

Design Guidance for Bolted Connections in Structures of Pultruded Shapes: Gaps in Knowledge

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SUMMARY

To help practitioners use pultruded FRPs in structures there is work to prepare an American pre-standard, with design of bolted connections based on existing practice. This paper presents our gaps in knowledge and explains how they may be addressed for connection design guidance to correspond to that used with traditional structural materials.

Keywords: Advanced Composite Materials in Construction, bolted connections, design guidance, frame structures.

ABSTRACT

The purpose of this paper is to introduce a brand new standard for the design of frame structures of pultruded Fibre-Reinforced Polymer (FRP) shapes, with an emphasis on the gaps in knowledge towards the mandatory design information for bolted connections. Structural engineering designers facing fee competition and unrealistic deadlines seek design methods that are simple to use and on the ‘safe’ side. They often have little knowledge of exactly ‘how safe’ their designs are, and with too little time to find out they will confidently follow a code of practice when working with a traditional structural material. Structural shapes of FRP have been available since the 1970s and, for this non-traditional material, designers have had to rely on information from the pultruders, since there is no code of practice to follow. Because this is an obstacle to market growth a project commenced in 2007 to write an American Society of Civil Engineers standard. As part of a team of ‘code writers’ the author works on the design guidance for a chapter on bolted connections. By way of a critical evaluation of what we know, and don’t know, the team has gained insight into where new academic research is required to cope with deficiencies in our knowledge and understanding. This paper lists twenty questions that require our attention and it provides advice on how they should be tackled to ensure that the research is not useless; ‘useless’ in the sense that results cannot be used for the basis of preparing design guidance.

INTRODUCTION

In 2007 the American Society of Civil Engineers (ASCE) and the American Composites Manufacturers Association (ACMA) signed a three-year agreement to develop a pre-standard for the *Load and Resistance Factor Design (LRFD) of Pultruded Fiber-*

Reinforced Polymer (FRP) Structures. This future LRFD standard is expected to help structural engineers and architects use pultruded FRP composites in building and transportation designs and bring benefits, such as its strength-to-weight ratio, resistance to corrosion, low maintenance and long life cycle, to US infrastructure [1].

The drafting of a brand new pre-standard is part of an effort that was initiated by ASCE and the Pultrusion Industry Council (PIC) of the Composites Institute of the Society of Plastic Industry in 1995. To date, ASCE has delivered two reports as a result of this initiative: the first one in 1996 and the second one in 1998. The 1996 report presented a literature search and an annotated outline of a design standard. The 1998 report presented an expanded outline of the design standard based on a review of the literature, and provided recommendations for three ancillary activities:

- development of a fabrication and installation standard (this is work in progress)
- a compilation of material properties data required for the standard
- development of testing standards for determining material properties.

An on-going multi-partner project [1] focuses on the development of a draft to an ASCE design standard with the following eight chapters [2]:

Chapter 1: General Provisions

Chapter 2: Design Resistance

Chapter 3: Tension Members

Chapter 4: Design of Compression Members

Chapter 5: Design of Members for Flexure and Shear

Chapter 6: Members under Combined Forces and Torsion

Chapter 7: Plates and Built-up Members

Chapter 8: Bolted Connections.

Each of the eight chapters have mandatory and non-mandatory commentary parts, and the resistance formulae that are mandatory shall be specified following reliability analyses for Load and Resistance Factor Design (LRFD), since this modern approach gives a quantitative basis for engineering decision-making [3].

The main class of construction to be designed by the ASCE standard [1] is for simple braced (non-sway) frames that may have simple shear (web-cleated) connections between members, and that uses bracing to transfer lateral loads to the ground (see Figures 1 and 2). The method of connection permitted is by steel bolting and so the types of frame connections scoped will correspond to the engineering drawings in the pultruders' design manuals, see [4] and Figure 2 (in imperial units). Justification for not permitting adhesive bonding is our inadequacy in understanding [5], its unsuitability for connecting steel-shaped FRP components, and a need for frames to be demountable for reuse and recycling. Note that adhesive bonding may be permitted by the LRFD standard for member stiffeners and for the joining of moulded or second-generation pultruded shapes (for which it is most suitable), such as for flooring and panelling and for other bespoke systems [6], some of which will be developed after the standard is in general use.

The purpose of this paper is to report on where there are gaps in knowledge for the preparation of the chapter with design guidance for bolted connections. The reasons for the gaps are discussed and are found to be linked to the 'youth' of the structural materials. The author provides advice on how we can address the lack of knowledge

(and understanding) so that design can, sooner, rather than later correspond to that found in other structural material codes of practice towards the limit state design of frame structures, e.g. [7] to [10].



Figure 1. Frame connections for structures of pultruded shapes ([4] and [5]).

DETAIL FOR W8, W10, C8, C10, I 8 or I 10

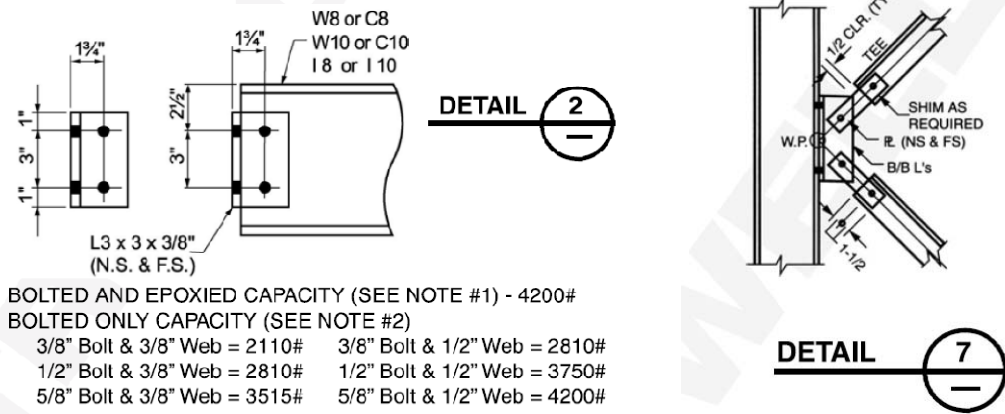


Figure 2. Typical frame connection detailings (left-side for beam-to-column and right-side for 'wind' bracing) from the Strongwell design manual [4].

To scope the types of connections and joints to be found in primary load bearing structures the LRFD chapter for bolted connections combines the need to design for frame joints, such as the web-cleated type shown on the left-side of Figure 2 (will classify as simple using the principles in BS EN 1993-1-8:2006 [11]), with the design of plate-to-plate connections, such as there is in each of the legs for the web cleats (left-side) and bracing members (right-side). Previous research reviewed in [12] and [13], and information from standards for steel and wood structures assisted the academic team in writing a draft for Chapter 8. One major outcome from this exercise is the first assessment of what we know, what we don't know, and how our understanding can be used to prepare universal design rules. Challenges do remain for the writing of the clauses for the design of members in Chapters 3 to 7 and for overall frame behaviour, but the gaps in knowledge are neither as large nor as demanding as those linked to bolted connections (and it is the author's opinion that preparing similar guidance for bonded connections, with or without a mechanical connection, would be even more demanding).

BOLTED CONNECTIONS: WHY GAPS IN KNOWLEDGE

It is appropriate in the paper to now justify why there are gaps in our knowledge. One reason for deficiencies is that the onus on production, design and fabrication has been with the pultruders themselves. They independently developed local expertise and published in-house guidance through their design manuals, see [4]. In America these manuals give designers load tables based on the allowable stress design method. Specific information for structural design was informed by in-house testing and on-site applications, and most of the information gained in this way remains proprietary.

To develop the justification further we also need to understand why academic research is done. Often the prime concern is to obtain new information that will be written-up for (peer-reviewed) publication. A small number of structural engineering academics do conduct research with the aim of transferring their results into design guidance (rules) that, when published by a standards' organisation, allows practitioners to execute structures that are expected to be reliable and safe over their working lives. Often the deliverables from such university research are the results from physical tests to determine structural properties and behaviour to ultimate failure of materials, members, connections, joints, sub-assemblies, and occasionally whole structures. With the advent of computational methods that can model imperfections and analyse the complex non-linearities occurring in real structures, academics have increasingly used numerical simulations to supplement the results gained from laboratory testing.

As Emeritus Professor R. P. Johnson said in his 2006 Gold Medal Address [14] to the Institution of Structural Engineers he had noticed, in the 1960s, that only a tiny fraction of the published research on structures had then been applied in practice. This led to him listing 'eight reasons why 80% of published research is useless'. Here the word 'useless' means only that the research results could not be used as a basis for preparing design rules.

Today, academics actively doing structural engineering research with traditional materials, such steels and timbers, may use Eurocode 0 [15] and other supporting information for a framework to help 'eradicate' the eight reasons, and thereby carry-out quality research that can readily be transferred into practice. But this has not always been the case as Professor Johnson found fifty years ago and the eradication of 'useless research' is a bigger challenge when the structural material is new, it has no recognised design rules, and it has its roots away from the construction industry. This is certainly true for the non-traditional structural material of FRPs.

From his list of eight reasons those found by the authors of Chapter 8 to be relevant to previous research, as given in the papers reviewed in [12] and [13], are:

- no clear definition of the domain of applicability of the work;
- no critical review of previous research relevant to that domain;
- test results that omit crucial data on properties of specimens;
- test specimens with materials having strengths different to typical design strengths.

Referees of peer-reviewed papers could improve matters by being more critical of such defects [14]; of course this can only happen if the referees are conversant with what code writers want. Another problem is that word limits imposed by editors often force omissions of salient information. A remedy, now available to everyone, should be to

cross-refer to a full report (with images showing the failure mode for every specimen), made freely available on the web.

These observations do not detract from the worthiness of the many incremental studies that do add value to what is known; they are simply stating the fact that for the purpose of specifying formulae in the ASCE standard a majority of the previous researches with pultruded bolted connections and joints ([12] and [13]) can be classified as ‘useless’.

It is also relevant, prior to listing the issues where our existing know-how is not strong enough, to give further information to the background to the bolted connection chapter, and what the content is likely to permit designers to work with.

It is assumed that a bolted connection (see Figures 1 and 2) can be classified as a bearing-type connection. This type is one where the transfer of connection force is entirely by way of bearing between the shaft(s) of the bolting and the connecting components. For the design of bearing-type connections it is assumed that there is no force transferred through friction between the connected components [7]. The design of bolted connections with FRP materials is much more complex than when the connecting material is, say steel. The principal reasons for this are the number of different failure modes and strengths, the changes in mechanical properties with orientation and the linear elastic response to yield, which often coincides with ultimate material failure. The lack of a ductile response reduces the ability of the FRP to alleviate stress concentrations by stress redistribution and reduces the degree of damage tolerance that increases the reliability in designing bolted connections.

This level of understanding is not new and for structural applications of FRP laminates it has resulted, after ‘thousands’ of man-years of work, in the design recommendations given in Part 3 of the MIL-17-HDBK [16]. To achieve the highest resistances it is known [16] that the design of mechanical fastened connections has to take account of the available ‘damage tolerance’ [17]. This is far from straightforward to do, and will require advanced finite element stress analysis to calculate the local stress fields and further physical testing to have the additional mechanical property of characteristic distances [16, 17]. Such a design methodology is too complicated, too expensive and too time consuming for the construction designer, and so the guidance in the ASCE standard must be based on closed form formulae that have a derivation and composition that corresponds to the failure modes being modelled.

If we restrict ourselves to considering the basic test configuration shown in Figure 3 of a constant thickness plate of width $2e_2$ we find that, under tensile loading, there are, for a single bolted connection, four distinct modes, if the FRP fails first. The failure mode that governs does however depend on many variables, of which the end distance (e_1), hole diameter (d_n) and bolt diameter are clearly important [12]. It is to be noted that mix modes (e.g. when the connection force is off-axis) are possible and block-shear is a mode when there are multiple rows of bolts [12]. Often series of tests use the double lap-shear configuration [12], and this removes the detrimental affect of the geometrical discontinuity in single lap-shear configurations. It can be seen that this latter type of plate-plate connection is often found in bracing systems (see Figure 2 (right-side)).

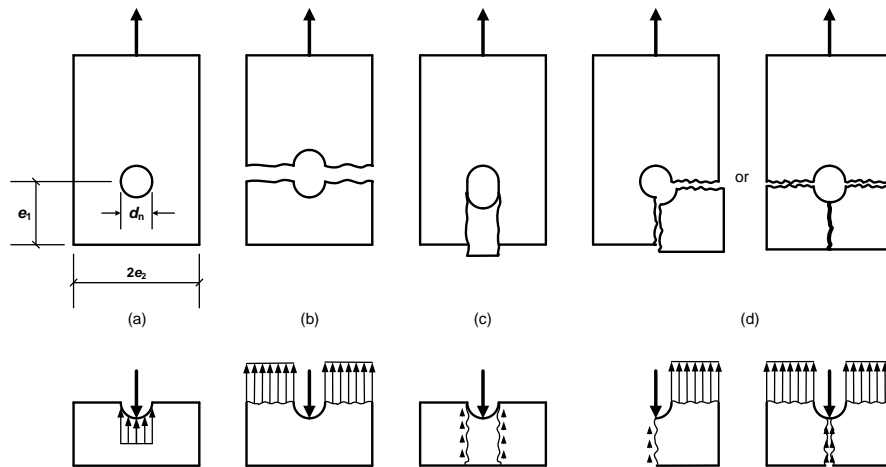


Figure 3. Plate-to-plate distinct modes of failure; (a) bearing, (b) net-tension, (c) shear-out, (d) cleavage.

Frame joints can be seen to comprise of the building blocks of plate-to-plate connections, with other structural features and details. New failure modes and structural responses need to be considered when detailing them (see left-side of Figure 1) as the actions taken by these joint can be out-of-plane with respect to the connection building blocks [13].

Regarding what is likely to be permitted in the ASCE pre-standard the following concerns connection detailing. Thicknesses of material are to be in the range from 6.35 mm (1/4 in.) up to, and including to 25.4 mm (1 in.). They are to be either of flat sheets or structural profiles (I, H, etc.) with E-glass fibre reinforcement; the latter profiles have the higher volume fraction of unidirectional rovings [4]. Bolts and nuts used will be to several ASTM standards (A193, A304, A307 and A316) and the range of diameters is from (9.53 mm) (3/8 in.) up to, and including, 25.4 mm (1 in.). Hardened flat circular washers are to have an outer diameter at least twice the nominal bolt diameter, and at least one washer is to be used at the head of the bolt and at the nut. Bolts are to be torqued to the snug-tightened condition, although the guidance for setting this relatively 'low' level of bolt tensioning is still to be identified. The nominal hole diameter, d_n , is to be 1.6 mm (1/16 in.) larger than the nominal bolt diameter and holes are to be drilled or reamed. The maximum number of bolts in a line either parallel (for rows) or perpendicular to the connection forced is to be three. Minimum geometries (i.e. values for e_1 , e_2 , etc.) are to be specified and these will depend on the number of bolt rows and/or the orientation of the material with respect to the direction of pultrusion. It is clear that new variables enter the arena when we consider the range of practical joint details, as, e.g., as illustrated in Figures 1 and 2 and in [4] and [5].

When we combine the complexities from having all possible connection and joint details with a non-ductile material, possessing directional strengths, it is unsurprising that our current information from previous 'unstructured research' is not without its gaps. To increase our thirst for new knowledge it is recognised that characterisation of structural performance is required after the connections and joints have been exposed to loadings and environmental aging that represents what the frame structures might experience during a service life extending over, say 30 years.

BOLTED CONNECTIONS: IDENTIFIED GAPS IN KNOWLEDGE

Following a critical evaluation of what is known (and not known) the authors of the bolted connection chapter have identified gaps in knowledge that can be addressed through answering the following 20 questions.

1. What are to be the recommended details for: connection geometries (e.g. hole clearance, end distance (e_1), side distance (e_2), pitch, etc.); bolt, nut and washer types; bolt installation torque?
2. Is it acceptable to have a joint with a single bolt?
3. What are the limitations (on strength and durability) for allowing bolt thread to bear against the FRP material?
4. Are there to be limits specified on maximum distances in connection geometry?
5. What is to be the standard test method that shall be specified to determine pin-bearing strength?
6. How does pin-bearing strength vary with environmental conditioning, bolt shaft flexure, position of bolt in clearance hole, orientation of 'bearing' force to the orientation of the FRP material?
7. What is the strength reduction factor when loading is for the single-lap plate-to-plate configuration and the basic resistance formulae are based on a double-lap test arrangement (see [12])?
8. How do we predict strength when there are two or more rows of bolting (i.e. when the by-pass loading exists and there is a requirement to know the open-hole stress concentration factor)?
9. What is the distribution of the connection force between the bolts in multi-rows?
10. What information do we need to prepare mandatory text for staggered bolt arrangements?
11. Are the closed formed formulae for clearly defined modes of failure, such as shown in Figure 3, necessary and/or sufficient?
12. How much does the material viscoelasticity affect how the force is transferred and how the connection fails?
13. How is the strength of connections affected by a combination of in- and out-of-plane actions (as found in frame joints)?
14. Do we have adequate information to verify a strength formula for the situation where the side distance is, on one or both sides of the bolt hole, relatively large? (Such a detailing is found for the beam member in Figure 2 (left-side).)
15. What is the strength of connections for bracing members with eccentric loading (see Figure 2 and right-side)?
16. What is the moment-rotation response of 'prescriptive' web-cleated ('pinned') connections that fail by the prying action causing the FRP cleats or columns to delaminate?
17. Is there localised bearing damage in frame joints when a structure is carrying serviceability loading (static and fatigue)?
18. Can the rotational and in-plane stiffnesses be characterised such that analysis can be used to check if frame deformation satisfies a serviceability limit state?
19. What is the tying force of frame joints, such as seen in Figures 1 and 2, that need to be present to control disproportionate collapse [15] (for Part A of Building Regulations, 2000)?
20. How are column of pultruded shapes to be connected to the ground?

We can expect that as these 20 questions are tackled some will be revised and new questions will appear, and so a feedback loop using ‘useful’ research and good practice experience will provide the information for design rules to be improved and verified.

THE WAY FORWARD

The work of the project team drafting the pre-standard is now towards the reliability analyses for the strength formulae to be specified according to the LRFD approach [3]. It is known that available test results may not be adequate or may lack appropriate documentation needed for direct reliability analysis. Some of the reasons for this are presented herein. This challenge will not prevent the authors from developing their chapters with the ‘best’ information that is available to them, and with deficiencies identified where they exist. Clearly, a rational ‘engineering judgment’ approach will be taken so that the guidance in the chapters is going to be fit for purpose. When compared to structures designed using the ‘mature’ guidance in [7] to [10] we can expect equivalent-sized structures of pultruded shapes (for members and connecting components) to be relatively more massive. In other words the ‘margins of safety’ used will inherently have to be higher to account for the greater uncertainties, owing to the gaps in knowledge leaving many ‘safety critical’ questions unanswered. It is anticipated that after the ASCE standard is published there will be a significant market growth in pultruded structures [1], and this will provide the economic impact to justify the need for the ‘useful’ research to remove the deficiencies. In themselves the identified gaps in knowledge, as given by the twenty questions above, provide the justification for targeted academic studies to be commissioned that can be the basis of transfer of research results into practice.

New underpinning research is needed to help prepare the scientifically-founded rules that shall be commensurate, in terms of health and safety, with those in existing codes of practice (see [7] to [10]). Because industry cannot be expected to have the capacity to do this, we must rely on applied university-lead research to produce the information that can address the questions that encapsulate the gaps in knowledge. It is essential for this research to be ‘useful’ for its scope to be informed by the content in the ASCE standard; one deficiency with some previous studies has been not to have a clearance hole that is always present in practice [12]. This recommendation provides a challenge since publication of the LRFD standard is not planned until 2011, at the earliest. To overcome this problem prior to its publication researchers are advised to communicate with the chapter authors when planning a new series of testing or numerical simulations.

To do the reliability analysis of any strength formula it is necessary to have test results for its mode of failure and measurements for every variable in its expression. Ideally the number of specimens in a batch should be 10 or higher; it is often much less (and can be one [12]). When a variable is a material strength the reliability analysis requires this strength to be determined in accordance to the standard test method that will be given in the design standard. A recurring deficiency with previous series of tests to determine the strengths of bolted connections is that, even when the material strength is measured using the same material, the coupon testing is either not to a ‘permitted’ standard or not to any standard. This deficiency is associated to Professor Johnson’s reason for ‘useless’ research of “test results that omit crucial data on properties of specimens” [14].

To illustrate the difficulty of having the right crucial data we can consider the nominal strength formula per bolt for bearing failure, see Figure 3(a), when the pultruded material is oriented parallel to the connection force. Its simple closed form expression is

$$R_{br} = t d F_L^{br} , \quad (1)$$

where t is FRP thickness, d is the steel bolt diameter and F_L^{br} is the specified Longitudinal pin-bearing strength. There have been a number of test series with single bolted connections of pultruded flat sheet material [12], in which some of the longitudinal specimens have failed in bearing. However, in none of these studies did the researcher measure F_L^{br} in Equ. (1), using, e.g., standard D953, which is likely to be in the pre-standard and has been used to obtain bearing strengths given in the pultruders' design manuals [4]. A review on the suitability of D953, and other bearing strength test methods, for FRP materials is given in [18]. This contribution from the author shows 'deficiencies' with the existing standards (which can easily be removed), and highlights to us, yet again, the need for new research to address the gaps in knowledge.

To guarantee new research is 'useful' it is advisable that its execution be informed both by what the ASCE standard is to permit and what supportive information is given in EN 13706 and Annex D (informative) *Design Assisted by Testing* of Eurocode 0 [15]. ASTM D7290 is to be used for the American design standard to evaluate material property characteristic values. This standard requires a minimum batch size of 10.

CONCLUDING REMARKS

In this paper the author has introduced a project that is drafting an American pre-standard for the *Load and Resistance Factor Design (LRFD) of Pultruded Fiber-Reinforced Polymer (FRP) Structures*. In many respects the heuristic design guidance in its eight chapters is to be similar to the rules in published codes of practice for our traditional structural materials. Because the new pre-standard is for pultruded members whose shapes are the same as sections in steelwork ([7] and [9]) the design information is mainly for simple frames with bracing that prevents sway. Connections and joints are made structural by using steel bolting. So far the project team have written a draft to the mandatory and non-mandatory commentary parts and now the work is towards the reliability analyses for the strength formulae to be specified in the LRFD format.

A major deliverable from the drafting of the bolted connections' chapter has been the identification of gaps in knowledge. These are introduced in the paper through twenty questions that provide the justification for new academic research, which must be 'useful' for the basis of developing improved design rules. It is noteworthy that to prevent research from being classified as 'useless' it is essential that its execution be informed both by what the ASCE standard is to permit and what advice there is in, for example, Annex D of Eurocode 0 for *The Basic of Structural Design*.

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