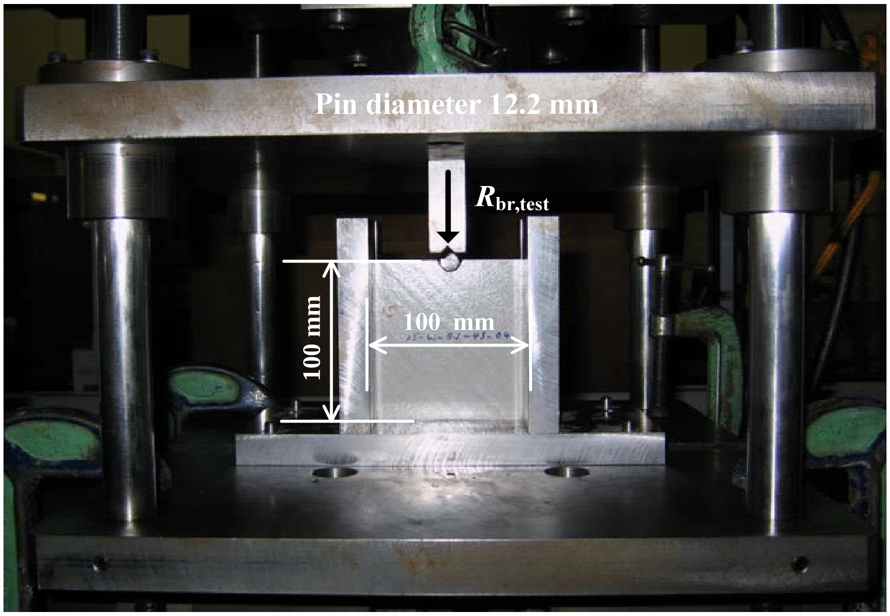

Fig. 7 JTM/BZ January 2011

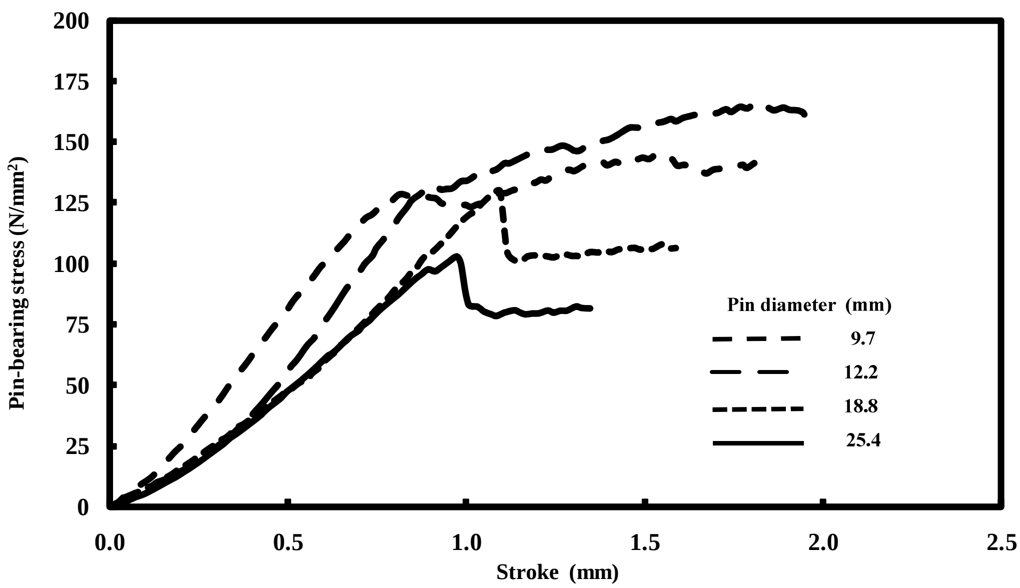

Fig. 8 JTM/BZ January 2011

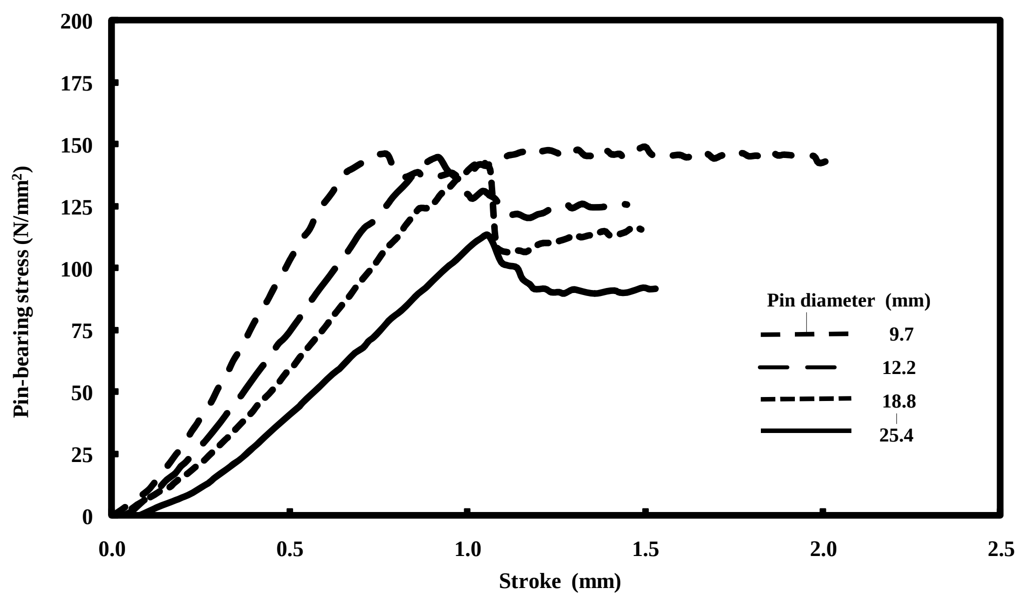

Fig. 9 JTM/BZ January 2011

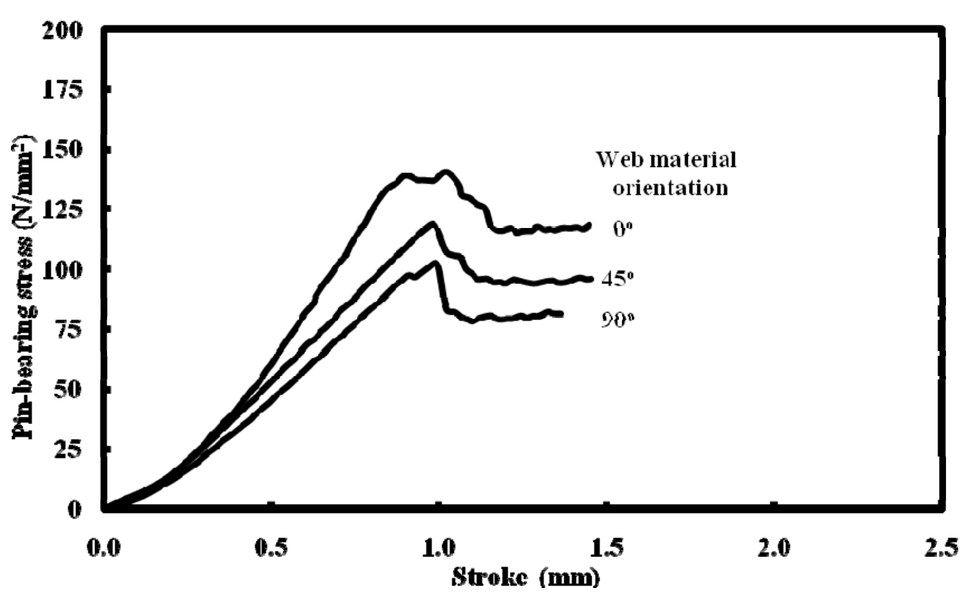

Fig. 10 JTM/BZ January 2011

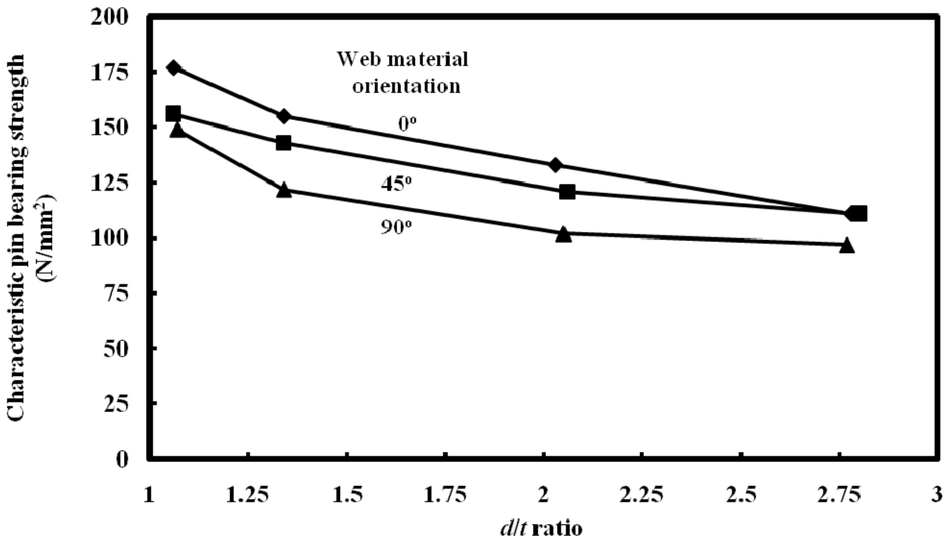

Fig. 11 JTM/BZ January 2011

End