INNOVATIVE 3-D FRP SANDWICH PANELS FOR BRIDGE DECKS

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ABSTRACT: The use of sandwich structures is growing very rapidly around the world. The need for light-weight structural elements with high stiffness for bridge applications and trucking industry increase the demand for sandwich construction technology made of composite materials. Currently, foam and honeycomb core sandwich composites are widely used in structural applications. Nevertheless, possibilities of core-to-face sheet delamination, crushing and buckling instability are major concerns. This paper presents two innovative alternative systems for FRP bridge decks and trucking industry designed to overcome delamination problems typically encountered in traditional FRP decks. Three-dimensional (3-D) fibers are used to connect the top and bottom GFRP layers using either weaving or injection technology. Addition of the through-thickness fibers increases the out of plane properties of the panel, delays delamination-type failures, allows low cost manufacturing and ensures full utilization of the panel strength. The study describes the fabrication process of 3-D FRP panels using the weaving technology. The behavior of an innovative 3-D FRP sandwich panels is presented. The panels consist of GFRP laminates and foam core sandwich where top and bottom skin GFRP layers are connected together with through-thickness fiber. The innovative core design provides an additional strength and stiffness over traditional foam core sandwich composites. Methods of assessment of the material characteristics in tension, shear and flexural are presented. Various means to test, design and optimize FRP sandwich panels are reviewed. The influence of the thickness of the panel, presence of filling material and density of 3-D fiber insertions are discussed.

Keywords: Core, deflections, fiber, flexure, FRP, polymers, sandwich panels, shear.

INTRODUCTION

Background

In the past decade, light-weight bridge deck systems made from Fiber Reinforced Polymer (FRP) composites have been developed and experimentally implemented in bridge structures. Composite sandwich construction is playing an increasingly important role in the design of structures because of its exceptionally high flexural stiffness-to-weight ratio. Typically, a sandwich composite consists of two thin, stiff and strong face sheets, separated by a thick, light and weaker core. The faces are adhesively bonded to the core to create a load transfer mechanism between the components. Historically, the advantages of the concept of using two co-operating faces separated by a distance go back to 1849[1]. Since the late 1940's, the technology of sandwich laminates has progressed significantly and a comprehensive use of the advantages of sandwich

laminates has been made. Commonly used face materials can be classified into two main groups: metallic and non-metallic materials. The former group includes steel, stainless steel and aluminum alloys. The later group includes plywood, cement and fiber composites. Light weight, High strength and excellent corrosion characteristics made fiber composites attractive face materials for manufacturers and engineers. Development of core materials has continued throughout the past sixty five years in an effort to reduce the weight of the sandwich laminate. The cores used in sandwich construction can be divided into four main groups; corrugated, honeycomb, balsa wood and foams. Balsa wood was the first core material to be used in sandwich construction. Honeycomb core materials were developed in the late 1940's for the aerospace industry. The core materials were produced in various forms and configurations. The continued high cost of honeycomb cores has restricted their applications predominantly to the aerospace industry. The advent of cellular foams in the early 1960's offered a greater shear strength- and stiffness-to-weight ratios of the composite sandwich [1].

Pultruded Modular FRP Bridge Decks

Pultruded modular FRP bridge decks consist of two thin top and bottom plates stiffened by longitudinal and transverse pultruded webs. Modular FRP bridge decks are becoming an attractive solution for replacement of deteriorated concrete bridge decks as well as for new bridges. Their non-corrosive, high strength and light-weight characteristics are the most efficient features. Furthermore, modular FRP bridge decks can be customized to the dimensions of the traditional concrete decks, which allow the economic reuse of existing support structures. Nevertheless, an examination of the published resources shows that proper characterization methods and generally accepted design and analysis procedures for FRP bridge decks have not yet been established [2]. Technical difficulties limit the development of low-cost large-scale FRP bridge decks. Test results by the authors as well as other researchers showed that delamination of the web from face sheets is the governing mode of failure for these types of bridge decks when subjected to wheel loads as shown in Fig. 1 [2].

Fig. 1 Typical delamination of the web from face sheets for pultruded modular FRP bridge decks [Nelson and Rizkalla, 2003]

Filament Wound FRP Bridge Decks

Filament winding technology is considered a quite improvement in comparison to the pultruded system due to the 2-D nature of the fabricated element. Williams et al., 2003[3] considered filament wound FRP bridge decks consist of triangular GFRP tubes approximately 8″ in height. A filament winding process is used to manufacture each tube due to its relatively low material costs in comparison to pultruded products. The tubes are adhered together with epoxy resin from the filament winding process. Pultruded GFRP plates can be bonded to the top and bottom surfaces of the tubes to create one modular unit. Instead of using pultruded plates as shown in Fig. 2, filament winding technique can also be used to over wrap the entire section. However, the waste of the fibers at the ends prohibited the use of this approach for economical reasons [3]. Test results showed that delamination of the pultruded plates from the tubes or buckling of the plate in compression are most likely the governing modes of failure as shown in Fig. 2 [3].

i- Buckling of the top plate
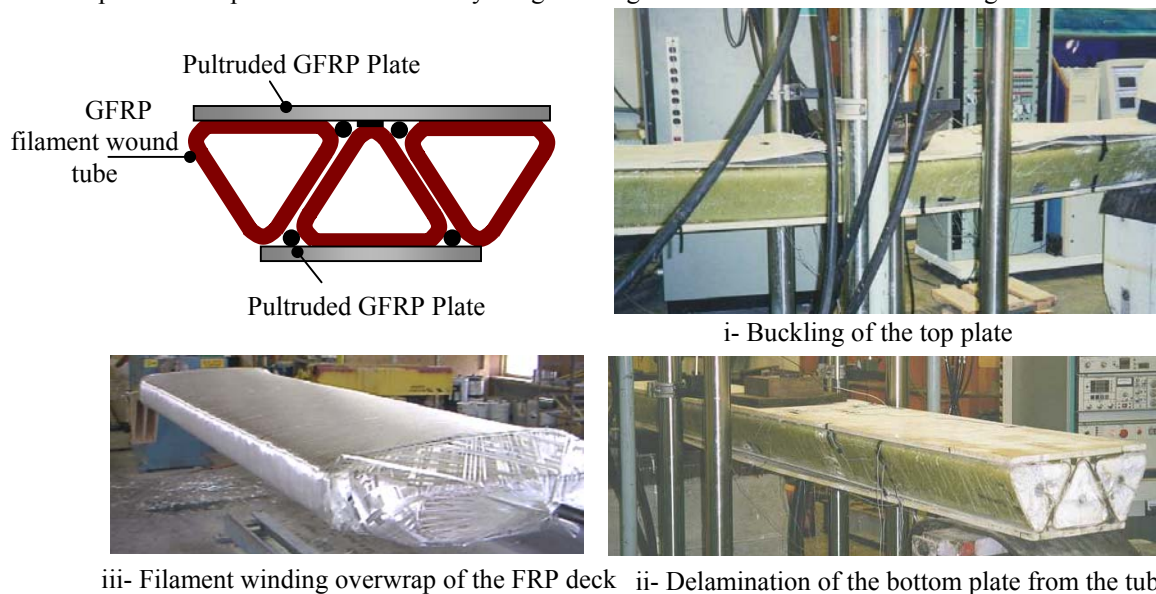
iii- Filament winding overwrap of the FRP deck   ii- Delamination of the bottom plate from the tubes

Fig. 2 Filament wound FRP bridge decks [Williams et al. 2003]

Woven 3-D FRP Panels

The principal components of woven FRP bridge deck panels are three yarns woven in a unique interlacing manner in an organized fashion in three dimensional space. The yarns are made of continuous glass fiber produced by PPO Industries, Inc, USA. The warp (x-direction) yarn is the primary yarn within the deck panel and is pulled straight through the machine to eliminate out of plane fiber and fiber waviness. The weft (y-direction) yarn is orthogonal to the warp and is of double insertion above and below the warp as shown in Fig. 3a. A third set of through-thickness yarns (z-direction) integrates all sets of yarns into a fabric. The z-yarns are normal to the fabric plane as shown in Fig 3b. The resulting fiber architecture is demonstrated in Fig. 3b. The behavior as well as the material properties of the 3-D woven FRP bridge decks are currently being investigated at the Structural laboratory at North Carolina State University, USA and the results will be presented by the time of the conference.
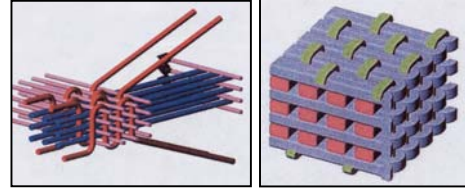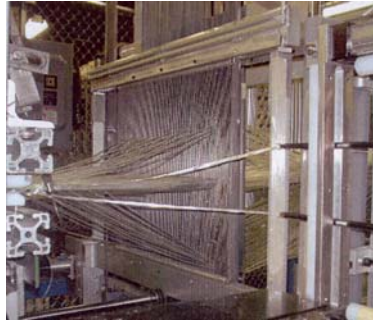
Fig. 3a Double insertion process for the weft above and below warp

Fig. 3b Resulting fiber architecture and z-yarns insertion

3-D FRP Sandwich Panels

Traditional foam core sandwich constructions exhibit low transverse stiffness, susceptibility to in-plane shear, face-to-core debonding and buckling instability[1]. 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 fiber as shown in Fig. 4. 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 6″ to 8.5′. The fiber insertion density can vary from 0 to 64/in². The panels can be fabricated with a total thickness up to 4″.
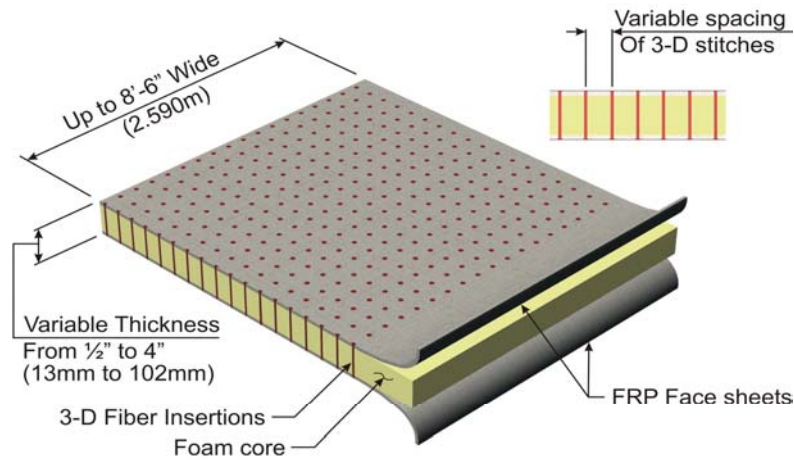

Fig. 4. Schematic of 3-D FRP sandwich panel

The light-weight foam core serves to place the stiffer GFRP face sheets further from the neutral axis and therefore increasing the flexural stiffness and strength. Addition of the through-thickness fibers increases the shear stiffness of the panel and delays delamination between the plies of a composite laminate. 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 2-3ft, trench covers, composite trailers and parking decks. Characteristics of various FRP sandwich panels investigated in the present study are summarized in Table 1.

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Table 1. Characteristics of 3-D FRP sandwich panels

Panel designation	No. of top or bottom GFRP plies	Quantity of 3D fibers/in^2	Face thickness (in)	Total thickness of the panel (in)	Weight lb/ft^2
13.3/55-1.5	5	13.3	0.125	1.5	4.7
8/88-2.5	8	8	0.25	2.5	6.6
16/88-2.5	8	16	0.25	2.5	8.0
23/88-2.5	8	23	0.25	2.5	9.8

EXPERIMENTAL PROGRAM

Shear Tests

To determine the core shear properties of the 3-D FRP sandwich panels, three specimens for type of the FRP panels were tested according to the ASTM C273 [4]. The shear strength parallel to the plane of the sandwich as well as the shear modulus in the plane normal to the facings were evaluated. The test specimens had a width equal to the thickness of the panel and a total length of 11.5″. ASTM C273 recommends that the total length of the specimen should not be less than 12 times the thickness of the specimen, which was neither practical nor economical to fabricate. The test specimens were rigidly supported by ¾″ thick steel plates bonded to the facing as shown in Fig. 5a. The relative displacement between the two steel plates was measured at different locations using two displacement transducers mounted on the center of the steel plates as shown in Fig. 5b.
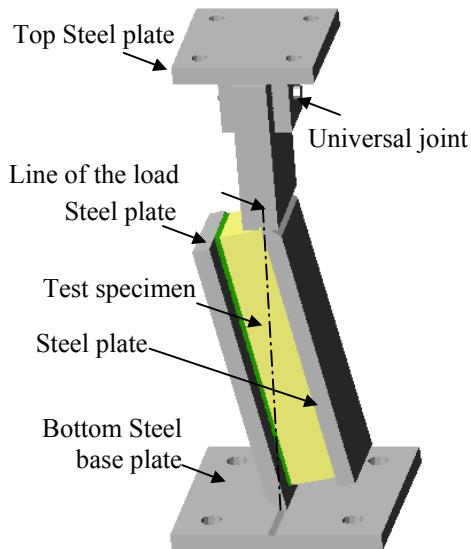

Fig. 5a. Compressive plate shear test

Fig. 5b Test setup for the shear tests

The steel plates were bonded using an epoxy adhesive produced by Master Builders, Inc, OH, USA. The test fixture was designed to have the line of the load action passes through the diagonally opposite corners of the sandwich as shown in Fig. 5a. The specimens were loaded in compression with a rate of loading of 0.02 in/min. Fig. 6 shows the load versus the average

relative displacement between the steel plates for the 2.5″ thick FRP panels with 8, 16 and 23 through-thickness fibers in the Z-direction per in^2.
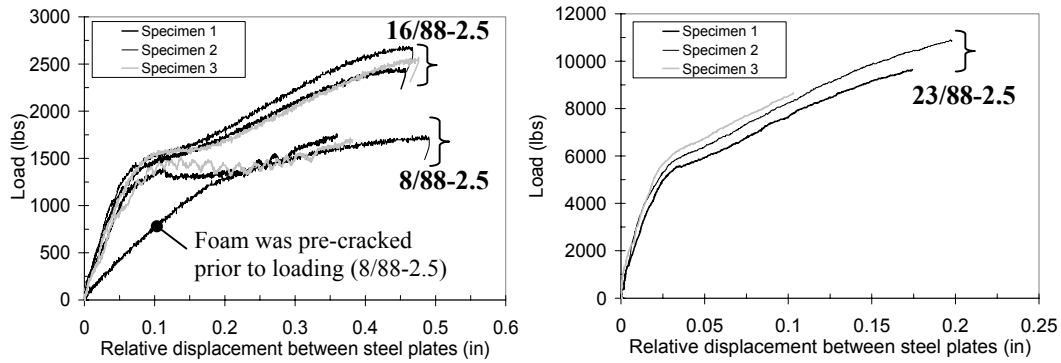

Fig. 6 Test results for the shear tests of the 2.5″ thick FRP panels

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. Upon cracking, the increase in the applied load was insignificant due to transfer of shear stresses from the foam to the surrounding fibers. Once the stresses were transferred, the specimen started to resist the applied load but with a reduced shear stiffness up to failure. Such a phenomenon was highly pronounced in the 8/88-2.5 specimens rather than in the 23/88-2.5 specimens. The influence of the filling material on the core shear modulus was investigated by cracking one 8-88-2.5 specimen prior to loading. The shear stiffness of the specimen with the cracked foam, expressed as the initial slope of the curve was about two times less than the stiffness of the panel with uncracked foam. Test results showed that the foam material has no strength by itself. However, uncracked foam plays an important role by confining the through-thickness fibers and therefore the shear modulus of the core is increased significantly. Failure of specimens 13.3/55-1.5, 8/88-2.5 and 16/88-2.5 was due to shear failure as shown in Fig. 7. Debonding of the steel plates was the governing mode of failure for specimens 23/88-2.5.
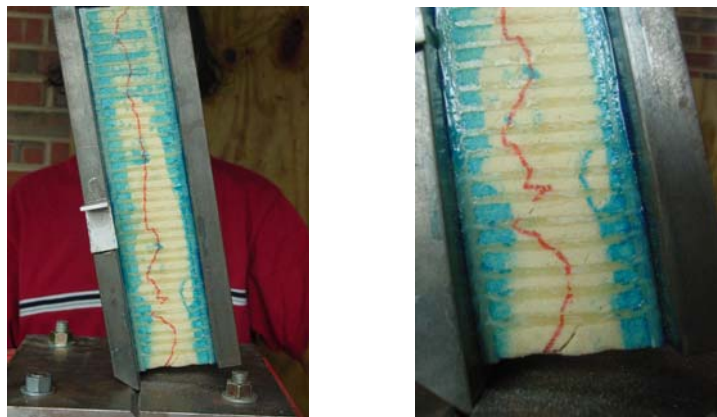

Fig. 7 Shear cracks at failure

The core shear modulus was calculated for each specimen using Eq. (1):

$$G = \frac{St}{Lb} \tag{1}$$

where G is the core shear modulus; S is the slope of initial portion of the load-deflection curve; t is the thickness of the core and b is the width of the specimen. Test results showed that the density of the through-thickness fibers significantly affect the core shear modulus. Increasing the density of the 3-D fibers from 16 to 23 per in^2 using a continuous web connecting the top and bottom face sheets, increased the core shear modulus by more than 8 times. Average shear test results for each type of FRP panels are summarized in Table 2.

Table 2. Summary of the shear test results

Specimen	Width (in)	Length (in)	Core shear modulus (ksi)	Shear strength (psi)	Failure mode*
13.3/55-1.5	1.44	11.50	2.32	148	S
8/88-2.5	2.36	11.42	1.53	65	S
16/88-2.5	2.35	11.48	1.88	95	S
23/88-2.5	2.46	11.59	15.33	>367	D

[Π] The shown results are the average of three specimens tested for each type of FRP panels.
[*] S refers to shear failure and D refers to debonding of the steel plates.

TensionTests

The in-plane tensile properties of the face sheets were determined according to the ASTM C3039. Three specimens for each type of sandwich panels were tested. Flat strips having a total width of 1.5″ and a total length of 17″ were cut from the sandwich panels using a diamond saw. The specimen length was selected to minimize bending stresses caused by minor grip eccentricities. Aluminum tabs were bonded to each end to prevent premature failure at the ends of the grips. The specimens were mounted in the grips of an MTS machine having a total capacity of ±220 kips and monotonically loaded in tension up to failure as shown in Fig. 8. The strain in the specimen was monitored using one strain gauge and an extensometer placed on the mid height of the gage length. A standard head displacement rate of 0.05 in/min was applied up to failure.

Fig. 8 Test set-up for the tension specimens

Increasing the density of the through-thickness fibers creates zones of imperfection and waviness among the fibers and reduces the elastic modulus as well as the tensile strength of the face sheets considerably. Test results showed that the modulus of elasticity and tensile strength for the 8/88-2.5 specimens were 2382 ksi and 50.3 ksi, respectively. Increasing the density of the through-thickness fibers to 16 and 23 per in^2 reduce the tensile modulus by 17% and 28%, respectively. Furthermore, the tensile strength was reduced by 25% and 39%, respectively. Failure of all the specimens was due to rupture of the GFRP within the gage length as shown in Fig. 9. The initial portion of the stress-strain relationship up to a strain level of 0.4% was not included in the calculation of the elastic modulus to avoid any kind of non-linearity as a result of early loading. Tension test results for various types of FRP panels are summarized in Table 3. The tensile modulus was calculated using the average of the strain gauge and extensometer readings for each specimen.

Fig. 9 Failure mode for the tensile specimens

Table 3. Summary of the tension test results

Specimen	Width (in)	Thickness (in)	Tensile modulus (ksi)	Tensile strength (ksi)
13.3/55-1.5	1.52	0.152	2301	41.0
8/88-2.5	1.46	0.236	2382	50.3
16/88-2.5	1.46	0.273	1975	37.9
23/88-2.5	1.44	0.274	1717	30.8

Flexural Tests

A total of 12 tests were conducted on the FRP sandwich panels to determine the sandwich flexural stiffness and the core shear modulus according to the ASTM C393. The results will be used to examine the applicability of the elementary sandwich theory for 3-D FRP panels and to verify the tension and the shear test results. The specimens were rectangular in cross-section. The depth of the specimen was either 1.5" or 2.5" depending on the type of the panel. The width of the specimen was set to twice the panel thickness. For each type of FRP panel, at least two different span lengths were tested. The flexural stiffness and the core shear modulus were determined by simultaneous solution of the deflection equations for each span. The load was applied using a 2,000,000 lbs capacity testing machine with a rate of loading of 0.5 in/min. Special steel testing fixture was fabricated and consisted of two movable steel supports connected to a steel base to

allow for testing various spans as shown in Fig. 10. A rubber pad was placed under the loading point to avoid local crushing of the panel.

Fig. 10 Flexural test setup using a single concentrated load

The load-deflection behavior of the 1.5″ and 2.5″ thick panels are shown in Figs. 11a and 11b, respectively. Linear behavior was observed up to initiation of flexural cracks in the foam followed by a non-linear behavior with a reduced stiffness up to failure. Failure of all the specimens was due to rupture of the face sheets as shown in Fig. 11b. It is worth mentioning that the tensile stresses in the face sheets can not be predicted using composite beam theory which does not account for the shear deformation. Test results showed that the maximum induced tensile stress in the face sheets is a function of the core shear modulus. Increasing the core shear modulus reduced the tensile stress in the face sheets at any given load. Consequently, higher failure loads were observed for the 23/88-2.5 specimens compared to the 8/88-2.5 and 16/88-2.5 specimens having the same span.
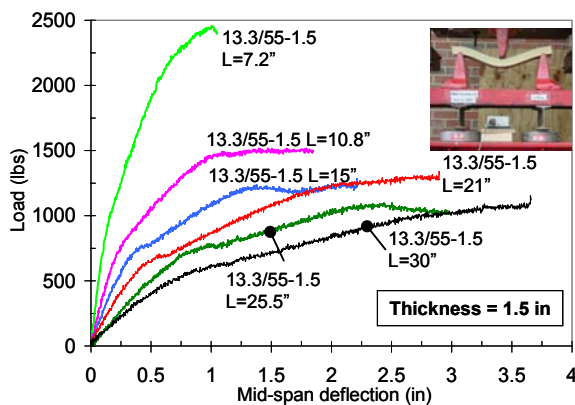

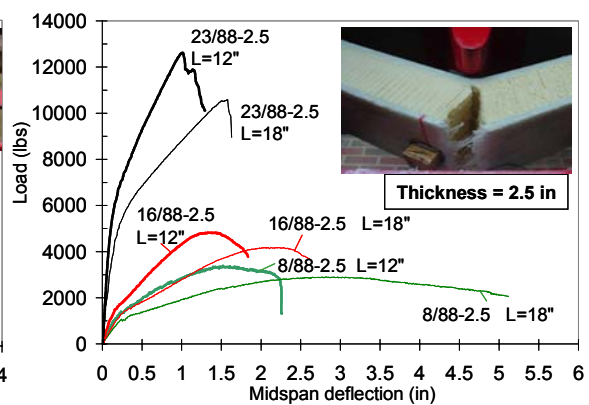Fig. 11a Load-deflection behavior of the 1.5" thick FRP panels

Fig. 11b Load-deflection behavior of the 2.5" thick FRP panels

The predicted deflection at mid-span using the elementary sandwich theory (EST) in which the total deflections are calculated using composite beam theory and accounting for an additional shear deflection associated with the shear strains in the core can be expressed as follows:

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$$\Delta = \frac{PL^3}{48D} + \frac{PL}{4U} \tag{2}$$

where, Δ is the total deflection; $D = \frac{E\left(d^3 - c^3\right)b}{12}$; $U = \frac{G\left(d + c\right)^2 b}{4c}$; E is the facing modulus; G is the core shear modulus; d is the sandwich thickness; c is the core thickness; L is the span length of the specimen; P is the applied load and b is the sandwich width. For FRP panels having a small L/d ratio, the face sheets bend locally in order to follow the shear deformation of the core and the additional shear deflections are significantly reduced. The deflection of these panels can be predicted using the advanced sandwich theory (AST) as follows:

$$\Delta = \frac{PL^3}{48EI} + \frac{PL}{4U}\left[1 - \frac{I_f}{I}\right]^2 \psi \tag{3}$$

where I is second moment of inertia of the faces about the centroid of the sandwich; I_f is the sum of the second moments of the area of the faces about their own centroids;

$\psi = 1 - \dfrac{\sinh\theta + \beta\left(1 - \cosh\theta\right)}{\theta}$; $\theta = \dfrac{L}{c}\left[\dfrac{G}{2E}\dfrac{c}{t}\left(1 + \dfrac{3d^2}{t^2}\right)\right]^{0.5}$; t is the face thickness; and

$\beta = \tanh\theta$. Detailed derivation of the deflection formulae can be found elsewhere [5]. Equation (2) can be rewritten in two forms:

$$\frac{\Delta}{PL} = \frac{L^2}{48D} + \frac{1}{4U} \tag{4}$$

$$\frac{\Delta}{PL^3} = \frac{1}{48D} + \frac{1}{4U}\frac{1}{L^2} \tag{5}$$

Equation (4) can be represented by a straight line in a plot of $\dfrac{\Delta}{PL}$ versus L^2. The slope of the line is $\dfrac{1}{48D}$ and the intercept with the Y axis is $\dfrac{1}{4U}$ as shown in Fig. 12 for various FRP sandwich panels. Similarly, Equation (5) can be represented by a straight line in a plot of $\dfrac{\Delta}{PL^3}$ versus $\dfrac{1}{L^2}$. The slope of this line is $\dfrac{1}{4U}$ and the intercept with the Y axis is $\dfrac{1}{48D}$. The flexibility, $\dfrac{\Delta}{P}$, for each sandwich panel was calculated from the flexural tests and the results were used to determine the tensile face modulus as well as the core shear modulus as illustrated in Fig. 12.
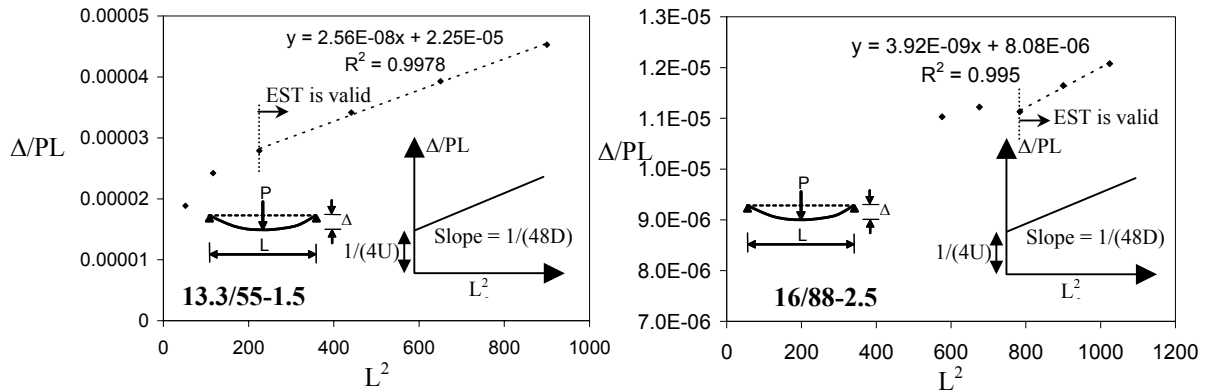
Fig. 12 Evaluation of the material characteristics using flexural tests

The analysis indicated that there exists a certain length for each FRP sandwich construction beyond which the elementary sandwich theory (EST) is valid and the material properties can be determined with a sufficient accuracy using the proposed flexural approach. The method provided very good results for the 13.3/55-1.5, 16/88-2.5 and 23/88-2.5 specimens. The calculated face elastic modulus and the core shear modulus were within 15% of the measured values using tension and shear tests. Unsatisfactory results were determined for specimens 8/88-2.5 using the EST where shear deformations of the core were quite large and a very large span length is required to be able to use EST. A comparison between the measured and the calculated material properties for various FRP panels are given in Table 4.

Table 4. Comparison between measured and calculated material properties

	Face Modulus (ksi)		Core Shear Modulus (ksi)		
Specimen	Tension Tests	Flexural Tests	Shear Tests	Flexural Tests	Minimum proposed length to use EST (in)
13.3/55-1.5	2301	2287	2.32	2.06	15
8/88-2.5	2382	N.A	1.53	N.A	N.A
16/88-2.5	1975	1759	1.88	2.10	28
23/88-2.5	1717	1679	15.33	13.0	12

CONCLUSIONS

Based on the findings of this investigation, the following conclusions can be drawn:
(1) The manufacturing procedures for producing woven 3-D FRP panels and 3-D FRP sandwich construction for bridge decks have been established.

(2) Weaving and injection technologies for producing 3-D FRP panels have a growing potential in providing safe, economic and easily maintained bridge decks where delamination-type failures can be precluded.

(3) Using through-thickness fibers is an effective technique to increase both the core shear modulus and the stiffness of the sandwich panel.

(4) Uncracked foam used as a filling material confines the through-thickness fibers and contributes in increasing the core shear modulus significantly.

(4) The structural behavior of an FRP sandwich panel can not be predicted using ordinary composite beam theory.

(5) Shear deformation within the core material should be accounted for in design using either the elementary or the advanced sandwich theory depending on the relative stiffness of the face and core materials as well as on the panel length.

(6) Flexural tests can be used to determine the material characteristics of FRP sandwich panels with a sufficient accuracy provided that the span length is greater than the proposed values.

ACKNOWLEDGMENTS

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