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Material Properties of 3-D GFRP Sandwich Panels for Civil Infrastuctures

by

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Abstract

This paper presents new 3-D fiber reinforced polymer (FRP) sandwich panels designed to overcome delamination problems typically encountered in traditional panels. The sandwich panels consist of GFRP laminate plates at the top and bottom, separated by a foam core, and rigidly connected by through-thickness fibers to achieve composite action. The use of the through-thickness fibers increases the out-of-plane properties of the panels, delays delamination-type failures, allows low cost manufacturing, and ensures full utilization of the material strength. The fundamental material characteristics of the panels in tension, compression, flexure and shear are critical for structural design and commercial application. This paper summarizes the findings of an experimental program undertaken to determine the effect of the material configuration on the material characteristics and behavior of these sandwich panels. The influences of panel thickness, through thickness fiber configuration and density, testing direction, and other parameters on the tensile, compression, flexure and shear behavior of the panels are discussed.

Introduction

International research efforts are continuously looking for new, improved, and more efficient construction materials. The main goal of these research endeavors is to improve the structural efficiency, performance and durability of the civil engineering and transportation infrastructure. New materials typically introduce new challenges to designers wishing to utilize them. In past decades, various sandwich panels have been incorporated into aerospace, marine, construction, and transportation industries. Light-weight, excellent corrosion resistance, and rapid installation capabilities have created tremendous opportunities for these sandwich panels in industrial type applications.

Typical sandwich composite construction consists of two thin, stiff, and strong faces which are separated by a thick, light, and weaker core. The face sheets and core materials are bonded together with an adhesive compound to facilitate the load transfer mechanism between the components and thus effectively utilizing all of the materials. The two faces are placed at a distance from each other to increase the moment of inertia, and consequently the flexural rigidity, with respect to the neutral axis of the structure.

In a typical sandwich panel, the faces carry the tensile and compressive stresses. The local flexural rigidity of each face is typically small and can be ignored. The core has several important functions. It should be stiff enough to preserve the distance between the two faces and also rigid enough to resist the shear forces and thus prevent sliding the faces relative to each other. Rigidity of the core structurally integrates the two faces to act together in composite action. If these conditions are not fulfilled, the faces behave as two independent beams or panels, and the sandwich effect is essentially lost. Furthermore, rigidity of the core should be sufficient to keep the faces nearly flat, therefore preventing the possibility of buckling of the faces under the influence of compressive in-plane stresses. The adhesive component between the faces and the core must be capable of transferring the shear forces between the face and the core.

Proposed 3-D FRP Sandwich Panels

Traditional sandwich structures consist of metallic skin sheets and a polyurethane foam core which also serves as an insulating layer. These conventional structures have been used widely for structural applications. However, the durability of these 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 (Zenkert, 1997). This study introduces innovative use of glass fiber reinforced polymer (GFRP) sandwich panels as an alternative and solution to many of these problems. The goal of the study is to examine the structural performance and material characteristics of innovative 3-D FRP sandwich panels. Through-thickness (3-D) fibers overcome the shortcomings of conventional sandwich structures by minimizing delamination and degradation of stiffness over time (Kim et al. 1999). Furthermore, the use of FRP offers a variety of advantages when compared to conventional materials including high strength- and stiffness- to-weight ratios, ease of handling, excellent corrosion resistance characteristics, and rapid on site installation.

The 3-D FRP sandwich panels presented in this study consist of GFRP laminate skins and foam core, where top and bottom GFRP layers are connected by through-thickness fibers as shown in Fig.1. The lightweight foam core increases the flexural stiffness and strength by placing the stiffer GFRP face sheets further away from the neutral axis. The through-thickness fibers increase the shear stiffness of the panel and prevent delamination between of the composite laminate plies. The panels are fabricated using a pultrusion process, during which the through thickness fibers are inserted. The width of the panels can vary from 6 in. to 8 ½ ft. The fiber insertion density can vary from 0 to 64 fibers per square inch. Currently, the panels can be fabricated with an overall thickness of up to 4 in. The use of GFRP face sheets produces a lightweight, corrosion-resistant panel which is relatively low in cost when compared to more exotic aerospace composite components. 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 resistance characteristics, and rapid on site installation. The cost of these panels is particularly favorable when compared to more conventional construction materials, especially when the reduced costs of installation and public inconvenience are considered.

Tensile Behavior

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

Three specimens for each type of face sheet and sandwich panel were tested. Typical tension specimens consisted of flat strips with a total width of 1.5 in and an overall length of 17 inches. 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 inside or at the end of the grips shown in Fig.2. The specimens were tested using a ±220 kip capacity MTS machine and monotonically loaded in tension up to failure as shown in Fig.3. The strain in the specimen was monitored using a uniaxial strain gauge bonded at the mid-length of the specimen.

The typical stress-strain relationship of the tension specimens is shown in Fig.4. The nonlinear behavior of the stress-strain curve is well approximated by a bi-linear relationship. The first 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, representing the reduced elastic modulus can be determined using regression analysis for the data between strains of 0.4 percent up to failure strain. Test results indicate that the initial modulus of elasticity of the face sheets was typically about 50 percent higher than that calculated over the range of 0.4 percent strain to failure.

Test results also indicated that increasing the density of the through-thickness fibers creates zones of discontinuity and imperfection throughout the fibers and therefore results in a reduction of the elastic modulus as well as the tensile strength of the face sheets considerably as shown in Fig.5 and Fig.6 respectively. Failure of all specimens was due to the rupture of the GFRP sheets within the gauge length as shown in Fig.7.

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 3-D FRP sandwich panels. A total of 44 specimens with different skin configurations, core thicknesses, 3D fiber insertion densities and patterns were tested using the experimental method provided by ASTM C273 for sandwich panels. It should be noted that due to the relatively large thickness of the sandwich panels 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 in these shear specimens could have an effect on stress distribution in comparison to typical thinner sandwich panels. Therefore, the measured shear strengths may be less than the actual shear strengths of these sandwich panels.

The typical test setup used for the shear tests is shown in Fig.8. The width of the test specimens was equal to the actual width of the sandwich panel specimen. The total length was 11.5 inches for all tested specimens. Sandwich shear test specimens were bonded to ¾ in. thick steel plates on each side using a two part, high-mod epoxy. The test fixture was designed to have the line of load action passing through diagonally opposite corners of the specimen. The specimens were loaded in compression using a 2000 kip capacity machine at a loading rate of 0.02 in/min. The relative displacement between the two steel plates was measured, at the center of the steel plates on both sides, using linear potentiometers. The shear modulus in the plane normal to the facing sheets was evaluated for each specimen using Eq.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” pattern in which the 3D 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, similar to a closely spaced picket fence, in one direction forming a rigid web. The layout of both patterns is illustrated in Fig.9.

Fig.10 illustrates the typical stress-strain relationship of the tested shear sandwich specimens, where shear stress is calculated by dividing the applied load by the shear resisting area and shear strain is calculated by dividing the relative displacements of the steel plates by the core 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 8 per in^2 to 16 per in^2 in the regular array pattern increased the core shear modulus by 33 percent as shown in Fig.11. Furthermore, the presence of a "continuous web" of 3-D fibers creates a mechanism similar to a shear wall mechanism, thus minimizing the stress concentrations at the connection between the 3-D fibers and the face sheets, resulting in an increase of the core shear modulus considerably. Test results showed that increasing the quantity of the 3-D fibers from 16 per in^2 in the regular array pattern to 23.3 per in^2 in the continuous wall pattern, increased the core shear modulus by 800 percent as shown in Fig.11.

Some of the 4.0 in thick sandwich panels were produced with several intermediate GFRP sheets resulting in reduction of the overall height of the through thickness fibers. Three different core configurations were investigated: single layer, double layer, and triple layer as shown in Fig.12. Test results suggest that increasing the number of layers reduces the amount of shear deformation in the core and provides additional confinement to the 3-D fibers. Test results showed that the core shear modulus increased by 22 to 23 percent when the triple core configuration was used instead of the double core configuration as shown in Fig.13.

Test results also suggest that increasing the thickness of the sandwich panel does not have a significant effect on the shear modulus of the sandwich panel. Increasing the thickness from 2.5 in. to 4.0 in. only decreased the shear strength of the sandwich panel by 30 percent. The reduction of the strength can be attributed to the increase of the buckling length of the through thickness fibers.

Flexural Behavior

A total of 112 specimens having different through thickness fiber densities, patterns, and varying thicknesses were tested according to ASTM C393. For each type of the 3-D FRP sandwich panel, several specimens were tested using variable span lengths. The elastic modulus and the shear modulus were determined by the simultaneous solution of the complete deflection equation for each span. The load was applied using a 2000 kips capacity testing machine with a loading rate of 0.5 in/min. A unique steel testing fixture which consisted of two adjustable supports connected to a steel frame allowed for testing various spans as shown in Fig.14. A neoprene pad was placed under the loading point to avoid local crushing of the panel.

Fig.15 shows the typical load versus mid-span deflection curve for 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 the failure. The predicted deflection at mid-span using the elementary sandwich theory (EST) in which the total deflections are calculated using composite beam theory which accounts 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 spans. The details of the method can be found elsewhere (Allen, 1969). The analysis indicated that there is a certain length for each FRP sandwich construction for which the material properties, face elastic modulus and core shear modulus, can be determined with a sufficient accuracy using the flexural testing approach. The calculated face elastic modulus and the core shear modulus were within 15 percent of the measured values using tension and shear material tests. Test results showed that the calculated 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. A total of 35 square specimens with dimensions of 3.5 in x 3.5 in were cut from the sandwich panels. The specimens were tested using an MTS machine having a total capacity of ± 220 kips and monotonically loaded in compression up to failure as shown in Fig.16.

The applied load and the displacement of the cross-head of the MTS machine were monitored during testing. A standard head displacement rate of 0.05 in/min was applied up to failure. The flatwise compressive modulus was calculated for each specimen using Eq. 5:

$$E = \frac{(S)(t)}{(A)} \quad (5)$$

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.

The typical stress-strain relationship of the tested compression sandwich specimens is shown in Fig.17. 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 modulus and compressive strength is linearly proportional to the increase in density of the 3-D fibers as shown in Fig.18 and Fig.19 respectively. The arrangement of the 3-D 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 and in turn results in a significant increase of the compressive strength of the panel. Fig.20 shows that, decreasing the thickness from 4.0 in to 2.5 in for the panels with 8 fipsi and 16 fipsi, increased the compressive strength 110 percent. Furthermore, test results suggest that, providing additional intermediate GFRP layers provides lateral support to the through thickness fibers which decreases the buckling load of the through thickness fibers resulting in the increase of the compressive strength of the sandwich panel. Test results showed that the compressive strength of the 4.0 in thick panel increased by 100 percent when the triple core configuration was used instead of the double core configuration. 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 Fig.21.

Conclusions

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 8 to 16 per in^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) Presence of mid layers in the core of the sandwich panel reduces the shear deformation of the core and provides additional confinement to the through thickness fibers. The initial core shear modulus increased 22 percent when triple core configuration used instead of double core configuration.

7) 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.

8) 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.

9) Providing additional intermediate GFRP layers provides lateral support to through thickness fibers which results in the increase in the compression strength of the sandwich panels.

Acknowledgements

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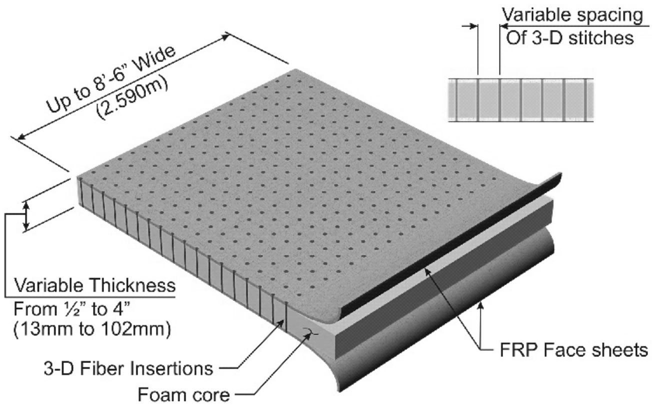


Figure – 1 Schematic of 3-D FRP Sandwich Panel

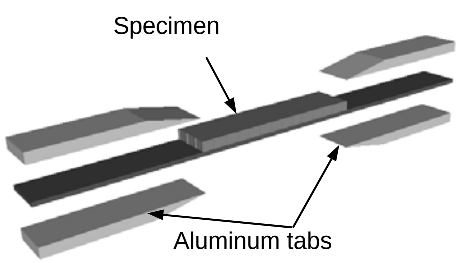


Figure – 2 Typical tension specimen

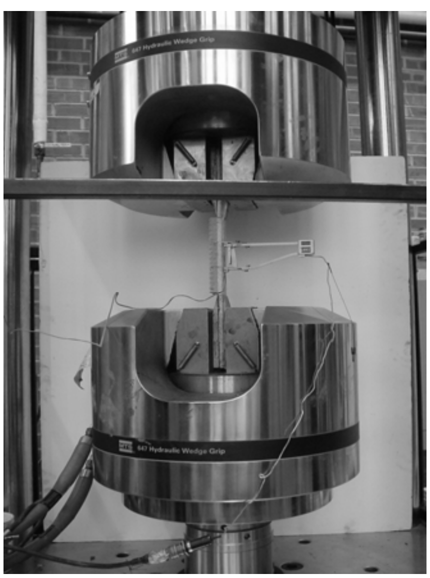


Figure – 3 Test set-up for tension test

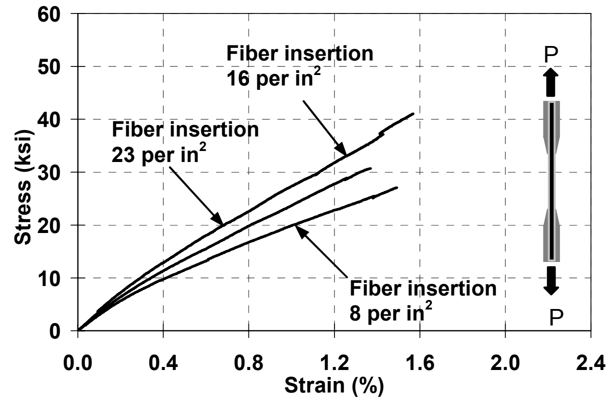


Figure – 4 Typical stress-strain behavior

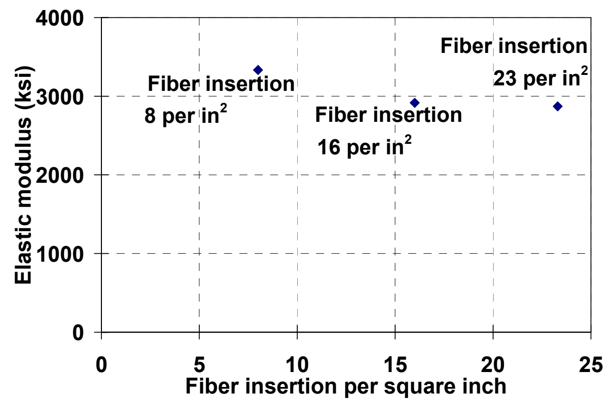


Figure – 5 Effect of fipsi on the the facing elastic modulus of skins of 2.5 in. thick panels

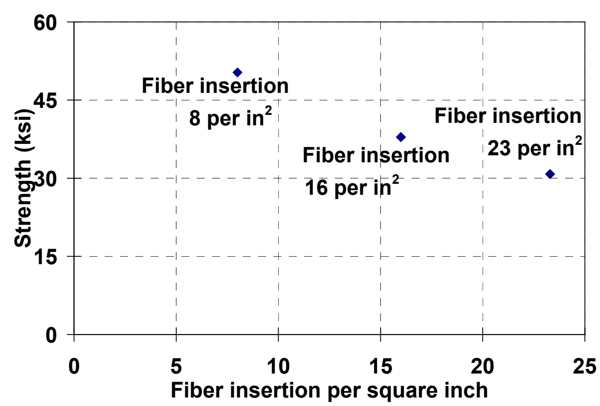


Figure – 6 Effect of fipsi on the tensile strength of skins of 2.5 in. thick panels

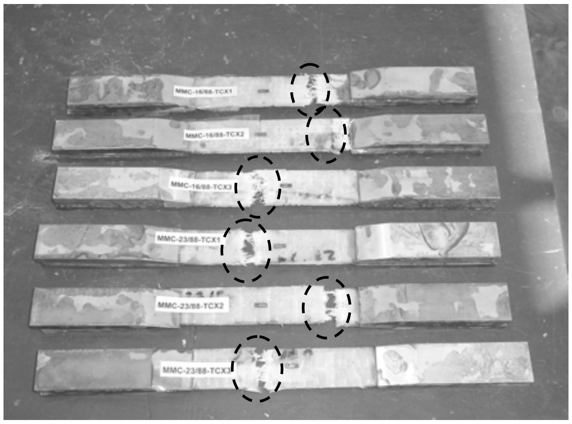


Figure – 7 Failure modes for the tension specimens

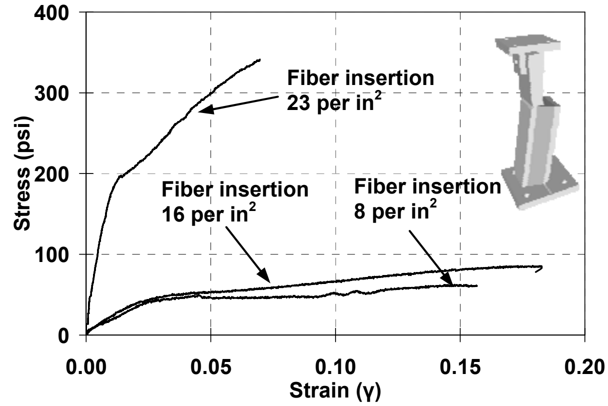


Figure – 10 Typical stress-strain relationship of shear specimens

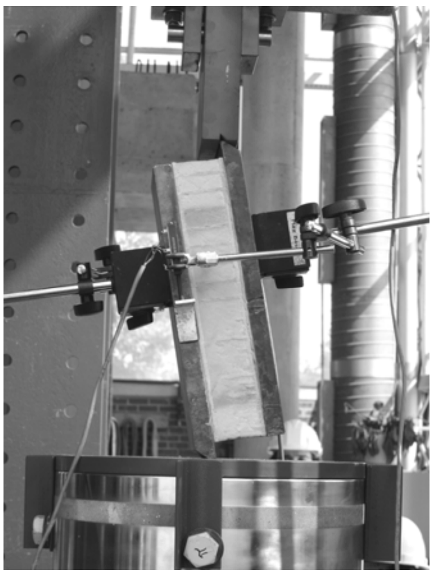


Figure – 8 Test set-up for shear test

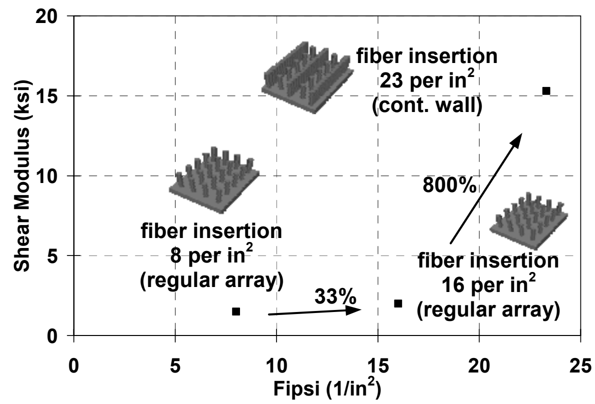
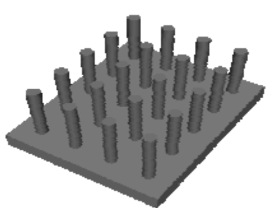
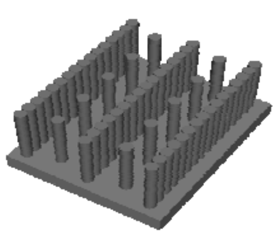


Figure – 11 Effect of through thickness fibers on the shear modulus

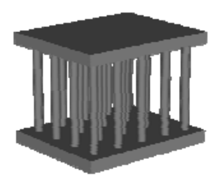


"Regular Array"

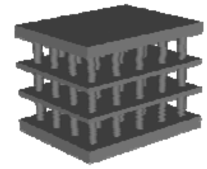


"Continuous Wall"

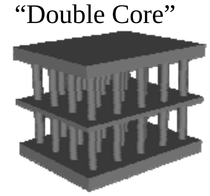
Figure – 9 Different arrangements of through thickness fibers



"Single Core"



"Double Core"



"Triple Core"

Figure – 12 Core configurations of 3-D FRP sandwich panel

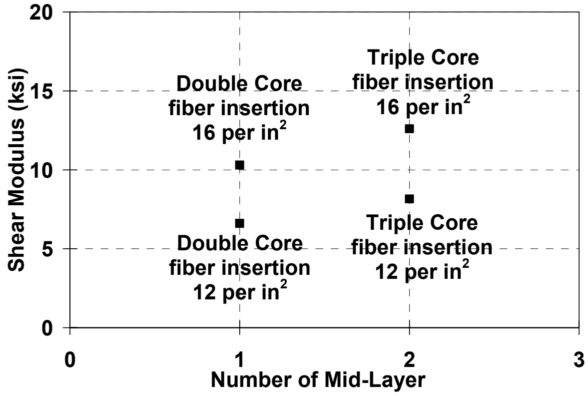


Figure – 13 Effect of mid-layers on the shear modulus

Figure – 14 Test set-up for flexural test

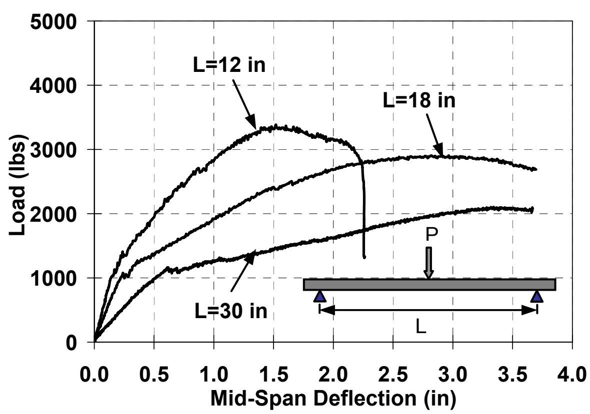


Figure – 15 Typical load-midspan deflection relationship of flexural specimens

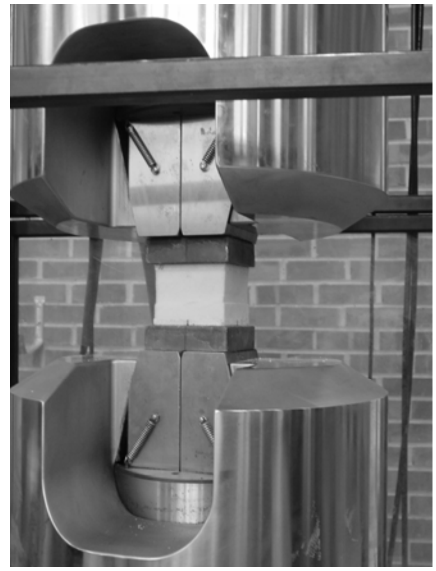


Figure – 16 Test set-up for compression specimens

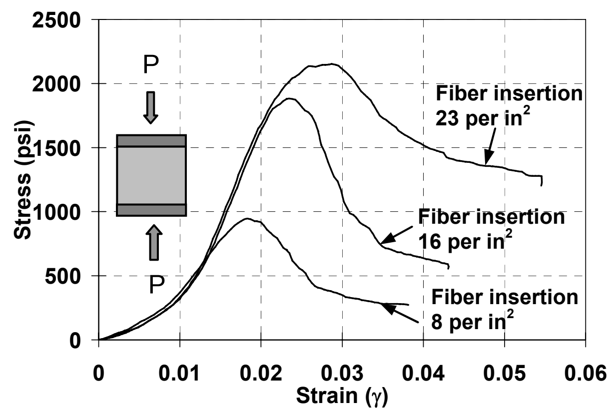


Figure – 17 Typical stress-strain relationship for compression specimens

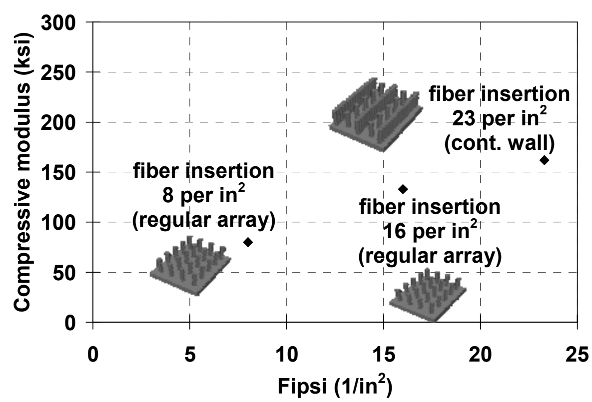


Figure – 18 Effect of through thickness fibers on the compressive modulus

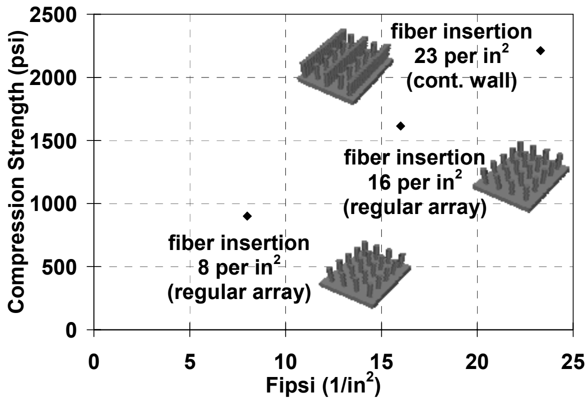


Figure – 19 Effect of through thickness fibers on the compression strength

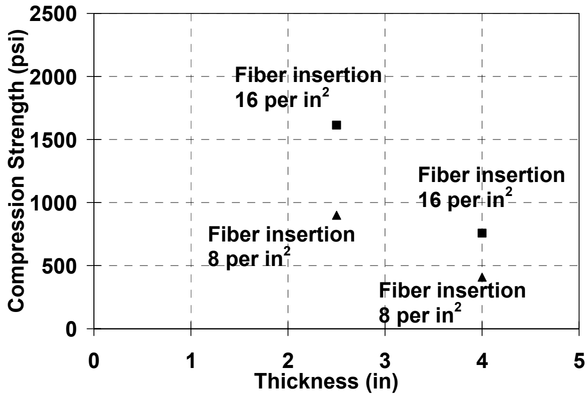


Figure – 20 Effect of the panel thickness on the compression strength

Figure – 21 Buckling of through thickness fibers at failure