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# BEHAVIOR OF FRP SANDWICH PANELS FOR TRANSPORTATION INFRASTRUCTURE

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**ABSTRACT:** In the past few years, various FRP composite panels have been implemented in highway and pedestrian bridge construction. Light-weight, excellent corrosion characteristics and rapid installation capabilities created tremendous opportunities for FRP composite panels in transportation industry. Nevertheless, proper characterization methods, analysis and design procedures for FRP composite panels have not been established. This paper examines the structural performance of innovative 3-D FRP sandwich panels. The panels consist of GFRP laminates and foam core sandwich where top and bottom skin GFRP layers are connected together with through-thickness fibers. Two full-scale FRP sandwich panels were tested using a concentrated wheel load at mid-span. Failure modes and mechanisms are investigated. Fundamental material properties in tension, compression and shear are evaluated. The influence of the panel configuration, density and arrangements of through-thickness fibers on the shear, compression and tension behavior of the panels is demonstrated.

## 1. INTRODUCTION

### 1.1 Background

The demand for the development of more efficient and durable bridge and parking decks as well as transportable lightweight matting is at the forefront of the priority of transportation authorities worldwide. Conventional steel reinforced concrete and steel decks are prone to corrosion, which drastically reduces their service life. Replacement or repair of concrete bridges and parking decks has also proven to be very costly, time-consuming and disruptive to traffic flow. This paper introduces innovative glass fiber reinforced polymer (GFRP) sandwich panels as an alternative and solution to these problems. A sandwich panel is normally a low-density core material sandwiched between two high modulus face skins to produce a lightweight panel with exceptional stiffness. The face skins act like the flanges of an I-beam carrying tensile and compressive loads. The core plays the role of the web, separating the face skins and carrying the shear loads. The faces are adhesively bonded to the core to create a load transfer mechanism between the components. The composite plies of the face sheets can also be oriented to maximize the structural properties for specific loading applications and therefore making the structure even more efficient. Conventional sandwich structures consist of a metallic skin sheets and polyurethane foam core material as an insulating layer. These conventional structures have been used very widely for structural components. However, the durability of those panels becomes degraded due to delamination at the bonding interfaces, corrosion of the face sheets and stiffness degradation through aging of the foam core over time [1]. Through-thickness (3-D) fibers overcome the shortcomings of conventional sandwich structures and minimize delamination and degradation of stiffness over time [2]. Furthermore, the use of FRP offers a variety of advantages compared to conventional materials including high-strength and stiffness-to-weight ratios; ease of handling, excellent corrosion characteristics; and rapid installation on site. This paper presents an experimental investigation used to study the behavior and evaluate the engineering properties of 3-D FRP sandwich panels produced by Martin Marietta Composites, NC, USA. The influence of the panel configuration, density and arrangements of through-thickness fibers on the shear, compression and tension behavior of the panels is elucidated.

### 1.2 3-D FRP Sandwich Panels

The 3-D FRP sandwich panels presented in this paper consist of GFRP laminates and foam core sandwich where top and bottom skin GFRP layers are connected together with through-thickness fibers as shown in Figure 1. The light-weight foam core increases the flexural stiffness and strength by placing the stiffer GFRP face sheets further from the neutral axis. The through-thickness fibers increase also the shear stiffness of the panel and delay delamination between the plies of a composite laminate. The panels are fabricated using pultrusion and the through thickness fibers are injected during the pultrusion process. The width of the panels can vary from 0.15 m (6 in) to 2.59 m (8.5 ft). The fiber insertion density can vary from 0 to 10/cm$^2$ (64/in$^2$). The panels can be fabricated with a total thickness up to 100 mm (4 in). The use of GFRP face sheets produces a lightweight, corrosion-resistant panel that is relatively low in cost when compared to more exotic aerospace composite constructions. The cost of these panels can be favorably compared to more conventional construction materials especially when the reduced costs of installation and public inconvenience are considered.

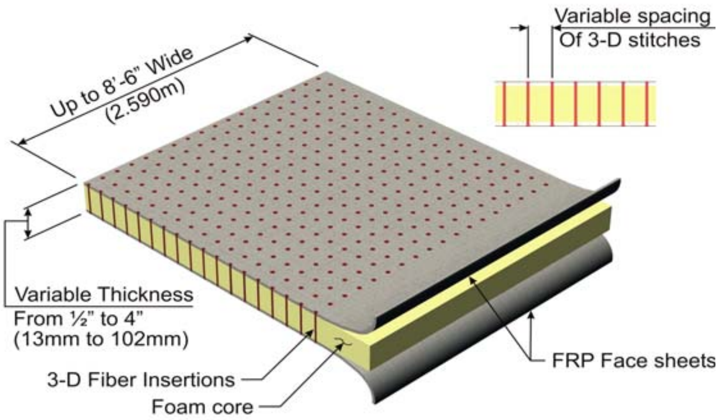

**Figure 1 – Schematic of 3-D FRP sandwich panel**

3-D fiber composite panels can serve in a variety of applications including pedestrian and county bridge decks where the spacing between the main girders is limited to 1.0 m (3 ft), trench covers, airfield matting and parking decks. 3-D FRP sandwich panels are ideally suited for the use in the construction of dry freight, refrigerated trailers and containers. FRP panels also provide superior strength, ease of maintenance and are esthetically pleasing.

## 2. EXPERIMENTAL PROGRAM

### 2.1 Full Scale 3-D FRP Sandwich Panels

The main objective of the testing program was to evaluate the behavior of 3-D FRP sandwich panels tested under a simulated truck wheel load. Two full-scale 3-D FRP sandwich panels having different thicknesses were tested. The stiffness, load-deflection behavior and failure modes of the FRP sandwich panels were evaluated. The specimens were 1.8 m (6 ft) long by 1.2 m (4 ft) wide and the thicknesses of the two panels were 40 mm (1.5 in) and 60 mm (2.5 in), respectively. The panel was supported on two rollers with 1.7 m (5.5 ft) clear span. The panel was fixed to the roller supports with four bolts at each side. Roller supports were mounted on I-beams, which were supported on two concrete blocks as shown in Figure 2. The panels were tested under simply supported conditions with a single load applied at the centre of its span. The Load was applied to the panel through a 2000 kN (450 kips) capacity actuator with a rate of 2.5 mm/min (0.1 in/min). To simulate the actual truck tire loading, special contact patches were made from actual truck tires reinforced with silicon rubber as shown in Figure 2. Deflections were measured using displacement transducers located at mid-span and at the supports. Strain gauges were also applied along the top and bottom surfaces to measure the strains at different load levels and locations.

Panel 1: Thickness = 40 mm

Panel 2: Thickness = 60 mm

**Figure 2 – Test Setup**

Figure 3a shows the load deflection behavior of the two FRP sandwich panels tested in this study. Linear behavior was observed up to the initiation of the first shear crack in the foam core followed by a non-linear behavior up to failure. Prior to cracking of the foam, shear deformations were negligible and the deflection was mostly due to bending of the panel. Therefore, increasing the thickness of the panel by 50 percent resulted in a significant increase in the flexural rigidity and a corresponding increase in the initial stiffness by 114 percent. However, after cracking of the foam, the shear stiffness of the panel reduced drastically and the shear deformation of the core was quite large. At this stage of loading, local bending of the face sheets was observed and the panel did not perform effectively as a sandwich as shown in Figure 3b.

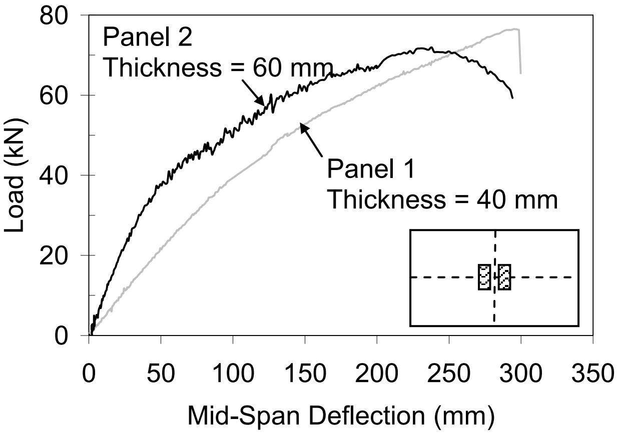

**Figure 3a – Load-Deflection behavior of panels 1 and 2 at mid-span**

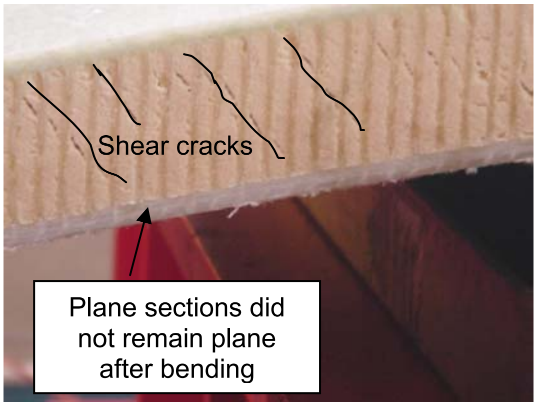

**Figure 3b – Shear cracking in the core foam**

Failure of panel 1 (40 mm thick panel) was due to crushing of the top face sheet along the width of the panel as shown in Figure 4. The maximum measured compressive strain at failure was 1.1 percent. The most prominent mode of failure for panel 2 (60 mm thick panel) was due to the excessive deformation of the panel, which resulted in overturning the roller supports as shown in Figure 5. Test results indicated that the behavior of 3-D FRP sandwich panels at high load levels could not be predicted using elementary sandwich theory and an in depth understanding of the material characteristics is mandatory to evaluate the structural performance of these panels under different loading conditions. The ability to undergo large deformation (see figure 5) while not delaminating nor completely failing is a unique aspect that poses testing challenges and application opportunities.

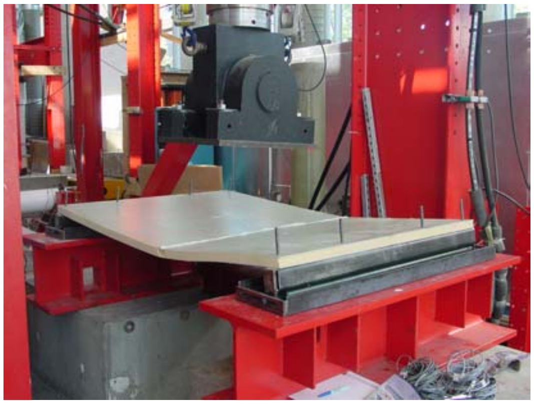

**Figure 4 – Failure mode of panel 1**

**Figure 5 – Failure mode of panel 2**

## 2.2 Material Properties

### 2.2.1 Shear Behavior

A total of 18 specimens were tested in shear to evaluate the influence of the through-thickness fibers on the core shear modulus of the 3-D FRP sandwich panels. The specimens had different 3D fiber insertion densities and patterns, different facing thickness and different overall sandwich thickness. The amount of 3D fiber insertions ranged from 1.2 to 3.6 insertions per $cm^2$. Sandwich thicknesses were 60mm (2.5 in.) and 100 mm (4 in.). Shear tests were conducted according to the ASTM C273 [3], with the exception of length to thickness ratio. The test specimens had a total length of 292 mm (11.5 in) and had a width equal to the thickness of the panel. Since the influence of panel thickness was a variable of interest, the recommended ratio of thickness to length could not be practically achieved in the thick sandwich panels. The shorter than recommended shear specimen may not have enabled a uniform state of stress to be achieved in the gage section. Hence, shear strengths are not reported. However, it was felt that the shear modulus was not significantly affected by the length of the specimens. Two 19 mm (¾ in) thick steel plates were bonded to the facings of the specimen using an epoxy adhesive. The specimens were loaded in compression with a rate of loading of 0.5 mm/min (0.02 in/min). The relative displacement between the two steel plates was measured at the center of the steel plates at both sides by using displacement transducers as shown in Figure 6. The core shear modulus in the plane normal to the facings was evaluated for each specimen using Eq. (1):

$$G = \frac{S\,t}{L\,b} \qquad (1)$$

where $G$ is the core shear modulus; $S$ is the slope of initial portion of the load versus the relative displacement between the steel plates; $t$ is the thickness of the core; $L$ is the length of the specimen and $b$ is the width of the specimen. Test results showed that the core shear modulus could vary from 12 MPa to

103 MPa (1.8-15 ksi) depending on the quantity and arrangement of the 3-D fibers. From the test results, it could clearly be seen that the density and configuration of the 3-D fibers affect the core shear modulus considerably. Increasing the quantity of the 3-D fibers and changing their pattern increased the core shear modulus by up to 800%. Detailed test results were reported elsewhere [4].

**Figure 6** – **Instrumentation and test set-up for shear tests**

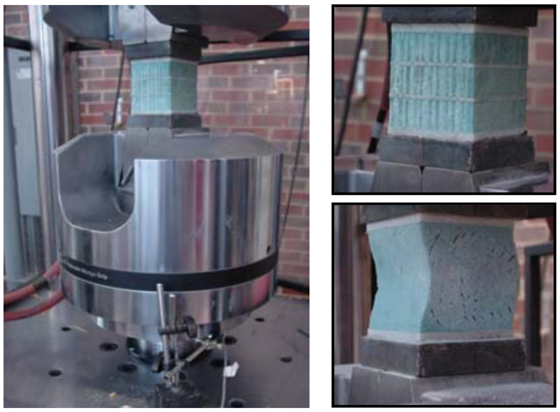

**Figure 7** – **Test set-up for the compression specimens**

2.2.2 Compression Behavior

The flatwise compressive properties of the sandwich panels were determined according to the ASTM C365 [3]. A total of 18 square specimens with dimensions of 89 mm x 89 mm (3.5 in x3.5 in) were cut from the same sandwich panels discussed above. The specimens were tested using an MTS machine having a total capacity of ± 980 kN (220 kips) and monotonically loaded in compression up to failure as shown in Figure 7. The applied load and the displacement of the crosshead of the MTS machine were monitored during testing. A standard head displacement rate of 1.27 mm/min (0.05 in/min) was applied up to failure. The flatwise compressive modulus was calculated for each specimen using Eq. (2):

$$E = \frac{S\,t}{A} \tag{2}$$

where $E$ is the flatwise compressive modulus; $S$ is the slope of initial portion of the load-displacement curve, $t$ is the thickness of the core and $A$ is the cross-sectional area of the specimen. Test results showed that, increasing the quantity of 3-D fibers increased the compressive shear modulus significantly. The increase in the compressive modulus is linearly proportional to the increase in density of the 3-D fibers. The arrangement of the 3-D fibers did not have a significant effect on the compressive modulus of the 3-D sandwich panels tested in this study. Failure of all the specimens was due to buckling of the 3-D fibers followed by a compression failure of the core material as shown in Figure 7.

2.2.3 Tensile Behavior

The tensile modulus of the face sheets was determined using thin flat strips cut from the 60 mm (2.5 in) thick panels. The specimens were mounted in the grips of an MTS machine having a total capacity of ± 980 kN (220 kips) and monotonically loaded in tension up to failure while recording the applied load as shown in Figure 8. Changing the density of 3-D fibers [4], appeared to have an effect on the tensile performance. However, the width of the tensile coupons was not significantly larger than the repeat pattern of the 3D fibers, and relatively few coupons were tested as of this writing. While the addition of the 3D fiber insertions may have an effect on the facings tensile performance, more study is required to document it conclusively. For the limited testing performed, the facing tensile strengths ranged from 200 to 350 MPa (30-50 ksi), while the modulus ranged from 12 to 21 GPa (1740-3000 ksi). Furthermore, the stress-strain curves demonstrated an initial non-linearity, making the resulting modulus sensitive to the range over which the initial slope is measured [4].

Figure 8 – Test set-up for the tension specimens

## 3. CONCLUDING REMARKS

Based on the findings of this investigation, the following observations can be drawn:

1. 3-D FRP sandwich panels may provide cost-effective and durable construction solutions for parking decks, trench covers and air force matting. However, there is still need for significant effort as related to design optimization of these panels.
2. The structural behavior of FRP sandwich panels depends critically on the shear properties as well as the intensity of cracking of the core materials.
3. At high load levels, due to the low shear stiffness of the core materials, the behavior of the 3-D FRP sandwich panels is no longer governed by the elementary sandwich theory.
4. Through-thickness fibers increase the shear stiffness of sandwich panels and delay delamination of the face sheets.
5. Both the shear and compressive modulus appear to be a function of the 3D fiber insertion density and pattern.

## 4. ACKNOWLEDGMENTS

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