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Affect of hot-wet aging on the pin-bearing strength of a pultruded material with polyester matrix

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Abstract

This paper presents test results to show the effect of hot-wet conditioning on the pin-bearing strength of a pultruded fiber reinforced polymer material. Knowledge of this strength property, taking account of any reduction over the service lives of structures, is required to reliably calculate bearing strength when designing bolted connections. Pin-bearing strength is determined using an in-house test method with batches of nominally identical specimens, cut from the web of a 203 x 203 x 9.53 mm wide flange shape. This shape is from the 1525 series of Creative Pultrusion Inc., having a polyester based matrix. Specimens were immersed prior to strength testing under water for 3000 hours at the constant temperature of 40° C. The paper discusses the accelerated aging protocol and its relation to service life, and an explanation is given to why the material was aged for an unknown number of service years. Variables in the test matrix are the direction of the bearing force (0°, 45° and 90° to the direction of pultrusion) and plain pin diameter (four sizes from 9.7 mm to 25.4 mm). Comparing aged pin-bearing strengths with equivalent strengths for non-aged material it is found that the average reduction in characteristic strength (calculated in accordance with Eurocode 0) of the 12 batches, is in the range of 18 to 31%. The extent of strength reduction is found to be independent of pin size, except when the diameter is 25.4 mm. For the 0° situation a comparison is made between the characteristic strengths for the four pin diameters determined using BS EN 1990:2002 and ASTM D7290 to show that the latter Weibull distribution values are lower, and by 4 to 18%.

Keywords: Pultruded structures, bolted connections, pin-bearing strength, hot-wet (water) conditioning.

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Notation

d	Bolt diameter and mean pin diameter, mm
d_n	Hole diameter and mean notch diameter, mm
e_1	End distance, mm
e_2	Side distance, mm
k	Rate constant or accelerated factor or acceleration factor
t	Constant thickness of FRP material and mean thickness of web material, mm
w	Constant plate width for single bolted connection, mm
A	Constant in Equation (2)
E_a	Activation energy, kJ mol^{-1}
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_{90}^{br}	Pin-bearing strength in the transverse (90^{o}) direction of pultrusion, MPa
F_{45}^{br}	Pin-bearing strength for 45^{o} to the direction of pultrusion, MPa
R	Universal gas constant, Jmol^{-1}K^{-1}
$R_{br,test}$	Compression bearing load or force applied in testing, kN
R_{br}	Pin-bearing strength (resistance) per bolt, kN
R_u	Design strength, kN
T	Absolute temperature, K
T_g	Glass transition temperature, ^{o}C
Ω	Data confidence factor in ASTM D7290

Introduction

Fiber-reinforced Polymer (FRP) components have been increasingly used in construction for over two decades and, today, are regularly applied in the retrofitting of buildings and bridges (Bank 2006). Although not growing at the same pace, FRP structural components from the pultruded manufacturing process are being used in new build (all-FRP) construction. Continuing progress with composites in construction is highlighted by the UK research and development project (Anonymous 2011d) to engineer a family of pultruded shapes for the factory assembly of a house that, with energy management, is to satisfy the UK Government's code level 6 requirements for zero carbon over the service life (Department of Communities and Local Government 2006). A demonstrator house unit was constructed at Bourne, Lincolnshire, England, in 2011 and will be monitored for its performance.

Having recognized that the lack of consensus on a design standard was a significant constraint to the use (and growth) of pultruded FRP shapes the Pultrusion Industry Council (PIC) signed an agreement with the American Society of Civil Engineers to develop a design standard to assist structural engineers. In November 2010 this project delivered a pre-standard for the *Load and Resistance Factor Design of Pultruded Fiber-Reinforced Polymer Structures* (Anonymous 2011c). It is now progressing through an American National Standards Institute (ANSI, Washington, D.C.) balloting process with the ASCE Fiber Composites and Polymers Standards committee, before it can be adopted as a national standard. The second author was a writer of Chapter 8 that has mandatory clauses and background commentary towards the design of bolted connections, with the bolts, nuts and washers of steel. To write the chapter Mottram (2009a) undertook a thorough review of what could be known, and this task identified where there are gaps in our knowledge and understanding. This evaluation found that there is need for standard test methods to determine the material (characteristic) strengths required to apply the pre-standard strength formulae for the different modes of failure observed from physical tests with bolted connections (Mottram and Turvey 2003). A characteristic value for a material (or product) property is the value having a prescribed probability of not being attained in a hypothetical unlimited test series. This value generally corresponds to a specified fractile of the assumed statistical distribution (two are used in this paper) of the particular property of the material (or product). When a low value of material property is unfavorable, as is the situation for strength, their characteristic values should be defined as the 5% fractile.

The design of connections is one of the most critical aspects when establishing that a primary load bearing structure, of any construction material, is safe and reliable. Steel bolting is the preferred method of connection in the pultrusion industry (Anonymous 2011a, b) because of the advantages of historical precedence, low cost, easy fabrication, readily dismantling, straightforward inspection procedures and manageable quality control. When a bolted connection is fabricated it can transmit load immediately and, by careful design, failure of the

FRP material can provide damage tolerance (Mottram and Turvey 2003), giving a warning before ultimate (brittle) failure (Hollaway 1993). For these reasons bolted connections are widely used.

Bank (2006) and Turvey (2000) show applications of steel bolted connections in pultruded frame structures. Figure 1 shows an engineering drawing of a typical clip angle type joint for non-sway simple frames with bracing (Mottram 2009a; Anonymous 2011b). It is this type of frame joint that the LRFD pre-standard permits. Alternative methods of connection are by adhesive bonding, and other mechanical fasteners, such as screws and rivets and mechanical interlock (Bank 2006). Adhesive bonding does offer the advantages of lightweight, low cost and no holes that raise stress levels in the connection (Hollaway 1993). However, bonding requires specific surface preparation and controlled on-site working conditions, and failure is likely to be brittle and instantaneous, unless a mechanical ‘fail-safe’ method of connection is present (Mottram and Turvey 1998). Combined with the lack of historical precedence to inform us of their long-term service performance, the writers of the LRFD pre-standard (2011c) decided that there was not the engineering understanding to have clauses for the design of adhesively bonded connections, with or without bolting or mechanical interlocking. Bonded structural connections are therefore not permitted.

Considered in this paper is the strength of plate-to-plate connections when its strength is to be determined by the distinct mode of failure known as bearing. We further restrict the discussion to plate-to-plate connections having the double lap-shear single bolted configuration, and with in-plane loading (Mottram and Turvey 2003). It is well-known that such bolted connections of pultruded material can fail ultimately in one of a number of failure modes. Figures 2(a) to 2(d) show the distinct modes of failure to be bearing, shear-out, net-tension and cleavage. It is standard practice that the chosen size (diameter) of the steel bolting is such that failure either by bolt rupture or by bolt pull-through will not occur (Mottram and Turvey 2003). The sketches in Figure 2 depict the fracture patterns for these distinct modes (for tension loading). There is a strength formula in the LRFD pre-standard for each of the four failure modes illustrated. These depend on geometry values (d_n, e_1 and e_2) and material failure strengths and the lowest value calculated using the formulae may be taken as the bolted connection’s strength. It should be understood that mixed modes (e.g. when the connection force is off-axis with respect to the direction of pultrusion) are possible with the single bolt situation, and that block-shear is a new mode when there are multiple rows of bolts (Mottram and Turvey 2003).

The distinct failure mode of bearing is depicted in Figures 2(a). It is characterized by a failure mechanism whereby delamination (i.e. splitting) failure occurs between layers of the fiber reinforcement, in the through-thickness direction, in the vicinity of the hole surface transferring the bearing force from the steel bolt into the FRP material. If we consider the connection detail in Figure 2 the plate is of constant thickness t and constant width w. Because the bolt is centrally placed the width is twice the edge (or side) distance e_2. Other relevant geometric parameters in establishing connection strength are the hole diameter d_n, and the bolt diameter d, which due to a hole clearance is less than d_n. Mottram and Turvey (2003) used the results from series of single-bolted double lap-shear tests to observe that the mode of failure can be made to change by varying the geometric ratios e_1/d (or e_1/d_n) and w/d (or w/d_n), with $w = 2e_2$. To make bearing failure the most likely mode, at room temperature, these two ratios need to be four or higher when the FRP material is pultruded (Turvey and Wang 2007). Turvey and Wang found that to maintain the distinct mode of failure after the material has been aged the size of the geometric ratios can change.

Bearing is the single distinct mode of failure with a strength formula (Bank 2006) having its specific 'material' strength (F_θ^{br}), and the formula is

$$R_{br} = t\,d\,F_\theta^{br}. \qquad (1)$$

For bearing mode of failure this is the reference strength formula in Chapter 8 of the LRFD pre-standard (Anonymous 2011c). It is important to recognize that F_θ^{br} is a directional (characteristic) strength, specific to the bearing load situation, and depending on the orientation (θ) of the connection force with respect to the direction of pultrusion. It is not a typical tensile, compressive or shear strength of the FRP material (Anonymous 2011a, b). F_θ^{br} has to be determined using a standard test method that is fit for purpose. By definition F_θ^{br} is the mean stress over the projected bearing surface (i.e. area dt) when failure is that of bearing. Its pin-bearing value is the lower bound strength because there is no through-thickness constraint that is known (Mottram and Turvey 2003) to increase the connection force prior to bearing failure.

For the purpose of design calculations, Equation (1) requires the characteristic value of F_{θ}^{br} per bolt. For a connection with two of more bolts the bearing strength of the connection (in kN) is to be the sum of the appropriate R_{br}s (using Equation (1)) times the number of bolts for each R_{br} calculated. To obtain the design strength (R_{u}) in the LRFD design approach nominal strength is multiplied by a resistance factor and a time effect factor, which are always less than 1. The nominal strength itself is obtained by multiplying the reference strength by knock down factors to account for environmental conditions.

When the connection force is aligned with the longitudinal direction of pultrusion (see Figure 1) we have $\theta = 0^{\mathrm{o}}$, and F_{0}^{br} is the highest pin-bearing strength. If $\theta = 90^{\mathrm{o}}$ the force is parallel to the transverse direction of pultrusion and F_{90}^{br} is the lowest pin-bearing strength. For the clip angle connection illustrated in Figure 1 the beam's connection bearing strength is $2R_{\mathrm{br}}$, with $F_{\theta}^{\mathrm{br}} = F_{90}^{\mathrm{br}}$, 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.) depending on the choice of bolt size.

It is well-known that bearing strength increases significantly on bolt tightening because a bolt torque provides stiffness constraint to oppose the 'free' through-thickness deformation that will encourage the initiation of delamination cracks (Cooper and Turvey 1995). Because there is no guarantee that bolting will not work loose over the service life of a structure (Mottram 2004), it is prudent to specify that the bearing strength in Equation (1) shall be that of the pin-bearing value. Other factors, not already mentioned, that influence bearing strength are; the fiber reinforcement architecture and material thickness, the bolt-flexibility, the presence of thread over the bearing surface, the bolt diameter-to-thickness (d/t) ratio, the size of the clearance hole and the aging (environmental) conditioning. It is the last influence linked to design for durability that is the topic for the research study reported in this paper.

In a previous paper Mottram and Zafari (2011) determined the characteristic pin-bearing strengths of the web material from the 203 x 203 x 9.53 mm Wide Flange shape. The Creative Pultrusions Inc. (Anonymous 2011a) product is from the 1525 series having a fire retardant matrix, comprised of a filled isophthalic polyester polymer. Reinforcement is in the form of alternative layers, but not necessarily continuous or of constant thickness, of unidirectional (UD) rovings and continuous strand mats (Mottram and Turvey 2003; Bank 2006). Specimens were prepared using lengths of the shape that had been stored outside and exposed to natural weathering conditions for up to 15 years. During the external storage period the only loading would have been that of dead weight in the pile of shapes. Strength testing with plain pins was carried out under ambient laboratory conditions (20^{o}C). To determine the pin-bearing strength the load taken from the strength test is the maximum attained (Mottram and Zafari (2011).

Because the influence on strength of aging had not been quantified, the pre-standard requires F_{θ}^{br} in Equation (1) to be for 'virgin state' pultruded material. To allow for the reduction to a reference strength, from in-service conditioning, the pre-standard uses knock-down factors and a time effect factor to obtain the design strength. To commence characterization work that will close the knowledge gap (so that affect of aging on strength can be quantified), this paper presents new test results, using the same web material, test matrix and test method, after specimens had been subjected to a known environmental conditioning in the form of hot-wet aging (3000 hours under water at 40^{o}C). For the text matrix there are three material orientations (0^{o}, 45^{o} and 90^{o}) and four plain pin diameters (9.7 mm, 12.2 mm, 18.8 mm and 25.4 mm) that are permitted in practice. These pin represented the smooth shafts of steel bolts of diameters 3/8 in., ½ in., ¾ in. and 1 in., respectively. The diameter of the hole was larger than the pin diameter, giving a clearance hole in excess of the minimum of 1.6 mm (1/16th in.) specified in the LFRD pre-standard (taken from the pultruder' design manuals (Anonymous 2011a,b)).

It is important that calculations made using Equation (1) give safe (design) strengths. The pin-bearing strengths presented in Mottram and Zafari (2011) are used to show that, for this to be true, it is essential that F_{θ}^{br} accounts for the strength reduction due to hole clearance and the maximum *d*/*t* ratio to be found in practice. This previous study also, importantly, shows that existing standard test methods (ASTM D953-02 and BS EN 13706-2:2002) are likely to give a non-conservative (too high) measurement because they specify a single specified pin diameter of 6.35 mm and there is no requirement for a clearance hole.

In this paper the authors report strength results after specimens (with bearing surface uncovered) had been subjected to a hot-wet protocol. The aim of this form of environmental conditioning was to accelerate aging of the material to simulate what could occur when bolted connections are exposed to weather over the service life of pultruded structures. One objective of the study is to find out if the 12 characteristic strengths, from the text matrix, are similarly lowered after the bearing surface has been subjected to the hot-wet aging. For this study to show that the strength reduction might be dependent on either material orientation or bolt size would add another consideration towards the development (and verification) of a standard test method that will overcome the known limitations, as discussed in Mottram and Zafari (2011), of the current test methods (ASTM D953-02 and BS EN 13706-2:2002).

Long–term Durability and Accelerated Aging

Prior to reporting on the new strength data with aged specimens it is necessary to review what is accelerated aging and why it is required for the property characterization (Karbhari 2007). FRP materials have a property portfolio that make them ideal candidates to contribute to us achieving sustainable construction, and pultruded materials are known to be resistant to many chemicals (Anonymous 2011a, b). One obstacle preventing the exploitation of FRP shapes and systems is the lack of long-term durability and performance data. This weakness manifests itself in design by the calculated nominal strength (for members and connections) in the LFRD pre-standard being modified by applicable adjustment factors (often < 1) that make allowance for material degradation due to service conditions. In what follows the authors present a review of previous durability research to explain why, today, we still cannot make reliable service life predictions for the strength of FRP members and connections.

Research with FRP materials exposed to aggressive conditions for prolonged periods of time has demonstrated that they can experience, up to, a significant loss in mechanical properties (Apicella *et al*. 1983; Bradley and Grant 1995; Liao *et al*. 1998; Sridharan *et al*. 1998; Phifer *et al*. 2000) and marked material degradation (Ghorbel and Valentin 1993; Chin *et al*. 1997; Prian and Barkatt, 1999). Many of the aging conditions applied by these workers could realistically be expected when structures of pultruded shapes (having bolted connections) are exposed to the vagaries of the weather in North America or elsewhere, and with required service lives of tens of years.

The use of accelerated aging testing to simulate field conditions is very common when we want to know the change of a property with time (measured in years). Such tests are conducted to determine residual mechanical property data that can be used to predict the loss after longer times in the field than the aging duration. Accelerated aging subjects the material to an acceleration factor, which upon multiplying by the actual aging time gives the expected life time to when the measured property is presumed to exist. Time acceleration is often achieved by increasing the temperature, according to the Arrhenius law (Karbhari 2007). What is essential to know is that this law assumes that the chemical degradation mechanism is the same at the elevated aging temperature as at the mean service temperature, and that a single mechanism controls the degradation process throughout (BS EN ISO 2578:1999; Bank *et al*. 2003).

The Arrhenius equation defines a function linking temperature to the rate of reaction, and it is

$$k = Ae^{-E_a / RT} . \quad (2)$$

In Equation (2), k is the rate constant (also accelerated factor or acceleration factor), A is a constant, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature in Kelvin. Thus, the effect of service lives may be simulated by increasing the temperature and keeping it constant for a shorter period of time, dependent on the value of the acceleration factor.

Since 1994 researchers have addressed the effects of simulated environmental conditioning on properties of pultruded materials from various manufacturers having various fiber architectures and matrix compositions. Preliminary studies presented by Schutte (1994), Bank *et al*. (1995), Chin *et al*. (1997), Gentry *et al*. (1998), Kellogg *et al*. (1999), Liao *et al*. (1999), Abeele *et al*. (2001), Nishizaki and Meiarashi (2002), Karbhari and Zhang (2003) and Robert *et al*. (2010) have involved the measurement of one or more property of flexural and tensile moduli and strengths, and fatigue resistance. Each study used a different accelerated aging condition, with a constant temperature in the range -50°C to 80°C; and immersion in water, or salt solution, or acetic acid, or ammonia; for a period of time from 12 hours up to 2 years. From these unconnected studies an overall finding from the reported test results (for several properties) is that they are differently reduced by their environmental conditioning. In other words the level of property change with aging remains to be quantified.

It will be instructive to the work reported to briefly summarize the contributions from a number of previous papers. In the work by Liao *et al*. (1999) rectangular specimens of a vinyl ester matrix material were subjected to four-point-bending fatigue. Cyclic loading was set from zero to 30% of the dry flexural strength. After first immersing the pultruded specimens in water at 75°C water for 2400 hours the fatigue test results showed a 40% reduction in the flexural strength. This high temperature aging over a time period (less than that used in this paper) demonstrates how large a reduction in a material strength can occur.

The study by Nishizaki and Meiarashi (2002) is of particular relevance to the authors' work as their exposure conditions included soaking coupons in water at the elevated temperatures of 40°C, 50°C and 60°C. The pultruded material had a matrix with a vinyl ester resin, which is known (Anonymous 2011a, b) to possess a greater resistance to chemical agents and temperature than when the matrix resin is a filled isophthalic polyester. Measurement of weight change (gain, which can be followed by a loss) and characterization of the material using chemical analysis methods showed how the material was degrading with time. Strength loss was established by flexural testing and this showed that when the temperature is 40°C there was a loss in strength of 20% after soaking for 9120 hours. When giving their study's conclusions, Nishizaki and Meiarashi wrote "Although it is hard to imagine that deterioration of glass FRP materials exposed in construction applications would be as rapid as that found for the specimens in the deterioration experiment exposure conditions, still, water and moisture levels are clearly factors contributing to the long-term deterioration of materials exposed to water".

Robert, Wang, Cousin, and Benmokrane (2010) observed that many previous researchers were selecting high temperatures (up to 80°C) relative to the polymer resin's glass transition temperature (T_g) to get the maximum rate of aging (the highest possible acceleration factor from Equation (2)). The weakness with this approach, for the evaluation of the durability of a FRP reinforced with glass fibers, is that too high a temperature can cause additional material degradation (that could not be experienced in the field) because the chemical degradation mechanism had changed. Knowing of this weakness, it can be observed that the outcome of forcing a high acceleration factor, by selecting a too high aging temperature, is to under estimate the actual durability.

Robert *et al*. (2010) also worked with a pultruded material having a vinyl ester based matrix. They observed that after conditioning in distilled water (a more aggressive solution than tap water) for 2880 hours at constant temperatures of 40°C, 60°C and 80°C, the loss in flexural strength is 11%, 19% and 46%, respectively, of the average flexural strength at 23°C (room temperature). These researchers used their study to conclude that the affect of temperature is the most important aging factor, with time and/or sustained loading of secondary importance.

Bank *et al*. (2003) outlines a material specification with Procedure B for the determination of long-term properties for material qualification. Their accelerated testing has the maximum aging temperature taken to be 0.8 of the (nominal) glass transition temperature (T_g) that can be based on data provided by Chateauminois *et al*. (1995). It is noteworthy that for the purpose of design, it has been recommended by Karbhari, Chin, Hunston, Behnmokrane, Juska, Morgan, Lesko, Sorathia, and Reynaud (2003) that the FRP material is to be chosen to have a T_g at least 30^{o}C above the maximum expected service temperature. From a private communication with the resin manufacturer the glass transition temperature of the Series 1525 polyester resin is 100^{o}C; well above the 40^{o}C in the hot-wet aging. This upper bound on T_g is without aging in water, which is shown by Chateauminois *et al*. (1995) to reduce the glass transition temperature.

Turvey and Wang (2007) have reported the effect of hot-wet aging on the strength of single-bolt tension joints. The material was EXTREN® 500 series pultruded flat sheet with a polyester resin matrix. Strongwell (Anonymous 2011b) recommended that their 500 series material should not be used at temperatures above 65^{o}C. They choose the joint geometries (see Figure 2 for geometric ratios w/d, e_1/d) to ensure that, for the tension loading, the mode of failure in the double lap-shear tests was one of the distinct modes of bearing or net-tension. They found that the failure loads for the ‘bearing’ joints are almost independent of the water immersion time under ambient temperature conditioning. After aging at constant temperatures of 60°C and 80°C in water for about 1100 hours joint strength (measured with the material at the aging temperature) was found to decrease by about 63% and 86% of the ambient temperature failure load. After another 1000 hours of immersion they found a further decrease of 7% and 3%. This finding suggests that there might be a limit to the loss in residual strength due to the long-term degradation of this pultruded material.

Like other workers, Turvey and Wang (2007) recognized that any choice of conditioning for accelerated aging cannot exactly replicate the long-term material degradation that FRP structures could probably experience in the field over their service lives. This fact informs us that a good measure of sound engineering judgment will be required when reduced mechanical properties are, for example, used in strength calculations for the design of FRP structures.

Equation (1) is a key strength formula for the design of bolted connections when one of the components in the joint is of FRP. This is the justification for work by the authors to develop a test methodology that can be used to determine reliable and relevant characteristic values for pin-bearing strength. Previous work reported in Mottram and Zafari (2011) had specimens tested without additional accelerated aging and the main findings are given in the next section of this paper. Knowing that adverse environmental conditions will cause a loss in strength there is a need to find out how pin-bearing strength might be affected when the bearing surface (of the bolt hole) is subjected to additional aging, which ideally should simulate field conditions and service lives.

Presented in Figure 10 of Robert *et al.* (2010) is a plot of the accelerated factor (0 to 140) as a function of temperature (0 to 100^{o}C). Multiplying the aged time by this factor gives the service time. Note that the term ‘accelerated factor’ is commonly written as ‘acceleration factor’, and it is the latter terminology that the authors use. The paper does not say how the values in the Arrhenius equation curve ($\textit{Accelerated factor} = 0.66e^{0.068(\textit{Temperature in oC})}$) were established, and it may be assumed that they are specific to the pultruded bar material, having a vinyl ester matrix. If the function, for Equation (2), in Figure 10 of Robert *et al.* (2010) is assumed to be valid for 1525 series material (with a fire retardant polyester matrix) it can be estimated that aging for 3000 hours at 40^{o}C is equivalent to 3.5 service years in Canada, where the mean annual (service) temperature is 6^{o}C.

Robert *et al.* (2010) do, however, provide the following cautionary observations on the application of the Arrhenius equation curve. “It has to be noted that in regions of large temperature variations such as Canada, one-year aging at an average temperature is not equivalent to one-year aging at temperatures varying around this median temperature. In fact, for two areas having the same average temperature, the material degradation will be lower in the region having the lowest temperature variation because, as the Arrhenius equation (Equation (2) shows material degradation is not linearly proportional to the temperature but increases exponentially.”

Beddows *et al.* (2002) uses Equation (2) as the basis of presenting a model that allows lifetime predictions for hot water accelerated aging of FRPs. To explain how the model can be used to predict service lives, a small amount of data was collected from flexural strength testing of aged pultruded material, which is from the same 1525 series Wide Flange shape (Anonymous 2011a) being used for the pin-bearing strength characterization reported herein. Although the data sets in Beddows *et al*. (2002) are far too small to give reliability the analysis gave the 1525 series material an activation energy (E_a) of 39000 $Jmol^{-1}$. The paper also reports the mean annual temperature is 10.4^oC in the UK. SaECaNet has an interactive web-page (www.saecanet.com/calculation_page/000376_000505_accelerating_factor.php) for *Calculation of Acceleration factor by Arrhenius equation*: To use the Internet calculator the activation energy (E_a) has to be in units of eV. To change units from $Jmol^{-1}$ to eV the activation energy, taken from Beddows *et al*. (2002), is multiplied by 1.036×10^{-5} $eVJ^{-1}mol$, which is the ratio of the Boltzmann constant (8.617×10^{-5} eVK^{-1}) and the universal gas constant (R is 8.314 $Jmol^{-1}K^{-1}$). Activation energy 39000 $Jmol^{-1}$ for 1525 series material is therefore 0.404 eV.

Inputting into the boxes on the web-page the ‘accelerated temperature’ at 40^oC (313.2 K), the ‘practical use temperature’ to 10.4^oC (283.6 K), and the other parameters of ‘activation energy’, ‘Boltzmann constant’ and ‘aging Term’ (time in number of hours), the SaECaNEt calculator gives the ‘Acceleration factor’ to be 4.8. With the ‘aging Term’ equal to 3000 hours the aging corresponds to 1.6 years of immersion in water at the constant annual mean UK (service) temperature of 10.4^oC. Note that for the ‘practical use temperature’ set to the Canadian mean annual temperature of 6^oC the calculator gives an ‘Acceleration factor’ of 6.2 and a corresponding service time of 2.1 years. This is less than 3.5 years using the curve in Figure 10 of the paper by Robert *et al.* (2010); one reason for the difference will be the change of polymer resin.

Having estimated the aged time in the UK as 1.6 years (which is not long for service lives of tens of years) there are further issues to consider if we are to reliably know what the actual aged time is for bolted connection design. To elaborate on this challenge, we can accept that, as long as: the bolting remains tightened; there are washers with the bolt head and nut; the surfaces in the bolt connection are flat and parallel, it will take a long time, if at all, before the ‘clearance hole’ void fills up with water. This issue alone suggests that the calculated 1.6 years is for a much longer service time. Other physical issues that will exist in field applications, such as the influence of stress and or other environmental factors (e.g. exposure to chemicals, UV radiation) could, however, be counter influences to speed up the rate (acceleration factor) of material degradation to bearing failure.

As a consequence of the review of previous research on accelerated aging of pultruded materials the authors recognize that the new test results in this paper can only be applied to give an insight into how pin-bearing strength might reduce over the service lives of pultruded structures assembled with bolted connections. This weakness in the work is acceptable because the series of tests were carried out with the aim of finding out whether or not the level of reduction in the pin-bearing strength, after hot-wet aging, is dependent on the bolt diameter to material thickness ratio.

Warwick University Test Method for Pin-bearing Strength

On reviewing the scope and limitations of the existing standard test methods (e.g., ASTM D953-02, BS EN 13706-2:2002) Mottram (2009b) found that none can satisfy the requirements needed to establish a characteristic pin-bearing strength for Equation (1). This review is furthered in the paper by Mottram and Zafari (2011), and one of the conclusions made is that we need a new test methodology. Reasons for this finding are that current standards do not require bearing strength to be determined when there is a clearance hole and the much larger material thicknesses and bigger bolt sizes permitted in practice. A fourth reason that was identified is that the size of the largest tension loaded coupon is too big to be cut from pultruded structural shapes, such as those tabulated in Anonymous (2011a, b) and shown in Figure 1. An alternative arrangement for applying the bearing load is sought that can accommodate a smaller coupon size that can be cut from structural shapes.

A preliminary study by Mottram (2009b), using 6.35 mm (1/4 in.) thick flat sheet material, is presented for a comparison of pin-bearing strengths determined by using two test methods to generate bearing failure. One method is in the spirit of Annex E to BS EN 13706-2 that has the tensile loaded specimen shown in Figure 3, while the second method, requiring a much smaller compression specimen, is in the spirit of the test method ASTM D5764-97a (reapproved 2007). A compression loading rig and specimen holder used at Warwick University (Mottram and Zafari 2011) for the latter test method is shown in Figures 4 and 5. This arrangement is based on compressing a plain pin (for no bolt thread and a smooth shank) into small rectangular specimens with a semi-circular notch positioned at the center of a shorter side. The specimen is held vertically in a steel holder having uniform grooves in the side walls to accommodate the material thickness. With the required specimen blank size of 125 by 100 mm, for the biggest bolt diameter of 25.4 mm, these plan dimensions remove the tensile specimen size problem of requiring (BS EN 13706-2) a blank 300 by 150 (6*d*) mm. It is possible only to cut the much bigger BS EN 13706-2 blank from flat sheet, and pultruders are not known to produce sheeting with the fiber architecture of their standard structural shapes. This justifies the search for a loading approach and test rig with a smaller coupon size. A key finding from the comparison made in Mottram (2009b) is that the two test methods do not give significantly different pin-bearing strength measurements. This important outcome provided the authors (Mottram and Zafari 2011) with the confidence to continue testing with the Warwick University method.

Figures 4 and 5 show an in-house compression die set with fixtures to apply compressive loading. By inspecting the surface texture of the web material it is observed that the specimens in the two figures have material orientations of 90^o and 45^o to the bearing load. In Figure 4 the pin, cut from the smooth shank of a black steel bolt (Grade 8.8), has diameter of 25.4 mm (1 in.) and in Figure 5 it has the smallest of the four diameters at 9.7 mm (3/8 in.). The specimen holder accommodates the nominal specimen thickness of 9.53 mm. The purpose of the holder is to keep the specimen vertical and to provide it with a degree of lateral restraint against out-of-plane flexural deformation. The width of the specimen is constant at 100 mm. The height of the specimen can be varied and is set at 100 mm because experience has shown that this height, which is four times 25 mm, does not affect the maximum load for bearing failure.

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 bearing 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 (as seen in Figures 4 and 5). 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 over 90 s.

Material and Hot-Wet Conditioning for Aged Specimens

Specimens were cut from the web of a 203 x 203 x 9.53 mm (8 x 8 x 3/8 in.) Wide Flange shape. This WF shape is from Creative Pultrusions Inc. (Anonymous 2011a) and the gray colored standard 1525 series product range. It has a fire retardant matrix, comprising a filled isophthalic polyester polymer. The material has the following tabulated mechanical properties (Anonymous 2011a):

- in the longitudinal (0^o or LengthWise (LW)) direction - compressive modulus (ASTM D695) = 20.7 kN/mm^2; compression strength (D695) = 231 N/mm^2; maximum bearing strength F_0^{br}, (D953) = 206 N/mm^2.
- in the transverse (90^o or CrossWise (CW)) direction - compressive modulus (D695) = 7.0 kN/mm^2; compression strength (D695) = 115 N/mm^2; maximum bearing strength, F_{90}^{br} (D953) = 124 N/mm^2.

These mechanical properties are averages based on random sampling and testing of production lots (Anonymous 2011a). In the Design Manual the longitudinal pin-bearing strength F_0^{br} is the Maximum Bearing Strength (LW). There are no accompanying notes to explain why the word ‘Maximum’ is used. ASTM D953-02 does define maximum bearing stress to be the maximum load in Newtons (or pounds-force) sustained by the specimen, divided by the ‘bearing’ area (*dt*). This is not the bearing strength, which is the bearing stress at which the bearing hole is deformed 4% of its diameter. Because Creative Pultrusions Inc. use the standard to determine the strength the word ‘Bearing’ ought to be ‘Pin-bearing’ as there is no lateral restraint. Such a casual use of words in the Design Manual (Anonymous, 2011a) is not helpful to practitioners, and it is an example of the numerous gaps that led the Pultrusion Industry Council (of ACMA) to support the project for the preparation of the LRFD pre-standard (Anonymous 2011c).

On the assumption that the web material in the Wide Flange shape can be classified as Grade 23 the material standard BS EN 13706-3:2002 stated that, at room temperature and no aging (i.e. ‘virgin state’ material), the minimum longitudinal (F_0^{br}) and transverse (F_{90}^{br}) pin-bearing strengths are to be 150 and 70 N/mm^2, respectively.

Because the WF shape (Figure 1) has a web depth of 180 mm it can just accommodate the 158 mm deep blanks (for length of a diagonal) needed for specimens having the 45^o material orientation; the 90^o blanks are smaller, at 125 mm high and 0^o blanks smallest at 100 mm high (for the specimen width). From the top of the flange junction there is a 10 mm depth of web that has a greater thickness and this web material cannot be used to prepare specimens. The maximum depth of web for cutting the specimen blanks is therefore 160 mm, 2 mm above the required 158 mm. Because the lengths of the WF shape had been stored outside, for over 15 years at the mean UK temperature of 10.4°C (Beddows *et al*. 2002), it would be economical with the truth to state that the material had not already experienced a level of aging. The extent of material degradation has to remain unknown because properties of the 'virgin state' material were not determined when the shapes arrived at the university. This fact does not detract from the added value of the study reported here since the comparison of aged material is made with test results (Mottram and Zafari 2011) using non-aged material from the same (15 year old) stock. In other words the starting state of material for the specimens in the two series of tests is going to be very similar, if not the same.

Holes are drill through the blanks using standard drill bits and a vertical drilling machine. To form the specimen with a half-notch a cut is then made, using a rotary saw, across the width of the blank at the level of the hole centre. After preparation, the specimens were immersed under tap water in a Grant SUB36 water tank and aged for 3000 hours at a constant temperature of 40^{o}C. The full surface of the semi-circular notch was in contact with the warm water for the duration of the aging process, which, earlier in this paper, has been estimated to be 1.6 years of service life, in the UK. The moderately elevated temperature of 40°C was selected because, at higher temperatures, another material degradation mechanism can amplify the property loss leading to a conservative determination of the actual long-term reduction (Nishizaki and Meiarashi 2002). It is noteworthy that should shapes of 1525 series material be constantly exposed at the moderated elevated temperature of 38^{o}C (100^{o}F) Creative Pultrusions Inc. recommend that the ultimate stress be taken as 85% of the tabulated value (refer to Table 6.1 in Anonymous (2011a)).

After 3000 hours of soaking in the warm water the specimens were tested for their pin-bearing strength at room temperature (see Figures 4 and 5), following a wipe down with a paper towel to remove surface moisture. It was observed that a number of the specimens had surface spots of a slightly dark brownish color. This was predominately on the cut edges of the specimens where the matrix and fibers are exposed. This localized color change maybe due to a possible chemical reaction that had occurred in the matrix. Nishizaki and Meirarashi (2002) reported seeing a similar color change after hot-wet aging of their vinylester pultruded material. They did not provide us with an explanation to the color change.

Test Results and Discussion

Presented in Tables 1 to 6 are pin-bearing strength test results and their statistical analysis for characteristic values. These characteristic values are determined using the guidance in Annex D7 (General principles for statistical evaluation) to Eurocode 0 (BS EN 1990:2002), and they may be associated with $F_{\theta}^{\rm br}$ for Equation (1). The Coefficient of Variation (CV) is typically between 3 and 10%, with a highest value for this normalized measure of dispersion of the probability distribution occurring with the largest pin diameter of 25.4 mm. It was therefore acceptable to calculate the characteristic strength on the assumption that CV is known *a priori*. Both BS EN 1990:2002 and the commentary by Gulvanessian *et al*. (2002) on Eurocode 0 give details on how characteristic properties are obtained. Tables 1, 3 and 5 are reproduced from Mottram and Zafari (2011) and are for pin-bearing strengths when the web material has material orientations $0^{\rm o}$, $45^{\rm o}$ and $90^{\rm o}$, respectively, and specimens had not received the hot-wet conditioning detailed above. These results shall be referred to as the non-aged strengths (the baseline results for comparison with the aged strength data). There is an evaluation and discussion by Mottram and Zafari (2011) on what these results mean towards the establishment of an acceptable test methodology. Moreover, it is believed that differences in test methods, statistical analysis and materials are the reasons why Creative Pultrusion’s LW and CW maximum bearing strengths (given earlier) are higher than the characteristic values for $F_{0}^{\rm br}$ and $F_{90}^{\rm br}$ in Tables 1 and 3, respectively. Tables 2, 4 and 6 have the same content for the material orientations of $0^{\rm o}$, $45^{\rm o}$ and $90^{\rm o}$, respectively, after the specimens had received the hot-wet aging at $40^{\rm o}$C for 3000 hours. As a consequence the test results in the even numbered tables will be referred to as the aged strengths.

The six tables have the following content. Column (1) gives the name of the property that has entries in the row of columns to the right of it. Columns (2) to (5) are for the four different plain pin diameters (*d*) of 9.7 mm, 12.2 mm, 18.8 mm and 25.4 mm. Measuring diameters with an outside micrometer their means to 0.01 mm are given in row three. Directly beneath the row with the column numbers the first to third rows list, for the batch of specimens, the mean thickness (t), the mean notch diameter (d_n), the mean pin diameter (d). It is found that the thicknesses of the aged batches are about ±1% different from those for the non-aged batches (Mottram and Zafari 2011). The difference of d_n - d is given in the fourth row and is for the mean hole clearance. Its magnitude is higher than the minimum 1.6 mm (1/16 in.) found in practice (Anonymous 2011a, b) and the clearance size was dictated by the available drill bit diameters. As would be expected, owing to natural variability in the pultrusion process, there are small differences in the geometries of the 92 and 84 specimens for non-aged and aged material.

The fifth row in the six tables is for the number of nominally identical specimens per batch. It is five or 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 higher at 10 or 11. For each batch the mean, Standard Deviation (SD), Coefficient of Variation (CV) and characteristic value are given in rows six to nine on the assumption that the strength population fits the Normal (Gaussian) distribution. The final (tenth) row entries in Tables 1 to 6 give the pin diameter-to-material thickness (d/t) ratios. Our previous study with non-aged material (Mottram and Zafari 2011) showed that as this geometric ratio increases there is a continuing reduction in the pin-bearing strength.

Prior to discussing and evaluating the results reported in Tables 1 to 6 the forms of the stress-stroke curves for the aged specimens will be presented. For non-aged specimens similar plots are given (Figures 8 to 10) in Mottram and Zafari (2011). Figures 6 and 7 present plots of pin-bearing stress (calculated using $R_{br,test}/td$, where $R_{br,test}$ (Figures 4 and 5) is the compressive force) against stroke. In the two figures, for the 0^o and 45^o material orientations, there is a curve for a single aged specimen with each of the four pin diameters (d). The stroke is that monitored 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 specimen. When the compressive load ($R_{br,test}$) is aligned with the pultrusion direction (0^o) the plots in Figure 6 show the curves to be virtually linear until bearing failure, when there is sudden loss in the load. As might have been expected, from the material's composition, the sudden load reduction at bearing failure is less noticeable when the orientation is 45^o; the same is observed for the 90^o material orientation. Figure 7 shows that, for a 'matrix' dominated deformation, the stress-stroke curve shows the presence of pseudo-ductility. It further identifies that, with pin diameters of

9.7 and 12.2 mm, the maximum load can be a little higher than attained at the end of the 'elastic' response. The curve for the specimen with the 18.8 mm pin diameter indicates that it gave a sudden loss in load. The results in Figures 6 and 7 show that, independent of material orientation, the load-stroke curves are often virtually linear to maximum load attainment. These plots show that the response of aged material is similar to non-aged (Mottram and Zafari 2011), although, for 45^o and 90^o material orientations the curves suggest there is material softening (degradation) following the environmental conditioning. Furthermore, the load-stroke plots support the authors' recommendation in Mottram and Zafari (2011) that pin-bearing strength is to be determined from the maximum failure load, and not by one of the other six choices for the failure load, which are defined in Johnson and Matthews (1979). It is the maximum load from testing that is required when establishing F_{θ}^{br} for Equation (1).

Plotted in Figure 8 are typical stress-stroke curves using a single aged specimen for each of the three material orientations of 0^o, 45^o and 90^o and the pin of 25.4 mm diameter. Their shapes are similar to those for non-aged material (Mottram and Zafari 2011), with the maximum load occurring at a stroke of about 1.0 mm and in descending magnitude with increase of orientation. After the initial embedding stage, the slope of the linear part of load-stroke curve can be assumed to be proportional to the directional modulus of elasticity. The ratio of gradients (for stroke between 0.4 and 0.8 mm) from the 0^o and 90^o tests is 1.3; we find that the 0^o and 45° measurements also give the same stiffness ratio. For the non-aged material the F_0^{br}/F_{90}^{br} ratio was higher at 1.7 (Mottram and Zafari 2011). Using the 0^o load-stroke gradient in Figure 8 the longitudinal modulus of elasticity is estimated to be 15 kN/mm^2. This is a 12% reduction from 17 kN/mm^2 for the non-aged material (Mottram and Zafari 2011), and is 30% higher than the modulus in the 45° and 90^o directions. This finding indicates that the web material has been degraded by the hot-wet conditioning process.

It will be instructive to compare the minimum values of the 0^o and 90^o characteristic strengths in Tables 2 and 6, respectively, after aging with bearing strengths reported by the pultruder (Anonymous 2011a) and in BS EN 13706-3:2002. Minimums were determined with the largest pin diameter of 25.4 mm, and, from Table 2, F_0^{br} is 91 N/mm^2 (CV is 10.1%) and, from Table 6, F_{90}^{br} is 67 N/mm^2 (CV 16.2%). Creative Pultrusions Inc. report F_0^{br} = 206 N/mm^2 and F_{90}^{br} = 124 N/mm^2 for non-aged material and for the longitudinal (LW) orientation their ‘maximum bearing strength’ is over two times higher than the characteristic strength in Table 2. The EN 13706 standard is for non-aged material and the minimum pin-bearing strengths that are required for Grade 23 can be read from Table 1 of Part 3. From the results in Tables 2 and 6 the minimum EN 13706 values of F_0^{br} = 150 N/mm^2 and F_{90}^{br} = 70 N/mm^2 cannot be met after the additional environmental conditioning. Had the strength testing itself been carried out at the evaluated temperature of 40°C the strength loss is likely to be higher still.

For the two pin-bearing strengths that are not expected to be governed by the stiffer UD roving reinforcement the ratio $F_{45}^{\mathrm{br}} / F_{90}^{\mathrm{br}}$ = 1.16, using the mean of the four characteristic strengths in Tables 4 and 6. The importance of this finding, which is similar to the non-aged ratio of 1.13 in Mottram and Zafari (2011), is that knowing F_{90}^{br} effectively gives us the strength F_{θ}^{br} for θ from 45 to 90. Testing with material orientations between 15° and 45° will identify the limit on θ when it will no longer be acceptable for F_{90}^{br} to be taken, in Equation (1), as the pin-bearing strength.

Table 7 has been constructed to report the percentage reductions in characteristic strength following the aging process using the results in Tables 1 to 6. Column (1) gives the name of the information entered in columns (2) to (5), which are for the four pin diameters of 9.7 mm, 12.2 mm, 18.8 mm and 25.4 mm. For each of the three material orientations the non-aged and aged characteristic strengths from their table are given and, directly below their row entries, the percentage difference is given using the expression (non-aged – aged)×100/(non-aged). To show the characteristic strengths they are plotted in Figures 9 to 11 against the pin diameter-to-material thickness (*d*/*t*) ratio. The Eurocode 0 strengths are taken from the ninth row in Tables 1 to 6 and the four values for *d*/*t* from the last row entries. The different pin diameters can be identified as *d/t* increases from 1.04 to 2.84 by the solid symbols for the batch test results. The non-aged batch results are given by the diamond symbols and the aged batch results by the square symbols. To construct the non-aged and aged strength curves in the three figures it is assumed that there is a piecewise linear relationship between the four (pin diameter) data points.

Mottram and Zafari (2011) found that for the non-aged material the characteristic strength decreases with increasing *d*/*t* ratio. This trend is seen in Figures 9 to 11 to be followed when the material has been subjected to hot-wet aging. This finding adds to the growing evidence that the pin-bearing strengths for Equation (1) must be determined using a standard test method that accounts for the most severe *d*/*t* ratio and clearance hole size found in practice.

When using the statistical derived characteristic values to evaluate whether the strength loss trend has changed due to the aging it has to be recognized that the Coefficient of Variation (CV) is not constant. Inspection of the row eight entries in Tables 1 to 6 show that the CVs are not too dissimilar for the three pin diameters of 9.7 mm, 12.2 mm and 18.8 mm. This inspection of the tables further identifies that the CV can be very different when the pin has its largest diameter of 25.4 mm. To further emphasize an important finding it can be seen from the information in Table 7 that reductions (to nearest percentage), ignoring the 25.4 mm pin, are 26 to 28% for 0^o orientation, and 19 to 21% and 20 to 22% for the 45^o and 90^o orientations. Taking the mean percentage reductions for pins of diameter 18.8 mm and lower, it is observed that the loss is highest, and over 25%, for the longitudinal (0^o) material when the UD roving reinforcement influence the resistance and is lower, at about 20%, when strength is less influenced by these fiber layers. It is further observed from the Table 7 analysis (for pin diameters from 9.7 mm to 18.8 mm) that the loss in characteristic strength is nearly a constant percentage of the non-aged strength. This finding is very important because it indicates that the number of batches can be reduced to a manageable number when characteristic strengths for Equation (1) are to be determined and a design standard no longer uses knock-down factors.

With the 25.4 mm pin size the percentage reductions from Table 7 are 18%, 28% and 31% for 0^o, 45^o and 90^o, respectively. Further research is required to explain why these characteristic strengths do not follow the orientation reductions (26 to 28% (0^o), 19 to 21% (45^o) and 20 to 22% (90^o)), obtained with the three smaller pin diameters. It is essential that we gain a physical understanding to explain this finding, since the test results presented in Tables 1 to 6 confirm the need to determine pin-bearing strength with the largest bolt diameter found in practice, and bolts up to 1 in (25.4 mm) in diameter may be used.

Characteristic values in this paper (in Tables 1 to 6) have been determined in accordance with Annex D7 in Eurocode 0 (BS EN 1990:2002) based on the Normal (Gaussian) probability distribution function. For LRFD design with FRP materials (i.e. polymeric composites) the statistically-based properties are to be determined in accordance with ASTM D7290-06 (2006). Now the probability distribution function is assumed to follow the two-parameter Weibull distribution. The characteristic value calculated represents the 80% lower confidence bound on the 5th-percentile value of a specified population and D7290 accounts for statistical uncertainty due to a finite sample (batch) size. This is achieved by specifying the value of the data confidence factor, Ω, which is used to adjust the sample's nominal value for uncertainty. To use D7290 a minimum of 10 samples (i.e. specimens per batch) must be tested for a characteristic value to be calculated (D'Alessendro 2009).

Because of the lower limit on batch size of 10, only the test results for the 0^o material (Tables 1 and 2) can be analyzed following the procedure given in D7290. This was done using the benchmarked spreadsheet written by D'Alessendro (2009). Figure 12 reproduces the characteristic strength plots of Figure 9 with the addition of characteristic values in accordance with D7290. The 'Weibull distribution' strengths (in N/mm^2) are given in the figure next to their solid symbol (diamond for non-aged and square for aged), and dashed lines are used to indicate the piecewise curves that D7290 give. It is seen from the plotting that D7290 strengths are lower and that the level of difference is batch dependent. The Eurocode 0 values, from row nine of Tables 1 and 2, can be used to show that the differences on using the two statistical analyses lie in the range 4 to 18% for the test matrix and batch (sample) sizes covered.

It is instructive, in finishing the discussion, to know that the material properties quoted earlier from the Creative Pultrusion Design Manual (Anonymous, 2011a) are those for standard structural shapes produced years ago. Because the 203 x 203 x 9.53 mm sections arrived at the University of Warwick in the mid 1990s these properties are associated to the material characterized in this paper. Current pultruded sections, such as the Pultex® Fiber Reinforced Polymer SuperStructurals from Creative Pultrusion Inc. (2011a), are likely to have a different construction and/or constituent material composition. As a result of advances in constituent materials and the manufacturing processes the detrimental effect of environmental conditioning on today's pultruded materials could be different to that reported in this paper.

Concluding Remarks

Aged pin-bearing strengths have been determined for the web material in a pultruded wide flange shape (of size 203 x 203 x 9.53 mm), after the specimens had received hot-wet conditioning to simulate aging for an unknown number of service years. To represent how bolted connections are found in practice the hole diameter is bigger than the plain pin diameter by a minimum of 1.6 mm. Test results for twelve batches are presented and the characteristic strengths are determined in accordance with Eurocode 0, allowing for the acceptable assumption that the coefficient of variations are not greater than 10%. The test matrix of three material orientations (0^o, 45^o and 90^o) and four pin diameter-to-thickness ratios (1.1, 1.3, 2.0 and 2.8 (to nearest 0.1)) is identical to that for the test results presented in Mottram and Zafari (2011), when the material had not received additional aging. By aging the specimens in water at a constant temperature of 40^oC for 3000 hours a pin-bearing strength is found to have reduced by 20 to 30% of its non-aged characteristic value. It is found that characteristic strengths determined with the biggest pin diameter of 25.4 mm do not fit in statistically with those obtained using the three smaller pin sizes. By ignoring results for this pin size, the mean reduction is highest, approaching 30%, for the longitudinal (0^o) material (when the unidirectional roving reinforcement layers govern), and lower, at about 20% for the 45^o and 90^o material orientations.

It is further observed from inspecting plots and tabulation of the Eurocode 0 characteristic strengths that the loss in strength, for pin diameters between 9.7 and 18.8 mm, is a constant percentage of the non-aged strength. This finding is important as it indicates that costly testing could be limited to a relative low number of batches with the outcome that we can more readily establish the characteristic pin-bearing strengths required for the design of bolted connections, when the mode of failure is bearing.

The lowest characteristic strengths are obtained with the largest pin of 25.4 mm diameter. For the 0^o orientation this strength is found to be 91 N/mm^2. It is 67 N/mm^2 when the web material is oriented at 90^o. With Creative Pultrusions Inc. giving, for non-aged material, these two orthogonal material strengths as 206 N/mm^2 and 124 N/mm^2, respectively, it is essential that designers recognize the appropriateness of the tabulated (maximum) bearing strengths in a pultruder’s design manual. In Part 3 to the European standard EN 13706 Table 1 reports, again, for non-aged material, the required minimum pin-bearing strengths. It is observed from the aged strengths reported herein that the 0^o and 90^o minimums of 150 and 70 N/mm^2 are not met after the web material had been subjected to the hot-wet aging. The strength loss is likely to have been higher still, had strength testing itself been carried out at the evaluated temperature of 40^{o}C. To mitigate against the risk of a unsafe design it is essential that the determination of pin-bearing strength is carried out with test conditions that allow for the worse probable reduction that could be realized at the end of the service life of a pultruded structure with bolted connections.

Because the number of specimens per batch for the 0^{o} material was above the minimum of 10 it was feasible to compare the characteristic values determined using the Eurocode 0 statistical procedure (BS EN1990:2002), based on the Normal (Gaussian) distribution, with those calculated using a different scheme in ASTM D7290 (2006), based on the two-parameter Weibull distribution. It is this latter standard that is to be used with the LRFD design standard (Anonymous, 2011c) to establish characteristic strength and stiffness values for the strength formulae. By making this comparison it is found that a characteristic strength calculated using D7290 is lower and that the difference between the two statistical analyses can be significant (up to 18%) and batch size dependent.

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Table 1. Statistical test results for non-aged longitudinal pin-bearing strengths using the Warwick University test approach with 9.35 mm web material from a 203 x 203 x 9.53 mm (8 x 8 x 3/8 in.) Wide Flange shape (from Mottram and Zafari 2011).

0^o orientation of web material				
(1)	(2)	(3)	(4)	(5)
Mean 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
Standard deviation, SD (N/mm^2)	6.2	9.1	12.7	14.8
Coefficient of variation, 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 2. Statistical test results for aged longitudinal pin-bearing strengths using the Warwick University test approach with 9.35 mm web material from a 203 x 203 x 9.53 mm Wide Flange shape.

0^o orientation of web material				
(1)	(2)	(3)	(4)	(5)
Mean thickness, *t* (mm)	9.14	9.19	9.16	9.28
Mean notch diameter, d_n (mm)	12.0	15.0	21.0	27.8
Mean pin diameter, *d* (mm)	9.7	12.2	18.8	25.4
Mean clearance, d_n - *d* (mm)	2.3	2.8	2.2	2.4
Number of nominally identical specimens	10	10	10	10
Mean pin-bearing strength F_0^{br} (N/mm^2)	147	128	115	107
Standard deviation, SD (N/mm^2)	11.1	8.0	20.6	9.2
Coefficient of variation, CV (%)	7.6	7.0	9.2	10.1
Characteristic[1] value of F_0^{br} (N/mm^2)	128	114	96	91
Mean *d*/*t* ratio	1.06	1.33	2.05	2.77

Note: 1. Mean – 1.72SD

Table 3. Statistical test results for non-aging 45° pin-bearing strengths using the Warwick University test approach with 9.35 mm web material from a 203 x 203 x 9.53 mm wide Flange Shape (from Mottram and Zafari 2011).

45° orientation of web material				
(1)	(2)	(3)	(4)	(5)
Mean 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 of nominally identical specimens	6	6	6	6
Mean pin-bearing strength F_{45}^{br} (N/mm^2)	174	158	134	118
Standard deviation, SD (N/mm^2)	10.3	8.4	7.5	4.4
Coefficient of variation, 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 4. Statistical test results for aged 45° pin-bearing strengths using the Warwick University test approach with 9.35 mm web material from a 203 x 203 x 9.5 mm Wide Flange shape.

45° orientation of web material				
(1)	(2)	(3)	(4)	(5)
Mean thickness, t (mm)	9.30	9.29	9.29	9.13
Mean notch diameter, d_n (mm)	12.0	15.0	21.0	27.9
Mean pin diameter, d (mm)	9.7	12.2	18.8	25.4
Mean clearance, $d_n - d$ (mm)	2.3	2.8	2.2	2.5
Number of nominally identical specimens	5	5	5	5
Mean pin-bearing strength F_{45}^{br} (N/mm^2)	142	123	105	92
Standard deviation, SD (N/mm^2)	7.4	4.2	5.2	6.9
Coefficient of variation, CV (%)	5.4	3.4	4.9	8.5
Characteristic[1] value of F_{45}^{br} (N/mm^2)	125	116	96	80
Mean d/t ratio	1.04	1.31	2.02	2.78

Note: 1. Mean – 1.80SD

Table 5. Statistical test results for non-aged transverse pin-bearing strengths using the Warwick University test approach with 9.35 mm web material from a 203 x 203 x 9.5 mm Wide Flange shape (from Mottram and Zafari 2011).

90° orientation of web material				
(1)	(2)	(3)	(4)	(5)
Mean 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 of nominally identical specimens	6	6	6	6
Mean pin-bearing strength F_{90}^{br} (N/mm^2)	168	146	120	110
Standard deviation, SD (N/mm^2)	10.5	13.7	10.1	7.2
Coefficient of variation, 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

Table 6. Statistical test results for aged transverse pin-bearing strengths using the Warwick University test approach with 9.35 mm web material from a 203 x 203 x 9.5 mm Wide Flange shape.

90° orientation of web material				
(1)	(2)	(3)	(4)	(5)
Mean thickness, t (mm)	9.16	9.16	9.07	8.95
Mean notch diameter, d_n (mm)	12.0	15.0	21.0	27.8
Mean pin diameter, d (mm)	9.7	12.2	18.8	25.4
Mean clearance, d_n - d (mm)	2.3	2.8	2.2	2.4
Number of nominally identical specimens	6	6	6	6
Mean pin-bearing strength F_{90}^{br} (N/mm^2)	126	110	94	86
Standard deviation, SD (N/mm^2)	5.5	7.0	8.2	10.9
Coefficient of variation, CV (%)	4.7	7.2	10.3	16.2
Characteristic[1] value of F_{90}^{br} (N/mm^2)	116	97	80	67
Mean d/t ratio	1.06	1.33	2.07	2.84

Note: 1. Mean – 1.77SD

Table 7. Percentage reduction in pin-bearing strength as a result of aging.

(1)	(2)	(3)	(4)	(5)
Pin diameter (mm)	9.7	12.2	18.8	25.4
Characteristic strength F_0^{br} (N/mm^2)	0^o material orientation			
Non-aged	177	155	133	111
Aged	128	114	96	91
% reduction based on non-aged	27.7	26.5	27.8	18.0
Characteristic strength F_{45}^{br} (N/mm^2)	45^o material orientation			
non-aged	156	143	121	111
Aged	125	116	96	80
% reduction based on non-aged	19.9	18.9	20.7	27.9
Characteristic strength F_{90}^{br} (N/mm^2)	90^o material orientation			
Non-aged	149	122	102	97
Aged	116	97	80	67
% reduction based on non-aged	22.2	20.5	21.6	30.9

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 2010b).

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. Steel tension loading fixture and FRP test specimen for BS EN 13706-2 (line drawing from standard). Key: 1 - Spacer plate (thickness = t + 1 mm); 2 - Hardened steel side plate; 3 - Hardened steel bushes, sliding fit in side plates (optional); 4 - Plain pin; 5 - Test specimen (t mm).

Figure 4. Pin-bearing strength test rig with 45^{o} specimen and largest pin diameter of 25.4 mm.

Figure 5. Pin-bearing strength test rig with 45^{o} specimen and smallest pin diameter of 9.7 mm.

Figure 6. Pin-bearing stress against stroke curves with pin diameters from 9.7 to 25.4 mm for longitudinal (0^{o}) web material after hot-wet aging.

Figure 7. Pin-bearing stress against stroke curves with pin diameters from 9.7 to 25.4 mm for 45^{o} web material after hot-wet aging.

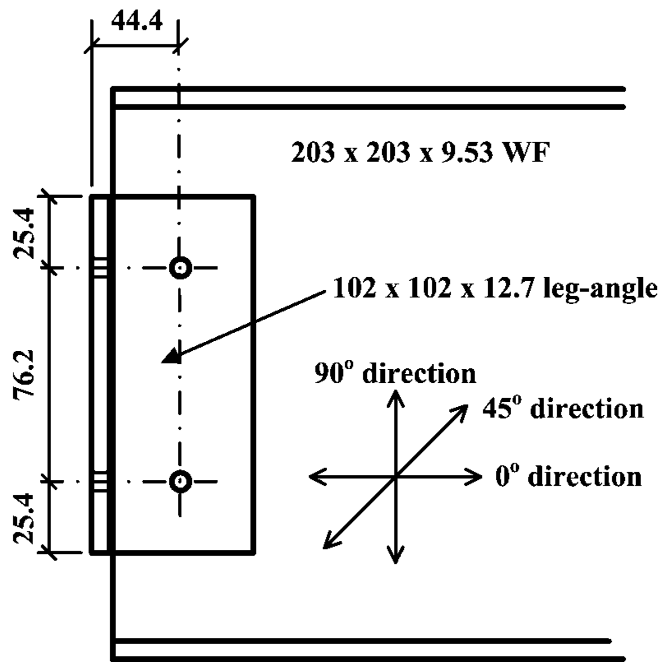
Figure 8. Pin-bearing stress with stroke curves for web material after hot-wet aging at the three orientation of 0^{o}, 45^{o} and 90^{o} with pin diameter of 25.4 mm (i.e. d/t = 2.84).

Figure 9. Characteristic pin-bearing strengths (in N/mm^2) of 0° material with d/t ratio.

Figure 10. Characteristic pin-bearing strengths (in N/mm^2) of 45° material with d/t ratio.

Figure 11. Characteristic pin-bearing strengths (in N/mm^2) of 90° material with d/t ratio.

Figure 12. Characteristic pin-bearing strengths (in N/mm^2) of 0° material in accordance with BS EN 1990:2002 and ASTM D7290.



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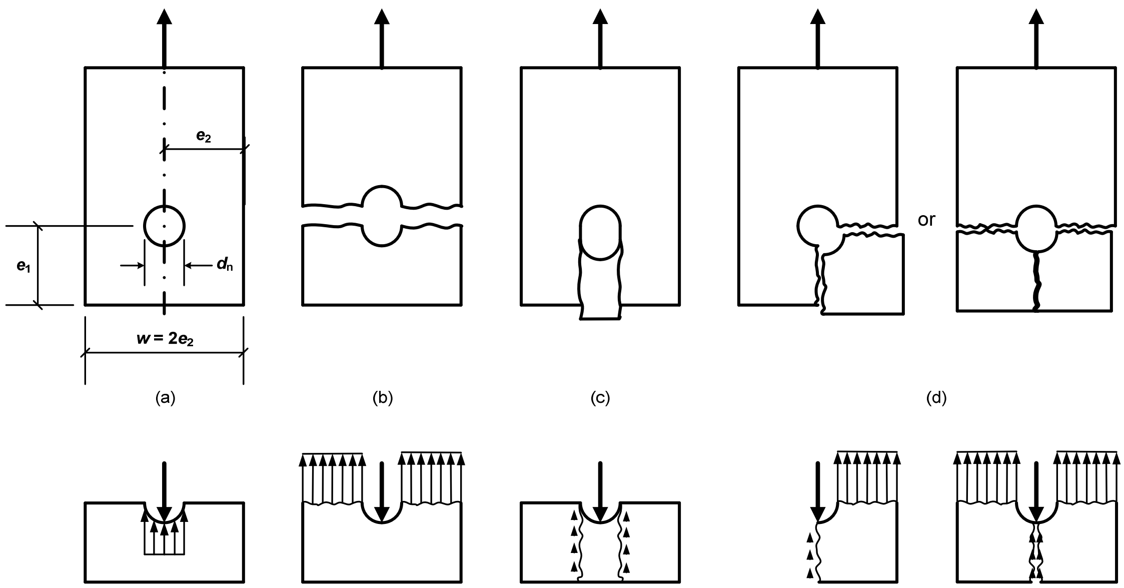

Figure 2. Plate-to-plate distinct modes of failure with a single steel bolt; (a) bearing, (b) net-tension, (c) shear-out, (d) cleavage.

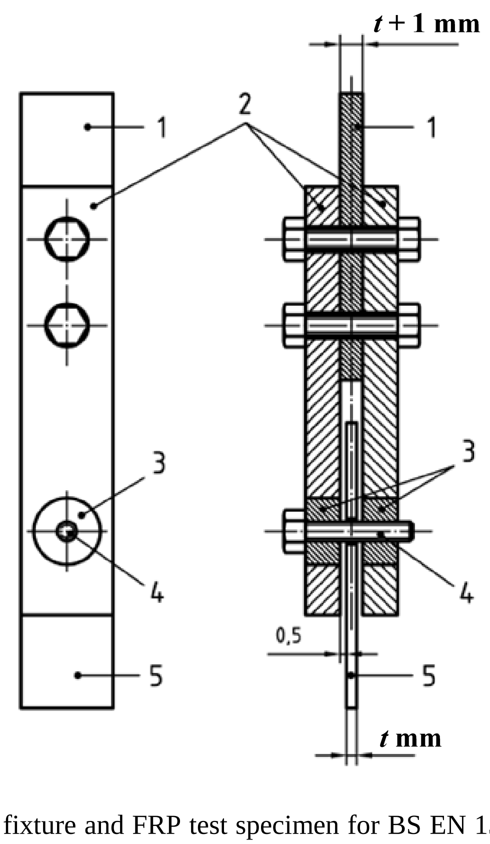

Figure 3. Steel tension loading fixture and FRP test specimen for BS EN 13706-2 (line drawing from standard). Key: 1 - Spacer plate (thickness = *t* + 1 mm); 2 - Hardened steel side plate; 3 - Hardened steel bushes, sliding fit in side plates (optional); 4 - Plain pin; 5 - Test specimen (*t* mm).

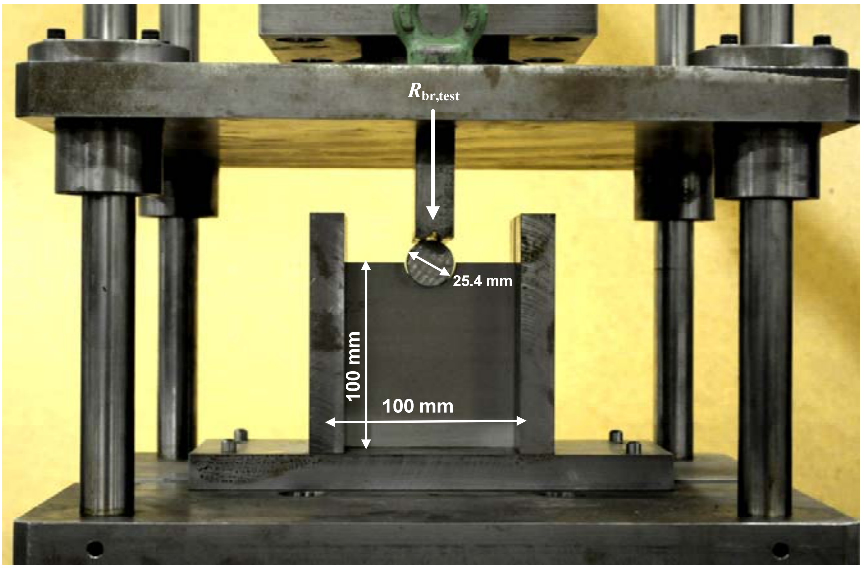

Figure 4. Pin-bearing strength test rig with 45^o specimen and largest pin diameter of 25.4 mm.

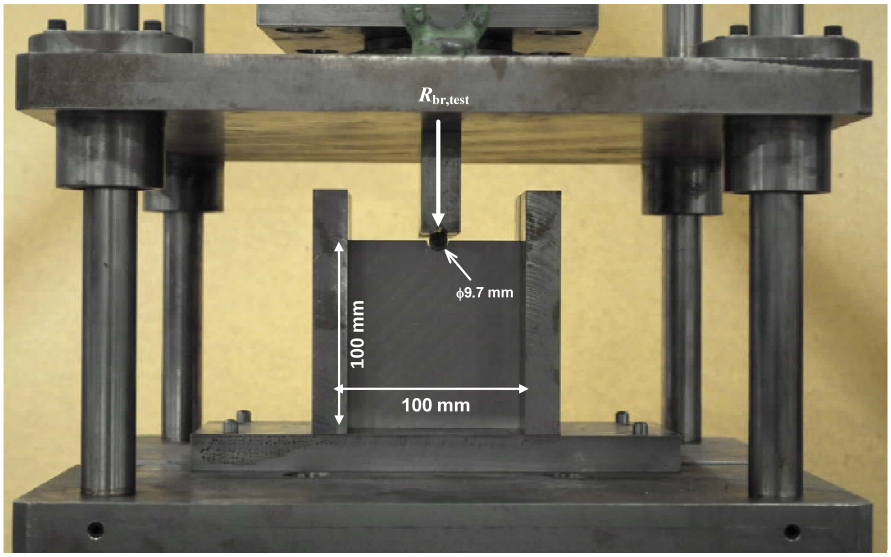

Figure 5. Pin-bearing strength test rig with 45^o specimen and smallest pin diameter of 9.7 mm.

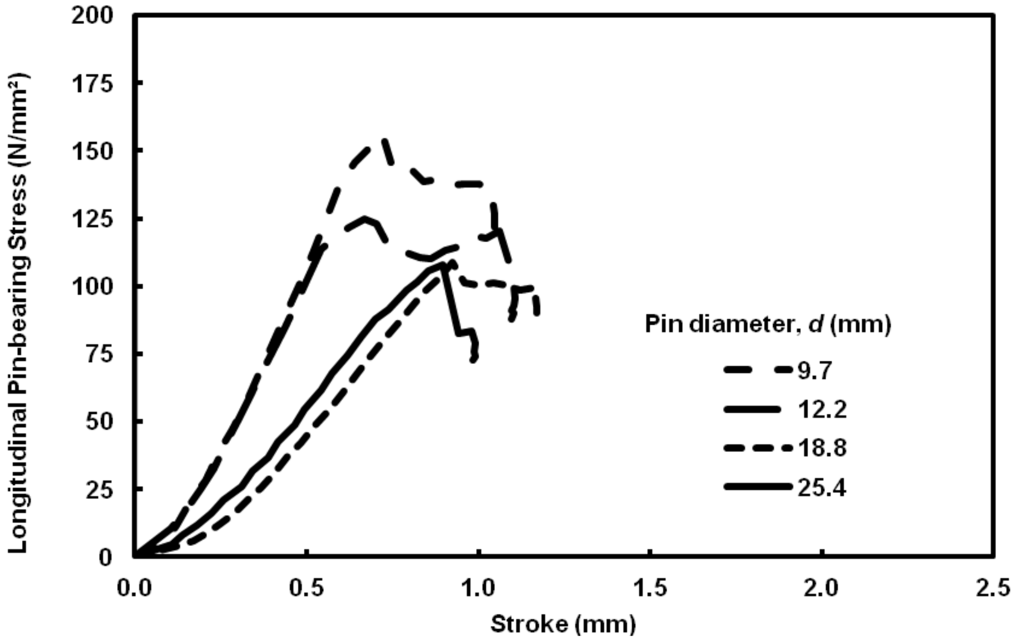

Figure 6. Pin-bearing stress against stroke curves with pin diameters from 9.7 to 25.4 mm for longitudinal (0^o) web material after hot-wet aging.

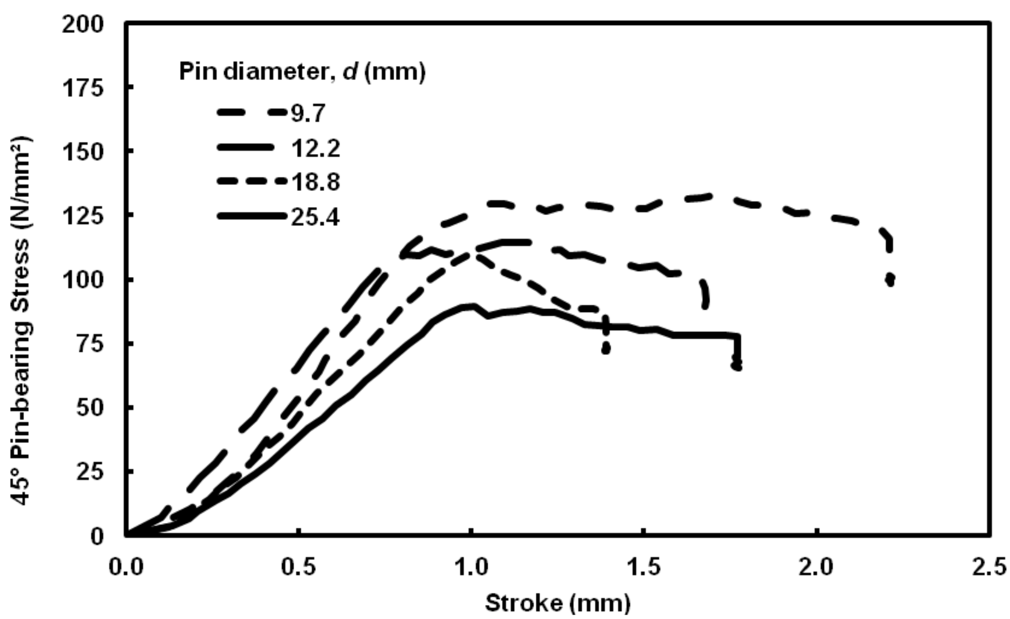

Figure 7. Pin-bearing stress against stroke curves with pin diameters from 9.7 to 25.4 mm for 45^o web material after hot-wet aging.

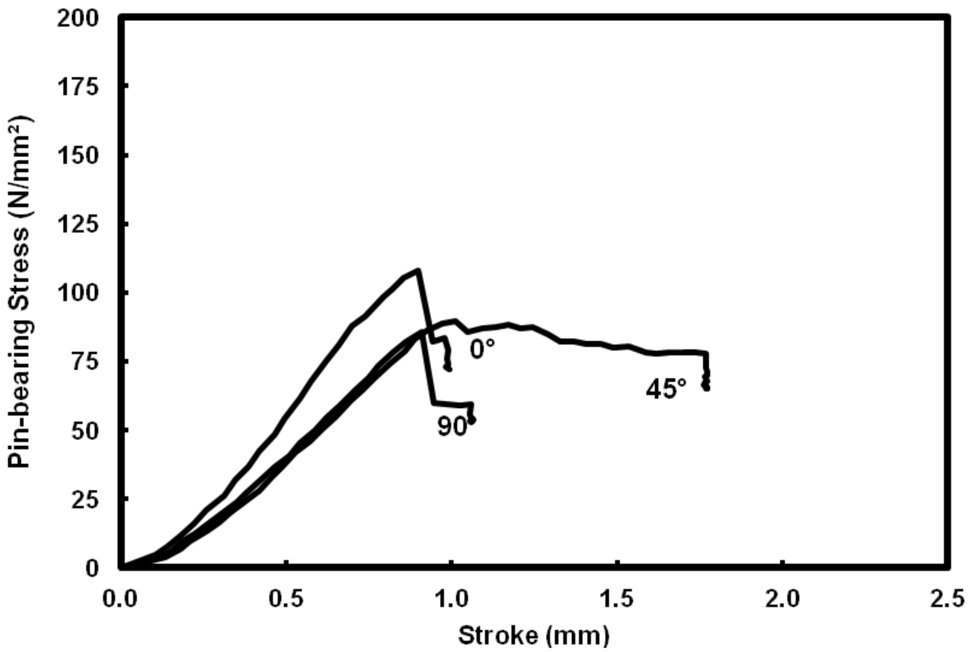

Figure 8. Pin-bearing stress with stroke curves for web material after hot-wet aging at the three orientation of 0^o, 45^o and 90^o with pin diameter of 25.4 mm (i.e. $d/t = 2.84$).

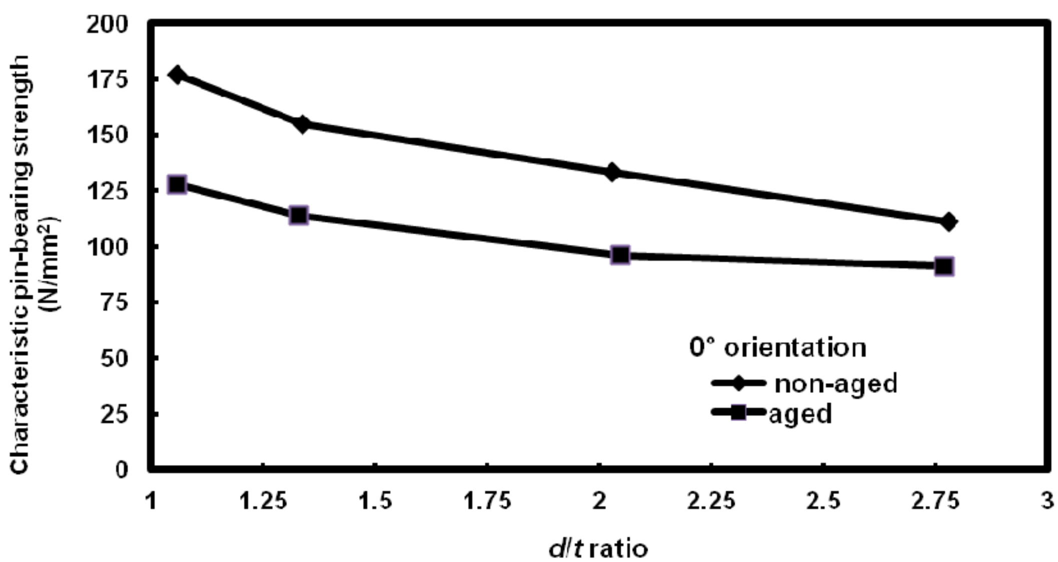

Figure 9. Characteristic pin-bearing strengths (in N/mm^2) of 0° material with d/t ratio.

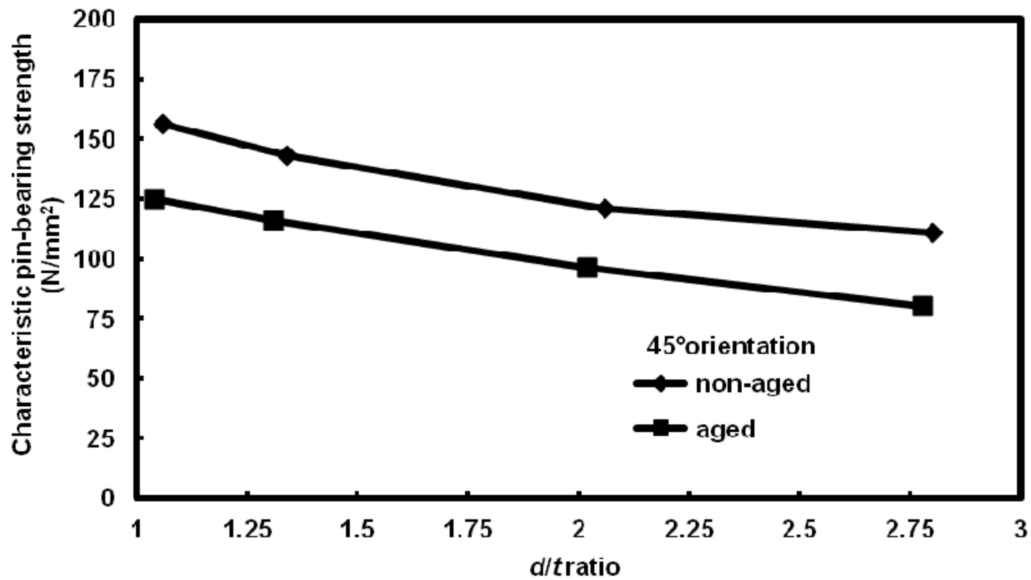

Figure 10. Characteristic pin-bearing strengths (in N/mm^2) of 45° material with *d*/*t* ratio.

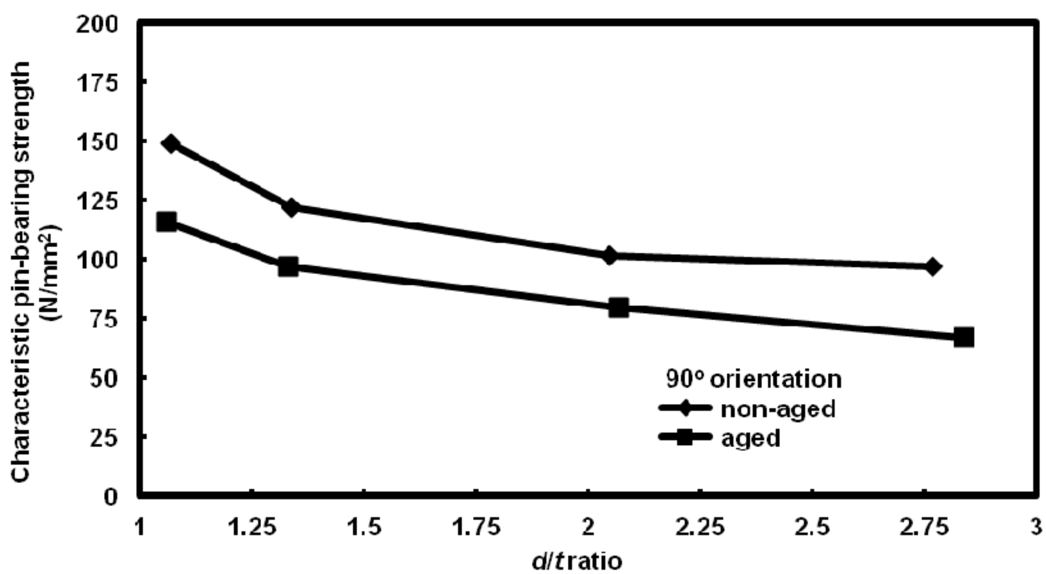

Figure 11. Characteristic pin-bearing strengths (in N/mm^2) of 90° material with *d*/*t* ratio.

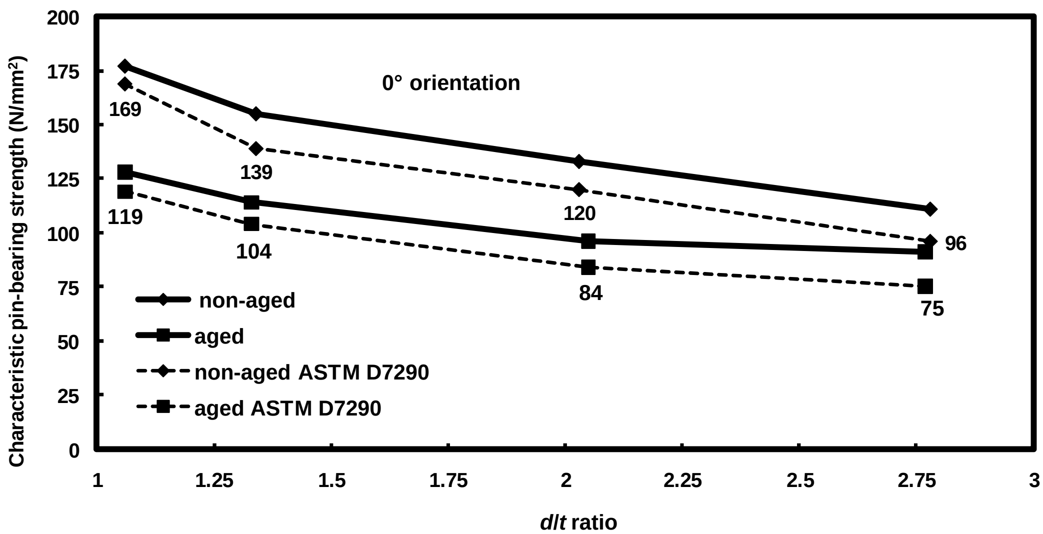

Figure 12. Characteristic pin-bearing strengths (in N/mm^2) of 0° material in accordance with BS EN 1990:2002 and ASTM D7290.