A review of FRP composite truss systems and its connections

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ABSTRACT: This paper presents an overview of the recent developments and initiatives on FRP trusses, which has been evolving and has become a viable construction system in civil infrastructure. The paper also discusses the different jointing systems used to assemble FRP components with the aim of determining the appropriate and reliable jointing connections for fibre composites trusses. The different parameters that affect the integrity of connections such as loading condition, material preparation (stacking sequence, volume fraction, etc.), joint configuration, joint geometry, and fastening method will be evaluated. It is anticipated that by addressing these connection issues, it will minimise some ambiguities and provide an understanding to designers and engineers on the potential of fibre composites trusses and advance its application in civil engineering infrastructures.

1 INTRODUCTION

Trusses are structural frames formed from one or more triangles. Each straight slender member of a truss, which theoretically carries only axial tension or axial compression, is connected at the joints. The joints are assumed to be frictionless hinges or pins that allow the ends of the members to rotate slightly thus, creating a stable shape or configuration. Trusses offer many advantages over solid web members especially on material and weight ratio which made trusses one of the prominent structural forms in the 19th century. It can also provide stiffness to a structure, support heavy loads over long spans and fast installation. Trusses are commonly used for bridges, towers, roofing in houses and have been acknowledged as one of the important types of load bearing component in civil infrastructure. An example of a truss system is shown in Figure 1.

Figure 1. Steel trusses in communication tower

The introduction of fibre reinforced polymers (FRP) or also known as advanced polymer composites in civil and structural field in the late 1970s had been a turning point in the application of composite trusses in adverse environments and conditions (Hollaway 2010). FRP is a composite material which is formed by the combination of two or more distinct materials, more specifically fibres and its binding matrix. This combination produces a material with enhanced properties and attractive attributes for application in civil structures. The fibres provide most of the stiffness and strength, and the matrix binds the fibres together, transfers load between fibres and between the composite and the external loads and supports. FRP exhibits high resistance to aggressive environment which contributes to lower life cycle cost, produce more lightweight structure and quick installation time (Keller 2001). However, the high initial cost and lack of engineering standards in designing FRP have become a challenge for this material to achieve more widespread acceptance against conventional materials. Engineers must rely on other sources of information and employ more rigorous design programs, usually involving testing, to ensure all design parameters and technical concerns are in satisfactory level (Vikrant 2002).

FRP pultruded members shown in Figure 2, produced mainly from glass fibre reinforced polyesters, are becoming a popular choice among other composite fabrication processes (molding or filament winding) for girder elements (David 1986). By continuous manufacturing process namely pultrusion, the pultruded members can have uniformity of cross-sections similar to steel and the fibers are oriented predominantly uniaxially (Keller 2001). In recent years, pultruded FRP members have been used as structural members in roof and bridge trusses. These truss systems are suitable components to be constructed using FRP as the low material usage in their production may address the cost disparities between traditional and fibre composite structures.

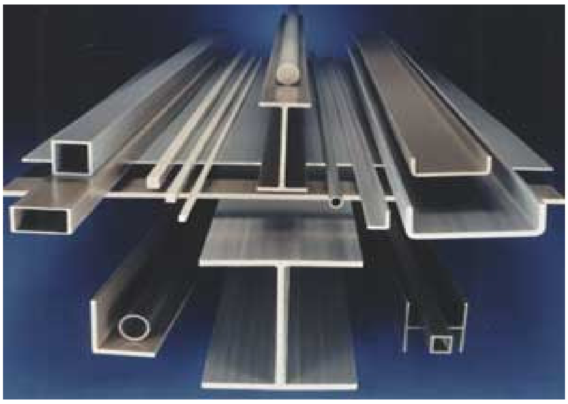

Figure 2. Various shapes and dimensions of Strongwell FRP Pultruded

2 RECENT FRP TRUSS SYSTEM

One of the remarkable developments in the jointing system of FRP truss were produced by Goldsworthy & Hiel (1998) when they introduced the award winning snap joint concept for overhead transmission lines (Fig. 3). While the joint design is quite simple, it is capable to distribute stresses over a wide area and had been successfully implemented in the construction of three Transmission Tower Structures near Los Angeles, USA. It has since, attracted the attention of other researchers to involve in the study and investigation on FRP truss system followed by the introduction of the Monocoque Fibre Composite (MFC) truss concept (Humpherys et al. 1999). They used double skins concept whereby the skins are separated by a core material. However, the MFC truss concept was not reliable in lapping joints and improvement had been made by introducing the concept of strength and fill layers. Bradford et al. (2001) had contributed their masterpiece for emergency shelters and bridge decks by developing a modular composite truss panel concept. The modular panel was optimized by integrating the connection within the panel. Investigation on FRP truss continues when (Keller et al. 2007), carried out long term performance study of a Glass FRP truss bridge built in 1997. The all-FRP composite Pontresina pedestrian bridge (Fig. 4) which main truss girders were connected by mechanically fastened and adhesive bonded had been tested under temperature -20°C to 25°C and structural safety, serviceability and durability were assessed after eight (8) years in service. In 2005, it was found that the bridge stiffness remains unchanged and the durability was mainly affected by inappropriate construction detailing.

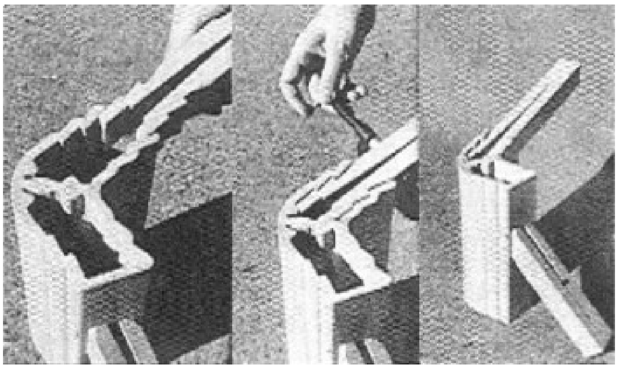

Figure 3. Snap joint concept by Goldsworthy & Hiel (1998)

Further concern on feasibility of repairing fibre damages on FRP members was highlighted by the authors (Keller et al. 2007). Investigation of a FRP truss in a military modular shelter system was carried out by Omar et al. (2007) at the University of Southern Queensland in Toowoomba. The deployable shelter concept required light-weight components to facilitate deployment and assembly without using heavy equipment. The main frames were constructed from modular fibre composite panels to fulfill the lightweight requirement and stressed in position by prestressing cables. One of the further research work suggested by the authors is to explore innovative joint systems due to the changing nature of the structure which affects its capacity and behaviour.

Figure 4. The all FRP composite Pontresina bridge (Keller et al. 2007)

Experimental tests on Glass FRP (GFRP) truss modules for dismountable bridge were investigated by (Pfeil et al. 2009). The authors adopted a bearing connection instead of bolting or adhesive bonded. This concept required the pre-stressing steel tendons to be inserted into tubular fibre sections to prevent tension forces during bridge service life. In order to achieve a higher failure load, the target of failure mechanism was designed to occur at the central region where fibers are continuous. Thus, the reinforcement using hand lay-up technique at tubular end section of the truss members had successfully increased 69% of compressive strength.

The abovementioned studies showed that fibre composites truss has the high potential to revolutionize the construction industry especially where the lightweight, high-strength structures with high durability is needed. However, it was also evident that the structural integrity of a FRP trusses largely depends on the joining system used to connect the individual components of a truss system. Thus, a reliable jointing system should be determined in order to use fibre composite trusses in practical applications.

3 JOINTING SYSTEM FOR FRP TRUSSES

A number of researches have been carried out on FRP laminates focusing on the connections, which is an integral part of any truss system. Mechanically fastened joint (bolting) and adhesive bonded are the two common types of jointing systems that have been extensively used in structural joints. This area continues to draw attention of researchers due to the many possibilities of failure modes, the complexity of stress relieving mechanism and the complex nature of the stress fields in the vicinity of the joint (Khashaba et al. 2006). The following paragraph discusses the advantages and disadvantages of commonly used jointing system for fibre composites.

3.1 *Mechanically fastened joint*

Connection is very important to ensure that the FRP can perform within its full potential. Bolting connection is a common jointing system and it is preferable due to low cost and ease of use. This type of connection is relatively easy to assemble and is capable of transferring the high loads. However for FRP material, poor quality of drilling techniques and accuracy of hole size will affect the joint strength (Persson et al. 1997). A number of researchers have identified the four (4) common failures mode related with bolted connection in FRP materials. These are net-tension; bearing, shear-out, and cleavage (refer Table 1 and Figure. 5).

Table 1. Common failures mode in FRP bolting joint.

Failures modes	Description
Net-Tension	-Failure occurs for small coupon widths -Develop for large widths if laminates deficient in longitudinal reinforcement (Vangrimde & Boukhili 2003)
Bearing	-Develop predominantly for combinations of large widths, large end distance and near quasi-isotropic lay-ups (Vangrimde & Boukhili 2003). -Failure leads to an elongation of the hole (Camanho & Matthews 1996).
Shear-out	-Failure occurs for coupon with small end distance. - Deficient in off-axis reinforcement leads the failure to occur in large end distance (Vangrimde & Boukhili 2003).
Cleavage	-Failure occurs for coupon with inadequate end distance (Camanho & Matthews 1996) -Develop for laminates that have low off-axis reinforcement content (Vangrimde & Boukhili 2003)

Bearing failure which is known as a process of compressive damage accumulation is the most desired form of failure. Bearing is the limiting factor for strength of a FRP connection (Xiao & Ishikawa 2005). The bearing strength in carbon fibre reinforced polymer (CFRP) increased when plies of $\pm 45^{o}$ until approximately 75% of the total laminate thickness are added to a 0^{o} or 90^{o} plies (Camanho & Matthews 1996).

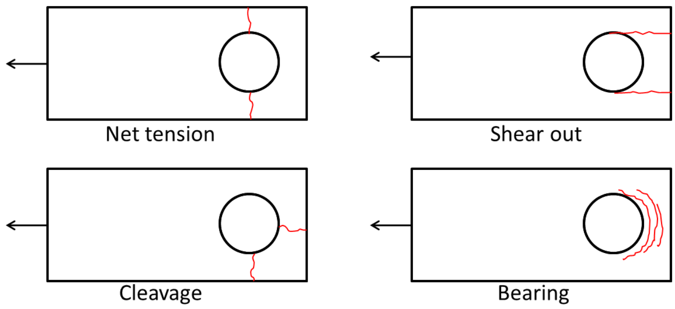

Figure 5. Failures mechanism of FRP mechanical connector

Stacking sequence is found to have influenced on joint strength as the bearing strength increased when 90^{o} layer was placed at the surface. It was concluded that the laminates produced lower bearing strengths when less homogeneous stacking sequence is presented (Camanho & Matthews 1996). The effects of tension direction relative to pultrusion direction on single-bolt tension joint tests were investigated by Turvey (1998). He observed that cracks propagated across the plate width once the off-axis angle exceeds 30^{o}. The load capacity of the joint increases as the off-axis angle decreases and both end distance ratio and width ratio increases (Turvey 1998). For the fabricated glass fibre reinforced epoxy (GFRE) laminates, the maximum bearing strength can be achieved with bolted joint with 18 mm washer size and 15 Nm tightening torque as it provides optimum lateral constrained area and contact pressure (Khashaba et al. 2006). Further research on column to beam connection using pultruded GFRP of open (I-Beam) and closed (rectangular shapes) sections (Fig 6.) were experimentally investigated.

Closed section (rectangular shapes) are generally better than open section (I-shapes) for any material because of improved local flange buckling characteristics, improved torsional rigidity, and improved weak axis strength and stiffness.

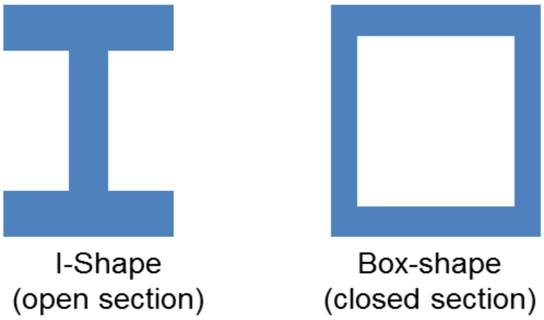

Figure 6. Example of open and closed section

The experimental results clearly showed that the standard box sections produced 14% increase in joint stiffness of entire frame compare to that of standard I-Beam. It is noteworthy that ultimate strength of the closed section was about 280% of the strength of the open section (Smith et al. 1998). It was suggested that closed section should be considered for temporary bridges as inappropriate selection of open section composite had caused undesirable local effects and damages (Keller et al. 2007). One of the interesting findings from finite element analysis done by (Turvey & Wang 2008) had highlighted the uncertainty on the validity of the simplified method for joint design given in the EUROCOMP. They found that friction between the bolt shank and the hole and the small hole clearance are the principal factors of increasing tension and caused significant changes in the stress distributions at critical locations. In multi-bolts FRP connection, the finite element analysis verified the uneven distribution of shear forces among the bolts when compared to steel connections of similar geometry (Nahla et al. 1996). Recent findings show that the distribution coefficient of shear forces are equal to 36% for the external rows and to 28% for central row (Ascione 2010). Structural performance of GFRP pultruded bolted connection had been tested under adverse environmental condition of ambient temperature, 60°C and 80°C. The specimens were also tested under moisture effect into two water immersion periods of 6.5 weeks and 13 weeks. It was concluded that, the period of immersion in water has caused lesser reduction in the load capacity of pultruded GFRP single bolt joints compared to temperature effect (Turvey & Wang 2007).

3.2 *Adhesive bonded joint*

Bonded connection can provide excellent sealing effect and there is no stress concentration presence due to the bolt holes. On the other hand, this type of connection requires curing time for bonding process and has high material cost. The failure mode of adhesive bonded FRP connection (Fig. 7) always occurs in the adherends and never in the adhesives or in the interface (Keller & Herbert 2004). Under quasi-static axial tensile loading, the adhesively double bonded stepped joint exhibited fibre tear-off failure mode which occurred in a brittle and sudden mechanism.

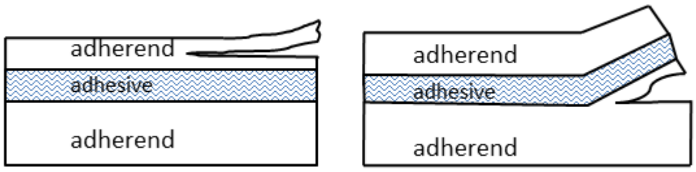

Figure 7. Typical FRP bonded joints failure

Unstable crack propagation occurred at crack lengths smaller than 20% of the overlap length (Zhang & Keller 2008). There is only a small influence of adhesive layer thickness on the stress distribution while joint efficiency is constant with increasing overlap length (Keller & Vallée 2005). Other researchers (Lee et al. 2009) conducted an experimental investigation to characterize the joint strengths, peel stresses and failure modes in adhesively bonded double-strap and supported single-lap GFRP joints. The bonded joint strength was almost autonomous and increased with overlap length (50% increase of joint strength was observed with overlap length of 100 mm in comparison with 50 mm length). An approximate adhesive layer thickness between 0.2 mm and 0.5 mm maximizes the joint strength of GFRP double-strap. Manalo & Mutsuyoshi (2012) studied the behaviour of hybrid FRP girder with joints at midspan connected with bolts alone and combination of bolts and epoxy adhesives. They found out that the beam connected using bolts and epoxy exhibited the same strength and stiffness as the beam without joints while using bolts alone resulted to a beam with only 65% of the stiffness of those without joints. Furthermore, the use of V-notched splice plates and adhesive bonded were investigated as one of the alternative ways to join the hybrid FRP (HFRP) beam (Hai & Mutsuyoshi 2012). The rough surface of V- notched splice plates had contributed to excellent bonding strength. They observed that V-notched splice plates and adhesive bonded had improved the joint stiffness. In 2008, a comparison study between plasticized adhesives and brittle adhesives was conducted (de Castro & Keller 2008). They observed that the joint strength of ductile joints with plasticized adhesive increases almost proportionally with increasing overlap length.

Another recent research that is interesting to highlight was the introduction of adherend coating with low viscosity epoxy resin which produced high adhesion outer adherend. This method led to 39% significant strength improvement (Hashim 2009). On fatigue performance test, FRP bonded connection did not fail after 10 million fatigue cycles. Furthermore, increased of stress ratio, has significantly increased the fatigue crack growth (FCG) and the fatigue threshold curve (Shahverdi et al. 2011).

4 DISCUSSION

Connection is the vital component in order to build or construct a reliable and strong FRP truss system. While the literature suggests that the combination of mechanical and adhesives joints show promising results for connecting FRP members, bolted connection alone is still widely used for joining structural members in civil infrastructure due to their ease of installation and maintenance, and capability of transferring the high loads. However, many researchers have focused on investigating the application of bolted connections using thin composite laminates. For civil applications where thicker members are generally used, only a number of researches have been conducted so far. Because of this, substantial additional research and development work in the area of bolted connections for pultruded FRP profiles and whole composite truss system is required before this can become and effective and accepted method of joining FRP truss members.

The behaviour of FRP composite sections and connection has been studied in some detail, but the systems behaviour of FRP composite trusses has received limited interest from researchers around the world. In a truss system, the behaviour of each FRP composite member is affected by its interaction to the other members which contributes to the overall performance of a structural assembly under service loads. In addition to that, one area of interest to be explored is the influence of eccentricity at the vicinity of jointing area. The effect of connection eccentricity on FRP members must be considered in order to develop efficient jointing system. Analytical and experimental investigation to determine the structural behaviour of composite truss systems made from pultruded FRP sections and the behaviour of its joints/connections should be conducted in order to have a detailed understanding on how the loads are resisted, transferred, and distributed to each component and to design them safely and economically. When this is achieved, it is anticipated that this effort will lead in the wider use and acceptance of pultruded FRP composites in a truss system.

5 CONCLUSIONS

FRP composites have becoming an alternative choice for the development of structural truss system. It takes advantage of the unidirectional properties of fibre composites as truss members are subjected only to axial forces and effectively utilise its material strength. The lightweight of FRP trusses also offer shorter construction time and the high durability of composite materials resulted in a reduced maintenance cost. The major drawback to utilise FRP composites in a truss structure is the reliability of its joints. Many researchers have carried out the investigation of bolting and bonded connection of FRP laminates, both experimentally and numerically in order to determine an effective connection method for composite materials. Fundamental investigation should therefore be conducted in order to gain a detailed understanding on the behaviour of pultruded FRP members with bolted joints and on the whole FRP truss system under extreme service loads and various environmental exposures in order to extend its application in civil engineering.

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