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Partial-composite behavior of sandwich beams composed of fiberglass facesheets and woven fabric core

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ABSTRACT

In this study, thin-walled sandwich composites made of glass fiber-reinforced polymer (GFRP) facesheets and a three-dimensional (3D) woven fabric core were studied. A total of 30 small-scale sandwich beam specimens were manufactured across six unique beam varieties with dimensions of 50 mm in width, and 200 or 350 mm in length to be tested under four-point bending up to failure. The load-deflection behavior, load-strain behavior, moment-curvature behavior, and neutral axis location were analyzed. Based on the test results, the flexural stiffness, shear stiffness, core shear modulus of the sandwich beams were calculated. Also, an analytical model is presented to consider the effect of core shear modulus on deformation and composite action of the test specimens. The model is capable to quantify the degree of composite action based on the geometry and material properties of sandwich beams. Overall, the sandwich beams displayed a partial-composite behavior raging from 15% to 91% of full-composite behavior, which was a function of the relative stiffness of the facesheets and the core plus the length of the shear span. It was shown that compatibility between the mechanical properties of the facesheet and core is a key factor in optimizing sandwich panels made of the core. The results will be used for the design of thin-walled sandwich liners for the rehabilitation of underground infrastructure including existing highway culverts and large diameter drainage systems.

1. Introduction

The use of sandwich structures are increasing as engineers look to maximize the efficiency of structures and to minimize their weight. Sandwich composites made of fiber-reinforced polymer (FRP) facesheets and lightweight, low-density core materials have been shown to be effective in reducing weight and increasing strength and stiffness in a variety of structural applications. The FRP facesheets resist the tensile and compressive stresses due to bending, while the core resists shear stresses, provides insulation, and increases the distance between facesheets resulting in an increased moment of inertia. Sandwich panels are often favored in high-performance structural applications due to their relatively light weight and high moment of inertia [1]. The use of various FRP facesheet materials such as fiberglass and carbon [2,3] as well as natural fibers such as flax [4] have been studied. Also, a variety of core materials have been explored for use in composite sandwich beams and panels. Foam materials have commonly been studied for sandwich composites providing a continuous core between the facesheets [5–7]. This study focusses on discrete core materials, particularly on woven core systems. The mechanics of sandwich beams and plates with discrete core have been investigated for various materials and core geometries, i.e. web-core, honeycombs, corrugated core, C- and Z-cores, etc. over last decades. Also, different materials have been considered ranging from metals to composites.

Three-dimensional (3D) woven fabrics have more recently been introduced and provide a viable alternative in sandwich construction [8–12]. Typically, 3D woven fabrics are manufactured multi-layered warp fibers in the structured direction, and two orthogonal sets of weft fibers which interlace with the warp fibers to provide structural stability in all directions [13]. These core materials provide a new generation of sandwich structures with a high facesheet to core debonding strength and reducing the weight and cost of the structure [14,15]. There is a large variety in possible core layouts and thus mechanical performance [16]. Numerous studies have previously been conducted on the failure mechanisms of sandwich composites with 3D fabric cores [17–24]. Furthermore, the dynamic behavior [25,26], damping properties [27], and impact performance [28,29] of the 3D core sandwich system have been studied. It has been shown that the mechanical properties of 3D core sandwich structures are significantly affected by the configuration of the woven core. Consequently, various styles of multi-dimensional cores must be studied to enhance strength and predictability surrounding sandwich composites manufactured with a 3D

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woven fabric core.

As compared to conventional core materials such as foam and honeycomb, a 3D fabric core may provide many significant manufacturing advantages. As the material is provided as a fabric, it is initially very flexible and can be used easily as a core in non-conventional applications such as curved surfaces and tubular sandwich structures. Whereas conventional cores may need to be cut to accommodate smaller radii, a 3D fabric can simply be rolled into place before the curing process. Furthermore, as the composite facesheets and core are cured at the same time, they will ideally have an improved structural unity and this may eliminate the risk of debonding and delamination, which is a common issue in sandwich panel construction [30,31]. Moreover, since 3D fabric comes in a roll, it is a very easy to transport material and long lengths of composite beams can be produced without any seams or overlap in the core.

In this paper, glass FRP (GFRP) facesheets are combined with a 3D woven fabric core to manufacture sandwich beams with zero, one and two layers of GFRP facesheets. In the manufacturing of these panels, both the facesheets and core were cured using the same epoxy resin at the time. The aim of the study is to analyze and evaluate the structural performance of sandwich beams consisting of GFRP facesheets in combination with a singular style of 3D fabric core. Based on existing information, it can be concluded that 3D fabric holds great potential in the world of sandwich composites. As new fabrics are manufactured exclusively for structural purposes, their structural performance must be evaluated. In this study, multiple small-scale sandwich beams were manufactured and tested under four-point bending. Structural properties such as strength and stiffness as well as core properties such as shear modulus are evaluated. Moreover, the interaction between the GFRP facesheets and the 3D fabric core is analyzed. Additionally, an analytical model is developed to calculate and predict the degree of full-composite behavior of the sandwich composites.

2. Research significance

This research is a part a project on application of thin-walled sandwich composite liners for rehabilitation of underground infrastructure including existing highway culverts and large diameter water/wastewater systems. Rather than applying layers after layers of expensive FRPs to achieve required thickness of a solid liners, a sandwich FRP system can be applied in place to achieve the same strength and stiffness of the solid liner. Since dry 3D fabrics are flexible, it is a very easy to saturate them in place and apply them on the inner surface of the culvert after a few layers of FRP layers and then apply a few layers of FRPs forming a sandwich liner with minimum expensive FRP materials. This paper focuses on the characterization of the 3D core using flat sandwich beams before moving forward with using the 3D core for a curved-shape sandwich liner. The key point is the flexibility of dry 3D fabric to accommodate the shape of the liner based on the actual shape and dimension of the existing culvert/pipe without a significant reduction of the cross-section of the culvert/pipe affecting the hydraulic of the system negatively. Other core materials such as honeycomb and foam core materials are not able to accommodate the required curvature. The outcomes of this research will help to find more sustainable and cost-effective solutions for aging underground infrastructure around the world.

3. Experimental program

3.1. Test matrix

A total of 30 sandwich specimens with a three-dimensional (3D) woven fabric core were fabricated to be tested under four-point bending. The variables were the number of layers of facing as well as the specimen span. Two different span lengths, 150 mm and 300 mm were tested. The long span was selected to ensure the sandwich beams will reach to failure without excessive deflections beyond the stroke capacity of the testing machine. The short span was selected to have two sets of load-deflection behaviors required for calculation of flexural and shear stiffness of the sandwich beams as it will be explained later. All specimens had an 8-mm nominal thick 3D woven fabric core and had either 1 or 2 layers of GFRP facesheet. As the 3D fabric had its own top and bottom facesheets, stiff enough to be considered as test specimens. So, a group of specimens were made without GFRP facesheets. Then 1 and 2 layers of GFRP facesheets were added as reinforcement of the 3D core. The test matrix is shown in Table 1. Five identical specimens were made for each case. The test specimens are identified with a specimen ID such as GX-SY where G stands GFRP, S stands for span, X identifies the number of GFRP facesheet layers and Y identifies the span length in mm. For example, G0-S150 is a 3D fabric core sandwich beam with zero (0) layers of GFRP facesheet tested with a 150-mm span.

Table 1
Test Matrix.

Case #	Specimen ID	Number of GFRP layers	Span (mm)
1	G0-S150	0	150
2	G0-S300	0	300
3	G1-S150	1	150
4	G1-S300	1	300
5	G2-S150	2	150
6	G2-S300	2	300

Note: Five identical specimens per case were tested.

3.2. Material properties

For the GFRP facesheets, a 915 g/m^2 (gsm) unidirectional fiberglass fabric was used. The fabric was made of glass fibers with a density of 2.55 g/cm^2, a tensile strength of 3.24 GPa, an elastic modulus of 72.4 GPa and a rupture strain (ultimate elongation) of 4.5% all as reported by the manufacturer (QuakeWrap Inc., Tucson, AZ, USA) for the dry fibers. For making the sandwich composites, a two-component epoxy resin mixture was used. The resin mixture comes in two parts: an epoxy and a hardener which are mixed in a 2:1 by-volume ratio respectively. The epoxy and hardener are reported to have densities of 1.13 kg/L and 1.00 kg/L respectively. This gives a density of 1.087 kg/L for the liquid resin when mixed in the specified ratio. Five samples of cured resin were created to compare the reported liquid density to a solid density. Across five samples, an average solid resin density was found to be 1.13 kg/L with a standard deviation of 0.04 kg/L. The resin, having been cured at room temperature for 48 h, was reported by the manufacturer to have a tensile strength of 49.3 MPa, a compressive strength of 65.4 MPa, and a tensile elastic modulus of 1995 MPa.

Five identical GFRP tensile coupons made of two layers of the unidirectional fabric and epoxy resin were prepared using wet hand layup method and tested according to ASTM D3039 [32]. The overall dimension of the coupons was 25 mm x 250 mm with two tabs attached on both sides on each end of the coupon. The tabs were made of the same GFRP material and had dimensions of 25 mm x 125 mm. These tabs were used to aid in the gripping of the coupon during the test and to ensure that the gripping did not produce any stress concentrations or premature failures. The tab dimensions are shown in Fig. 1. A 100 kN universal testing machine with a displacement rate of 2 mm/min was used. A strain gauge was applied on each side of the coupons, centered in the longitudinal direction of fibers/coupon to measure the axial strain. Fig. 1 shows the tensile test results based on the nominal ply thicknesses of 1.3 mm as reported by the manufacturer. The average tensile strength of the GFRP coupons was 583 MPa with a standard deviation of 31 MPa. As shown in Fig. 1, the GFRP coupons displayed a nearly linear behavior up to the point of rupture. The average elastic modulus of the GFRP coupons was 21.75 GPa with a standard deviation of 0.58 GPa.