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Mechanical performance of two-way modular FRP sandwich slabs

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ABSTRACT

This paper presents a modular GFRP sandwich assembly for two-way slab applications. The sandwich assemblies were built-up sections made from pultruded web-core box profiles incorporated between two flat panels, connected via adhesive bonding or novel blind bolts. Two different pultrusion orientations were examined: flat panels with pultrusion directions either parallel (unidirectional orientation) or perpendicular (bidirectional orientation) to the box profiles. The effects of pultrusion orientation, shear connection and the presence of foam core materials on strength and stiffness were investigated by testing two-way slab specimens until failure. Sandwich slabs with unidirectional orientation showed premature cracking of the upper panel between fibres, whereas those with bidirectional orientation showed local out-of-plane buckling of the upper flat panel. The unidirectional slab also showed greater bending stiffness than bidirectional slabs due to the weak in-plane shear stiffness provided by the web-core profiles, which introduced partial composite action between the upper and lower flat panels of the bidirectional slab. Finite element models and analytical techniques were developed to estimate deformation, failure loads and the degree of composite action, and these showed reasonable agreement with the experimental results.

1. Introduction

Over the past several decades the use of glass fibre reinforced polymers (GFRP) has become prominent as primary load-carrying structural members in civil engineering applications. GFRP has high strength and offers many advantages over traditional construction materials, such as corrosion resistance, low thermal conductivity and light weight [1,2]. Furthermore, the embodied energy of GFRP structures is lower than that of equivalent structures made of steel or concrete [3,4]. However, due to its low elastic modulus [2], the material stiffness of GFRP is 10–20% that of steel. Hence the design of GFRP is usually governed by serviceability limits rather than strength. Moreover, the fibre architecture of pultruded GFRP results in materials in which strength and stiffness in the pultrusion direction (also known as the longitudinal fibre direction, where the majority of the fibres run) are much greater than in the direction perpendicular (transverse) to the pultrusion direction. Web-flange sandwich systems can address both these problems at the structural level by improving the second moment of area (and hence increasing bending stiffness) and by incorporating multiple pultrusion directions into the one sandwich assembly [5–7].

Extensive studies into GFRP web-flange sandwich systems have focused on bridge deck construction, where it has been shown that strength and stiffness criteria can be met [8–12]. These decks are usually composed of built-up or cellular cross-sections with webs and flanges, supported on two sides by steel girders (i.e. as one-way systems), and connected via adhesive and/or shear studs. The decks are assembled so that their pultrusion directions, which exert the majority of the strength, lie in the direction perpendicular to traffic. Due to the orthotropic material properties and the cellular configuration of pultruded FRP decks, differences in mechanical properties in the pultrusion direction and transverse pultrusion direction (i.e. the direction of traffic) are apparent. For example, rectangular modules loaded in four-point bending in the pultrusion direction show linear load-deflection behaviour, but when loaded in four-point bending in the transverse direction these rectangular modules exhibit non-linear load-deflection responses [13–15]. Partial composite action is also present between the upper and lower flat panels of rectangular or trapezoidal decks when loaded in the transverse direction because transverse webs provide reduced in-plane shear stiffness [16,17]. Case studies have also shown cracking along the fibres in the pultrusion direction, such as in the Pontresina Bridge in Switzerland [18]. Debonding of joints connecting adjacent GFRP modules have also been observed in the longitudinal

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pultrusion direction in road bridges, caused by tensile stresses developed within joints when traffic travels across the deck [19,20]. This results in cracking of wearing surfaces in the direction transverse to traffic, i.e. along the pultrusion direction of the GFRP components. Such consequences are primarily a result of the relatively low strength in the transverse pultrusion direction compared to that in the longitudinal direction.

One way to prevent premature cracking is to provide additional reinforcement in the perpendicular pultrusion directions within the one sandwich structure. This is achieved in the modular GFRP web-core sandwich system presented in this paper. Furthermore, research into the bending behaviour of GFRP decks has focused predominantly on one-way systems, and hence existing research into bridge decks cannot be applied directly to two-way floor slabs (which can be supported on three or four sides). It is important, therefore, that the structural performance in both directions is characterised for two-way FRP slabs. While studies have been performed on one-way FRP floors [21,22] and on FRP building systems such as the Startlink modular system for low-cost housing [23,24], studies of two-way slabs with FRP for building applications have primarily focused on hybrid FRP systems and strengthening [25,26]. The use of pultruded GFRP in modular two-way slab systems have therefore been very limited.

This paper presents modular two-way web-core sandwich slabs as built-up sections consisting of GFRP box-profiles incorporated between two flat panels, connected via adhesive or novel blind bolts. The pultrusion direction of the flat panels is perpendicular to the pultrusion direction of the box profiles, creating a slab with bidirectional pultrusion orientation. This feature is not often seen in existing pultruded GFRP modular units, where the majority of the fibres, and hence the unit's strength, lie in the same direction, since only one pultrusion direction is achieved. With bidirectional pultrusion orientation, it is expected that the structural performance of the deck can be improved in the transverse slab direction by enhancing the junction between the GFRP face panels and box profiles, thereby preventing cracking between fibres along the pultrusion direction of GFRP components under transverse bending. An experimental investigation was undertaken into modular GFRP sandwich structures under two-way bending when subjected to a static load up to failure. The effects of pultrusion orientation, connection type (adhesive or mechanical blind bolts) and the addition of lightweight foam core materials on strength and stiffness were examined. Following this, finite element (FE) models were used to predict structural stiffness, and analytical techniques were developed to evaluate structural deformation and predict load-carrying capacity.

2. Experimental investigation

Four two-way modular GFRP sandwich slab specimens were fabricated and tested under static loads. Parameters that were tested were the pultrusion orientation of the GFRP components, the connection between GFRP components and the effect of foam as an additional core material. Box profiles were used as the web-core, with specimens designated according to the following naming convention: the first letter refers to the pultrusion orientation (U = unidirectional, B = bidirectional), the second letter refers to the connection type (A = adhesive, B = bolts) and the third letter, if present, refers to the presence of additional core materials (F = foam). Finally, a fixed span-to-depth ratio of 24 was adopted to illustrate bending behaviour.

2.1. Materials

All sandwich slabs were fabricated with 50 × 50 × 6 mm box profiles and 6 mm-thick flat panels, and consisted of E-glass fibres and polyester resin. ASTM D3171, Procedure G [27], was used to determine the resin volume fraction (52%) and the fibre volume fraction (48%) of the flat panels. The fibre architectures of both the box profiles and flat panels were similar, consisting of a roving layer embedded between two mat layers. The resin in the box profiles and flat panels were also the same. The tensile properties of the box profiles and flat panels are given in Table 1 as an average of five specimens. Tensile properties were characterised in accordance with ASTM D3039 [28], taken as an average of five specimens. The interlaminar shear strength of the box profile was 28 MPa, found as an average of 10 specimens via short-beam shear tests in accordance with ASTM D2344 [29].

Table 1
Measured material properties of 50 × 50 × 6 mm box profiles and flat panels.

Material	Tensile strength (MPa)[a]	Tensile modulus (GPa)[a]
Box profiles	362.5 ± 21 (L)	32.2 ± 2.1 (L)
Flat panels	393.1 ± 7.0 (L)	31.7 ± 0.7 (L)
	22.0 ± 2.1 (T)	5.0 ± 0.2 (T)

[a] Longitudinal (L) or transverse (T) fibre (pultrusion) direction.

The in-plane shear modulus of the flat panel was found via off-axis coupon tests [30]. Five coupons with an off-axis fibre direction of 10° of 250 mm length and 25 mm width were tested in tension using an Instron 100 kN testing machine at a loading rate of 2 mm/min. The in-plane shear modulus was found to be 3.5 GPa. Appropriately sized off-axis coupons could not be cut from the box profiles, and hence the in-plane shear modulus of the box profiles was assumed to be the same as that of the flat panels due to the similar fibre architecture. Furthermore, the in-plane shear strength of the box profile was characterised by testing two single box-profiles under four-point bending. These beams were simply supported and loaded with a Baldwin 500 kN testing machine. The overall length of each profile was 500 mm, and the span length was 450 mm. The point loads were transferred from the machine and applied directly onto the single profiles at a distance of 155 mm from the support, and loading was applied at a displacement control of 1 mm/min. The corresponding in-plane shear strength was 28 MPa.

Araldite 420 epoxy adhesive was used as the adhesive connection and M10 (class 10.9) blind bolts were used as the mechanical connection. The Araldite 420 epoxy had a tensile strength of 28.6 MPa, a tensile modulus of 1.9 GPa and a shear strength of 25 MPa [31]. The blind bolts had a bolt diameter of 10 mm, an overall length of 140 mm and a thread length of 35 mm. In addition, the nominal tensile strength was 1000 MPa and the proof load stress was 900 MPa according to the manufacturer. Divinycell P120 Foam was used as a core material. The nominal density was 120 kg/m^3, the compressive modulus was 115 MPa, the shear modulus was 32 MPa and the shear strength was 0.91 MPa according to manufacturer data [32].

2.2. Specimens

Four modular GFRP sandwich slab specimens were fabricated and tested. All specimens had the same geometry, where seven 50 × 50 × 6 mm GFRP box profiles were sandwiched between 6 mm-thick flat GFRP panels as shown in Fig. 1. Each sandwich slab had a total depth of 62 mm, an overall length and width of 1.5 × 1.5 m, a span of 1.45 × 1.45 m, and was supported on all four sides by steel rollers with a diameter of 30 mm. The steel rollers allowed both longitudinal and transverse sliding. Fig. 2 shows the pultrusion orientations of the slab specimens. In all cases, the box profiles were placed in the longitudinal slab direction (along the *x*-axis in Fig. 2). Three sandwich slabs (UA, BA and BAF) had an adhesively bonded connection. Sandwich slab UA had a unidirectional pultrusion orientation with adhesive bonding, as shown Fig. 2a where the pultrusion direction of the upper and lower flat panels lay parallel to the pultrusion direction of the box profiles (i.e. along the *x*-axis).

Sandwich slabs BA, BAF and BB all had bidirectional pultrusion orientations, where the pultrusion direction of the upper and lower flat panels lay in the transverse slab direction (along the y-axis), perpendicular to that of the box profiles as shown in Fig. 2b. Sandwich slabs