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System transverse in-plane shear stiffness of pultruded GFRP bridge decks

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ABSTRACT

The static transverse behavior of two pultruded GFRP deck systems with trapezoidal (*DS*) and triangular (*AS*) cell cross-sectional geometry was experimentally investigated in order to study their transverse in-plane shear stiffness. Symmetric three-point bending experiments up to failure were performed on 200-mm-wide beams. Their stiffness, strength and failure modes were compared. Different load transfer mechanisms were found in the *DS* (frame-dominated) and *AS* (truss-governed) systems depending on the cell geometry. The *DS* beams exhibited a lower apparent bending stiffness (24–30 times less) and degree of composite action between the flanges (14–17 times less) than the *AS* beams. These dissimilarities were attributed to the lower transverse in-plane shear stiffness provided by the trapezoidal core than by the triangular core. The low bound values for both system in-plane shear moduli were estimated from the experimental deflection results. The system in-plane shear modulus of the *DS* beams represented approximately 2–3% of that of the *AS* beams.

1. Introduction

Glass fiber-reinforced polymer (GFRP) bridge decks are one of the most developed applications of FRP structural materials in the civil engineering domain. During the last decades, GFRP bridge decks have been increasingly employed in vehicular and pedestrian bridges, both for new construction and rehabilitation purposes, owing to favorable characteristics compared to traditional reinforced concrete (RC) decks. Advantages of GFRP decks comprise high specific strength, corrosion resistance, light weight (about 10–20% of the structurally equivalent RC deck [1], which in replacement applications enables increase of the live load capacity through dead load reduction), easy and rapid assembly, short field installation times with minimum traffic disruption, and lower life-cycle costs. Several all-FRP and hybrid FRP-concrete deck systems have been designed, experimentally studied and implemented. Reviews regarding their development and use can be found in [1–5].

Based on the manufacturing and assembly process, GFRP decks can be classified into two categories: sandwich and pultruded decks. Sandwich bridge decks are composed of two GFRP face sheets and a lightweight material core (e.g. foam, honeycomb panel, balsa wood). Pultruded deck systems consist of an assembly of hollow shapes (also called profiles) manufactured by the pultrusion process and adhesively bonded together to form the slab. Unit profiles with different cell geometries (e.g. triangular, rectangular, trapezoidal, hexagonal) and profile-to-profile joint configurations have been proposed. The shapes' pultrusion direction is generally aligned transversely to the traffic direction, with the profiles spanning across the bridge's longitudinal girders [6].

Pultruded GFRP decks exhibit orthotropic structural behavior due to material orthotropy and different load-bearing mechanisms in their longitudinal (parallel to pultrusion) and transverse (perpendicular to pultrusion) directions. In the longitudinal and main working direction, the deck system can be considered as a group of contiguous box or I-beams formed by the deck's webs and flanges [7,8]. In its transverse direction, the deck's load transfer mechanism depends on the system's cellular cross-sectional geometry. Truss and Vierendeel frame load-bearing mechanisms have been found to govern the transverse in-plane shear behavior of pultruded deck systems with triangular and trapezoidal core geometries, respectively [9]. The characteristics of the web-flange junctions and joints between adjacent profiles also influence the deck's transverse structural performance [10]. Numerous laboratory and field experimental investigations have been conducted, for several pultruded deck systems, to study their global stiffness, strength, failure modes and fatigue performance under vehicular loads [8,11–14]. Experimental research has also focused on the

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characterization of the deck's longitudinal behavior by means of beam tests on specimens composed of one to three single profiles [14–16]. Few experimental studies are available for the transverse-to-pultrusion direction however, notwithstanding the influence of the deck's transverse behavior on its performance in two structural functions, namely: (i) the transmission of concentrated traffic loads to the underlying superstructure (i.e. the bi-directional bending action depends on the transverse behavior) and (ii) the participation in transferring loads in the bridge's longitudinal direction when acting as the upper chord of the hybrid main girders.

Pultruded bridge decks distribute and transmit the traffic loads to the main girders. The deck's structural performance as a slab and its orthotropy ratio are influenced by the contribution of the transverse-to-pultrusion direction to carrying applied concentrated loads. The deck's response to concentrated loading is influenced by the applied wearing surface and its failure mode governed by local effects [17]. Park et al. [16] conducted bending tests in the transverse-to-pultrusion direction of a bridge deck with rectangular cell cross section; contrary to the response in the longitudinal direction, the observed load–displacement behavior was strongly nonlinear and failure was caused by the flexural failure of the web-flange junctions. Analogous findings have been reported for another pultruded GFRP deck with rectangular cells by Zi et al. [18].

Additionally, pultruded GFRP decks can participate in transferring loads in the bridge's longitudinal direction, acting as the top chord of the main girders when there is sufficient composite action between the girder and the deck, which is dependent on the shear performance of the deck-to-beam connection. The contribution of the GFRP deck has been proven to be significant in terms of stiffness and strength in GFRP deck-steel/RC beam hybrid members with bonded connections [9,19]. Furthermore, the participation of GFRP decks as the upper chord of main girders also depends on the shear transmission within the deck itself (from its bottom to its top flange) in the bridge's longitudinal direction, i.e., the deck's transverse direction. The level of composite action within the deck depends on its transverse in-plane shear stiffness and load transfer mechanisms, both related to the core configuration. Experimental research conducted on composite beams with pultruded GFRP decks has shown that a triangular cell core is able to provide almost full composite action between the deck flanges [20] while a trapezoidal/rectangular cross-sectional geometry only enables partial contribution of the deck's upper flange [21,22]. The transverse in-plane shear behavior of the deck has also been found to influence a more/less ductile response of the hybrid beams (the trapezoidal core, with nonlinear in-plane shear stiffness, enhanced the ductility of the hybrid beam system by local failures in the deck, occurring during the yielding of the steel girder [9]). Transverse in-plane shear modulus values for pultruded GFRP deck systems have been experimentally obtained via in-plane shear tests and included in analytical equations for composite girders, assimilating the core to a flexible shear connection and abstracting from its actual geometry [9]. Nevertheless, the aforementioned experimental approach is restricted to the deck's behavior as the upper chord of composite beams but not adapted to evaluate its performance as a slab, as global bending effects in the deck are not considered.

The aim of this work was to experimentally investigate the effect of the core geometry on the system transverse in-plane shear stiffness of pultruded GFRP decks and to understand the locally occurring load distribution and failure mechanisms – in order to establish a basis for the evaluation of (i) the bi-directional behavior of decks (effective width) and (ii) the composite action behavior of hybrid beams. To achieve this objective, three-point bending experiments were conducted on deck specimens transverse to the pultrusion direction. Stiffness, strength, failure modes and load transfer mechanisms were investigated. Lastly, the experimental results were analyzed to obtain the transverse in-plane shear modulus of both systems.

2. Pultruded GFRP bridge deck systems

2.1. Description of system geometry

Two pultruded GFRP bridge deck systems with different transverse cross sections were investigated: DuraSpan (*DS*) and Asset (*AS*).

The *DS* unit module profile cross-sectional geometry comprises two trapezoidal cells formed by vertical and slightly inclined webs connected to the deck's flanges. The adjacent unit module profiles are bonded along their vertical webs. A tongue-and-groove connection between panels is provided by lip extensions and steps in the deck's flanges. Detailed dimensions of the *DS* unit shape are shown in Fig. 1(a).

The cross section of the *AS* unit profile consists of a parallelogram with an inner diagonal which creates two triangular cells. Dual-cell profiles are bonded to the adjacent ones along their outer diagonals. Lip extensions are provided in the flanges in two of the profile corners and grooves in the two opposite ones in order to facilitate the bonded profile-to-profile connection. The unit shape geometry is depicted in Fig. 1(b).

2.2. Material properties

The *DS* and *AS* decks are composed of E-glass fibers embedded in an isophthalic polyester resin. The fiber architecture of the *DS* laminates consists of a sequence which alternates unidirectional roving, multi-ply structural fabrics and additional non-structural mats. The *AS* laminates comprise a core of unidirectional roving in between multi- and/or cross-ply structural fabrics on each side; additional mats are used for the unit shape outer layer. The typical fiber architectures of the laminates from both deck types are shown in Fig. 2. The in-plane material properties for the flanges, webs and/or diagonal elements are given in Table 1. Table 2 lists the properties of the adhesives employed for the profile-to-profile joints.

3. Experimental program

3.1. Specimen dimensions and manufacture

The experimental program was conducted on three beams from each deck design. Specimens were labeled *DS-1*, *DS-2*, *DS-3* and *AS-1*, *AS-2, AS-3* for the *DS* and the *AS* series, respectively.

A 3500-mm-long deck panel composed of four *DS* unit module profiles had been provided for a previous investigation [23]. The dual-cell shapes were bonded using a structural polyurethane adhesive. Three 200-mm-wide specimens were cut from the aforementioned panel perpendicularly to its pultrusion direction. The transverse cross section of each *DS* specimen therefore comprised eight cells (see Fig. 3(a)). The *DS* specimens' global length and height were 1230 and 194.6 mm, respectively.

The *DS* specimens did not exhibit constant height at one end due to steps in the flanges intended for the tongue-and-groove profile-to-profile connection. Additional GFRP plates were bonded in those areas to prevent premature failure in the support location. Moreover, the *DS* specimens' outer vertical webs – simple webs – exhibited a smaller thickness than their inner vertical webs – double-bonded webs – due to the absence of contiguous profiles to complete the specimens' ends. Aluminum reinforcements were