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

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ABSTRACT

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

1. Introduction

Pultrusion is a composite material processing method that produces continuous thin-walled sections of Fibre Reinforced Polymer (FRP) material [1,2]. Standard structural shapes mimic steel sections (I, H, box, leg-angle, etc.), and are used in civil engineering works to construct, for example, non-sway braced frame structures [3]. Members can be connected together by conventional stainless steel bolting [1–6]. These connections provide ease of assembly and low long-term maintenance, as well as being immediately capable of transferring the actions experienced in primary load bearing joints. Safe and reliable design of bolted connections with Pultruded FRP (PFRP) is critical to ensuring sound structural performance, and will involve a fundamental understanding of failure modes [6,7]. Due to the orthotropic and layered nature of PFRP laminates these failure modes can vary significantly [7]. Both damage and mode of failure at ultimate failure (for Ultimate Limit State design [6]) are dependent on connection detailing [6], material and fastener specifications, such as geometry, fibre reinforcement architecture, bolt type, clearance hole size, bolt loading, bolt tightening, etc. It is known [7] that bearing failure (for localised compression failure in the laminate adjacent to the bearing steel bolt), is one of the distinct failure modes observed in failed PFRP bolted connections [6,7]. This failure mechanism is preferred in design owing to its potential to give a progressive pseudo-ductile response [8]. Other distinct failure modes, including net-tension, cleavage and shear-out, are avoided, if practical, since they will are more likely to yield catastrophically without a level of beneficial damage tolerance [8]. Beneficial damage tolerance is when the FRP experiences noticeable material failure without ultimate failure. The bolted connection continues to have an acceptable resistance to what the strength was prior to material damage being present.

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

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

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

2. Pin-bearing strength

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

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

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

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

3. Experimental programme

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

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

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

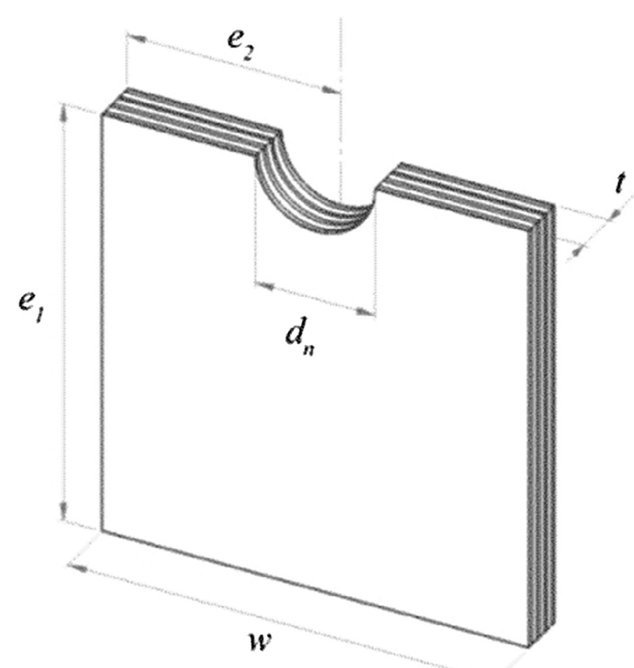

Fig. 1. Schematic of pin-bearing test specimen geometry.