

AN ANALYSIS OF THE PROPERTIES OF CARBON FIBER ALIGNED DISCONTINUOUS PREPREG TAPE

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ABSTRACT

Pepin Associates, Inc. has developed an aligned, discontinuous carbon prepreg tape. The goal of the tape is to increase efficiency of fabricating complex composite shapes by eliminating the need to cut and dart during layup and for the technician to create a preform. The purpose of this research is to manufacture a cost-effective prepreg tape and test the mechanical properties of laminates made with this tape. The test program will consist of standard ASTM composite material tests, including in-plane shear, tensile and compressive strength, and forming trials to determine the formability of the tape. These tests will be performed using continuous carbon prepreg tape along with aligned discontinuous carbon tape for comparison. The test matrix will determine if the mechanical properties of the aligned discontinuous tape are competitive, both in performance and cost, in the advanced composite materials industry.

1. INTRODUCTION

Unidirectional, preimpregnated reinforcement fiber tape has been a composite material standard for many years for use in fabricating composite parts and structures within many different industries. This tape is commonly used in a number of fiber-reinforced composite applications, can be fabricated with a variety of reinforcement fibers and matrix systems and typically comes with a contact-paper backing to facilitate application.

Unidirectional tape prepregs allow composite parts with high strength and stiffness to be fabricated. They are very effective for large parts or parts with gentle contours. Tapes can be laid into molds manually or placed onto tools with automated tape laying machines. Complex, three-dimensional contours are difficult to lay up with continuous unidirectional tape, since the tape will not stretch along the fiber axis, so wrinkling and “bridging” of the tape can occur. Current solutions include cutting and darning the tape, which is time consuming and leads to inconsistency in fiber alignment, which in turn affects mechanical properties. Another approach is using very narrow tapes more easily laid into complex contours, but this is very time consuming.

One study done by Lehigh University’s Department of Mechanical Engineering and Mechanics describes using small staggered cuts that can be tailored to the complexity of a mold while retaining high tensile strength. Cuts are made in the prepreg using a pneumatic CNC cutter and programmed to a determined length to create clean, consistent cuts. While custom cuts make forming easier in locations where more stretching is needed, this process can be costly.

Pepin Associates, Inc. has developed a means by which continuous, unidirectional prepreg tape is cut into narrow, discrete segments while maintaining alignment and adherence to its contact paper backing. The result is an aligned, discontinuous unidirectional tape. The discontinuous nature of the tape allows it to stretch in its reinforcement direction, permitting the forming of complex shaped layups from simple initial shapes such as flat plates and tubes.

The prepreg tape is processed by means of a specialized machine, which cuts the tape into discrete segments using a rotary die. The die is geared to and turns against an anvil, and can be designed to cut the segments in lengths tailored to a specific application. The pattern of the cuts can also be varied. The segment length is a compromise between two competing interests. The first is the formability of the prepreg tape into the required contour. The tape stretching occurs when the fiber segments slip relative to one another. The force required to stretch the tape is a function of the segment length and segment width. The second is the retention of mechanical properties of the discontinuous composite compared to the baseline continuous fiber composite. Generally the longer fiber segments have better properties. The equipment used to fabricate the aligned, discontinuous unidirectional tape permit varying the segment length and other architecture features to tailor the prepreg for specific part design and manufacturing process.

Discontinuous, unidirectional preimpregnated reinforcement tape begins with standard preimpregnated unidirectional reinforcement tape of any fiber type and any matrix system. The standard unidirectional tape is processed in a machine designed to cut the continuous fibers of the unidirectional tape into discrete segments. The patterns of these segments are governed by the required mechanical properties of the part and the contours to be formed. One typical design would be a brick-like pattern, with rows having their junctions midway between the junctions of the segments in the adjacent row. This pattern would allow tape stretching while still retaining shear contact from one segment to its adjacent or neighboring segment.

The machine uses a set of initial nip rollers to gather the continuous unidirectional tape as it feeds from an adjacent spool and separates the plastic separation layer typically used during fabrication. The separation layer is then passed over the die on a hemispherical guide plate and rejoined with the tape at a final set of nip rollers after it passes through the die and anvil. The processed tape is taken up on a constant tension textile spool winder, modified to wind tape. An articulated final single roller called a dancer arm is mechanically linked to a mechanism on the winder, which modulates the winder speed to ensure a constant tension on the tape.

The rotary die and anvil can be manually operated with a hand wheel, or an electric clutch can engage a motor drive to advance the unidirectional prepreg tape between the rotary die and anvil. The die cuts the prepreg tape as it is pressed against the anvil. The die is referred to as a "flex die," which is etched onto a thin substrate and adheres to a magnetic roller. This type of die facilitates pattern changes and replacement.

The die design makes only crosscuts in the unidirectional tape, taking advantage of the natural tendency of the filaments to slide axially relative to each other due to their attachment only by a matrix. This method avoids the problems of segments adhering to the die cavities and being pulled from their backing as the tape is cut. The resulting crosscuts are overlapped to ensure that all filaments are cut, and to account for lateral drift in axial filaments.

2. EXPERIMENTATION

The purpose of this study is to understand the behavior of the aligned discontinuous prepreg tape. Initially, forming trials were conducted to determine which flex die pattern offers the best formability results with the prepreg. Once the pattern is selected, coupons are cut from cured panels and tested following ASTM Composite Standards. Testing includes tensile, compression, in-plane shear and interlaminar shear testing. The flex die pattern chosen for this study is a straight cut design with segments spaced 1.65 cm apart.

2.1 Materials

Hexcel® HexPly® IM7-G/8552 with resin content 35.2% was used to prepare eight panels: four control continuous panels and four aligned discontinuous panels.

Laminates measuring 33 cm x 33 cm were fabricated by PAI. Laminate thickness for each panel follows the ASTM requirements for each test. All panels were cured following the Hexcel® 8552 resin system shown in Figure 1.

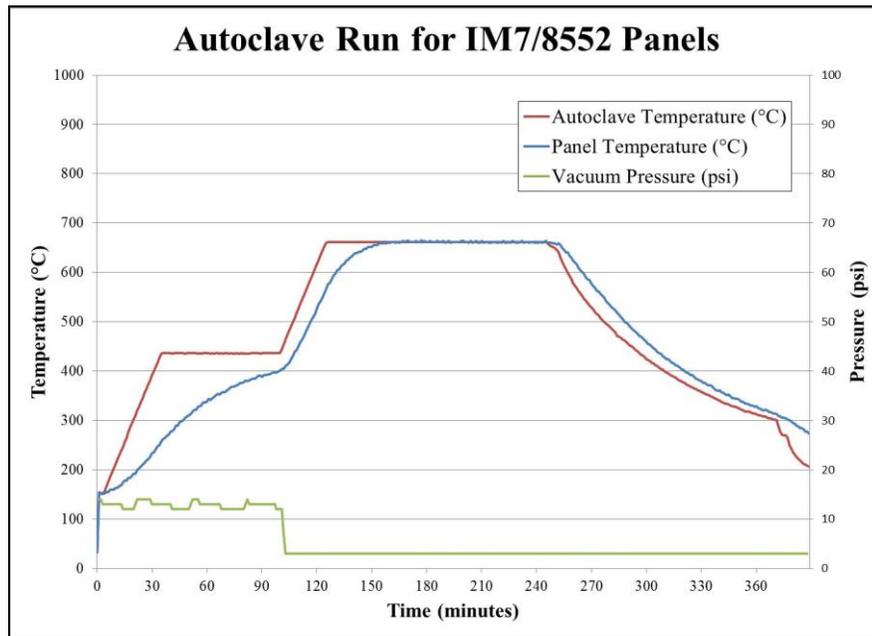


Figure 1. Graph of recorded data during one of two autoclave runs. The IM7/8552 cure cycle is approximately 6 hours. Temperature inside the autoclave (*red*), temperature seen by the panels (*blue*), and vacuum pressure (*green*) are recorded during the run.

2.2 Dome Forming

The scope of work done for the forming trials will determine the workability of the aligned discontinuous prepreg over a male hemisphere. Once a flex die pattern has been tested and provides satisfying forming results, pattern will be used to fabricate panels for mechanical property testing.

The test set up shown in Figure 2 consists of a 40.6 cm x 45.7 cm double diaphragm forming frame with the prepreg forming around a hard 10.2 cm male hemisphere tool. The forming frame consists of two silicone sheets forming a flat vacuum bag above the chamber while the hard hemisphere tool is positioned in the bottom chamber of the frame.

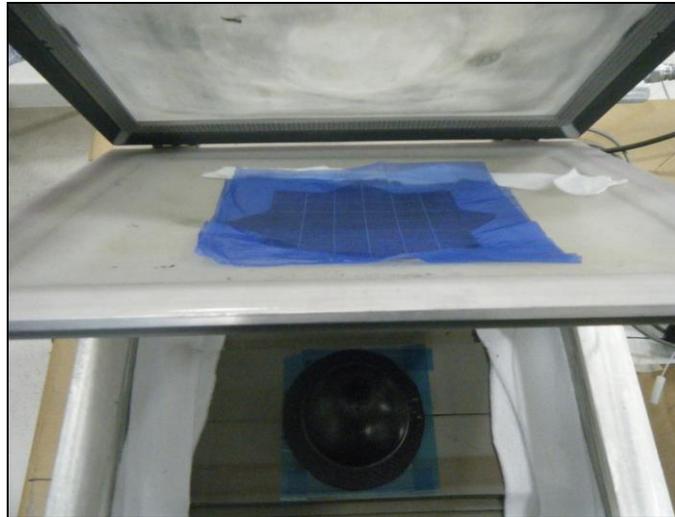


Figure 2. Double diaphragm forming frame layers. The two top silicone sheets make up the flat vacuum bag where the prepreg layups are positioned in the center. The hard hemisphere tool is seen in the bottom chamber.

2.2.1 Procedure

The prepreg blank size is placed in the top vacuum bag between two sheets of HTF621 Teflon release film. A breather strip is placed between the Teflon sheets and prepreg to evacuate air trapped between the layers. Once the air is evacuated from the top silicone vacuum bag, two heat pads are placed on the double diaphragm frame; one on top of the silicone vacuum bag and one inside the bottom chamber touching the bottom silicone sheet of the vacuum bag. The heat pads are heated to 109°C. A thermocouple is used to accurately measure the temperature above the top silicone layer. Once the desired temperature is reached and held for 5 minutes, the bottom chamber is evacuated at full vacuum and the prepreg inside the vacuum bag forms over the tool. The preform may be removed once the forming frame has cooled between room temperature and 30°C.

2.3 Mechanical Testing Procedures

2.3.1 Load and Strain Recording

In order to record strain readings during each test, strain gauge amplifiers are connected to a digital image correlation software developed by Correlated Solutions. Strain gauges are wired to the amplifiers which are connected to the program. This set up is also used to record the load applied during each test. Two load cells will be used during each test; one connected to the digital image correlation software, and the other connected to the test machine to control the load cycle for each test. Load and strain data is collected at a rate of 4 readings per second and saved to the computer in the form of a spreadsheet.

2.3.2 ASTM Composite Standards

Table 1 lists the ASTM Composite Standards that Pepin Associates, Inc. used to perform the tests. These tests will be used to define the mechanical properties of the laminates prepared with the aligned, discontinuous unidirectional prepreg tape. Coupon layups shown in the table are chosen based on the ASTM minimum thickness requirements for each test.

Table 1. ASTM Coupon Test Matrix

| ASTM Standard | Test Type | Coupon Layup | Coupon Width (mm) | Coupon Length (mm) | Crosshead Speed (mm/minute) | No. of Replicates |
|---------------|--------------------|---------------------|-------------------|--------------------|-----------------------------|-------------------|
| D2344 | Interlaminar Shear | [0] ₄₂ | 25.4 | 38 | 1.3 | 5 |
| D3039 | Tensile | [0] ₈ | 13.0 | 254 | 3.2 | 3 |
| D3410 | Compression | [0] ₁₄ | 13.0 | 114 | 1.3 | 5 |
| D3518 | In-Plane Shear | [±45] _{5s} | 25.4 | 254 | 3.2 | 5 |

2.3.2.1 Interlaminar Shear Test Procedure (ASTM D2344)

Flat, short beams are subjected to three-point loading to determine the short-beam shear strength of a composite material. The fixture shown in Figure 3 consists of a flat plate with two notches to hold 0.32 cm supports. The distance between supports was calculated using the required span length-to-measured thickness ratio of 4. The loading nose attached to the load cell is 0.63 cm diameter. Once the short beam is centered on the supports, the loading nose applies load at the recommended crosshead speed of 1.3 mm/minute.

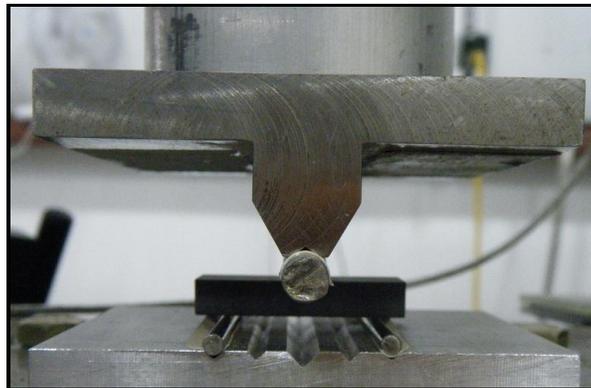


Figure 3. Set up for the short-beam shear test.

2.3.2.2 Tensile Test Procedure (ASTM D3039)

Coupons are gripped at both ends with the bottom grip fixed. The top grip will pull the coupon at a set crosshead speed shown for each test in Table 1 above. Glass tabs are bonded to the gripped ends of each coupon to prevent gripping damage during testing. The crosshead speed was chosen based on testing development and initial trials. Slower crosshead rates caused the coupons to slip between the grips. Load applied and axial strain at three points during each test will be recorded.

2.3.2.3 Compression Test Procedure (ASTM D3410)

A Wyoming Modified Celanese Compression Test Fixture will be used shown in Figure 4. The minimum thickness was determined using Table 3 of ASTM D3410 Standard and the compression strength and longitudinal modulus found on the Hexcel data sheet for IM7/8552 prepreg. Force is applied to the top of the test fixture while load and strain are recorded for each replicate. Tabs were not used for this test because of the thickness requirement needed for the coupons to fit precisely in the test fixture.

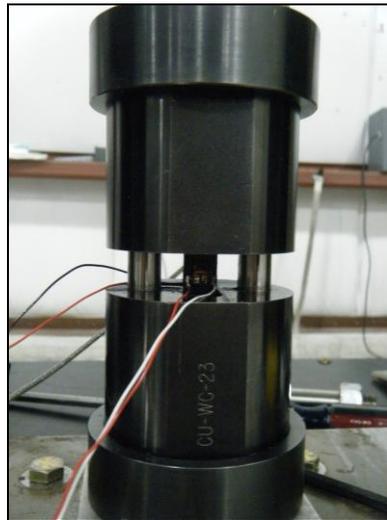


Figure 4. Wyoming Modified Celanese Compression Test Fixture with coupon and strain gauges attached.

2.3.2.4 In-Plane Shear Test Procedure (ASTM D3518)

In-plane shear properties will be determined following the test ASTM D3039 test procedure. Both axial and lateral strains will be measured along with the applied load.

3. RESULTS

The ASTM testing shows that the straight cut pattern provided results similar to the continuous specimen for both in-plane shear and interlaminar shear tests. Issues seen during compression and tensile testing included the test specimens slipping in the grips, tabs not properly bonded to the test specimen, and the strain amplifiers reaching maximum output resulting in lost data. Comparisons between the successful tests are shown in Figure 5. Because some tests were not completed successfully, additional test should be prepared to support the test program.

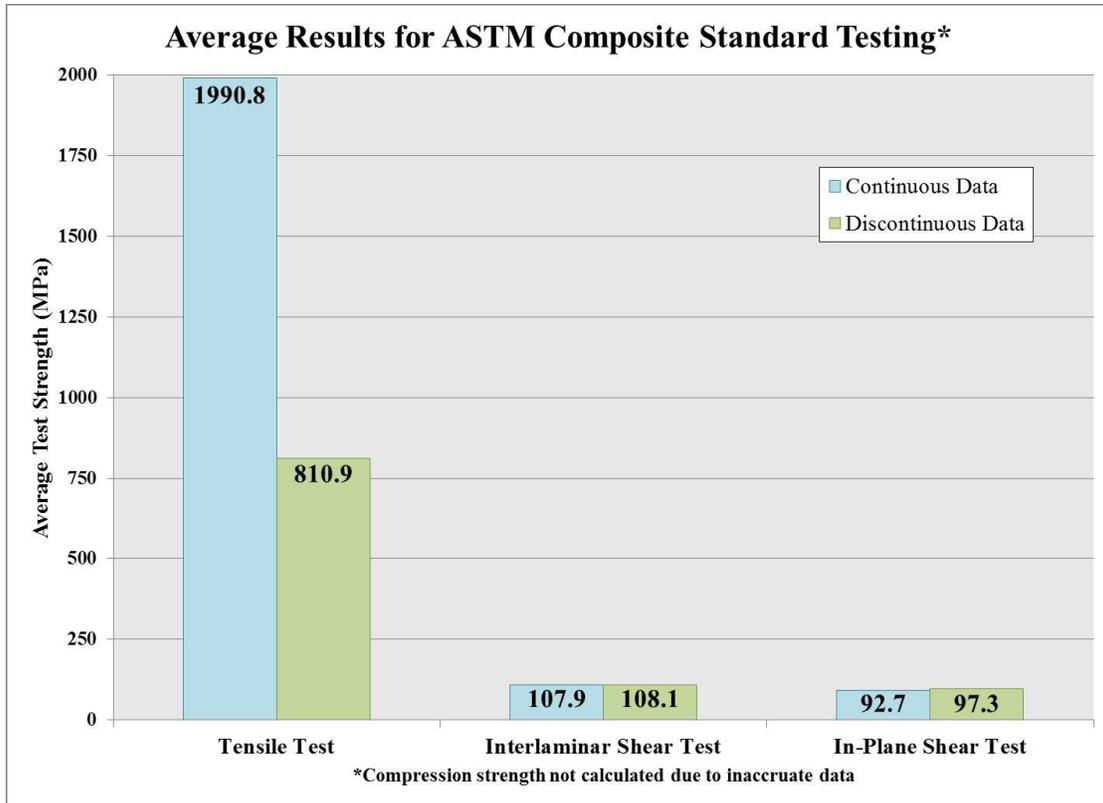


Figure 5. Average results for each ASTM test conducted. Additional compression tests will be conducted due to inaccurate data.

While the graph shows that the tensile strength is reduced approximately 60%, Table 2 indicates that the tensile modulus for discontinuous prepreg is almost equivalent to continuous prepreg.

Table 2. Average Tensile Modulus Comparison

| | Continuous Tensile Modulus (GPa) | Discontinuous Tensile Modulus (GPa) |
|---------|----------------------------------|-------------------------------------|
| Average | 161 | 156 |

3.1 Mechanical Testing Results

3.1.1 Interlaminar Shear Test (ASTM D2344)

The short-beam strength was calculated using the maximum load recorded from the test machine and the cross sectional area of the short beam. Table 3 shows a comparison of the short-beam strength between the continuous and discontinuous beams. Failure occurred in all specimens when the load drop exceeded 30%. Mode of failure for all specimens was due to interlaminar shear. Figure 6 shows a discontinuous short beam after testing. Because the values for each test are almost identical, the straight cut segments can be said to have a negligible impact on the short-beam shear strength.

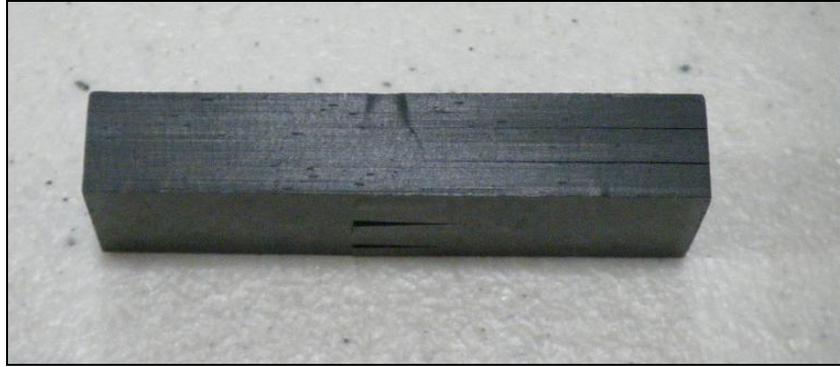


Figure 6. Discontinuous prepreg short beam after testing. Segments splitting on the bottom are dependent on how close the cuts are to the center of the beam.

Table 3. Short-Beam Strength Comparison

| Specimen Number | Continuous Short-Beam Strength (MPa) | Discontinuous Short-Beam Strength (MPa) |
|-----------------|--------------------------------------|---|
| 1 | 110 | 110 |
| 2 | 110 | 107 |
| 3 | 103 | 107 |
| 4 | 106 | 109 |
| 5 | 110 | 108 |

3.1.2 Tensile Test (ASTM 3039)

Based on the results shown in Table 4, the discontinuous straight cut pattern reduces the composite tensile strength by approximately 60%. However, there is a discrepancy between what is published by Hexcel Corporation (approximately 2700 MPa tensile strength) and the results for the continuous data shown. Additional testing will be done to determine the cause for inconsistent data.

Attaining results closer to the published work may increase the tensile strength reduction. Alternatively, Table 5 indicates that the discontinuous tensile modulus is comparable to the continuous tensile modulus. Figure 7 shows a continuous and discontinuous sample after testing.

Table 4. Tensile Strength Comparison

| Specimen Number | Continuous Tensile Strength (MPa) | Discontinuous Tensile Strength (MPa) |
|-----------------|-----------------------------------|--------------------------------------|
| 1 | 2082 | 773 |
| 2 | 1745 | 839 |
| 3 | 2144 | 819 |

Table 5. Tensile Modulus Comparison

| Specimen Number | Continuous Tensile Modulus (GPa) | Discontinuous Tensile Modulus (GPa) |
|-----------------|----------------------------------|-------------------------------------|
| 1 | 157 | 157 |
| 2 | 169 | 155 |
| 3 | 158 | 155 |



Figure 7. Continuous (*left*) and discontinuous (*right*) samples after testing. Because the glass tabs on the discontinuous samples shifted while the adhesive was curing, additional testing will be done to determine if the positioning of the glass tabs effects the tensile strength.

3.1.3 Compression Test (ASTM 3410)

Because of the minimum thickness requirement, tabs were not bonded to the coupons so they would fit inside the Wyoming Modified Celanese Test Fixture. This caused all specimens to slip inside the grips, consequently providing inaccurate data. All tests will be repeated to complete the test matrix.

3.1.4 In-Plane Shear Test (ASTM 3518)

All specimens tested failed due to delamination and brooming shown in Figure 8. One continuous specimen was not completed successfully. The discontinuous in-plane shear stress is higher than the continuous shown in Table 6.

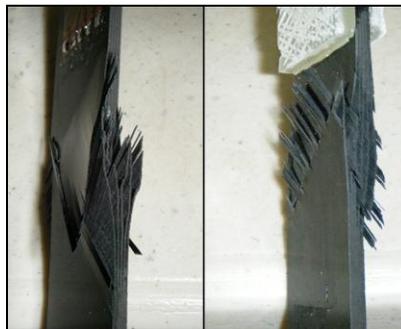


Figure 8. Comparison of continuous (*left*) and discontinuous (*right*) in-plane shear tests. The cut segments can be seen in the discontinuous sample.

Table 6. In-Plane Shear Test Comparison

| Specimen Number | Continuous In-Plane Shear Strength (MPa) | Discontinuous In-Plane Shear Strength (MPa) |
|-----------------|--|---|
| 1 | N/A | 95.7 |
| 2 | 88.6 | 97.0 |
| 3 | 96.4 | 98.3 |
| 4 | 90.1 | 97.2 |
| 5 | 95.6 | 97.0 |

3.1 Dome Forming Trial

Various layups were tested shown in Table 7. A 2.5 cm grid was drawn on each layup to measure the amount the unitape stretched after forming. Results show that the prepreg continues to stretch when the layup thickness increases.

Table 7. Average percent stretch for layups used in forming trials.

| Layup | Average Stretching (%) |
|-------------------------|------------------------|
| (0/90) | 13.4 |
| (0/90) _s | 14.2 |
| (0/90) ₃ | 10.2 |
| (0/90) _{2s} | 10.3 |
| (0/±45/90) | 13.2 |
| (0/±45/90) _s | 10.9 |

Early testing indicated that the straight cut design stretches uniformly. The preforms are examined for defects. For example, Figure 9 shows a (0/90) preform with holes as its defect. In Figure 10 the next layup (0/90)_s was assessed to having no defects, concluding that when the layup thickness increases, the amount of defects would decrease.



Figure 9. Back side of a (0/90) straight cut unitape hemisphere. The hemisphere is held up to a light to show the location of holes.



Figure 10. Back side of a $(0/90)_s$ straight cut unitape hemisphere. Holding up to a light indicates that holes decrease as layup thickness increases.

4. CONCLUSIONS

4.1 Mechanical Testing

The cut segments do not affect short-beam shear strength and increase in-plane shear strength. The discontinuous prepreg tape has a 60% tensile strength reduction based on the testing completed for the program. Additional tensile tests will be done for both continuous and discontinuous laminates due to tab positioning and to understand the differences in tensile strength seen by the continuous specimen and the published data. All compression tests will be repeated to complete the test program.

4.2 Dome Forming Trials

Dome forming trials were successful in demonstrating the formability of the aligned, discontinuous prepreg tape. As the prepreg stretches, holes are noticeable in the smaller layups but decrease as the layup thickness increases. Forming trials will continue using more complex shapes.

4.3 Additional Work

To improve the tensile strength of the aligned discontinuous tape laminates, the width of the segments will be reduced. A herringbone pattern is being incorporated with rows of 45° crosscuts at opposing angles. The width of the herringbone cuts are half of the straight cut pattern. Decreasing the width of the cuts will ultimately provide the discontinuous unidirectional prepreg tape a higher tensile strength. Initial forming trials have been completed using the same layups for the straight cut design and stretched between 10-14%. The preforms have a smoother surface and fewer visible holes in the smaller layups. Laminates will be prepared using the herringbone pattern and follow the same test program.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. ASTM Standard D2344/D2344M-00, 2006, "Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates" ASTM International, West Conshohocken, PA, 2006, DOI:10.1520/D2334_D2334M-00R06, www.astm.org.
2. ASTM Standard D3039/D3039M-08, 2008, "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials" ASTM International, West Conshohocken, PA, 2007, DOI:10.1520/D3039_D3039M-08, www.astm.org.
3. ATSM Standard D3410/D3410M-03, 2003, "Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading" ASTM International, West Conshohocken, PA, 2003, DOI:10.1520/D3410_D3410M-03R08, www.astm.org.
4. ASTM Standard D3518/D3518M-94, 2007, "Standard Test Method for IN-Plane Shear Response of Polymer Matrix Composite Materials by Tensile test of a $\pm 45^\circ$ Laminate" ASTM International, West Conshohocken, PA, 2001, DOI:10.1520/D3518_D3518M-94R07, www.astm.org. [Insert reference 4]
5. Grenestedt, Joachim. "Stretchable Unidirectional Fiber Reinforcement." Final Report under U.S. Army Research Office Contract Number W911NF-08.
6. "HexPly® 8552 Epoxy Matrix Product Data." http://hexcel.com/Resources/DataSheets/Prepreg-Data-Sheets/8552_us.pdf. December 2007. Hexcel Corporation, Stamford, CT, USA.