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Laterally Unrestrained Bearing Strength of Hot-Wet Conditioned Pultruded FRP Material

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ABSTRACT

Presented in this paper are test results of a study pertaining to the reduction in bearing strength due to the effect of hot-wet conditioning on specimens cut from a polyester matrix based pultruded FRP structural shape. A total of 100 coupons (for 20 batches of five) were immersed in distilled water for three and six months at a constant temperature of 40°C. Subsequently, they were load tested using stainless steel 'pins' of M10 and M20 sizes with material orientations of 0^o, 45^o and 90^o to the direction of pultrusion. Furthermore, this test series considered the effect of loading with and without bolt thread in the bearing zone. Testing employed a non-standard set-up that accommodates smaller test coupons, allowing material to be sourced from the web and flange of a 254×254×9.53 mm wide flange shape. An evaluation of the salient results provides characteristic bearing strength values (in accordance with Annex D of EN1990) and comparisons are drawn between equivalent strengths for non-aged (zero months) material from a previous test series. The degree of strength reduction is found to be influenced by both the 'pin' size and type, and observations are drawn towards the safe and reliable design of bolted connections.

INTRODUCTION

Applications in construction of Pultruded Fibre Reinforced Polymer (PFRP) composites have been steadily growing for several decades. Thin-walled shapes and systems of this material are being used in primary load bearing structures. For a recent example there is the East Midlands Parkway Railway Platform [1], which has non-sway braced frames. Pultruded members can be connected together by conventional stainless steel bolting [2]. These connections provide ease of assembly and maintenance, as well as being capable of transferring the actions in primary load bearing structures.

The design of bolted connections of FRP is critical in ensuring sound structural performance and involves a fundamental understanding of failure modes. Due to the orthotropic and layered nature of PFRP these failure modes can vary significantly [2]. The damage and mode of failure is dependent on connection detailing, material and fastener specifications, such as geometry, fibre volume fraction, and bolt tightening, etc. It is well-known that bearing failure in PFRP bolted connections (one of the distinct failure modes illustrated in Figure 1), is preferred in design because of its potential to offer a progressive pseudo-ductile response [2, 3]. It is also recognized with FRP materials that resistances can be lowered by exposure to aggressive environments which influence the material and its structural properties [4].

Environmental degradation will include influences from temperature, UV radiation, water or moisture. Material changes will affect the ability of any FRP to maintain its mechanical properties over time [4]. Any durability issue is a concern to structural engineers as design lives in civil engineering works are measured in decades. It is essential for confidence in durability performance that there is characterisation work with PFRPs' to understand the material's long-term performance (strength and stiffness) under adverse conditions. It can be expected that years of (continuous) exposure in an aggressive environment will cause irreversible and detrimental changes within the FRP material.

Previous studies summarized in reference 4 have highlighted the importance of both moisture and temperatures on the mechanical properties of PFRP and other FRP materials. The severity of these two factors will depend on geographical location and climatic (changing) conditions,

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and needs to be taken into account during the design process. Failure, insofar as the material, component, sub-assembly, structures is no longer fit-for-purpose, could occur due to cumulative damage to the polymer matrix, interfacial separation between matrix-fibre bond, and chemical attack of the fibres. Indeed, the overall environmental degradation occurs as a combination of two or more of these processes [4] with the net effect resulting in loss of mechanical integrity.

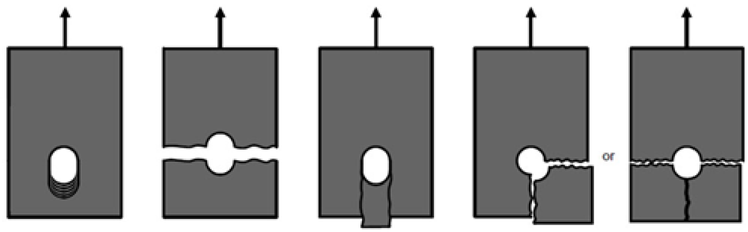

Figure 1: Distinct failure modes of single bolted connections – (a) bearing; (b) net section; (c) shear-out and (d) two forms for cleavage [2]

The design and verification of bolted connections in PFRP frames is a complex exercise that has considerable gaps in knowledge [5]. One key knowledge gap is that designers/fabricators often allow bolt thread to be in bearing, in particular when several different material thicknesses are connected within a pultruded frame. The effect this has on bearing strength of PFRP material, if any, is not fully understood [6, 7]. Furthermore, the 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. Recent studies for bearing strength have focused on plain shafts for pin-bearing [8, 9]. The specific topic for this study is to compare the laterally unrestrained bearing strength property with and without bolt thread present for a PFRP material subjected to hot-wet conditioning. Another variable are the two different fibre architectures found in the flange and web of the 254×254×9.53 mm Wide Flange (WF) shape from Creative Pultrusions Inc. [10].

Pin-Bearing Strength

Bearing failure caused by a transfer of a bolt connection force, involves the crushing and piling-up of material directly beneath the metal-FRP contact, with delamination fractures between the fibre reinforcing layers. Empirical studies [6-9] have found that the strength and response of bolted connections failing with the bearing mode 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 tightening, a higher bearing strength is achieved [2]. This increase is caused by lateral stiffness that opposes the inherent through-thickness deformations, which cause the localized tensile stresses for delamination failure. It would be difficult to fully account for all influences on the bolt bearing strength for use in structural design. To be conservative and safe, the pin-bearing strength measure (where there is no lateral restraint or clamping force) is chosen to calculate the bearing resistance (R_{br}) per bolt [8, 9]. The strength formula for bearing failure is

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

Equation (1) requires the pin-bearing strength (F_{θ}^{br}) measured with respect to the direction of pultrusion (θ). Herein the term ‘pin-bearing’ means the bolt is laterally unrestrained. Conventionally, the orientation of the applied force, when parallel to the pultrusion direction gives $\theta = 0°$ (longitudinal) and when orthogonal has $\theta = 90°$ (transverse). The projected area of bearing is given by the thickness of the material (t) multiplied by the diameter of the bolt (d). It should be noted that the bearing strength given by Equation (1) is a specific strength property that needs to be determined by a recognised standard test method. Mottram and Zafari [8] discuss the merits and weaknesses of the available standard test methods for the determination of a bearing strength. This review shows that none are suitable, without modification, for application with material from PFRP shapes.

EXPERIMENTAL PROGRAMME

Material and Test Specimen Preparation

Specimens were prepared using web and flange material from a Pultex® SuperStructural 1525 series WF shape of size 254x254x9.53 mm [10]. Coupon dimensions are nominally 80 mm square and thickness (*t*) is 9.53 mm. Material is a thermoset polyester (Class FR1) matrix reinforced with E-glass fibres of UniDirectional (UD) rovings and a three-layered (90°, ±45^o) cross-stitched mat. Figures 2 shows the fibre architecture consisting of cross-stitched mat layers interspersed with 'constant' thickness layers of UD and covered with an outer (non-structural) surface veil. As seen in this figure the fibre composition is not the same in the web and flange and this is reflected in different mechanical properties reported in [10].

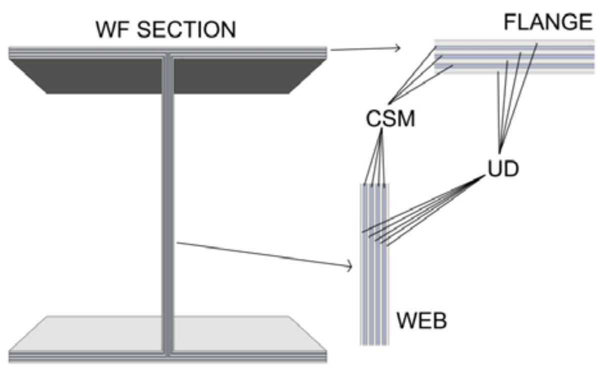

Figure 2: WF section fibre architecture

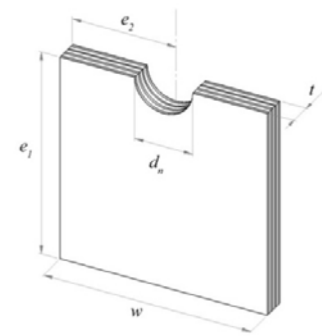

Figure 3: Schematic of test specimen and major geometry variables

Preparation of specimens involved cutting material, using a diamond edged circular saw with water coolant to minimise machining-induced damage, into 100 x 80 mm blanks. A schematic with the principal plan dimensions for the semi-notched coupon is given in Figure 3. The hole centre is located centrally within the width for a 40 mm side distance and end distance of 80 mm. The drilling method of circle-interpolation (or orbital drilling) was used. Firstly, the process uses solid carbide 10 mm stub drill bit for all specimens. Holes are finished with solid carbide 10 mm and 16 mm four flute end mills for clearance hole diameters of 12 mm and 22.4 mm, respectively. Support is given at the tool exit side to minimise surface damage, as well as the use of soluble oil to reduce excessive tool wear.

Post-drilling, the coupons were finalised by cutting at 80 mm to obtain the semi-circular notched coupons. The fabrication procedure ensured longevity of drill bits, optimised time and the accuracy of test specimens produced. This was confirmed by dimension measurements taken using an inside micrometer screw gauge for each hole prior to final cutting. The largest variation is an under-sizing of the clearance hole by a maximum value of 0.02 mm. The thickness of each specimen was measured using an outside micrometer screw gauge to the nearest 0.01 mm with average thicknesses being reported in Tables 1 to 3. The web material thickness ranged from 9.58 to 9.84 mm, and the flange between 9.57 mm and 10.37 mm.

Environmental Conditioning of Specimens

Environmental conditioning of the specimens was conducted by full immersion in heated baths of distilled water, as shown in Figure 4, at a temperature of 40°C for periods of three and six months. In accelerated aging studies [4], it has been noted that conditioning of FRP at temperatures close to the glass transition temperature (T_g) can cause effects that are not representative of aging at service temperatures due to different levels of mechanical and chemical degradation [11]. The immersion temperature used within this study was a least 60^{o}C below the T_g. It has been established [4, 11] that distilled water can offer a more aggressive environment than tap or salt water due to the ability of the free radicals reacting and diluting readily. Most studies indicate that the moisture uptake due to conditioning should be assessed to some extent and so specimens were weighed prior to both conditioning and strength testing. A mass balance accurate to 0.01 g was used, and after removal from the water baths, the wet surfaces were wiped before a specimen was weighed. It should be noted that this is not a specific study into the diffusion behaviour and moisture uptake process. The mass change will give a qualitative relationship between the moisture uptake and strength degradation.

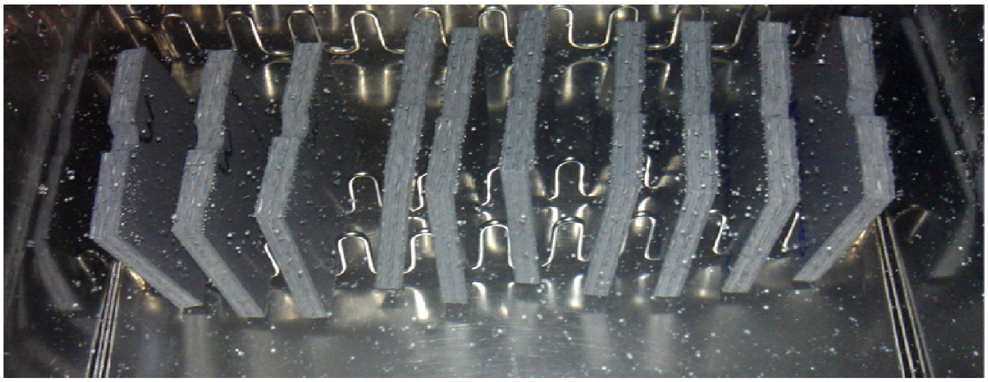

Figure 4: PFRP test specimens immersed in distilled water at 40^{o}C

Test Matrix and Configuration

A total of 100 specimens were tested to determine the effect of 'pin' type, plain or threaded, on the bearing failure load. There were 20 batches having five nominally identical specimens. Web material was tested with respect to three material orientations of 0, 45 and 90° and flange material for the longitudinal and transverse directions only. This was because the flange outstand width at 120 mm is too small for the 45^{o} coupon. The threaded pins, were cut from standard A2 stainless steel bolts of M10 and M20 size diameter (*d*), with 1.5 and 2.5 mm (coarse) pitch for M10 and M20, respectively. A clearance hole of 1.6 mm plus the maximum allowable tolerance of 0.4 mm and 0.8 mm was used [6], giving hole diameters of 12.0 mm and 22.4 mm respectively. The measured 'pin' diameters, for both plain and threaded types, are 9.81 mm for M10 and 19.78 mm for M20. An unthreaded pin represents the smooth shaft of a bolt, whereas a threaded pin is for a conventional fully threaded bolt.

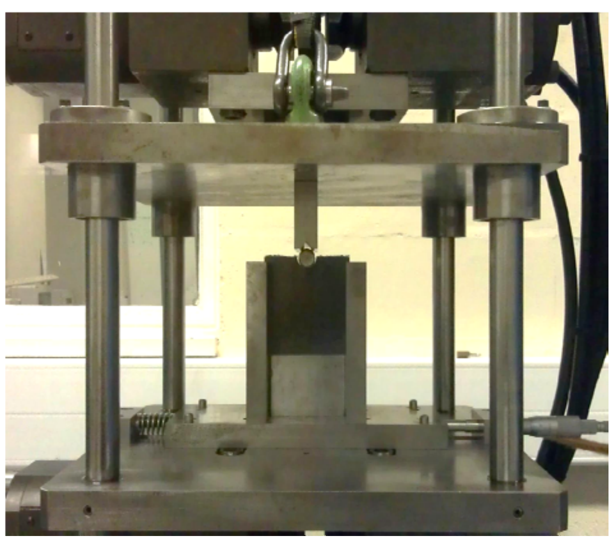

Figure 5: WU test configuration for pin-bearing strength tests

Monotonic load testing was performed using a 250 kN DARTEC servo-hydraulic testing machine with a 250 kN load cell equipped with the compression die set for bearing strength tests. The test rig is shown in Figure 5. The advantages of this non-standard test method and set-up have been discussed in the context of previous characterization work [3, 8]. Loading is transferred in-plane ensuring purely bearing damage occurs. The uniaxial compressive load is applied under a constant stroke rate of 0.01 mm/s with load and machine stroke recorded once every half a second by data acquisition software; the failure load is defined as the maximum recorded load [8]. Stroke is predominately governed by the deformation of the specimen, due to the relatively high axial stiffness of the metallic testing machine, test fixtures and pins. The maximum compressive force inclusively accounts for the dead weight of the top plate and rocker fixture, at 0.321 kN.

TEST RESULTS AND DISCUSSION

In order to understand the level of pin-bearing strength retention it is appropriate to summarize the test results from a series of non-conditioned batches (referred to as '0 month' material), corresponding to the same test matrix detailed above. A total of 200 specimens were tested using M10 and M20 pins, with and without bolt thread. The testing was conducted at ambient temperature (approximately 22°C) with no prior conditioning. Presented in Table 1 are test data for 20 batches with 10 specimens per batch. There is not space in this paper to compare and contrast these test results with tabulated pin-bearing strengths in [10].

Table 1: Non-conditioned bearing strength test results

Test batch ID	Specimen thickness (mm)	Mean maximum failure load (kN)	Mean bearing strength (MPa)	SD (MPa)	Char. value* (MPa)	CV (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Plain						
F/0/P/M10	9.77	20.1	210	20	175	9.5
F/0/P/M20	9.66	37.9	199	18	168	8.9
F/90/P/M10	9.96	13.8	142	5.3	132	3.8
F/90/P/M20	9.61	17.6	92.6	3.0	87.4	3.3
W/0/P/M10	9.61	18.7	198	16	170	8.2
W/0/P/M20	9.65	33.5	176	16	149	8.8
W/45/P/M10	9.63	15.3	162	4.9	154	3.0
W/45/P/M20	9.66	22.9	120	4.9	112	4.1
W/90/P/M10	9.62	15.0	159	7.1	146	4.5
W/90/P/M20	9.64	20.3	106	5.0	97.7	4.7
Threaded						
F/0/T/M10	9.76	18.7	195	12	174	1.9
F/0/T/M20	9.64	27.0	141	6.3	136	4.5
F/90/T/M10	9.96	15.4	158	7.2	145	4.6
F/90/T/M20	10.3	20.4	100	3.3	94.9	3.2
W/0/T/M10	9.61	18.3	194	12	173	6.4
W/0/T/M20	9.64	24.1	126	9.0	111	7.1
W/45/T/M10	9.65	15.9	168	9.7	151	5.8
W/45/T/M20	9.64	23.7	124	7.0	113	5.6
W/90/T/M10	9.61	16.6	175	8.9	160	5.1
W/90/T/M20	9.63	22.3	117	7.5	104	6.4
*Characteristic Value = Mean – 1.72×SD (10 specimens per batch)						

In this, and Tables 2 and 3 to follow, column (1) defines the test batch ID. It is to be read as corresponding to Material type: Flange (F) or Web (W) / Material Orientation: (0°, 45°, and 90°) /

Pin Type: Plain (P) or Threaded (T) / Pin Size: (M10 or M20). Label W/0/P/M20 is for Web material tested longitudinally (0^o) with a Plain M20 sized 'pin'. Columns (2) and (3) report the measured mean thickness and mean maximum failure load. Using Equation (1) with specimen measurements column (4) presents the mean bearing strength for the batch.

The strength population of a batch is assumed to fit a Gaussian normal distribution. Columns (5) and (8) in Tables 1 to 3 are used to give the Standard Deviation (SD) and Coefficient of Variation (CV). The characteristic strength value in Column (6) was calculated in accordance with the guidance in Annex D of EN1990 [11]. To permit the number SDs taken from the mean to be 1.72 (10 specimens) and 1.80 (five specimens) it has been assumed that prior characterisation has yielded a CV < 10%. The calculated characteristic strengths may be used as the pin-bearing strength in Equation (1) for the design of bolted connections where the FRP is a SuperStructural shape. It is noteworthy that the largest CVs at 8.2 to 9.5% are found with 0° (web and flange) material when the 'pin' is plain and for web material only when the 'pin' is threaded. Overall, the populations have considerably less scatter for bearing strength determined with than without (bolt) thread.

New Hot-Wet Conditioned Strength Test Results

A summary of the results for the 20 batches tested after being subjected to hot-wet conditioning is given in Tables 2 and 3. Table 2 is for the plain situation and Table 3 when 'pin' is threaded.

Table 2: Plain bearing strength results for hot-wet conditioned PFRP material

Test batch ID	Specimen thickness (mm)	Mean failure load (kN)	Mean bearing strength (MPa)	SD (MPa)	Char. value* (MPa)	CoV (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
3 months						
F/0/P/M10	9.70	16.6	174	12	153	6.8
F/0/P/M20	9.76	30.2	157	5.2	147	3.3
F/90/P/M10	10.3	12.5	124	13	99.5	11
F/90/P/M20	10.0	16.8	84.8	3.2	79.1	3.8
W/0/P/M10	9.66	16.3	172	14	148	7.9
W/0/P/M20	9.65	28.3	148	6.3	137	4.2
W/45/P/M10	9.63	13.2	140	7.7	126	5.5
W/45/P/M20	9.66	20.2	106	3.2	99.9	3.1
W/90/P/M10	9.62	13.1	139	4.9	130	3.5
W/90/P/M20	9.61	19.0	100	4.9	91.2	4.9
6 Months						
F/0/P/M10	9.60	18.4	195	25	151	12
F/0/P/M20	9.76	29.1	151	11	130	7.5
F/90/P/M10	10.1	12.2	123	6.8	111	5.5
F/90/P/M20	9.67	16.0	83.3	7.7	69.4	9.3
W/0/P/M10	9.67	16.6	174	13	152	7.3
W/0/P/M20	9.65	30.1	158	23	117	14.3
W/45/P/M10	9.64	14.0	148	4.4	140	3.0
W/45/P/M20	9.60	20.4	107	3.3	101	3.1
W/90/P/M10	9.62	12.4	131	4.9	123	3.7
W/90/P/M20	9.62	18.6	97.7	4.5	89.5	4.6
*Characteristic Value = Mean - 1.80×SD (5 specimens per batch)						

Plotted in Figures 6 and 7 are the mean pin-bearing strengths and corresponding standard deviations for the batches conditioned for 0, 3 and 6 months. Comparing strength results presented in Tables 1 and 2 and Figures 6 and 7 it is obvious that after three months a measureable strength reduction is found for all batches. Furthermore, this reduction is more prominent in specimens tested with material orientation of 0°. The trend for the six month conditioned specimens is less perceptible. Generally, the higher mean values correlate to a larger batch variation, as given in Tables 1 to 3 by higher SDs and in Figures 6 and 7 by the larger error bars. The specific physical cause, if it can be assumed to be singular in nature, of this deviation from the anticipated continual lowering (or levelling off) of strength [4] is yet to be determined. A factor known to contribute to this change in strength populations is the smaller specimen batch size of five compared to the 10 specimens in the non-conditioned series of tests. Nevertheless, the variation in strength results is somewhat dealt with by computing the characteristic values in accordance with EN1990 for five specimen batches [12], given in columns (7) of Tables 2 and 3.

Table 3: Threaded bearing strength results for hot-wet conditioned PFRP material

Test Batch ID	Specimen Thickness (mm)	Mean Failure Load (kN)	Mean Bearing Strength (MPa)	SD (MPa)	Char. Value* (MPa)	CoV (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
3 months						
F/0/T/M10	9.69	16.4	172	12	150	7.0
F/0/T/M20	9.93	25.5	132	6.8	119	5.2
F/90/T/M10	10.1	13.6	138	5.2	128	3.8
F/90/T/M20	10.3	20.2	99.7	6.4	88.2	6.4
W/0/T/M10	9.63	14.8	156	10	138	6.7
W/0/T/M20	9.66	22.8	119	10	101	8.6
W/45/T/M10	9.62	14.6	155	3.4	149	2.2
W/45/T/M20	9.64	21.6	113	7.0	101	6.2
W/90/T/M10	9.62	14.4	153	6.4	142	4.2
W/90/T/M20	9.61	20.7	109	3.8	102	3.5
6 months						
F/0/T/M10	9.78	17.4	181	12	159	6.9
F/0/T/M20	9.81	26.7	138	8.8	122	6.4
F/90/T/M10	9.77	12.8	134	7.1	121	5.3
F/90/T/M20	9.67	16.0	106	8.4	91.0	7.9
W/0/T/M10	9.82	20.6	168	9.6	151	5.7
W/0/T/M20	9.63	15.9	119	7.8	105	6.6
W/45/T/M10	9.63	15.1	159	8.9	143	5.6
W/45/T/M20	9.64	21.8	114	7.4	101	6.5
W/90/T/M10	9.62	14.7	155	7.5	142	4.8
W/90/T/M20	9.62	20.6	108	8.2	93.4	7.6
*Characteristic Value = Mean - 1.80×SD (5 specimens per batch)						

The clear distinction between mean pin-bearing strengths for web and flange material is that the latter are higher for 0° material and the former are higher for the 90° material for all batches (both conditioned and not conditioned). The strength characteristics for threaded pins differ for both web and flange material when compared with equivalent plain 'pin' batches. In the longitudinal direction web and flange materials show a reduction in strength due to thread in bearing for the three conditioning time periods. In contrast, in the transverse direction a strength increase is exhibited, with a larger difference in strength between the two pin types with the web material than the flange material.

Table 4 is used to present the change in mean characteristic strength, by dividing the threaded value by the plain value. Column (1) lists the batch ID and Columns (2) to (4) give the ratio for the zero, three and six months of hot-wet conditioning. It is of note that eight out of 30 batches showed an increase in strength and that the highest at 1.10 is for F/90/M10 at 0 months. At all three ages the largest reduction from having a thread in bearing is with W/0/M20. A reduction of about 30% is found for the batches exposed to zero, three and six months conditioning.

Table 4: Effect of thread on mean bearing strength

	Reduction from plain characteristic bearing strength from having thread in bearing		
Test Batch ID (1)	0 months (2)	3 months (3)	6 months (4)
F/0/M10	0.99	0.86	0.91
F/0/M20	0.78	0.71	0.72
F/90/M10	1.10	0.97	0.91
F/90/M20	1.09	1.01	1.04
W/0/M10	1.02	0.81	0.89
W/0/M20	**0.74**	**0.68**	**0.71**
W/45/M10	0.98	0.97	0.93
W/45/M20	1.01	0.90	0.90
W/90/M10	1.09	0.97	0.97
W/90/M20	1.07	1.04	0.96
Mean	0.99	0.89	0.89

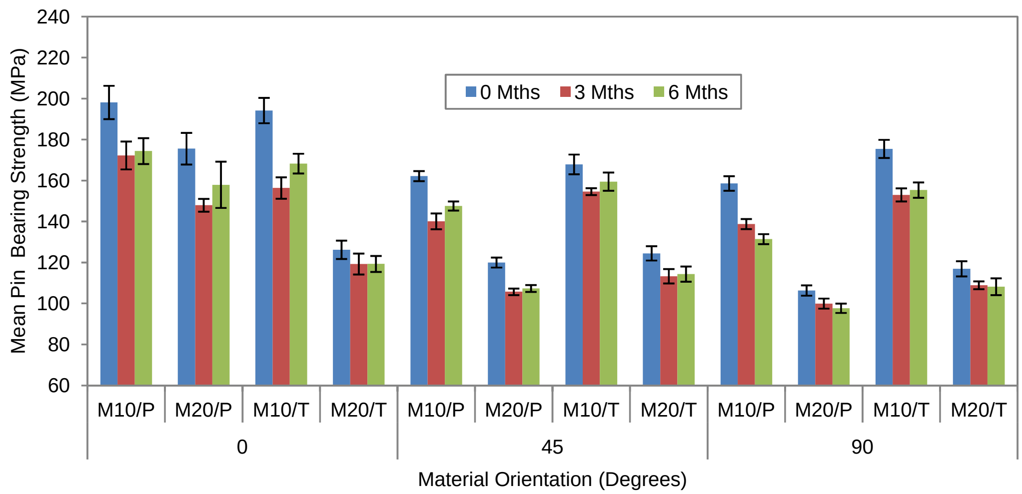

Figure 6: Comparison of mean pin-bearing strengths for web material after hot-wet conditioning for 0, 3 and 6 months

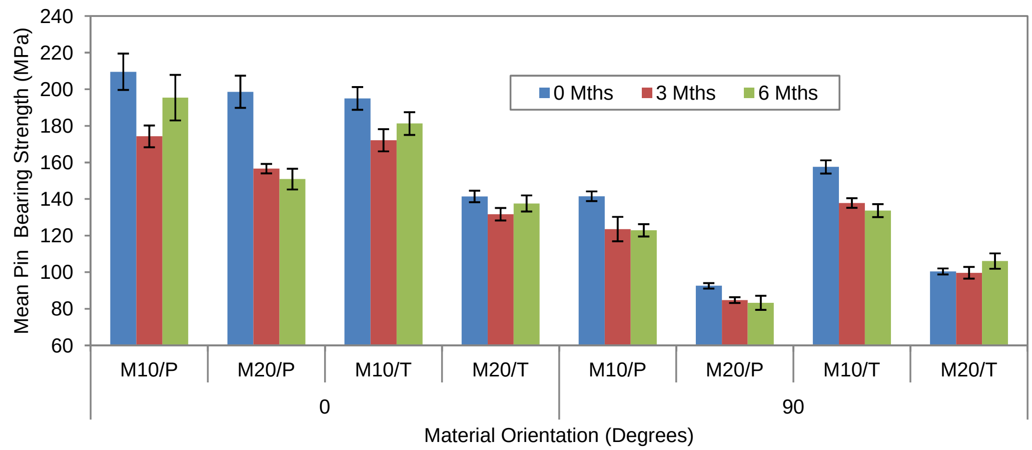

Figure 7: Comparison of mean pin-bearing strengths for flange material after hot-wet conditioning for 0, 3 and 6 months

The governing factor in hot-wet aging is moisture and so the level of material degradation should be related to moisture uptake [4]. The change in specimen mass from moisture uptake after hot-wet conditioning for three and six months is presented in Table 5. The average mass change (%M(*time*)) due to the distilled water that diffuses into the material during the immersion period of months (*time*) is given separately for each bolt size and web and flange material. The plain and threaded specimens can be combined into a single batch for mass gain evaluation.

Table 5: Average mass gain of hot-wet conditioned PFRP after 3 and 6 months immersion in distilled water at 40°C

	0°		45°		90°	
Batch*	%M(3)	%M(6)	%M(3)	%M(6)	%M(3)	%M(6)
Flange M10	0.81	1.14	-	-	0.83	1.07
Flange M20	0.82	1.03	-	-	0.88	1.10
Web M10	0.84	1.00	0.92	1.16	0.78	1.02
Web M20	0.87	0.97	0.96	1.16	0.82	1.02
*Values for 10 specimens (5 plain and 5 threaded)						

The change in mass was determined using

$$\%M(t) = \left(\frac{M_{\text{cond}} - M_{\text{dry}}}{M_{\text{dry}}} \right) \times 100 \quad (2)$$

In Equation (2), M_{cond} is the mass after the hot-wet conditioning and M_{dry} is the mass of the dry material immediately prior to exposing the specimens to the aging process. The mass uptake is calculated as a percentage of M_{dry}. The key assumption, in employing Equation (2) to establish mass gain, is that there is no loss in water-soluble matter over the aging process. If necessary a correction can be made to account for a dissolution phenomenon. A simple way to address the level and composition of leachate from the hot-wet aging process would be to characterise the distilled water after removing specimens.

The mass gain for the 10 batches at three months ranges from 0.78 to 0.88 % and at six months from 0.97 to 1.14%. Given that doubling the time has increased the water intake by 25% there is evidence that the gain is reducing as is predicted by the Fickian diffusion model [4].

It is of interest to consider how the conditioning relates to field conditions [9]. The specimens within this study (Tables 2 and 3) were fully immersed in distilled water with the full (unstressed) bearing area exposed. A bolted connection between two or more plates of PFRP will be expected to include bolt tightening [2] and washers (of diameter twice the bolt diameter) on either side of the connected plates. This arrangement is most likely to give a physical barrier that severely impedes, if not prevents, moisture ingress for there to be continuous water contact over the bearing surface. As a consequence the moisture uptake from the macro scale measurements (Table 4) can be classified as a worst case situation. In addition, it is well known [4] that the moisture absorption rate increases as a result of higher temperatures. Without further information it can be assumed that moisture gains for hot-wet exposure at 40°C will be speculative against real service life conditions. However, it is recognized that FRP components will, depending on geographical location, be exposed to prolonged periods of either (rain or river or sea) water or humidity. Therefore, structures with bolted connections will have the capability to absorb water to their maximum capacity (saturation) regardless of diffusion rates [4].

Figures 8 to 10 are for plots of typical load-stroke curves for the non-aged and hot-wet conditioned web material specimens for the M20 sized ‘pin’. Part (a) is for the plain situation and part (b) for the threaded case. Each of the three figures is for the three material orientations of 0^{o}, 45^{o} and 90^{o}, respectively. Similar load-stroke characteristics were exhibited by specimens in the other batches whose salient test results are given in Tables 1 to 3. The load-stroke behaviour in Figures 8 to 10 indicates an initial ‘bedding-in’ stage, after which there is a nearly linear (probably elastic) increase to the maximum test load, when bearing failure occurs and there can be a sudden loss in resistance. Specimen stiffness determined from the initial load-stroke plots in parts (a) and (b) are considerably lower when thread is present. This is due to thread embedment over the contact area. It is noted that for the threaded case post-failure response shows a small, if any, loss in bearing capacity, even for the 0° material in Figure 8(a) which has a 30% loss when compared to a plain situation. The measured stiffness for specimens subjected to hot-wet conditioning over six months does not significantly deviate from the 0 month material.

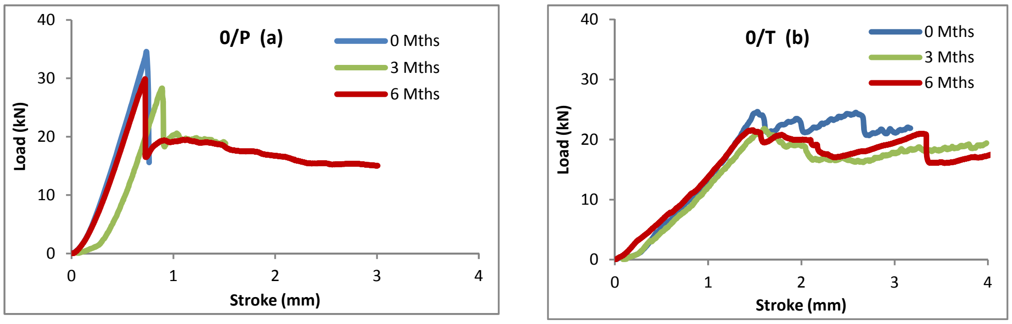

Figure 8: Load-stroke plots for 0° material (a) plain and (b) threaded.

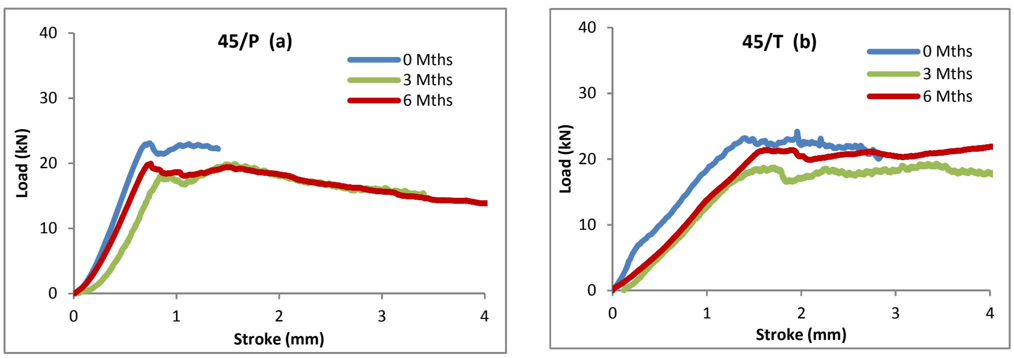

Figure 9: Load-stroke plots for 45° material (a) plain and (b) threaded.

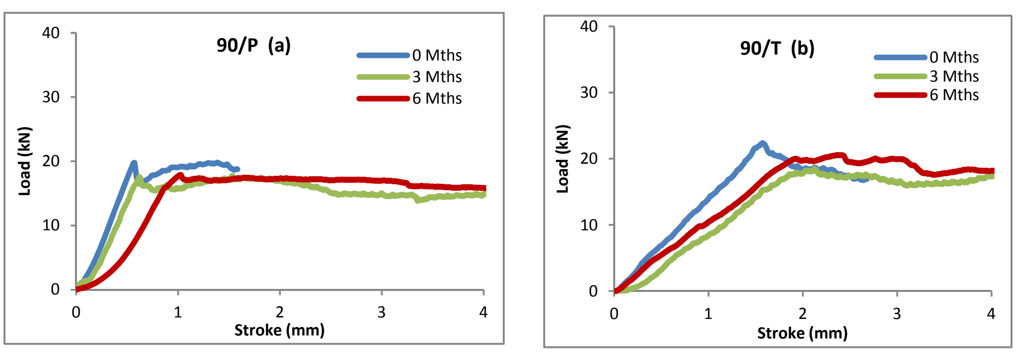

Figure 10: Load-stroke plots for 90° material (a) plain and (b) threaded.

A further study is under way that will look to establish the diffusion coefficient at different temperatures and the activation energy akin to hot-wet degradation of the specific PFRP material. Supplementary conditioning is being conducted in distilled water at 30°C and 50°C, as well as a wider periodic assessment of mass uptake due to the diffusion process. Having established the thermo-chemical properties of the material an estimation of the lifetime degradation will be calculated using the Arrhenius principles [4, 11]. The aim of the authors' research is to establish a viable indication of the level of pin-bearing strength retention that PFRP materials exhibit having been exposed to commonly found aggressive environments such as temperature and moisture. This will allow justification of the reduction (knock-down) factor to pin-bearing strength resistance with respect to aging as will be specified in an American Society for Civil Engineers Load Factored Resistance Design standard for PFRP standard shapes [13].

CONCLUDING REMARKS

An experimental investigation to investigate the effect of hot-wet conditioning upon the laterally unrestrained pin-bearing strength has been described. Presented are novel test results for laterally unrestrained bearing strengths when the bearing bolt is threaded. Results with a plain bolt are reported using an identical test matrix. A reduction in characteristic strength is found for all batches conditioned for three months when compared to their non-conditioned equivalents. A less obvious trend occurs for the batches after six months of conditioning. Eight out of 30 batches show an increase in strength when compared to their equivalent three-month value. When the material is loaded in the direction of pultrusion a reduction in strength is observed and the largest reduction is 30%. The measured load-stroke stiffness was discernibly lower for the threaded situation.

The mass uptake due to immersion for six months at 40°C is found to be 25% higher than the change after three months.

A further study is underway to relate the bearing strength reduction with hot-wet conditioning to real life services times and the associated degradation expected over that period. The test results and implications towards design of bolted connections shall be disseminated in due course.

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REFERENCES

1. Mottram, J. T. Does Performance Based Design with Fibre Reinforced Polymer Components and Structures Provide any new Benefits and Challenges? *The Structural Engineer*, **89(6)**, 23-27 (2011).
2. Mottram, J. T. and Turvey G. J. Physical Test Data for the Appraisal of Design Procedures for Bolted Joints in Pultruded FRP Structural Shapes and Systems. *Progress in Structural Engineering and Materials*, **5(4)**, 195-222 (2003).
3. Mottram, J. T. Determination of Pin-bearing Strength for the Design of Bolted Connections with Standard Pultruded Profiles presented *at 4th International Conference on Advanced Composites in Construction (ACIC 2009)*, Edinburgh, September 1-3, NetComposites Ltd, Chesterfield, 483-495, 2009.
4. Karbhari, V. M. (Ed.), *Durability of Composites for Civil Structural Applications*, Woodhead Publishing, Cambridge, UK (&, CRC Press, Boca Raton) (2007).
5. Mottram, J. T. Design Guidance for Bolted Connections in Structures of Pultruded Shapes: Gaps in Knowledge presented at *17th International Conference on Composite Materials (ICCM17)*, Edinburgh, Paper A1:6, p 12, July 27-31, 2009.
6. Matharu, N. S. and Mottram, J. T. Laterally Unrestrained Bolt Bearing Strength: Plain Pin and Threaded Values presented at *6th Inter. Conf. on FRP Composites in Civil Engineering (CICE 2012)*, Section 14: Codes and Design Guidelines, Paper 311, pp. 8, Rome, June 10-12, 2012.
7. Troutman D. and Mosteller, J. An Investigation of Pin Bearing Strength on Composite Materials presented at *2010 CTI (Cooling Tower Institute) Annual Conference*, Houston, Texas 77056, p. 8, February 7-11, 2010.

8. Mottram, J. T. and Zafari, B. Pin-bearing Strengths for Design of Bolted Connections in Pultruded Structures. Structures and Buildings, **164(5)**, 291–305 (2011).
9. Zafari, B. and Mottram, J. T. Effect of Hot-wet Aging on the Pin-bearing Strength of a Pultruded Material with Polyester Matrix. *Journal of Composites for Construction*, **16(3)**, 340-352 (2012).
10. *The New and Improved Pultex® Pultrusion Design Manual*. Creative Pultrusions Inc., Alum Bank, PA. (www.creativepultrusions.com/library.html) (April 13, 2013)
11. Bank, L. C., Gentry, T. R., Thompson, B. J. and Russell, J. S. A Model Specification for FRP Composites for Civil Engineering Structures. *Construction Building Materials*, **17**, 405-437 (2003).
12. BS EN 1990:2002. *Eurocode 0 - Basis of Structural Design*. British Standards Institution, United Kingdom (2002).
13. *New Pre-standard for Pultruded FRP Composites Funded thru ACMA Means Increased Applications*, American Composites Manufacturers Association (ACMA) press release. //old.acmanet.org/pressreleases/2011/011711.html (April 13, 2013)