Material Characteristics of 3-D FRP Sandwich Panels

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Abstract

This paper presents an innovative 3-D fiber reinforced polymer, (FRP), panels designed to overcome delamination problems typically encountered in traditional sandwich panels. The sandwich panels consist of GFRP laminates and foam core. The top and bottom consist of GFRP plates connected together with through-thickness fibers to achieve the composite action. The fundamental material characteristics of the panel in tension, compression, flexure and shear are critical for the use and structural design of these panels. This paper summarizes the findings of an extensive experimental program to determine the various parameters believed to affect the material characteristics of these sandwich panels. The influence of the panel thickness, through thickness fiber configuration and density, and other parameters on the tension, compression, flexure and shear behavior of the panels are discussed.

Keywords: fiber reinforced polymers, sandwich panels, 3-D fibers, core shear, flexure, tension, compression

INTRODUCTION

International research efforts continuously looking for new, better and efficient construction materials. The main goal of these research works is to improve the structural efficiency, performance and durability of civil engineering and transportation applications. The introduction of new materials typically brings new challenges to designers to utilize the new properties of these materials. In the past decades various sandwich panels have been utilized in the construction of aerospace, marine, architectural and transportation industry. Light-weight, excellent corrosion characteristics and rapid installation capabilities created tremendous opportunities for these sandwich panels in the industry. Sandwich construction provides an efficient use of the materials and utilization of each component to its ultimate limit. The sandwich structure offers also very high stiffness-to-weight ratio. It enhances the flexural rigidity of a structure without adding a substantial weight therefore it provides significant advantageous in comparison to the use of the material alone for structural system. Sandwich constructions have superior fatigue strength and excellent acoustical and thermal insulation.

Historically, the principle of using two cooperating faces separated by a distance in between was introduced in 1820 by Delau. The first extensive use of sandwich panel was during the World War II. In the “Mosquito” aircraft, sandwich structure was used, mainly because of the shortage of other materials in England during the war. The faces were made of veneer while the core consisted of balsa wood. One of the early uses of sandwich structures in an aerospace application was in 1937 where balsa wood core and cedar plywood face sheets was used in the construction of De Havilland albatross airplane.

During World War II the first theoretical analysis of sandwich theory was published. By the completion of World War II and in the late 1940's, some of the first theoretical works on sandwich constructions were documented.

Sandwich beams with parallel skins and a metallic honeycomb were considered by many researchers. Allen [1] and Plantema [2] had summarized the information available up to the end of the 1960s in two text books. Paydar and Libove [3] presented a small deflection theory to determine the stresses and the deflections of a sandwich plate with a variable height but symmetric about its midheight surface. Ko [4] analyzed the flexural behavior of a rotating sandwich beam. The core and the skins were modeled as either Timoshenko or Euler-Bernoulli beams, and the core was assumed to be incompressible in the vertical direction. Gordaninejad and Bert [5] analyzed a straight sandwich beam with thick skins considered as Timoshenko beams and the core was assumed to be of antiplane type. High-order theory for the analysis of beams and plates was used by researchers, Reddy [6-8] and Krishna [9]. They assume that the height of the beam remains unchanged and that the longitudinal displacement through the depth of the beam is expressed by a high-order polynomial with coefficients that are functions of the longitudinal coordinate and are determined by the boundary and the overall equilibrium conditions of the section. Frostig and Baruch [10] and Frostig et al. [11] studied the behavior of a uniform sandwich beam with identical and non-identical skins and a soft core using a superposition approach that determines the effects of the core flexibility on the stresses, on the deflections, and on the overall beam behavior. An enhanced high-order theory was developed for beams using a superposition method. It was improved with a refined high order theory that uses a rigorous systematic approach which based on variational principles. A general systematic rigorous theory was developed by Frostig [12,13], a variational high-order theory that defines the vertical normal and the shear stresses at the skin-core interfaces as well as in the core.

The present study is aimed to provide the characteristics of a new type glass fiber reinforced polymer (GFRP) sandwich panels. The sandwich panels presented in this study consist of GFRP laminates and foam core sandwich where top and bottom face sheets are connected together with through-thickness fibers as shown in Figure 1. The top and bottom GFRP face sheets are formed by the laminates layed-up in a 0/90 degree fiber orientation. E-glass fibers having density of 2.54 g/cm^3 were used as the reinforcing material in the laminates. The number of the laminates in either face sheets may vary depending on the use of the sandwich panel. The sandwich foam used as a core material is polyurethane modified polyisocyanurate cellular plastic. “Through-thickness” unidirectional glass fibers are inserted through the top and bottom face sheets, and the foam core. The amount of the glass fibers forming the “through- thickness” fibers is 227 m/kg. The sandwich panel is fabricated using pultrusion process. After the glass fiber laminates and the foam core are sandwiched the “through-thickness” fibers are inserted in dry condition. Afterwards, the whole assembly goes into the resin tank and the heated die.

TENSILE BEHAVIOR

The in-plane tensile properties of the face sheets of the various 3-D FRP sandwich panels were evaluated. A total of 33 tension specimens, having different number of plies and different configurations of through-thickness fibers, were tested according to ASTM D3039. The modulus of elasticity, stress-strain behavior and failure modes of the tension specimens were evaluated.

Three repeated specimens for each type of the GFRP face sheet cut from different sandwich panels were tested. Typical tension specimen consists of flat strips with a total width of 38 mm and a total length of 430 mm. The specimen length was selected to minimize possible bending stresses which could be induced by minor grip eccentricities. Aluminum tabs were bonded to each end of the specimen to prevent premature failure at the ends of grips. The specimens were mounted in the grips of a ±980 kN capacity MTS machine and monotonically loaded in tension up to failure. A standard head displacement rate of 0.13 cm/min was used to load the specimen up to failure. The strain in the specimen was monitored using a strain gauge located at the mid-length of the specimen.

A non-linear measured stress-strain relationship was observed for all tested tension specimens. Since the coupon specimens were cut from 3-D panels, the non-linear behavior could be due to one or combination of the presence of the fibers in the other direction, presence of the veil and the end insertions of the through thickness fibers. Typical stress-strain relationship of tension specimens having different through thickness fiber densities is shown in Figure 2. For design purposes, the nonlinear behavior of the stress-strain relationship could be approximated by two linear behaviors with different stiffness. The initial portion can be used to determine the initial elastic modulus using regression analysis for the data up to 0.2 percent strain. Due to the significant nonlinear behavior observed beyond the strain level of 0.2 percent, the second slope, conservatively representing the reduced elastic modulus can be determined approximately based on the data measured between strains of 0.4 percent up to failure strain. These two calculated slopes are extended between 0.2% and 0.4% strain until they intersect each other in order to obtain the whole approximation of the tensile behavior of the face sheets of the panels as shown in Figure 3. Test results indicate that the initial modulus of elasticity of the face sheets was typically about 50 percent higher than the value within the range of 0.4 percent strain to failure.

Test results indicated that that increasing the density of the through-thickness fibers creates zones of imperfection and waviness among the fibers therefore results in reduction of the elastic modulus as well as the tensile strength of the face sheets considerably as shown in Figure 4 and Figure 5 respectively. Failure of all specimens was due to the rupture of GFRP sheets within the gauge length of the specimen.

SHEAR BEHAVIOR

The main objective of the shear testing program was to evaluate the influence of the through-thickness fibers on the shear modulus of the proposed 3-D FRP sandwich panels. A total of 44 specimens with different skin configurations, core thicknesses, through thickness fiber insertion densities and patterns were tested using the configuration provided by ASTM C273 for sandwich panels. It should be noted that due to the relatively large thickness of the sandwich used in this program, the length to the thickness ratio did not satisfy the ASTM C273 requirements. The recommended length-to-thickness ratio could not be practically achieved for these sandwich panels. The low length to depth ratio used for these shear specimens could have an effect of stress distribution in comparison to typical thin sandwich panels. Therefore, the measured shear strengths reported in this paper may be less than the actual shear strengths of these sandwich panels.

The width of the test specimens was equal to the width of the sandwich specimen. The total length was 290 mm for all tested specimens. Sandwich test specimens were bonded to 19 mm thick steel plates on each side using an epoxy. The test fixture was designed to have the line of the load action passes through the diagonally opposite corners of the specimen. The specimens were loaded in compression using a 9000 kN capacity machine and a rate of loading of 0.05 cm/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. A 1100 kN capacity load cell was used to measure applied load. The shear modulus in the plane normal to the facing sheets was evaluated for each specimen using Equation. (1);

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

where, G is the 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. Two different configurations of through-thickness fibers were investigated. The first pattern was a "regular array of through thickness fibers" pattern in which the through-thickness fibers were evenly spaced in each direction. The second pattern was a "continuous wall" pattern in which the through-thickness fibers were arranged in semi-solid rows, like in a closely spaced picket fence, in one direction forming a rigid web. The layout of both patterns is illustrated in Figure 6.

Figure 7 shows the typical stress-strain relationship of the tested shear sandwich specimens, where shear stress is determined based on the applied load and the shear resisting area while shear strain is determined by using the measured relative displacements parallel to the steel plates divided by the thickness of the sandwich specimen. The results indicate a typical linear behavior up to the initiation of the first shear crack in the foam core followed by a non-linear behavior with significantly low shear modulus up to failure. It is observed that the significant reduction in the shear stiffness is mainly due to the cracking of the foam and possible formation of the plastic hinges at both ends of the through thickness fibers. Test results showed that the density and configuration of the 3-D fibers affect the core shear modulus considerably. Increasing the quantity of the 3-D fibers from 1.25 per cm^2 to 2.5 per cm^2 in the regular pattern increased the core shear modulus by 33 percent as shown in Figure 8. Furthermore, presence of a continuous web of 3-D fibers creates a mechanism similar to shear wall mechanism, therefore minimizing the stress concentrations at the connection between the 3-D fibers and the face sheets results in increase of the core shear modulus considerably. Test results showed that increasing the quantity of the 3-D fibers from 2.5 per cm^2 in the regular array pattern to 3.6 per cm^2 in the continuous wall pattern, increased the core shear modulus by 765 percent as shown in Figure 8.

Test results suggest that increasing the thickness of the sandwich panel does not have significant effect on the shear modulus of the sandwich panel. In fact, increasing the thickness from 60 mm to 100 mm decreased the shear strength of the sandwich panel 27 percent. The influence of the filling material on the core shear modulus was investigated by cracking one of the 60 mm thick panels prior to loading using a chisel. The shear stiffness of the specimen with the uncracked foam, based on the initial slope of the curve was about twice the stiffness of the panel that with cracked foam as shown in Figure 9. It was observed that uncracked foam plays an important role by confining the through-thickness fibers and therefore the shear modulus of the core shear increased significantly. All shear tests conducted in this program were terminated at a certain stage due to the large shear deformation and limitation of the stroke of the testing machine. Typical shear cracks formed in the shear test are shown in Figure 10.

FLEXURAL BEHAVIOR

The main objective of the flexural testing program was to evaluate the flexural behavior and to determine the flexural and shear stiffness of the 3-D proposed FRP sandwich panels. A total of 112 specimens having different through thickness fiber insertion densities, patterns, and different thickness were tested according to ASTM C393. For each type of the 3-D FRP sandwich panels, several specimens were tested using variable span length. The elastic modulus and the shear modulus were determined by simultaneous solution of the complete deflection equations for each span. The test specimens were supported by two steel blocks mounted on two steel angles. The supporting blocks and the steel frame rested on two load cells. The specimens were loaded by a 9000 kN testing machine with a rate of loading of 1.3 cm/min. A rubber pad was placed under the loading point to avoid possible local crushing of the panel. Two 220 kN capacity load cell was used to measure applied load.

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 the failure as shown in Figure 11. 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:

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

$$D = \frac{E\left(d^3 - c^3\right)b}{12} \tag{3}$$

$$U = \frac{G\left(d + c\right)^2 b}{4c} \tag{4}$$

where, Δ is the total deflection; 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.

The elastic modulus and the shear modulus of the sandwich panel can be determined by solving the deflection equation for different span. Equation (2) can be rewritten in two forms:

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

$$\frac{\Delta}{PL^3} = \frac{1}{48D} + \frac{1}{4U}\frac{1}{L^2} \tag{6}$$

Equation (5) is represented by a straight line relationship using the vertical and the horizontal axis as $\frac{\Delta}{PL}$ versus L^2 respectively. In this case, the slope of the line represent $\frac{1}{48D}$ and the intercept with the vertical axis represent the value of $\frac{1}{4U}$ as shown in Figure 12 for various FRP sandwich panels. Similarly, Equation (6) is represented also by a straight line relationship using $\frac{\Delta}{PL^3}$ and $\frac{1}{L^2}$ for the vertical and horizontal axes respectively. The slope in this case represents $\frac{1}{4U}$ and the intercept with the vertical axis represents $\frac{1}{48D}$ as shown in Figure 13. The flexibility, $\frac{\Delta}{P}$, for each sandwich panel was determined from the flexural tests and the results were used to determine the elastic modulus and the shear modulus of the sandwich panels. The details of the method can be found elsewhere [1]. The analysis indicated that there is a certain length for each type of the GFRP sandwich construction for which the material properties, face elastic modulus and core shear modulus, can be determined with a sufficient accuracy using the above flexural testing approach. The predicted face elastic modulus and the core shear modulus were within 15 percent of the measured values using tension and shear tests. Test results showed that the predicted flexural and shear properties of 3-D sandwich panels compared very well with the measured values from tension and shear tests.

COMPRESSION BEHAVIOR

The flatwise compressive properties of the sandwich panels were determined according to the ASTM C365. Specimens with dimensions 90 mm by 90 mm were cut from the sandwich panels. The specimens were tested using an MTS machine with a total capacity of 980 kN and monotonically loaded in compression up to failure. The applied load and the displacement of the crosshead of the MTS machine were monitored during testing. A standard head displacement rate of 0.13 cm/min was applied up to failure. The flatwise compressive modulus was determined for each specimen using Equation. (7);

$$E = \frac{(S)(t)}{(A)} \tag{7}$$

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.

Figure 14 shows the typical stress-strain relationship of the tested compression sandwich specimens. Test results showed that, increasing the quantity of 3-D fibers increased the compressive shear modulus and compressive strength significantly. The increase in the compressive strength is linearly proportional to the increase in density of the through thickness fibers as shown in Figure 15. The arrangement of the through thickness fibers did not have a significant effect on the compressive modulus and compressive strength of the 3-D sandwich panels tested in this study. Also test results showed that decreasing the thickness of the panel, increases the buckling load of the through thickness fibers, resulting in the increase of the compressive strength of the panel significantly. Decreasing the thickness from 100 mm to 60 mm for the panels with through thickness fiber density of 1.25, and 2.5, increases the compressive strength 110 percent. 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 16.

FINITE ELEMENT MODELING OF SHEAR BEHAVIOR

Finite element study was conducted using ANSYS, finite element modeling/analysis (FEM/FEA) software. The shear behavior of the 3-D GFRP sandwich panel was determined based on the shear test configuration used to measure the shear behavior of the sandwich panel. The objective of this analysis is to determine the initial shear modulus of 3-D GFRP sandwich panel with specified dimensions, facing material thickness, through thickness fiber density and specified transverse fibers configuration.

The finite element model used for the shear test configuration of a 60 mm thick 3-D GFRP sandwich specimen is shown in Figure 17. The foam core material is sandwiched between the two face sheets on either side and the through thickness fiber elements are running through the outer face of the facing sheets. The two steel plates used in the test to transmit the load were also considered in the model. Figure 17 represents the loading and the constraints implemented into the finite element model. To simulate the loading conditions used in the test, all the nodes at the top corner of the bottom steel plate were constrained while a displacement was applied along the bottom corner of the top steel plate where the line of load passes through the opposite corners of the steel plates. A 3-D structural solid element, SOLID45, was used to model the face sheets, foam core and steel plates bonded to the panel shear specimens and used to transfer the load. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The through thickness fibers were modeled using an elastic straight pipe element, PIPE16. It is a uniaxial element with tension-compression, torsion, and bending capabilities. The element has six degrees of freedom at two nodes: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes. This element is based on the 3-D beam element and includes simplifications due to its symmetry and standard pipe geometry.

The GFRP facing sheets were assumed to be isotropic since the material properties through the thickness and in the transverse direction do not have significant effect on the shear test modeling. The material properties for the facing sheets were obtained from the tension test results for each type of sandwich panel. An elastic modulus, E, of 14 MPa was used for the foam as obtained from the compression test and a Poisson's ratio, ν, of 0.3 based on the published value was used. The elastic modulus of the 3-D fibers was calculated based on the "rule of mixtures". The amount of the glass fibers forming the 3-D fibers in the sandwich core is 227 m/kg. The elastic modulus of the glass fiber and the resin used in the 3-D fibers were 74 GPa and 3.4 GPa respectively. The diameter of the through thickness fibers is 3 mm. The elastic modulus of the 3-D fibers was determined to be 23 GPa using the “rule of mixtures”. The elastic modulus and the Poisson’s ratio of the steel plates of the test fixture were 206 GPa and 0.25 respectively.

The predicted behavior was linear based on the elastic analysis used since the goal was to determine only the initial shear stiffness of the 3-D GFRP sandwich panel. The relationship of the relative displacement between the steel plates and the applied load based on the finite element modeling and the measured values for a 60 mm thick specimen is shown in Figure 18. The comparison indicates that the finite element model is capable to predict the linear behavior, prior to cracking of the foam, at which the through thickness fibers become laterally unsupported and significantly affect their connection to the GFRP facing sheets.

The predicted initial shear modulus of the 60 mm thick specimen based on the FEM analysis and the measured values were found to be 10.6 MPa and 9.8 MPa respectively. Table 1 summarizes the initial shear modulus prediction of three different types of sandwich panels. However, it should be noted that the proposed finite element modeling was able to predict the initial shear modulus of the sandwich panels with a “regular array” of through thickness fibers. This study did not include modeling of sandwich panels with “continuous wall” type of core. When through thickness fibers are inserted closely, the space in between is typically filled with resin and consequently provides additional significant shear strength to the panel. The resin between the through thickness fibers could be modeled as shell elements; however, the effective thickness and the material properties of this element should be determined and calibrated based on the test results. This study is currently under consideration and therefore is not included in this paper.

FINITE ELEMENT MODELING OF FLEXURAL BEHAVIOR

The flexural test of 3-D sandwich panels was modeled using ANSYS. The objective of this study is to predict the behavior of the 3-D sandwich panels with known core shear modulus and the elastic modulus of the FRP facing sheets. The typical finite element model used for the sandwich panel for flexural test is shown in Figure 19. The facing sheets were modeled using 3-D structural solid elements, SOLID45. The material property of the facing sheets is bi-linear and was determined based on the tension test results of each type of facing sheet of the sandwich panels. The core of the sandwich panel was modeled by 3-D structural solid elements, SOLID45, having a smeared material property for the foam and the through thickness fibers. The core elements of sandwich panel, which represent combination of foam and through thickness fibers, have orthotropic material properties. The elastic modulus, E_y, in the direction of through thickness fibers was determined based on compression tests of the sandwich panel. The elastic modulus of the core in the other two directions, E_x and E_z, were determined based on the elastic modulus of the foam only, therefore, neglected the contribution of the through thickness fibers. The shear modulus of the core, G_{yz} and G_{xy}, were approximated as bi-linearly behavior based on the results of shear test of the sandwich panels. The shear modulus G_{xz}, which has negligible effect in this problem, was obtained based on the foam material only since the through thickness fibers are not expected to provide any contribution to shear stiffness in that direction. All the nodes on the bottom face sheet, at 50 mm from each end, were constrained in the *y* and *x* direction. The movement in the *z* direction was allowed at the supports. However, in order to maintain the stability of the finite element model, the nodes on the bottom face sheet at the symmetry plane were constrained in the *z* direction. A displacement was applied at the mid-span of the specimen through a master node where the master node was constrained with the nodes on the top face sheet at the center.

Prediction of the flexural behavior requires prediction of the shear and elastic modulus of the core and the facing sheets respectively. Figure 20 shows the approximated bi-linear shear behavior of 38 mm thick shear specimen tested in the direction perpendicular to pultrusion direction. Initial shear modulus of the specimen, up to shear strain of 0.016 is 60 MPa followed by a shear modulus of 3.9 MPa up to failure. Tensile behavior of the GFRP face sheets of the sandwich specimen based on the general behavior of the facing sheets of sandwich panels, shown in Figure 21, was used as approximation of the tension stiffness of the flexural specimen. The initial elastic modulus of the face sheet up to a strain of 0.003 is 20.6 GPa followed by the elastic modulus 13.8 GPa up to the failure. Figure 22 shows the FEA results and the hand calculation results, based on the sandwich theory [1], of the flexural test of the 38 mm thick specimen for spans of 1040 mm, 1290 mm and 1550 mm, tested in the direction perpendicular to pultrusion direction. The predicted behavior based on the FEA for spans 1550 mm and 1290 mm appears to match very well with the test data. Since the shear deformation is significant for the specimen with of 1040 mm, the approximation used for the shear stiffness appears to reduce the predicted deflection. Hand calculation prediction for the linear part was almost identical to the prediction using finite element modeling. The maximum difference between the predicted and the measured mid-span deflection was within the 15 percentage.

CONCLUSION

Based on the experimental work presented in this paper, the following conclusions can be drawn for the characteristics of the new proposed 3-D FRP sandwich panels.

1) The behavior of the face sheets under tension is bi-linear which could be caused by the presence of the fibers in the perpendicular direction. The behavior is independent of the presence and the amount of through thickness fibers embedded in the face sheet. The reduction in the stiffness is approximately 33 percent for all face sheets tested in this study.

2) It is observed from the test results that increasing the density of through thickness fibers creates waviness among the fibers and reduces the strength of the face sheets significantly. There is a 25 percent decrease in tensile strength of the face sheet by increasing the amount of through thickness fiber insertions from 1.25 to 2.5 per cm^2.

3) A bi-linear behavior is observed in the shear behavior of the 3-D sandwich panels. There is a significant reduction in the shear stiffness which is mainly due to the cracking of the foam and the formation of plastic hinges at both ends of the through thickness fibers.

4) The presence of a semi-solid continuous web formed by the through thickness fibers affect the core shear modulus significantly.

5) The thickness does not have any significant effect on the initial core shear modulus. However, increasing the thickness reduces the shear strength considerably.
6) Increasing the amount of through thickness fibers increases the compression strength of the 3-D sandwich panels. The configuration of the through thickness fibers does not have any effect on the compression strength.
7) Decreasing the thickness of the panel increases the buckling load of the through thickness fiber, resulting in the increase of the compression strength of the sandwich panel.
8) It was observed that uncracked foam plays an important role by confining the through thickness fibers and the initial core shear modulus increases significantly.
9) The initial core shear modulus of 3-D GFRP sandwich panel with "regular array" can be accurately predicted using finite element modeling.
10) Based on the concepts presented in this paper, the flexural behavior of 3-D GFRP sandwich panels can be accurately predicted by either the finite element modeling and/or by the sandwich theory (Allen, 1969).

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LIST OF FIGURES

Figure 20. Approximation of shear behavior for 3.8 cm thick panel

Figure 21. Approximation of tensile behavior for 3.8 cm thick panel

Figure 22. FEA& Hand calculation results of 3.8 cm thick panel

Table 1. Prediction of Shear Modulus

Panel thickness (mm)	Fiber insertion (per cm^2)	Test Data(MPa)	FEA Prediction (MPa)
38	2.00	20.5	19.3
60	1.25	9.8	10.6
60	2.50	14.8	15.6

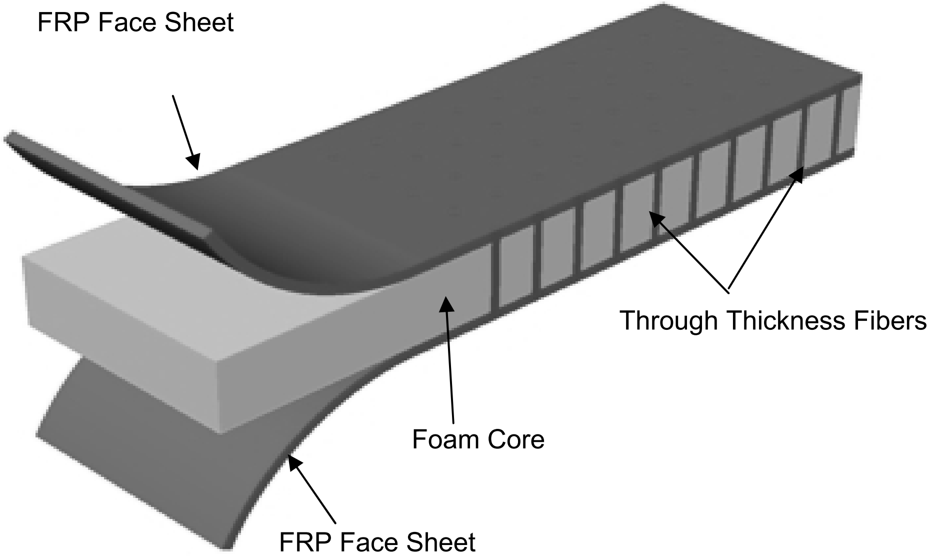


Figure 1. Schematic illustration of innovative 3-D FRP Sandwich Panel

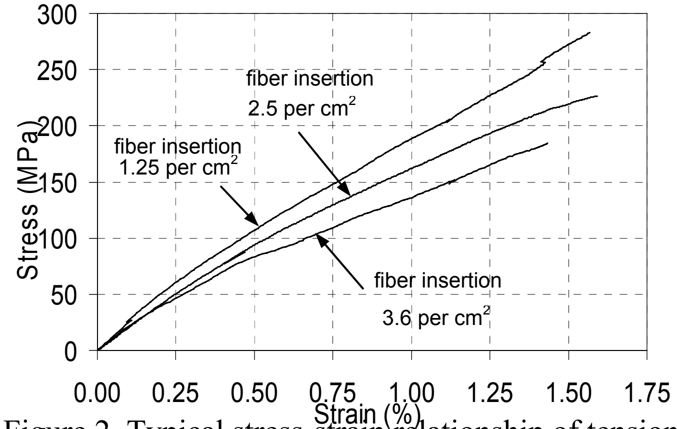


Figure 2. Typical stress-strain relationship of tension specimens

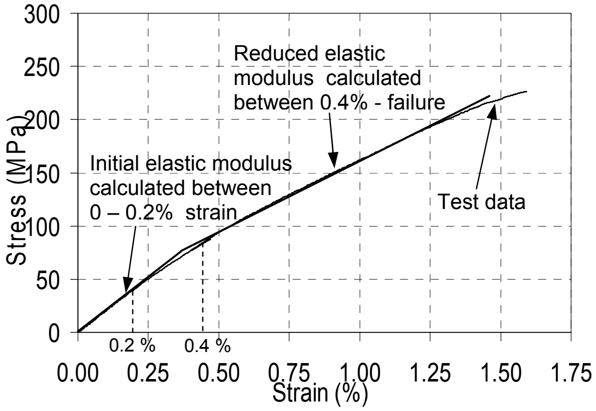


Figure 3. Approximation of tensile behavior of face sheets

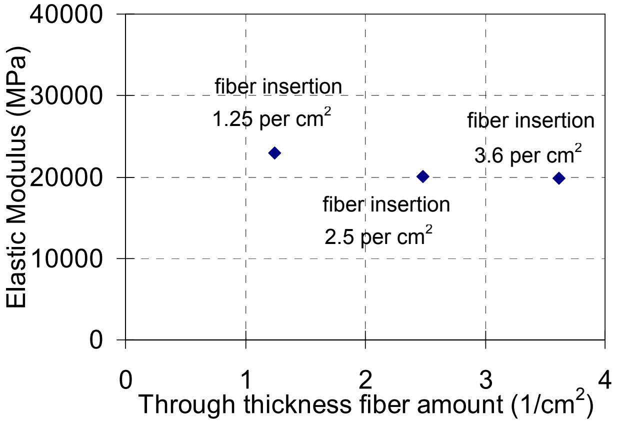


Figure 4. Effect of through thickness fibers on the facing elastic modulus

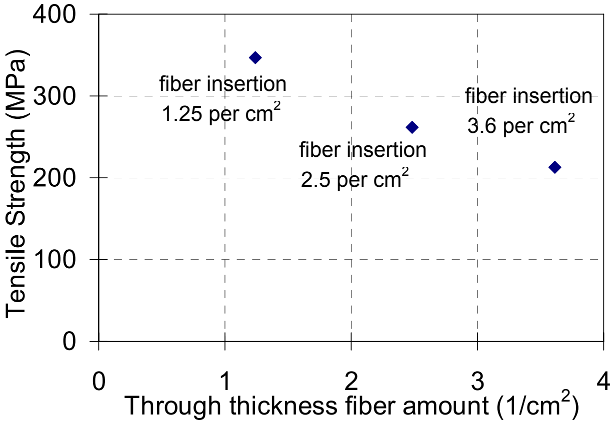
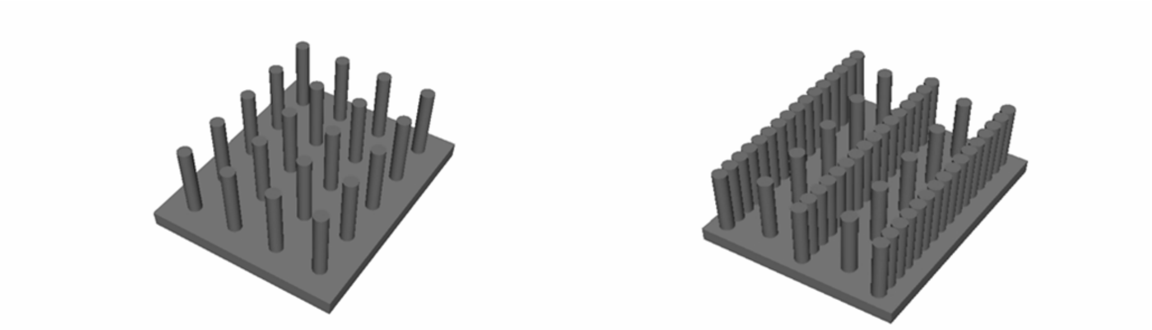


Figure 5. Effect of through thickness fibers on the facing strength



Regular array of through thickness fibers

Continuous wall

Figure 6. Different arrangements of through thickness fibers

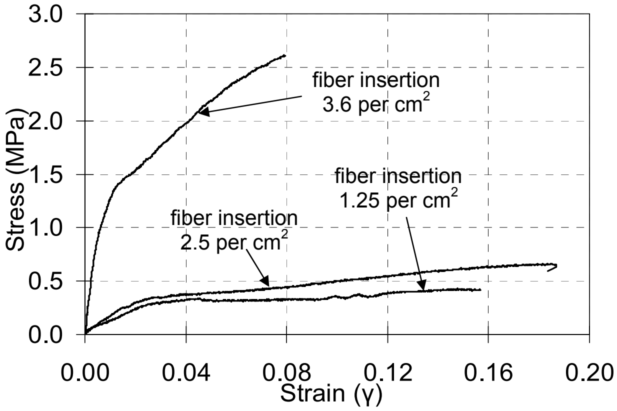


Figure 7. Typical stress-strain relationship for shear specimens

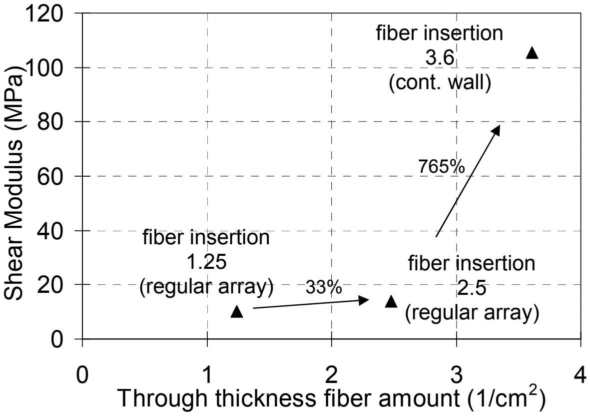


Figure 8. Effect of through thickness fibers on the shear modulus

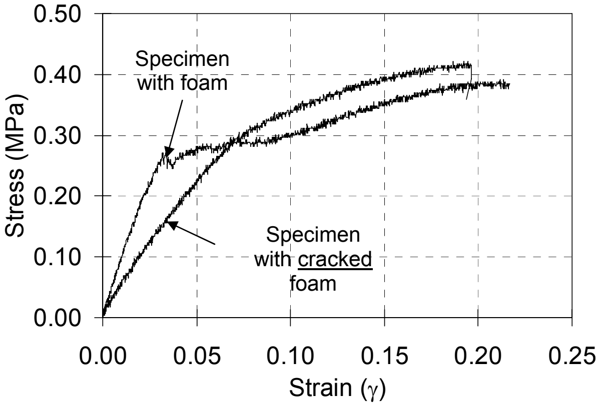


Figure 9. Influence of the foam on the shear modulus

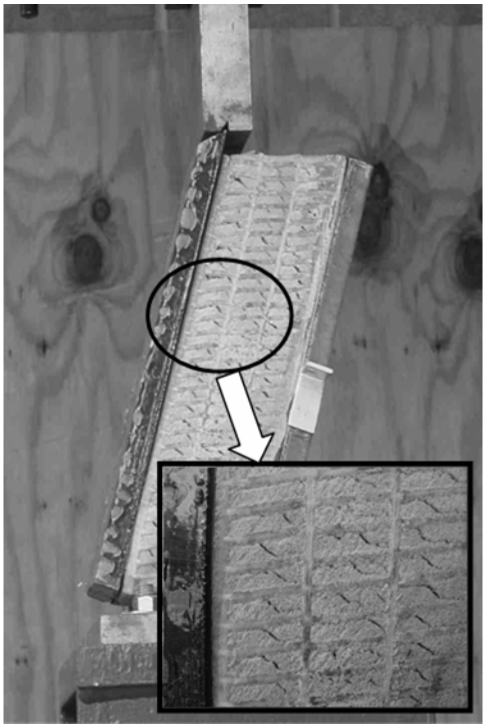


Figure 10. Shear cracks in shear test

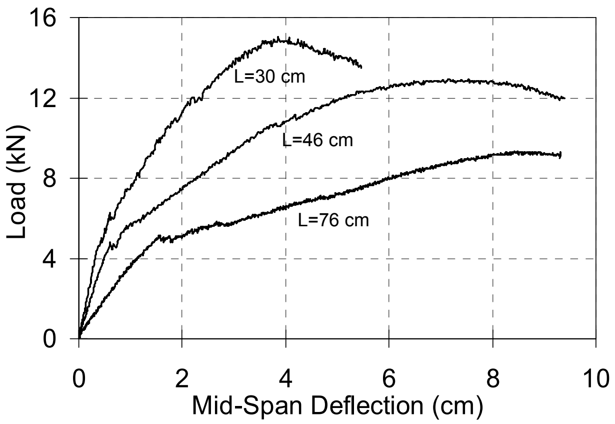


Figure 11. Typical flexural behavior of 3-D FRP sandwich panels

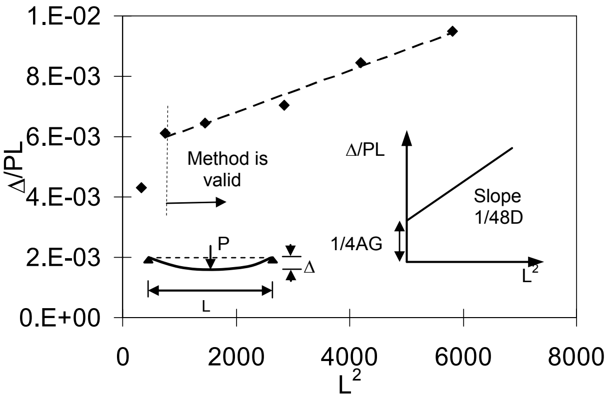


Figure 12. Evaluation of material characteristics using flexural test

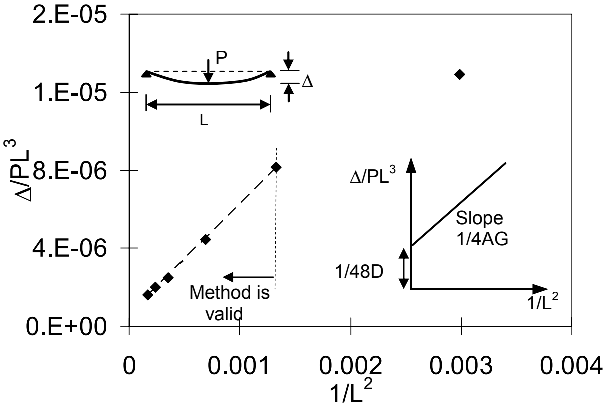


Figure 13. Evaluation of material characteristics using flexural test

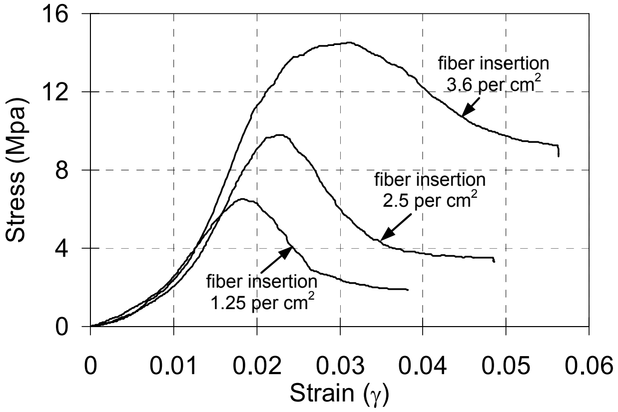


Figure 14. Typical compression behavior of 3-D FRP sandwich panels

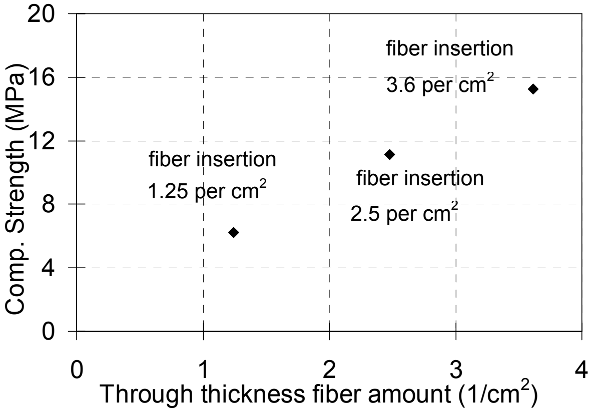


Figure 15. Effect of through thickness fibers on the compression strength

Figure 16. Buckling of through thickness fibers at failure

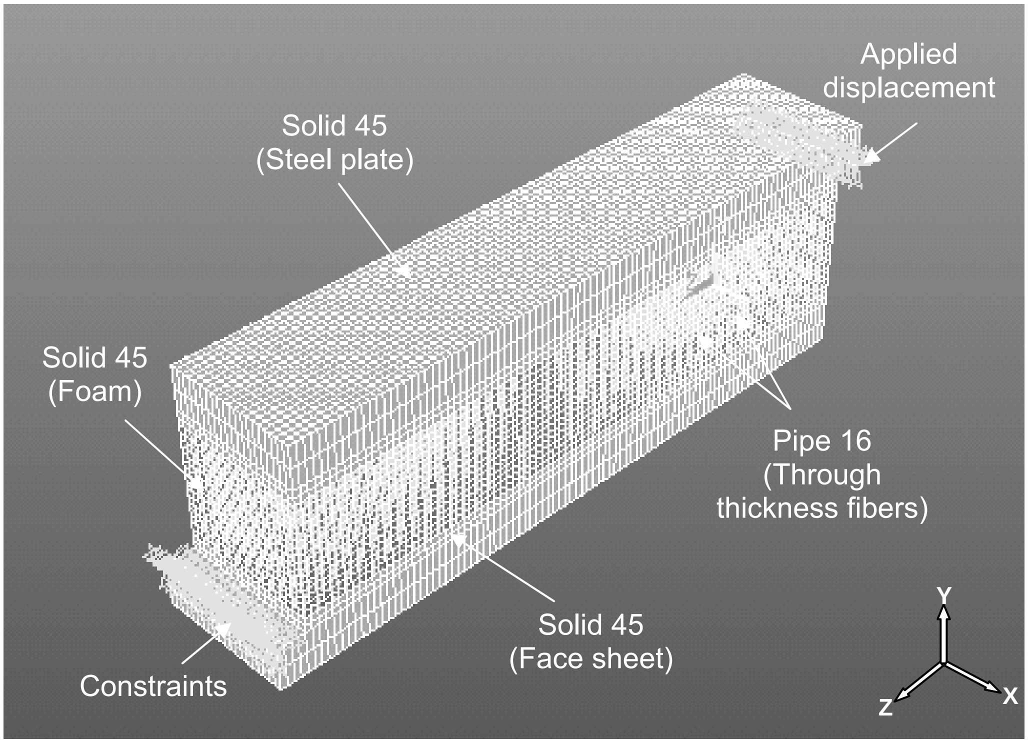


Figure 17. Sandwich panel shear test model with constraints

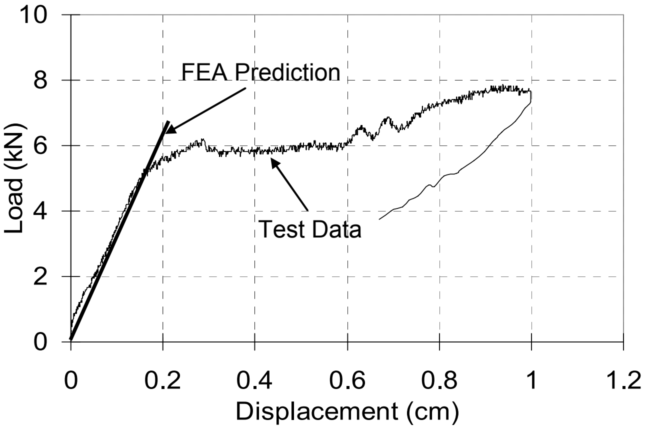


Figure 18. FEA prediction of shear behavior of 6 cm thick specimen

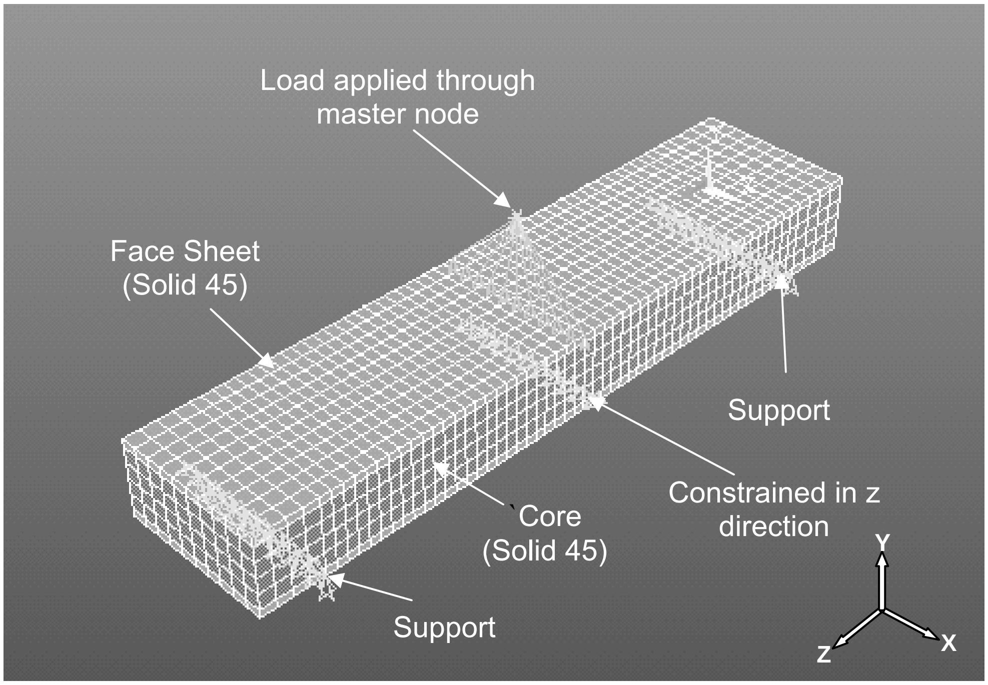


Figure 19. Sandwich panel flexural test model with constraints

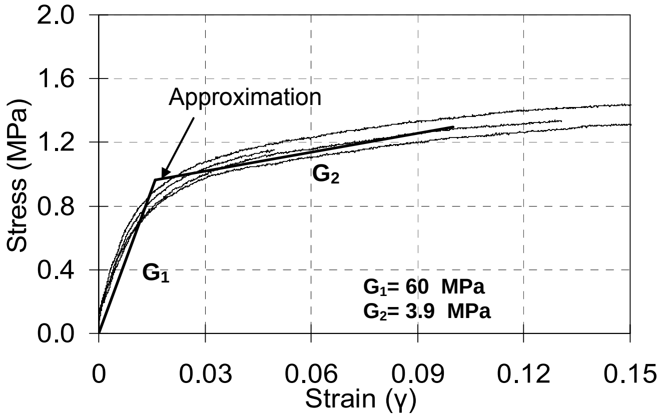


Figure 20. Approximation of shear behavior for 3.8 cm thick panel

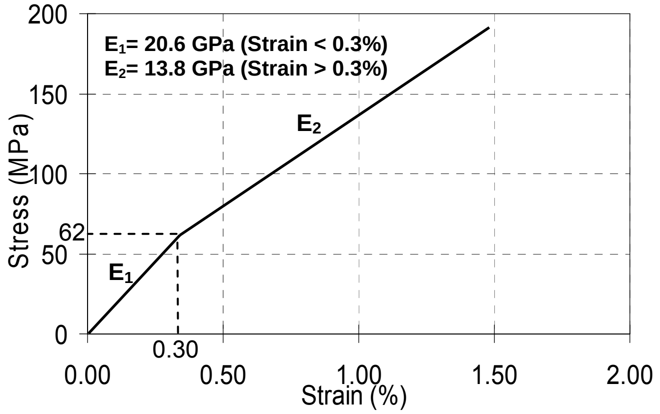


Figure 21. Approximation of tensile behavior for 3.8 cm thick panel

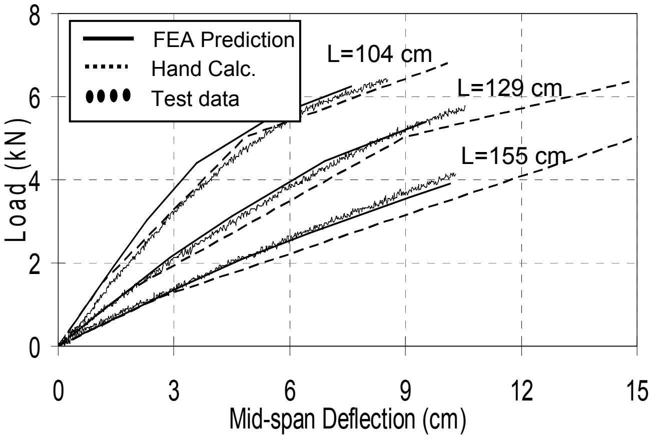


Figure 22. FEA& Hand calculation results of 3.8 cm thick panel