Test Methods for Measuring Material Properties of Composite Materials in all Three Material Axes

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ABSTRACT

Material properties were determined for fiber-reinforced polymers (FRPs) with respect to all three material orientations using existing ASTM standards when applicable. Determining strength and stiffness properties both in-plane (load applied parallel to fiber orientation) and out-of-plane (load applied perpendicular to fiber orientation) is important in designing for ballistic protection. Shear strength, shear modulus, compressive strength, compressive modulus, tension strength, tensile modulus, and Poisson's ratio were all measured in the plane of the fibers and out-of-plane. In order to measure certain out-of-plane material properties, unique testing standards were developed. Test standards that are available for obtaining out-of-plane properties are tedious to perform particularly since premature failures occur at bonds between the composites and fixtures. In addition, there are currently no existing standards intended for measuring out-of-plane compressive properties and Poisson's ratio. Finally, materials tested in this research had a defined thickness ranging from 1.91 cm to 3.81 cm which caused conflicts with existing standards meant to be performed with longer specimens. This paper provides solutions for measuring each material property by summarizing all testing and fabrication procedures required.

1. INTRODUCTION AND BACKGROUND

The United States Army Tank Automotive Research Development and Engineering Center (TARDEC) has recently funded a research project to determine the mechanical properties of seven fiber reinforced polymer materials. The primary objective of this research was to determine the strength and stiffness (tension, compression, and shear) of new innovative composites in all three material orientations and under a wide range of temperatures.

This paper discusses fabrication and testing procedures that were employed in conducting the experimental investigations and focuses on the "out-of-plane" testing procedures. Information is included on how the test is performed, specimen fabrication and geometry, material properties measured, equipment used, test fixtures, and strain gauge configurations. This paper does not discuss the results of the materials that were tested. This paper is intended to be viewed by practicing engineers designing with fiber reinforced composite materials and manufactures of such materials.

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14. ABSTRACT
Material properties were determined for fiber-reinforced polymers (FRPs) with respect to all three material orientations using existing ASTM standards when applicable. Determining strength and stiffness properties both in-plane (load applied parallel to fiber orientation) and out-of-plane (load applied perpendicular to fiber orientation) is important in designing for ballistic protection. Shear strength, shear modulus, compressive strength, compressive modulus, tension strength, tensile modulus, and Poisson?s ratio were all measured in the plane of the fibers and out-of-plane. In order to measure certain out-of-plane material properties, unique testing standards were developed. Test standards that are available for obtaining out-of-plane properties are tedious to perform particularly since premature failures occur at bonds between the composites and fixtures. In addition, there are currently no existing standards intended for measuring out-of-plane compressive properties and Poisson?s ratio. Finally, materials tested in this research had a defined thickness ranging from 1.91 cm to 3.81 cm which caused conflicts with existing standards meant to be performed with longer specimens. This paper provides solutions for measuring measuring each material property by summarizing all testing and fabrication procedures required.

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Fiber-based composites are used more and more frequently for several applications in the military, the construction industry, the transportation industry, and other industries. Composites are currently being used or considered for both personal and vehicle ballistic protection. Fiber reinforced composites are often used for vehicle components since they are lightweight with favorable strength and stiffness properties.

Traditionally, the fibers within composite materials are oriented along two axes designating a plane associated with the fibers. In design, the composite systems are oriented such that the fibers resist the applied loads. Normal stresses that develop from axial loads and moments are distributed to and therefore resisted by both the fibers and the resin. Test standards have been established for testing composite materials in tension or compression in which axial force is applied parallel to the fibers ("in-plane"). However, the through thickness ("out-of-plane") mechanical properties are often not influential in the design. In tension, the load is primarily resisted by the strength of the resin [1].

Unique loading scenarios can cause high out-of-plane stresses in composites used for ground vehicles. The high stresses, both interlaminar shear and out-of-plane tensile, can result in premature failure of the material in comparison to what was anticipated. Capacities associated with interlaminar shear and out-of-plane tension are both weak from the interlaminar bonding. The ability of current modeling techniques to adequately account for these stresses is tied to the ability to accurately capture the weave architecture in the model. Experimental data is needed to validate and augment current modeling capabilities. Graham [2] indicates that thin-shell theory cannot be used for composite structures since; they tend to be thicker than equivalent steel structures, the through-thickness modulus is normally much lower than the in-plane moduli, the through-thickness shear modulus can be significantly lower than the in-plane moduli giving rise to significant shear deformation, and the interlaminar (out-of-plane) strength is much smaller than the in-plane strength. Therefore, other methods have to be employed that consider all interlaminar shear and normal force properties.

Accessibility of the through-thickness stiffness and strength properties of composites are extremely limited, and testing methods are unclear [1]. Current test standards have been established for measuring the out-of-plane tension strength of composites [3]. However, several issues are encountered when performing this type of testing. In order to test the material, a bond stronger than the strength of the material tested must exist between the specimen and the fixture or end tabs. Finding an epoxy with this level of strength is cumbersome, especially considering that it is used to bond two different materials.

Hara et al. [4] studied the out-of-plane tensile strength of CFRP laminates using the direct tensile method with specimens of various size and geometry. In this research, the authors considered experimental and analytical testing of spooled specimens and cylindrical specimens which were connected to metal end tabs. The authors indicated that testing should be performed on spooled specimens and thick specimens provide a more accurate measurement of the uniaxial and uniform tensile strength. However, if the initial composite plate has a small thickness, spooling to a reduced gage section may be difficult to achieve.

Other out-of-plane properties of interest include the compressive properties, the shear properties, and the Poisson's ratio. Very limited research has been performed on how to measure these properties for a particular laminate. Test methods must be established to obtain these properties and to therefore understand the complete mechanical behavior of a composite system.

The United States Army has a continuing interest in idealizing composite materials in ground vehicles for the design of armor against ballistic attacks and for general component design. The ground vehicles of interest include but are not limited to humvees and tanks. Composite materials are significantly lighter in weight than conventional materials such as aluminum or steel. Therefore, the use of composites can be more economical over the life of the vehicle since lightweight ground vehicles are easier to transport and are much more fuel efficient. In 2007, TPI Composites (TPI) unveiled the first light-weight, all-composite truck cab with built-in carbon fiber composite armor [6]. The design has been shown to save approximately 4003 N from the weight of previous humvees using conventional materials [6]. The cab was designed to be lightweight, durable, and strong enough for heavy armor and mine blast protection. The design assists in fuel, range, maneuverability, and field transportability.

2. EXPERIMENTAL PROGRAM

The experimental program included seven materials with different compositions of fibers and epoxy. Descriptions of the different compositions are summarized as follows:

- Materials 1, 3, and 4: Huntsman PolyUrethane (PU) Rencast 6405/ S-2 Glass Plain Weave (PW) 24oz./yd.2 [0/90, 45/-45] 26S
- Materials 2, 5, and 6: Applied Poleramic (API) SC-15 Epoxy/ S-2 Glass PW 24oz./yd.2 [0/90, 45/-45] 26S
- Material 7: Huntsman PU Rencast 6405/ Ductile Hybrid Fabric, Ultra-high modulus carbon fibers, high modulus carbon fibers, E-glass fibers,[8], [0, 45, -45] (DHF).

In general, there are three material compositions. One parameter included in this study was the nominal material thickness of the composite plate. This parameter was studied to indicate if there are any differences in material properties when fabricated with different thicknesses. The thickness of Materials 1 and 2 was 3.81 cm. The thickness of Materials 3 and 5 was 2.54 cm and the thickness of Materials 4, 6, and 7 was 1.91 cm.

For each material and each test type, all material properties were measured at three different temperatures. Each testing procedure had to accommodate the three chosen temperatures of -40 °C, 21 °C (ambient), and 60 °C. Small-scale environmental chambers were obtained. The test setup had to accommodate placing the specimens inside the chambers. Each environmental chamber had holes on the top and bottom that allowed either the specimen or fixture attachments to pass through into the chamber. To perform the environmental tests at cold temperatures, nitrogen tanks were purchased and connected to the environmental chamber via hoses.

Fibers of fiber reinforced composites are generally oriented in a plane associated with two material axes. These material axes are identified as ‘x’ and ‘y’ and properties associated with testing in this plane are identified as ‘in-plane’ properties. The other material axis which is oriented along the thickness of the composite plate is identified as the ‘z’ axis. The properties associated with this material axis are identified as ‘out-of-plane’ properties.

The test matrix shown in Table 1 includes 7 “test types”. The testing procedure accounts for measuring the tensile strength, the tensile modulus, the compressive strength, the compressive modulus, the shear strength, the shear modulus, and the Poisson’s ratio in all three material axes. Hence, the testing procedure obtains the multi-axis material properties of the composite materials.

In Table 1, '*E*' represents the elastic modulus when subjected to tensile stresses and '*EC*' represents the elastic modulus when subjected to compressive stresses. '*v*' represents the Poisson's ratio when subjected to tension stresses and '*vC*' represents the Poisson's ratio when subjected to compressive stresses. '*ST*' represents tensile strength, '*SC*' represents compressive strength, and '*S*' represents shear strength. Table 1 also lists the ASTM standard that was followed in order to perform the tests. For the out-of-plane compression and out-of-plane Poisson tests, no particular standard was followed. However, loading rates and other useful information were obtained using ASTM D7291 when applicable.

All properties listed in Table 1 were determined for each material and each temperature by taking the average results of five specimens tested. All elastic properties were computed using changes in stresses and strains from a load corresponding to 20% of the maximum load at failure to 50% of the maximum load at failure. All elastic properties were computed for each specimen as the average value as interpreted from multiple strain gauges.

Table 1. Test Types with Measured Material Properties

Test Type	Elastic Properties	Strength Properties	ASTM Ref.
In-Plane Tension	E_x, E_y, ν_{xy}	ST_x, ST_y	D 3039
In-Plane Compression	EC_x, EC_y, νC_{xy}	SC_x, SC_y	D 6641
In-Plane Shear	G_{xy}	S_{xy}	D 7078
Out-of-Plane Tension	E_z	ST_z	D 7291
Out-of-Plane Compression	EC_z	SC_z	-
Out-of-Plane Shear	G_{yz}, G_{xz}	S_{yz}, S_{xz}	D 5379
Out-of-Plane Poisson	ν_{yz}, ν_{xz}	-	-

1.1 In-Plane Tension Tests

In-plane properties were determined using typical ASTM standards with some slight variations as required. The in-plane tension test was conducted using ASTM D 3039/D 3039M "Standard Test Method for Tensile Properties of Polymer Composite Materials" [8]. As shown in Table 1, this test was used to measure the in-plane elastic modulus, E_x or E_y, the in-plane tensile strength, ST_x or ST_y, and the in-plane Poisson's Ratio, ν_{xy}.

The tension specimens were 66.0 cm long by 1.91 cm thick. The width of the tension specimen was equal to the nominal thickness of the composite plate which ranged from 1.91 cm to 3.81 cm. The specimens were gripped at the top and bottom along the width. The composite materials with S2 glass fibers failed by delamination along the length. However, other composite materials failed at the minimum cross-section which was often within the grips or at localized imperfections. Therefore, for some composite materials (e.g. DHF), the specimens were spooled in order to measure strains and stresses in a localized area. In this research, the DHF materials were spooled to have a 1.02 cm thickness (as opposed to 1.91 cm).

Vishay 125LT strain gauges were used to measure both the longitudinal and transverse strain and were attached on opposite sides of the specimen, along the width. On one thickness, a Vishay 20CBW strain gauge was attached to the specimen. This is a longer gauge (approximately 6.35 cm) and was used to verify the measurements of the other two strain gauges over a longer length of the specimen. Therefore, Poisson's ratio was determined along two sides of the specimen and elastic modulus was determined along three sides of the specimen. This procedure general provided fairly consistent results between five specimens tested at the same temperature.

1.2 In-Plane Compression

The in-plane compression test was conducted using ASTM D 6641/D 6641M "Standard Test Method for Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) Test Fixture" [9]. For this test type, the experimental procedure followed this ASTM designation without any special considerations.

As shown in Table 1, this test was used to measure the compressive strength, SC_x or SC_y, the compressive elastic modulus, EC_x or EC_y, and the in-plane compressive Poisson ratio, vC_{xy}. The specimens were 14.0 cm long by 2.54 cm thick. The width of the compression specimen was equal to the nominal thickness of the composite plate which ranged from 1.91 cm to 3.81 cm. Four Vishay 125LT strain gauges were attached to the specimen, one on each of the four sides.

1.3 In-Plane Shear

The in-plane shear test was conducted following ASTM D 7078/D 7078M "Standard Test Method for Shear Properties of Composite Materials by V-Notched Rail Shear Method" [*10*]. As shown in Table 1, the test was used to measure the in-plane shear strength, S_{xy}, and the in-plane shear modulus, G_{xy}. The nominal specimen dimensions as recommended in ASTM D 7078 were modified significantly. The shear specimen was 12.7 cm long and had a width of 10.7 cm. The thickness of the shear specimen was equal to the nominal thickness of the composite plate which ranged from 1.91 cm to 3.81 cm. Figure 1 shows an illustration of the shear specimen.

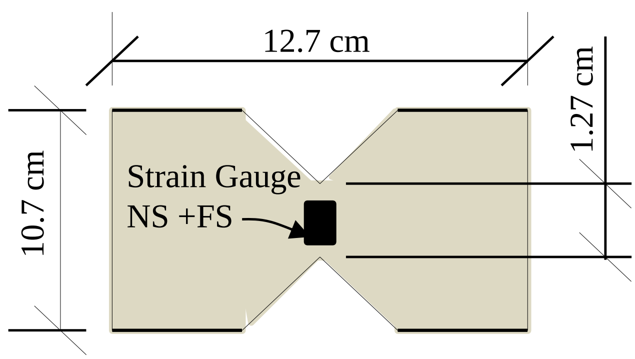

Figure 1. Specimens dimensions for in-plane shear testing

The shear specimens were clamped on each end between two pairs of loading rails creating a shear force in the reduced section of the shear specimen. The initial shear fixture used to perform the experimental investigations was found to be inadequate for the shear strength of the composite materials. Therefore, a specially designed shear fixture was fabricated to accommodate the shear stress capacity. Figure 2 shows a picture of the shear fixture within the testing machine. In Figure 2, the location of the specimen is noted. The 'torque bolts' identified in Figure 2 were tightened to a torque of 54.2 N-m.

Two Vishay N2P-08-C032A-500 strain gauges were attached on each side of the specimen (near side and far side in Figure 2). These strain gauges measure the shear strain and were therefore used to determine the in-plane shear modulus of the material.

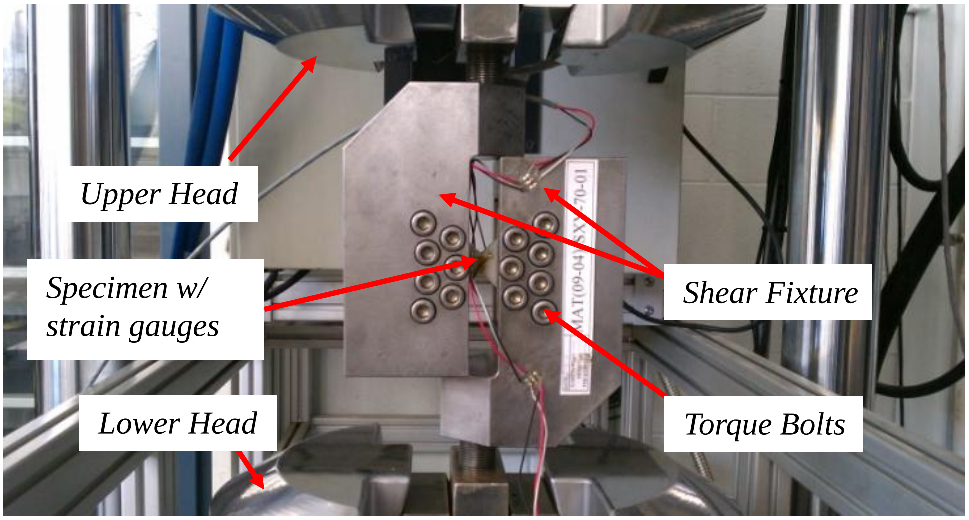

Figure 2. Test setup for in-plane shear

1.4 Out-of-Plane Compression

The out-of-plane compression test was used to measure the through-thickness compressive properties. As shown in Table 1, the test was used to determine the out-of-plane compressive strength, SC_z, and the out-of-plane compressive elastic modulus, EC_z. A cylindrical specimen was set into a uniaxial test machine making direct contact with the upper and lower platens. A compressive force was applied at a rate of 0.127 cm/min until failure. Figure 3(a) shows a picture of a compressive specimen in the test machine and Figure 3(b) shows the specimen dimensions. The length was equal to the nominal thickness of the composite plate ‘t’.

Initially, a diameter of 2.86 cm was used. However, localized failures occurred in the platens due to a high out-of-plane compressive strength of the material which was far higher than the in-plane compressive strength. In order to limit the maximum length/diameter ratio to 2.0, the smallest diameter considered was 1.91 cm. However, applying strain gauges was tedious at this small diameter. A final diameter of 2.16 cm was then chosen.

a) Test Setup b) Dimensions/Strain Gauge Locations

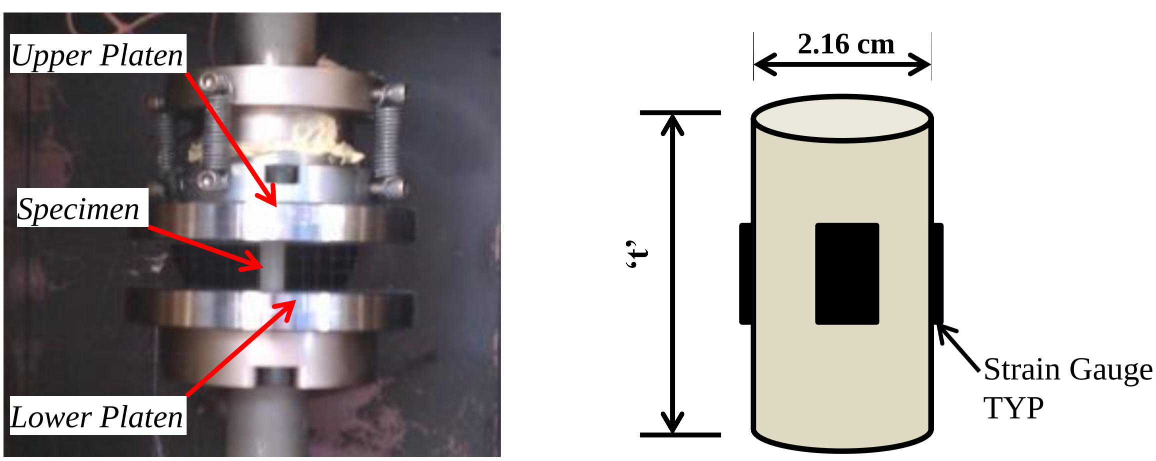

Figure 3. Test setup for out-of-plane compression w/ specimen dimensions

Three Vishay CEA-06-125UW-350 longitudinal strain gauges were placed on the cylindrical specimen 120° apart from each other and were used to determine the elastic modulus, EC_z.

1.5 Rational of end tabs for out-of-plane tension, shear, and Poisson

Out-of-plane tension, out-of-plane shear, and out-of-plane Poisson specimens were fabricated by the research team after receiving composite 'blocks' from TARDEC. In all three test conditions, the research team was not able to perform testing on a specimen with a thickness equal to the thickness of the composite plate which ranged from 1.91 cm to 3.81 cm. Instead, for different reasons, the specimens were connected to end tabs that were made of either the same composite material or other composite materials.

The out-of-plane shear specimens were tested using ASTM D5379/D 5379M [11] which is described in Section 1.8. In order to accommodate the fixture used to perform the test, the specimens were required to have a total length of 7.62 cm. The length of the specimen in this test was oriented along the thickness of the plate. Therefore, end tabs were required on either side of the center piece in order to extend the length of the specimen to 7.62 cm. The notch that was fabricated in the out-of-plane shear specimens was within the center pieces. Therefore, all data obtained in this test represents the shear behavior of the material tested.

Several iterations in the testing procedure were performed in order to finalize the out-of-plane tension testing. Initially, cylindrical specimens were provided to the research team. However, the research team could not find an adequate epoxy for bonding the specimen to the test fixture especially at high temperatures. Failures occurred at the bond between the specimen and the fixture which was either due to weaker epoxy or accidental eccentricities in the test setup. Therefore, the research team purchased a special test fixture for performing out-of-plane tension testing in which the specimens were pinned to the test fixture. It was impractical to fabricate pin holes in the material tested because localized failures would occur due to bearing stresses. Therefore, it was more practical to add end tabs and connect the end tabs to the text fixtures via pins. Initially, metal end tabs were used. However, issues still existed in the bond between the end tabs and the composite material. The end tabs were therefore made of composite materials and had fibers orientated parallel to the direction of loading. Therefore, failure would never occur in the end tab prior to failure in the material tested. However, bond line strength was still dependent on the material tested, the epoxy that was used, and the maximum temperature.

End tabs were also bonded to the material for conducting the out-of-plane Poisson tests. Since only elastic properties were measured, it was not required to reach the tensile strength. However, end tabs increased the stress at failure which generally occurred at the bondline in lieu of localized failures at the pin-holes. More accurate readings of the Poisson ratio were obtained.

1.6 Fabrication of out-of-plane tension, shear, and Poisson specimens

Three blocks were epoxied together prior to fabricating the completed specimens. The center block was made of the material tested and the top and bottom blocks became end tabs. These blocks were later separated into several specimens. Figure 4 shows a picture of three blocks that were later epoxied together and fabricated into test specimens. When received, the 'test block' was 30.5 cm x 3.81 cm x 't' where 't' is the nominal thickness of the composite plate. The two 'end tab blocks' were 30.5 cm x 3.81 cm x 3.81 cm. LTU reduced these dimensions as required to accommodate the test performed. However, the nominal thickness 't' was never reduced.

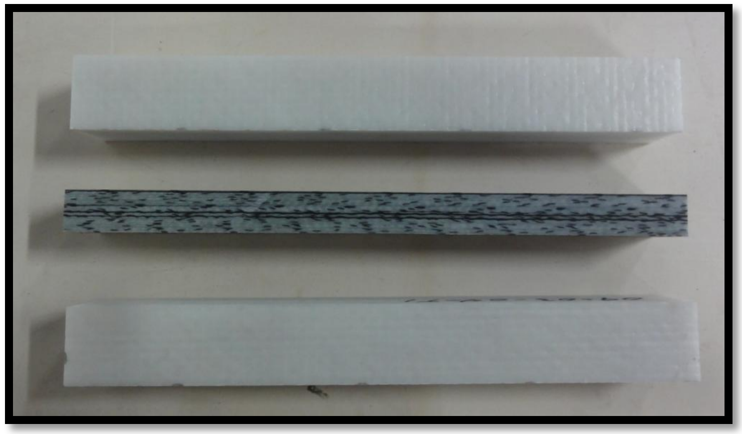

Figure 4. Individual 30.5 cm blocks provided by TARDEC to research team (Center block DHF)

Prior to bonding the blocks together, the individual blocks were squared. All corners of the blocks were specified to have 90° angles using a CNC mill. Custom polycrystalline diamond (PCD) indexable cutting inserts were used to mill the material to the desired surface profile. The PCD cutters enhance the life of the cutting tools when cutting glass composite materials. All CNC milling procedures were performed using PCD cutters.

Once the individual blocks were squared, they were epoxied together. The research team attempted to use several different epoxies during the acceptance testing phase of the project. Certain epoxies performed more favorably for different composite materials and in different temperature conditions. It was determined that the best epoxy for several applications was a two part epoxy provided by 3M (Designation DP420) with 0.25-0.50 mm diameter glass beads added to the epoxy. Prior to and during curing, the specimens were 'C-clamped' together.

The epoxy was cured by means of oven heating for 60 minutes at 60 °C. The 'bonded blocks' were left at ambient temperatures for a period of 24 hours prior to further fabrication efforts. Then, the bonded blocks were squared using the same CNC mill that was used to square individual blocks. Figure 5a shows a picture of a bonded block in the CNC mill prior to squaring and Figure 5b shows another block after squaring.

a) Prior to Squaring Specimen b) After Squaring Specimen

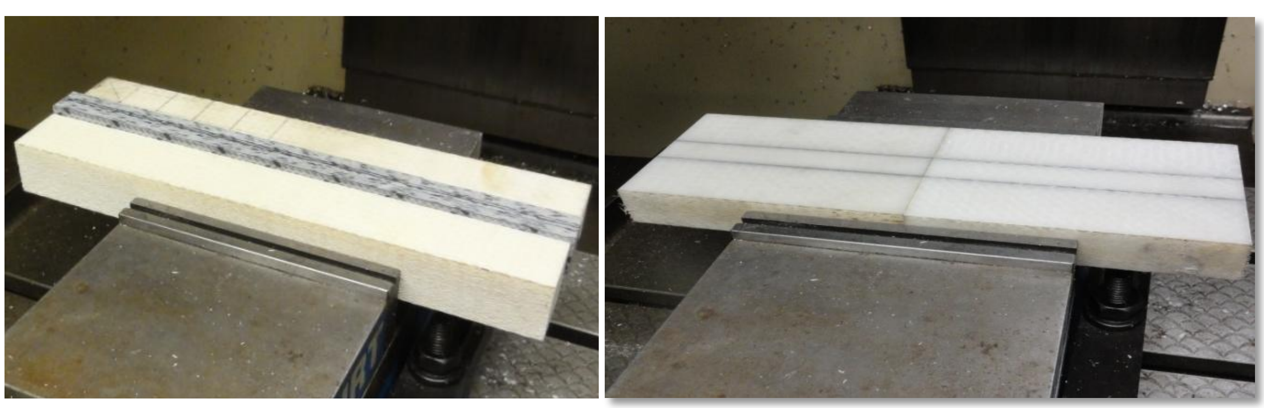

Figure 5. Bonded block in CNC mill prior to (a) and after (b) squaring all sides

The 30.5 cm bonded blocks were separated in half (15.2 cm long) using a horizontal band saw. Further fabrication efforts were dependent on the individual out-of-plane test that was performed on the material. Therefore, prior to individual fabrication efforts for a specific test, the bonded blocks were approximately 15.2 cm long, 3.81 cm thick, and had a width equal to 7.62 cm plus the nominal thickness of the composite plate.

The blocks that were used to fabricate out-of-plane tension and out-of-plane Poisson specimens were cut and grinded down to a thickness of 2.54 cm using a surface grinder with custom electro plated diamond coated wheels as shown in Figure 6. The 15.2 cm long by 2.54 cm thick blocks were separated into five pieces, each with a length of 2.67 cm using the horizontal band saw. These individual pieces were fabricated into five individual specimens. Figure 7 shows a piece saw cut from the 15.2 cm long block. Once the individual pieces were removed, the 2.67 cm dimension was further reduced to 2.54 cm using the surface grinder (See Figure 6). The reduced block now had a width equal to 2.54 cm, a thickness equal to 2.54 cm, and a length equal to 7.62 cm plus the nominal thickness of the composite plate.

Figure 6. Blocks reduced to a thickness of 2.54 cm using surface grinder and custom electro plated diamond coated wheels

Figure 7. Composites saw cut into 2.54 cm thick by 2.67 cm wide blocks

The specimens used for the out-of-plane tension and out-of-plane Poisson testing were connected to a text fixture using pins. Therefore, the specimens were placed into a Bridgeport mill and 0.714 cm diameter holes were drilled in the end tabs to accommodate the pin connections. This procedure is shown in Figure 8. This completed the specimen fabrication efforts required to perform the out-of-plane Poisson testing. The blocks will further be referred to out-of-plane Poisson specimens. More fabrication work was required for the out-of-plane tensile specimens.

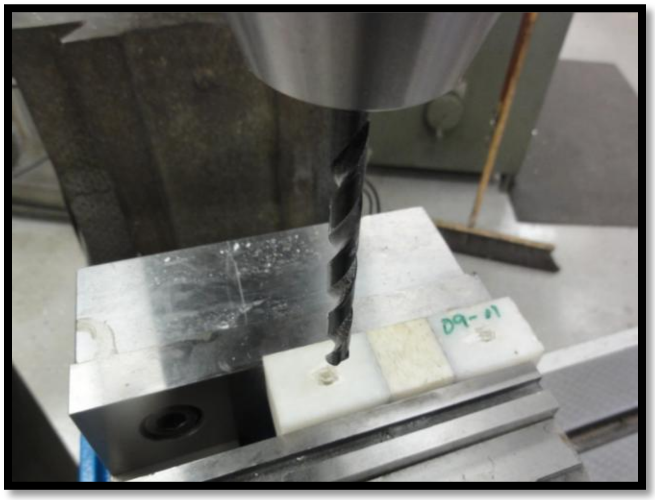

Figure 8. Holes drilled in end tabs to connect to text fixture using Bridgeport Mill

To complete the fabrication of the out-of-plane tension specimens, center drill holes were located at the top and bottom face of the specimen using the Bridgeport Mill. The holes allow the block to be mounted on electro precision centers. The spinning center was placed on the surface grinder. The mid-section of the material being tested was spooled using a custom profile diamond coated grinding wheel. Figure 9 shows the process that was used to spool the specimen. This completed the fabrication procedure for the out-of-plane tension specimens.

Figure 9. Spooling of out-of-plane tension specimens

Specific fabrication procedures for the out-of-plane shear specimens began after fabricating the 7.62 cm long and 3.81 cm thick bonded blocks. The blocks were cut and grinded down to a thickness of 2.03 cm using the surface grinder with custom electro plated diamond coated wheels. The 7.62 cm long by 2.03 cm thick blocks were placed on a sine plate which mounted on a Bridgeport Mill in order to machine the V-notch. The parts were cut and grinded to final dimensions of 2.03 cm wide x 1.27 cm thick x 7.62 cm long using a horizontal saw and surface grinder. Figures 10-13 show two completed out-of-plane Poisson specimens, a completed out-of-plane tension specimen, and a completed out-of-plane shear specimen.

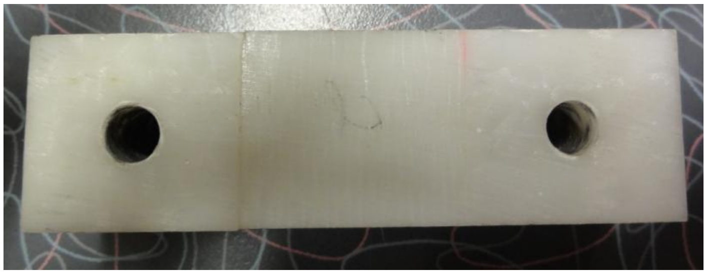

Figure 10. Completed out-of-plane Poisson specimen

Figure 11. Completed out-of-plane Poisson specimen with higher surface area at bond

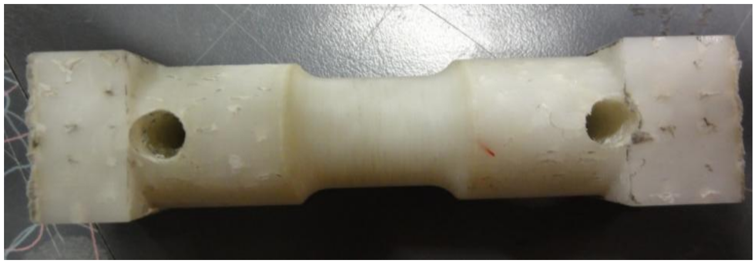

Figure 12. Completed out-of-plane tension specimen

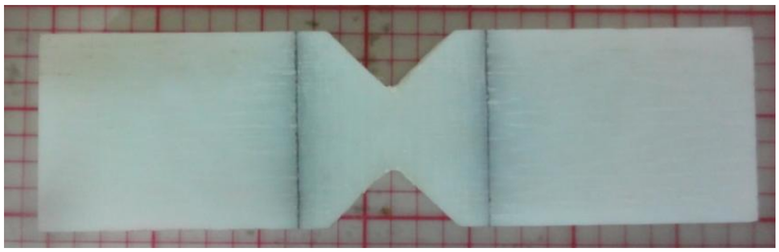

Figure 13. Completed out-of-plane shear specimen

1.7 Out-of-Plane Tension

The out-of-plane tensile test was conducted using ASTM D 7291/D 7291M “Standard Test Method for Through-Thickness “Flatwise” Tensile Strength and Elastic Modulus of a Fiber-Reinforced Polymer Matrix Composite Material” [10]. As shown in Table 1, the test was used to measure the through-thickness “flatwise” tensile strength, ST_z, and elastic modulus, E_z, of the composite materials.

The material tested was adhesively bonded to end tabs fabricated from either the same material or other composite materials consisting of SC-15 resin and S2 glass. Final dimensions varied for different materials tested at different temperatures. However, most of the specimens were spooled to a final diameter of 1.91 cm in the test area. The final diameter had to ensure that failure occurred in the test area and not at the bond between the material being tested and the end tabs. Figure 14 shows a picture of the specimen within the test fixture.

During out-of-plane tension tests, it was critical to ensure that bending stresses were not developed due to misalignments or related issues. It was determined that using one universal joint causes a consistent but unacceptable failure mechanism. All specimens failed at the bottom near the epoxy line due to eccentricities that develop upon loading. Therefore, a fixture was obtained that would allow pinned joints (free to rotate) on the top and bottom. Figure 14 identifies this custom test fixture as the ‘Wyoming’ test fixture [13].

Three Vishay CEA-06-125UW-350 longitudinal strain gauges were placed on the cylindrical specimen 120° apart from each other and were used to determine the elastic modulus, E_z.

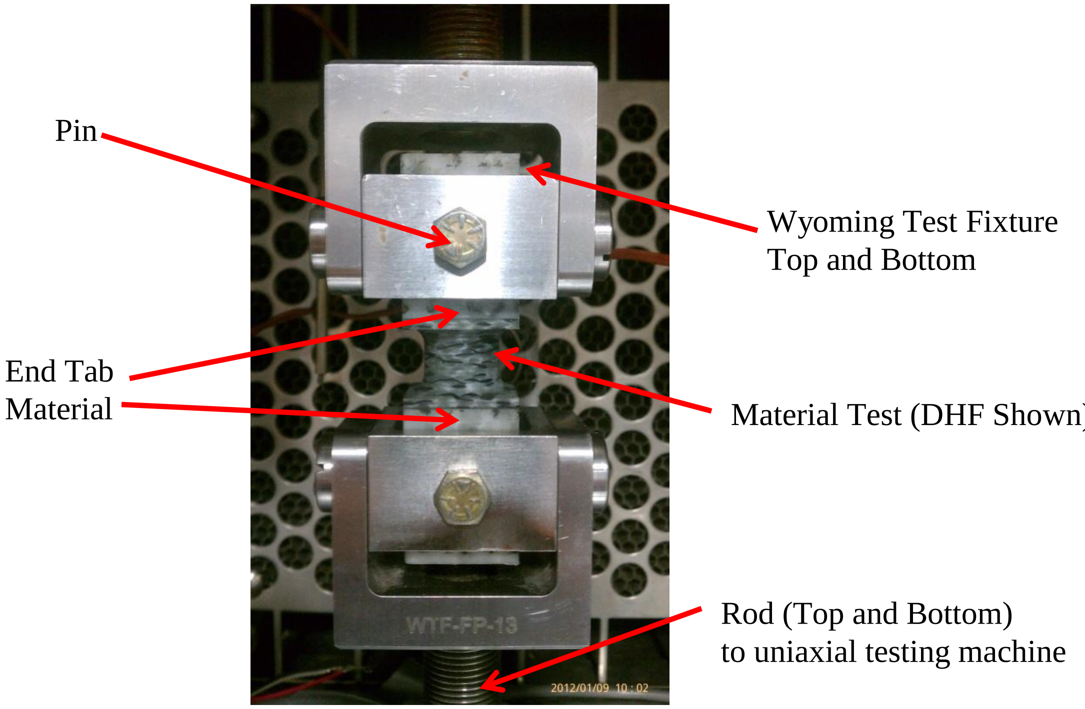

Figure 14. Out-of-plane tension test specimen within test fixture

1.8 Out-of-Plane Shear

The out-of-plane shear test was conducted using ASTM D 5379/ D 5379M "Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method" [11]. During this test, fibers were oriented along the width and the thickness of the specimen. As shown in Table 1, the out-of-plane shear test measures the out-of-plane shear modulus, G_{xz} or G_{yz}, and the out-of-plane shear strength, S_{xz} or S_{yz}.

The fabrication of the test specimen was previously discussed. The material being tested was adhesively bonded to end tabs fabricated from either the same material or other composite materials consisting of SC-15 resin and S2 glass. The total specimen length including the end tabs was 7.62 cm. The thickness of the specimen was 1.27 cm. and the width of the specimen was 1.91 cm. The specimen width was reduced to a notch width of 0.610 cm. Shear stress was computed using the cross-sectional area associated with this notch height. Figure 15 shows a picture of an out-of-plane shear specimen within the shear test fixture.

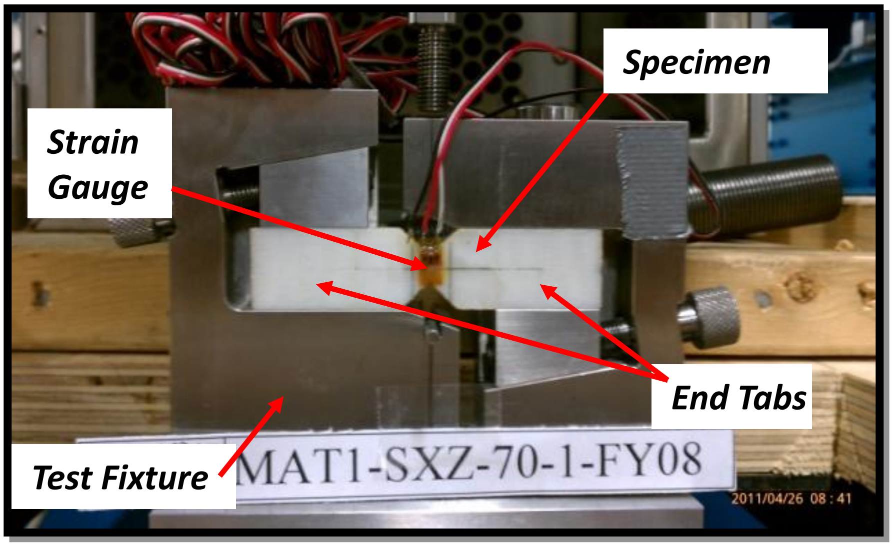

Figure 15. Out-of-plane shear test specimen within test fixture

Two Vishay CEA-06-062UV-350 strain gauges were attached on each side of the specimen. These strain gauges measure the shear strain and were therefore used to determine the out-of-plane shear modulus of the material.

1.9 Out-of-Plane Poisson

The out-of-plane Poisson test was conducted similar to the out-of-plane tension test. ASTM D 7291 [3] which was used for the out-of-plane tension test was also used as a guide for the out-of-plane Poisson test. However, instead of using a cylindrical specimen, a cubic specimen was used to perform the test since transverse strain gauges must be applied to a flat surface. As shown in Table 1, the out-of-plane Poisson test was used to calculate the Poisson's Ratio, v_{xz} or v_{yz}.

The fabrication of the test specimen was previously discussed. The material tested had cross-sectional dimensions of 2.54 cm x 2.54 cm and a length equal the nominal thickness of the composite part which ranged from 1.91 cm to 3.81 cm. The material tested was adhesively bonded to end tabs fabricated from either the same material or other composite materials consisting of SC-15 resin and S2 glass. Figure 16 shows a picture of a Poisson specimen adhesively bonded to end tabs and within the text fixture.

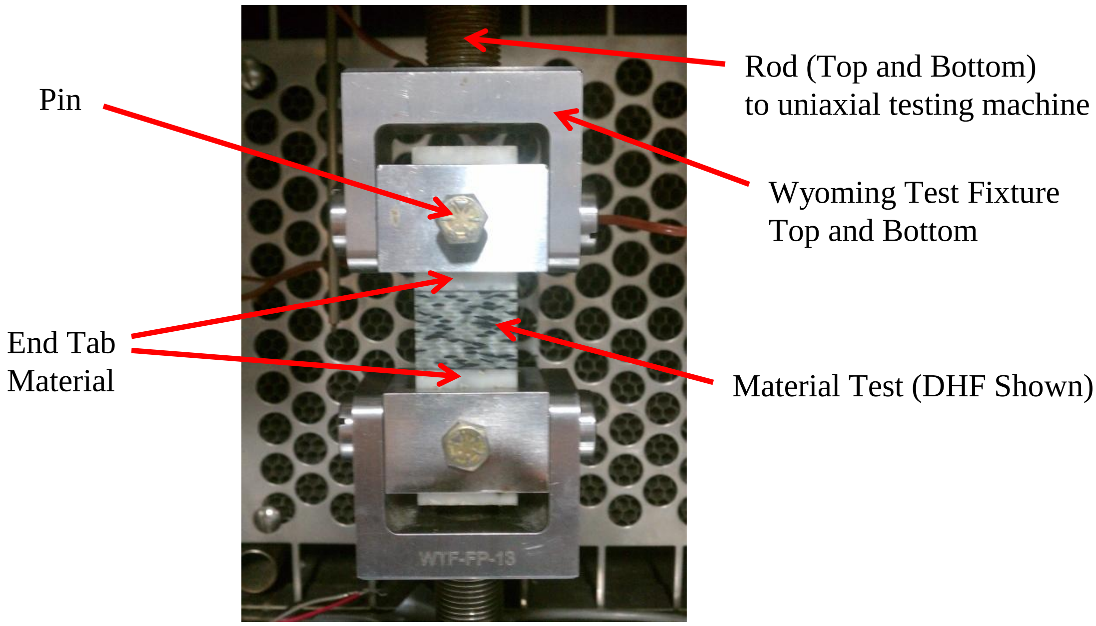

Figure 16. Test setup for out-of-plane poisson

The design of the test specimen did not ensure failure would occur in the material tested. Instead, the test was considered acceptable if the stress reach 50 % of the maximum stress prior to bondline failure. Therefore, the elastic property, Poisson's ratio, could be computed using loads corresponding to 20 % and 50 % of the maximum axial loads. The maximum load was estimated using the maximum stress obtained from the out-of-plane tension testing when the same materials were subjected to the same thermal temperatures.

Two Vishay 125LT strain gauges were placed on adjacent sides of the specimen and were used to determine the transverse strain (ε_t) and the longitudinal strain (ε_l) which were then used to determine the out-of-plane Poisson's ratio, v_{xz} or v_{yz}. Average values as interpreted from the two gauges were used to define the Poisson's ratio of the specimen.

3. SUMMARY

This paper is written to educate the composite industry of methods available for determining the material properties of composites with respect to all three material orientations. The parameters in developing experimental procedures include; the properties measured, the nominal thickness of the composite plate, and the type of composite. In all, seven test types were discussed. The elastic properties include the elastic modulus when subjected to tension (E), the elastic modulus when subjected to compression (EC), the Poisson's ratio when subjected to tension (v), and the Poisson's ratio when subjected to compression (vC). The strength properties include the tension strength (ST), the compressive strength (SC), and the shear strength (S).

Available ASTM specifications used for in-plane tension, in-plane shear, and in-plane compression are in general adequate for determining the in-plane properties. For some composite materials, localized failures may occur. Therefore, the specimens must have a reduced cross-sectional area along a gage length.

To determine the out-of-plane compressive strength and stiffness properties, a new testing procedure was developed in this research. The specimens were positioned in direct contact with the platens of the text fixture. Preliminary research must be conducted in order to select a diameter for the specimen which is dependent on the equipment available to perform testing.

Existing ASTM standards were used as guides for performing out-of-plane shear and out-of-plane tension tests. However, the material thickness of 1.91 cm to 3.81 cm, which becomes the length of the out-of-plane specimens, was smaller than the recommended specimen length per ASTM D 5379 [12] for performing out-of-plane shear tests. In addition, an epoxy was not found strong enough to bond the specimen directly to the fixtures when performing the out-of-plane tension tests per ASTM D 7291 [4]. Therefore, for both of these tests, the material tested was bonded to end tabs made of composite materials. The research team used a custom grinding wheel to spool the out-of-plane tension specimens. The final diameter of the spooled specimen should be small enough to ensure failure occurs within the reduced portion of the specimen and not at the bond between the end tabs and the material tested. In addition, the diameter must be large enough to ensure that strain gauges can be bonded properly to the specimen. The higher the temperature, the more susceptible is the test to fail at the bond line.

ASTM D 7291 was used as a guide for performing the out-of-plane Poisson tests. However, instead of using cylinder specimens, rectangular specimens were fabricated and bonded to end tabs. This provided a flat surface for attaching longitudinal and transverse strain gauges. The test was considered successful if the maximum tensile stress reached 50 % of the maximum tensile stress prior to bondline failure. The maximum stress needs to be interpreted from the out-of-plane tension results of the same composite material tested at the same temperature.

Rigorous fabrication methods and testing procedures must be performed to measure all material properties of composites in all three material orientations. Each type of composite, each test type, and each maximum temperature may have unique issues and therefore, unique testing requirements. Therefore, obtaining the material properties must be accomplished with careful planning, testing experience, and patience.

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