Thin-Walled Structures 122 (2018) 182–192

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Folded hybrid FRP-timber sections: concept, geometric design and experimental behaviour

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ARTICLE INFO

Keywords:
Thin-walled structures
FRP-timber structures
FRP-timber hybrid structures
Folded sections
Geometric design

ABSTRACT

Driven by an increasing demand for sustainable and easy-to-construct timber infrastructure, recent research at The University of Queensland (UQ) has led to the development of a new class of structures called 'folded hybrid FRP-timber' (FHFT) structures. In FHFT structures, FRP (fibre reinforced polymer) is combined with timber veneers to create high-performance, lightweight, easy-to-construct structural members. In such FHFT members, the fibre directions of FRP and timber are appropriately oriented to produce optimal composite properties, while the geometry of the cross section is designed to optimize the load bearing capacity for a given amount of material. This paper presents two highly innovative fabrication processes for FHFT sections that enable new geometric and material possibilities in the design of FHFT structural elements. The new fabrication processes are first demonstrated for the manufacture of regular structural hollow sections. A geometric design method is then presented for the fabrication of any folded structure with a uniform cross-section specified as a non-intersecting polygonal chain. An experimental study comparing the compressive capacity of FHFT and plywood-only columns is then presented. It is seen that the two fabrication methods produce FHFT hollow sections with similar capacities to each other and double the capacity relative to plywood-only sections. The new sections are also shown to have a weight-specific compressive strength comparable to that of existing commercial steel hollow sections.

1. Introduction

Timber structures have started to gain research much attention again in recent years. Many advantages of timber construction, such as relatively low construction effort, clean construction sites, and low carbon footprint, have been the drivers for the increasing demand for timber construction. Engineered wood products such as laminated veneer lumber and cross laminated timber have been introduced to overcome some of the disadvantages of timber, such as low dimensional stability, inhomogeneity, and limited maximum cross-section size. The use of advanced composites such as fibre reinforced polymers (FRPs) to increase the performance of timber structures has recently received much attention [1–5]. While most of the existing studies on the structural use of FRP with timber have predominantly been concerned with the strengthening of existing timber structures [6–8], a few studies have investigated FRP-timber elements for new construction [9,2,10]. These have demonstrated that the use of a small amount of FRP can significantly enhance the performance of low quality solid flexural wood members [11].

A small number of recent studies have also indicated a performance enhancement from the FRP strengthening of low-grade timber thin-walled sections [12,13]. Such sections constitute a new class of structures called "hybrid fibre reinforced polymer-timber (HFT) structures" [5]. HFT structures are formed by combining thin FRP layers with timber veneers. In a HFT section, the grain orientation of the veneers is parallel to the longitudinal axis while the FRP fibre orientation is predominantly perpendicular to the longitudinal axis. HFT structures can be manufactured using compression moulding, which is achieved by utilising the veneers' natural tendency to roll towards one side; they can be easily pressed into half-shapes around a mandrel with the veneer grain oriented in the longitudinal direction. This grain orientation means weak timber properties in the transverse direction, so FRP layers with fibres oriented in the transverse direction are adhesively bonded to enhance the material properties in this direction. In particular, the bonded FRP layers can significantly enhance the resistance to local buckling failure, which is typically the critical failure mode of thin-walled sections. Once veneers and FRP layers are bonded together around the mandrel, pressure is applied to maintain the shape until the

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http://dx.doi.org/10.1016/j.tws.2017.10.007
Received 21 June 2017; Received in revised form 28 September 2017; Accepted 2 October 2017
Available online 13 November 2017

adhesive is fully cured. The initial work carried out at UQ has demonstrated the effectiveness of HFT structures by fabricating and testing a series of HFT wall panels [12]. HFT wall panels showed enhanced performance compared to similar pure timber veneer wall panels. The load carrying capacities of HFT panels were additionally found to be on par with those of similar commercially available steel stud walls, while the former are significantly lighter. Existing HFT wall sections were fabricated using compression-moulding, which is only suitable for thin veneers (up to 2 mm in thickness) and simple geometries such as Cee-sections and rectangular hollow sections. In order to optimize the performance of HFT structures, geometrical optimization of the section and the corresponding ability to manufacture more complex 3D geometries is necessary.

Folding fabrication processes enable complex 3D parts to be manufactured from a 2D sheet [14], with previous applications including consumer products and thin-walled structural steel members [15,16]. Recent renewed interest in folding fabrication processes has been seen [17–19], with integration of origami-inspired geometries and active materials to create a wide range of novel, self-folding structures and devices. The majority of these studies utilised a uniform panel thickness and relied on an embedded crease arrangement to enable them to fold into a target 3D shape. A smaller number of studies have investigated an alternative approach whereby panels are thickened and shaped to constrain a final folded configuration [20]. The FlexiArch, a flat-packed precast concrete bridge system [21], is an example of this and has been installed in over 40 locations in the UK and Ireland [22]. The system utilises trapezoidal voussoir segments (hereafter called "trapezoidal segments" for brevity) attached to a flat polymeric membrane, with the assembly then transported to site and lifted into an arch form. The trapezoidal segments can be solid or hollow [23] and have a form designed to match an arch of a target span and rise. A deployable tied arch form was proposed in [24] with rigid timber segments connected with door hinges. The segments were flared on the underside of the arch to enable a compact, rolled transportable form. A structure with lenticular rigid voussoirs stiffened by a tensioned through-cable was proposed in [25] and it was demonstrated to be capable of forming general freeform surfaces.

The combination of a folding fabrication process and hybrid FRP-timber materials has led to the development of novel folded-HFT (FHFT) structural systems, shown in Fig. 1, that are the subject of the present paper. Section 2 first presents two new low-cost and flexible manufacturing methods that allow HFT materials to be folded into structural HFT sections. Section 3 then presents a generalised geometric design method that enables the manufacturing method to be applied to generate any structure that has a uniform cross-section corresponding to a non-intersecting polygonal chain. An experimental study is presented in Section 4 on square, circular, and octahedral hollow sections to establish a preliminary benchmark of the structural performance of FHFT sections under uniaxial compression manufactured with the new methods. This is followed by a discussion in Section 5 as to their structural feasibility, strength, and failure modes relative to plywood-only and steel thin-walled sections.

2. Folding fabrication processes

A conceptual FHFT section is shown in Fig. 1. It consists of flat, wood-based *segments* attached to a flat, continuous FRP sheet. The FRP sheet contains *hinge regions*, located between adjacent segments and consisting of thin strips of FRP that have relatively low bending stiffness compared to the surrounding material. In addition to the other benefits of HFT sections, the wood-based segments in FHFT sections create a convenient way to locate FRP hinges while the use of FRP allows the flat configuration to be folded into a three-dimensional configuration, leading to a low-cost and flexible manufacturing method.

However such an arrangement generates competing performance requirements: the FRP needs to be flexible in the unfolded state to enable adequate hinging for fabrication, while the FRP also needs to be rigid in the folded state for structural adequacy. To resolve this, two manufacturing methods have been developed that allow *transient hinges*, that is hinges that possess the requisite flexibility during folding and are otherwise rigid. The remainder of the section presents two methods for achieving such hinges, with the first termed the *differential curing* fabrication method and the second termed the *thermomechanical hinge* fabrication method.

2.1. Differential curing fabrication method

Shown in Fig. 2a is a glass fibre sheet marked with lines corresponding to the hinge regions of an unrolled hollow section. A slow-curing hinge resin is applied to regions where adjacent segments are to be hinged, see Fig. 2b. A fast-curing panel resin is applied to regions in continuous contact with segments, see Fig. 2c. For this study, a bisphenol-A epoxy resin, Gurit AMPREG 22, was used. For the fast-curing resin formulation the 'Fast' AMPREG 22 hardener (Pot life @25 °C = 0:25 h and demould time @ 25 °C = 3:00 h) and for the slow-curing formulation the 'Slow' AMPREG 22 hardener (Pot life @25 °C = 2:15 h and demould time @ 25 °C = 25:00 h) was used. The trapezoidal segments are then attached to the dual-resin impregnated glass fibre sheet, see Fig. 2d, and the assembly placed under vacuum. After an initial curing period of three hours, a glass-fibre reinforced polymer sheet (called "GFRP sheet" hereafter) is created in which the panel resin has been completely cured but the hinge resin has only just reached the gel point. The assembly can thus be rolled into a 3D form as shown in Fig. 2e, without straining the hinge region and also without detaching timber segments from the GFRP sheet in the panel regions. The starting and finishing ends of the assembly are connected together via an overlap of glass fibre sheet which extends from the finishing end and wraps once completely around the section before the application of resin. The hollow section is then left for a second curing period of twenty-four hours, after which the hinge resin is completely cured and the structural hollow section is completely rigid, see Fig. 2f.

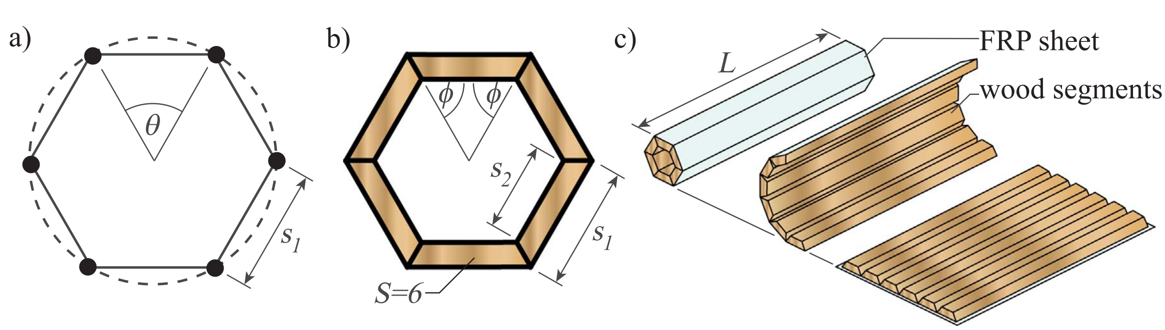

Fig. 1. Folded hybrid hybrid FRP-timber section concept. a) Specification of polygonal geometry. b) Generation of trapezoidal wood segments. c) Unrolled section with FRP hinging connections.