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Effect of bolt threads on the double lap joint strength of pultruded fibre reinforced polymer composite materials

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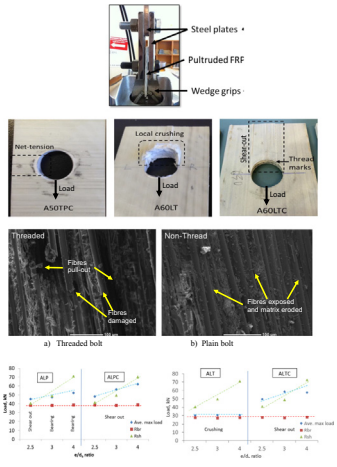
HIGHLIGHTS

- Investigation on the effects of threaded bolt and clamping pressure on the strength of bolted FRP joints.
- Strength of bolted joint with different edge-to-distance ratios and fibre orientation.
- Testing and analysis of 150 double lap joints.
- Joint strength behaviour, failure mechanisms and joint efficiency.
- Determination of reduction factor for the design of FRP connections using threaded bolts.

GRAPHICAL ABSTRACT



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ABSTRACT

The ability to provide effective and adaptable joints for pultruded fibre reinforced polymer (PFRP) is crucial for its widespread application in civil infrastructure. This experimental based study on 150 double lap joints specimens investigated the effects of threaded bolt and clamping pressure on the joint strength behaviour, failure mechanisms and joint efficiency of bolted joints in PFRP. Double lap joints in both longitudinal and transverse directions of the laminates and with different edge distance-to-bolt diameter (e/d_b) were prepared and tested in accordance with ASTM D5961 standards. The joint strength in the longitudinal laminates with plain bolt increased for e/d_b ratio for up to 4 and with no appreciable strength gain after exceeding this ratio. On the other hand, about 30%–40% reduction in joint strength was observed in the longitudinal direction due to the bolt thread tearing through the laminates. This leads to a recommendation of 0.6 reduction factor in preliminary design of PFRP bolted connections with bolt thread present. Meanwhile, only a marginal difference of 7% was observed in transverse direction. Furthermore, the introduction of lateral clamping pressure had increased the joint strength by 60%–90% and this has lessened the thread casualty effect on the pultruded composite joints.

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1. Introduction

The interest in using fibre reinforced polymer (FRP) composites in civil engineering and construction applications has increased significantly in recent years. This advanced material was initially introduced in structural applications as strengthening material for beams and columns of bridges and buildings [1–3]. With advanced manufacturing process such as pultrusion, standard structural shapes for instance box section, I-beam, etc., which resemble closely that of structural steel sections, are now readily available for the construction industry. The attractive attributes such as high strength-to-weight ratios, high resistance to corrosive environment, and low life cycle cost have made FRP composites as material of choice in structures built in aggressive environment. In spite of these attractive features, the limitation in providing effective and reliable joining method has impeded the widespread use of pultruded FRP (PFRP) sections, especially in frame structures [4–8].

The ability to provide joint versatility for PFRP in civil structures industry is crucial for its application demands. Although there are many types of connection system available, the conventional steel bolt is mostly used to join the structural components due to low cost, ease of assembly, ease of performing maintenance and inspection checks, and familiarity to the practitioners. Extensive research on bolted connections in FRP has been conducted by many researchers, focusing on the evaluation of joint performance as well as its failure modes and failure mechanism [9–21]. This also has been well recognised in the recent design guidelines, i.e. 'Pre-Standard for Load Resistance Factor Design (LRFD) of Pultruded FRP structures' and 'Guide for the Design and Construction of Structures made of FRP Pultruded Elements (CNR-DT 205/2007)' wherein the detailed parameters and design requirements for joining composite materials are presented in Chapter 8 [22] and Chapter 5 [23], respectively. As recommended by the both guidelines, fastening parameters such as joint geometry (width, spacing, end distance and bolt diameter), material thickness, clamping pressure, bolt hole tolerance, and loading conditions need to be carefully considered when designing FRP bolted connections. These parameters significantly influence the failure modes (Fig. 1) for instance bearing, shear-out, net tension and combinations of these which eventually dictate the strength of the joint connection. Meanwhile, recent review papers by Coelho and Mottram (2015) [24] and Correia et al. (2015) [25] provide a comprehensive list of published contributions covering bolted FRP joint behaviour and its mechanical response against various range of joint parameters and environment exposure conditions. Other than metallic fasteners, FRP fasteners (solid rod or bar) are adopted in rocks and soil engineering application as anchorage or strengthening strips [26]. These FRP fasteners have the potential to be used in a variety of applications whereby its strength and stiffness properties are engineered according to different connection modes. It is ideal for applications that require fasteners to be non-corrosive, low in conductivity or no electromagnetic waves [27]. FRP threaded rods are made by machining a thread on an FRP solid rod which can be used with metal hex nuts if the threads formed are a direct match and fit. Generally, however, the forming of thread has caused defects on the screw connections which resulted in a lower connection strength, about 20%–40% of the strength of the FRP solid bar itself [28]. Moreover, unlike steel fasteners, FRP threaded rods possesses linear elasticity and brittleness with anisotropic properties, making them ineffective as a joining component for advanced composites.

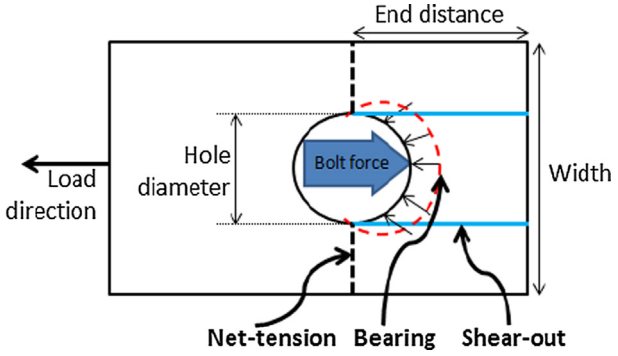

Fig. 1. Type of failure modes in composite bolted joint.

Currently, the use of fully-threaded steel bolts (technically known as screws or all threaded rods) for connection cannot be eliminated in large construction where full FRP sections with thick walls are involved, as it speeds up the construction process while minimizing installation errors. Moreover, it can also reduce the number of different bolts on site, allowing better stock holding and improve construction efficiency. This material combination can be found in large scale constructions involving structural truss system such as industrial cooling towers, electric transmission towers and bridges. The use of FRP composite materials for these structures are expected to show rapid growth in the near future [29]. It effectively exploits the FRP's high unidirectional strength as truss members are subjected only to axial forces. Studies on the effect of threaded bolts on the behaviour of bolted joints for PFRP, however, are very limited and the design guidelines considering the use of threaded bolts in PFRP construction is still not available. In the American pre-standard, ASCE [22], it is recommended that, for bolted joint, smooth bolt shank must be in bearing into the FRP material. For assembly purposes, the thread length should not exceed one third of plate thickness. Matharu and Mottram (2012) [30] also mentioned that the presence of bolt thread in the contact zone of composite material is detrimental to the strength of connections in long term exposure, especially in an aggressive environment. Since the bolt threads may cause tearing through the pultruded layers creating narrow gaps between the bolts and the FRP, the connection system becomes more susceptible to moisture entry.

Application of threaded bolts in joining PFRP components to produce advanced composite structures are currently restricted in design and its performance in service is limited. Instead of looking to a new modern joining method, the latter case can be resolved through experimental investigations which results in adaptability and awareness of the issues among a wider group of practitioners. It is the aim of this paper to provide a better level of understanding associated to the influence of bolt threads with the recognised joining parameters and to advice a factor that account the bolt threads effect in the preliminary FRP bolted design. This paper also reveals the joint behaviour of bolt threads on FRP materials in microscopic scale to refine the understanding on the finding mode of failures and its mechanism.

This paper presents the results of an extensive experimental work, including the scanning electron microscope (SEM) imaging which investigates the effects of bolt threads on the joint strength and failure mechanisms of a double lap joint for composite laminates cut in the longitudinal and transverse directions of PFRP. Bolted FRP joints subjected to compression are less sensitive to joint geometry and are generally stronger than joints subjected to tensile forces [31]. For this reason, FRP bolted connections in this paper were tested under axial force (tensile) to assess its strength and reliability. Assessment of bolt threads reduction factor in FRP bolted design, as well as the comparison of pultruded FRP joint strength and efficiency between plain bolts, threaded bolts, and clamped specimens were also presented.