Measuring the Mechanical Properties of a Newly Developed Discontinuous Carbon Fiber and Epoxy Composite

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Approval Page

Project Title: Measuring the Mechanical Properties of a Newly Developed Discontinuous Carbon Fiber and Epoxy Composite

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Abstract

Engineering firm Pratt & Miller have developed a new and previously untested carbon fiber/epoxy composite using a spray lay-up process similar to a process commonly used in fiberglass production. This new composite is made by using a pneumatic chop gun that simultaneously cuts the carbon fibers to a specific length and deposits the chopped fibers and resin onto surface of an exposed mold surface. The composite is then rolled down to flatten and better wet the fibers and then the whole mold is vacuum bagged at room temperature to cure. The flexural stiffness and flexural strength of the composite with 1” and ¾” average fiber lengths were found using three-point bend testing. The bend test samples had dimensions of 50.8 mm x 12.7 mm x 1.40 mm as per ASTM 790-03 for thin sheet materials. Because initial tests showed that there was too much scatter in the data due to thickness variations within the samples, they were flattened using a belt sander to within 0.1 mm of their average thickness. The material exhibited an average flexural stiffness of 28 GPa and an average ultimate flexural strength of 400 MPa.

Keywords: Materials Engineering, Carbon Fiber, 3-Point Bending, Discontinuous Fiber Composite, Spray Layup

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1. Introduction

1.1 Project Synopsis

Pratt & Miller Engineering (New Hudson, MI) has developed an untested method for making a discontinuous, or chopped, carbon fiber composite using a process widely used in fiberglass composite production. This process, commonly known as spray layup, utilizes a pneumatic chop gun that both chops the carbon fiber into small lengths and mixes them with resin before being sprayed out of the gun onto the surface of a mold. Once the surface of the mold has been covered by the resin/fiber combination it is then vacuum bagged to remove air bubbles or voids and to consolidate and cure the final composite. Because this manufacturing process has not been formally tested, three point bend tests were performed to determine the material's flexural stiffness and flexural strength to see whether or not it can be used in structural body panels for high performance automotive racing applications.

1.2 Technical Background

1.2.1 Carbon Fiber in Automotive Racing Applications

In the ever-evolving and high-speed world of top tier automotive racing, even the slightest advantage can mean the difference between winning and losing. With stringent rules regulating engine size and power output in most race series, race teams must look to pushing the boundaries of all available areas of technology to increase their odds of winning.

In 1981 when McLaren introduced the world's first carbon fiber composite chassis Formula 1 car (Figure 1), many thought that the idea was crazy and that this mysterious "black plastic" could never be the future of car racing.[1] The competition thought that it was not nearly strong enough to withstand the rigors of racing and certainly not strong enough to withstand a crash at high speeds. However, in the following three seasons, the car went on to win six races and driver John Watson's crash at the 1981 Monza Grand Prix proved that the car was much safer than its aluminum chassis counterpart.[2] The

combination of the carbon fiber composite's decreased weight and increased stiffness compared to the other cars in the field meant that the McLaren was a faster and more nimble racecar. By the end of 1983, all the critics were silenced and the era of carbon fiber in racing had arrived.[1]

Figure 1. Chassis of the McLaren MP4/1, the world's first carbon fiber chassis.[3]

While Formula 1 was the first race series to use carbon fiber composites in building a majority of the non-drivetrain parts of the car, it took longer for other race series to adopt such a widespread use of the material. This is due to the much higher budgets of Formula 1 teams and that Formula 1 cars do not have to be based on road going passenger vehicles. Although most closed-wheeled racecars today still do not use carbon fiber for their chassis and other main structural components, most race teams strive to utilize as much carbon fiber as possible to reduce weight and increase rigidity. Nearly every external body panel, spoiler, and interior piece must be made of a carbon fiber composite for a modern racecar to be competitive.

Pratt & Miller Engineering have been a dominant force in American and European race series for over a decade. They have led Chevrolet and Corvette Racing to eight consecutive manufacturer and team wins in the GT1 class of the American Le Mans Series along with class wins in the 24 Hours of Le Mans, Seabring 12-hours, and Rolex-24 at Daytona (Figure 2). They also run GM's Cadillac and Pontiac race teams and have

won manufacturer titles in both series.[4] With such a strong presence in multiple race series across the globe, Pratt & Miller must keep up and push the boundaries of carbon fiber composite technology to maintain their winning history.

Figure 2. Pratt & Miller C6R in an American Le Man's Series endurance race.[5]

1.2.3 Continuous Carbon Fiber Composites and the Bag Molding Process

Today the majority of all carbon fiber components for race applications are made using continuous carbon fiber composites. These composites are made of a sandwich of multiple materials including layers of woven sheets of carbon fibers, resin, and sometimes a lightweight honeycomb core to provide additional thickness (Figure 3). Because of the low production rate requirements of a race team that operates only two vehicles per series, a hand layup, vacuum bag, and autoclave method is usually used to make these composites.

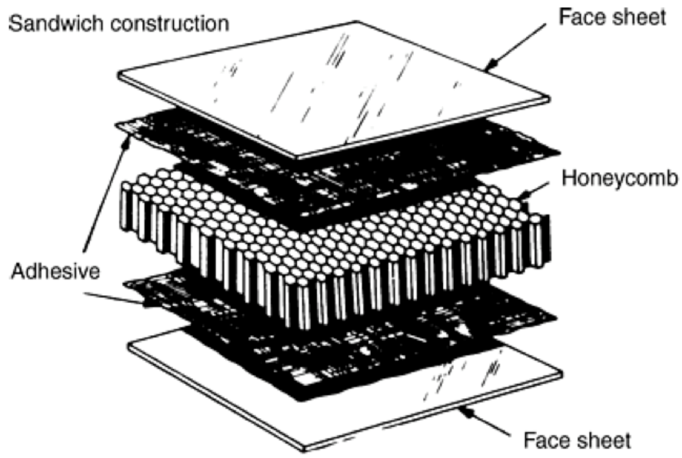

Figure 3. Cross-sectional view of typical composite laminate. Woven carbon fiber sheets are used as the face sheets that are bonded around a lightweight honeycomb core.[6]

To start the hand layup process a thin layer of Teflon-coated glass fabric is laid into the mold to prevent the final composite to sticking to the mold surface. The woven carbon fiber sheets are then layered on top of the Teflon fabric, which will become the outside layer of the final laminate. The carbon fiber sheets used typically contain partially cured (B-staged) epoxy resin, called a prepreg sheet, to ensure uniform resin distribution throughout the composite and make it so that resin does not have to be pumped into the laminate during vacuum bagging. A layer of porous Teflon and bleeder papers are then placed on top of the prepreg. The porous Teflon layer makes it easier to remove the other fabric layers from the final laminate and the bleeder papers absorb excess resin that is squeezed out of the prepreg during processing.[7] Figure 4 shows the layering of fabrics in a typical vacuum bagging process.

After the layup is complete, a vacuum bag is placed around the outside of the mold and laminate. A vacuum is then applied to the laminate, pressing it firmly into the mold and squeezing some of the resin out of the prepreg at elevated temperatures. The vacuum applied also serves to remove air or other volatiles that could hinder performance. The vacuum bag set up is then loaded into an autoclave that heats and further pressurizes the laminate against the mold. During the initial heating, the viscosity of the B-staged resin drops and allows it to uniformly distribute itself within the laminate and completely wet

the fibers. After a certain time, the resin begins its curing phase and begins to cross-link. The temperature in the autoclave is then raised to full curing temperature and held until the desired degree of cure is reached, after which the temperature is slowly lowered. Pressure is applied throughout the whole process to maintain the composite's shape and also to help squeeze out any residual air bubbles.[7] After the bag and mold assembly are removed from the autoclave, the final composite is removed from the vacuum bag and is ready to be used.

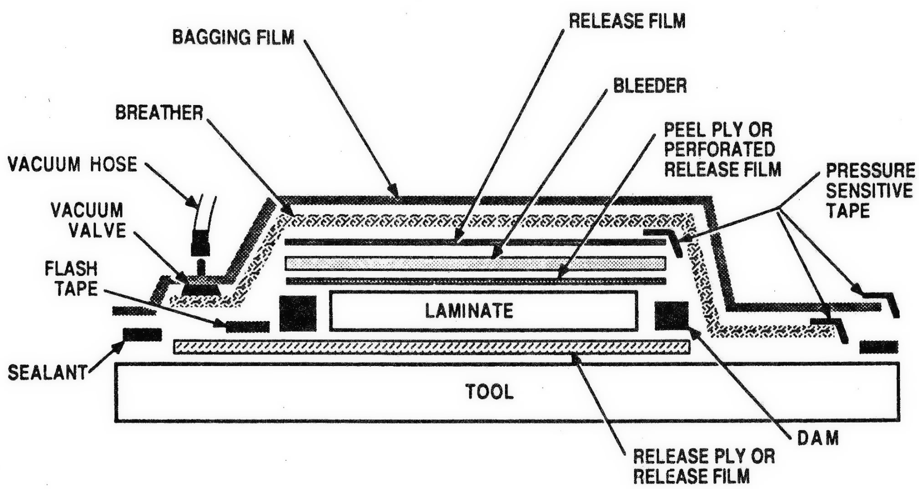

Figure 4. Schematic of vacuum bag molding process illustrating necessary materials in addition to the vacuum bag itself.[7]

1.2.4 Discontinuous Carbon Fiber Composites

Despite the fact that most composites used in racing today contain long and continuous carbon fibers, the use of discontinuous carbon fiber composites has increased in the last few years.[9] In discontinuous carbon fiber composites, the fibers are cut or chopped into short lengths and randomly distributed throughout the matrix material. The composite gains its strength from the matrix transferring stresses to the short fibers that support the load. Discontinuous fiber composites are generally less strong than continuous fiber composites because there are fewer fibers supporting the direction of loading coupled with a usually a lower volume fraction of fibers in discontinuous fiber composites.[7]

Most discontinuous carbon fiber composites today are made using a sheet molding compound (SMC) which is compression molded. Like carbon fiber prepreg, this SMC material contains both fibers and partially cured resin, but the fibers in SMC are chopped into small lengths. To make a composite using SMC, first the mold of the part must be made of high carbon steel. This mold must be made in such a way that when the SMC charge material flows throughout the mold, the part contains a correct ratio of fiber to resin. Once the mold is made, a pre-calculated amount of SMC, called a charge, is loaded between the two mold halves. The two mold halves are then closed under high pressure and temperature to make the SMC charge flow throughout the mold. Figure 5 shows a charge being loaded in a mold and the following compression step. The mold is then held shut for 10-15 minutes at high temperature to allow the composite to cure.[9] The composite is then removed from the mold and can be used right away or sent to other machining steps.

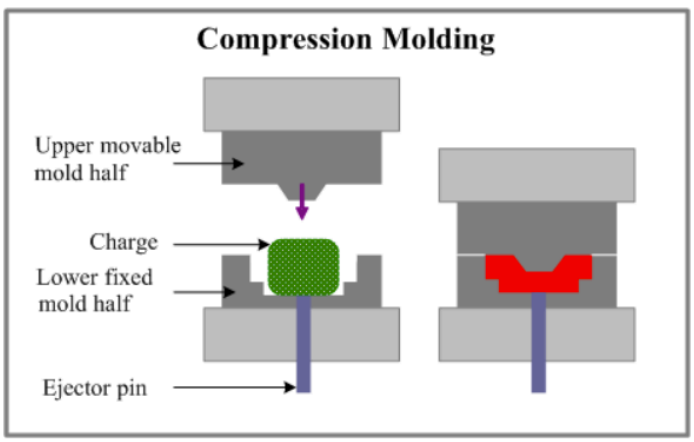

Figure 5. Diagram showing compression molding process. The green rectangle (left) represents the blank charge of material loaded between the mold halves. When the mold halves are forced together the charge is formed into the desired part in red (right).[9]

The benefits to using SMC and compression molding are numerous: much higher production rate compared to other manufacturing methods, nearly no material loss during processing, and the simple creation of complex 3-D shapes. The negative aspects of using this method come mainly from the production of expensive steel molds that require extensive engineering to ensure that the final part maintains a proper fiber-to-resin ratio throughout the piece.[10] Decreased materials properties compared to continuous fiber

composites are also a negative aspect of the SMC process. American company HexCel reports that their final SMC material typically has flexural stiffness around 29 GPa and flexural strengths around 400 MPa.[10] SMC and compression molding is generally used when the high initial investment is outweighed by the increase in production rate.[9]

1.2.5 Spray Layup Process

Recently, Pratt & Miller Engineering has developed a new way to make carbon fiber composites using a spray layup method similar to what has been used for fiberglass for years. In this method, a continuous carbon fiber tow is fed through a chop gun that cuts the fibers into a pre-specified length. As the fibers are cut, they are then mixed with resin and sprayed out of the gun onto a mold surface. When the entire mold surface is covered, the fiber/resin mixture is rolled down with a paint roller to smooth out and compact the surface after which another layer may be sprayed on (Figure 6). Once the desired thickness is reached, the mold is then vacuum bagged to remove any air bubbles or other volatiles. The composite is allowed to cure at room temperature for 2 hours and is then removed from the bag and mold. The short length fibers and random fiber orientation can be seen in Figure 7.

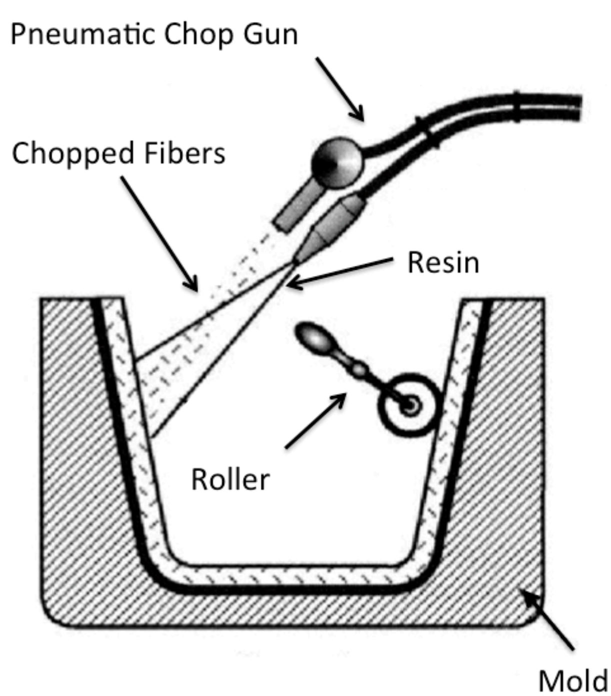

Figure 6. Diagram of spray layup process showing chop gun spraying fiber/resin mixture onto surface of the mold. Roller used to press fibers into the resin is also shown.

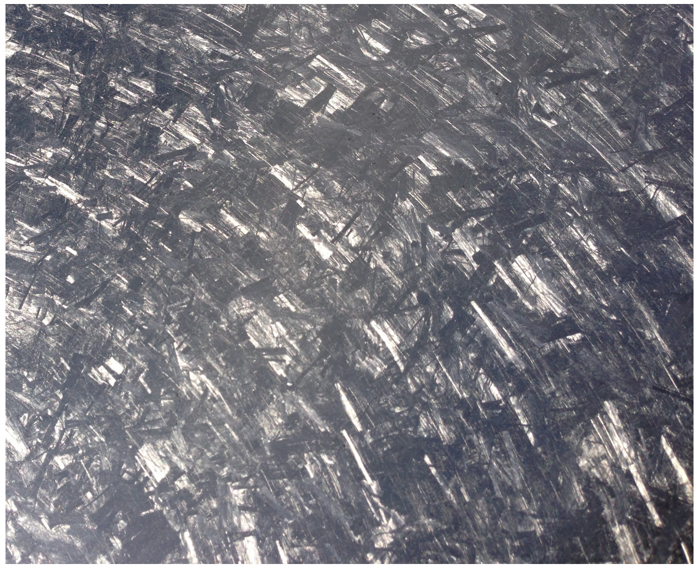

Figure 7. Image of composite panel showing fiber length and random orientation. The appearance of radially oriented fibers comes from the lighting above the panel.

While the spray layup method is new to the world of carbon fibers, it has been used in making fiberglass composites for years and the benefits are well known. It is an economical way to make composite parts, as there is no expensive tooling or highly skilled labor required. Molds can be made out of many materials and do not have to be nearly as strong or heat resistant compared to steel SMC molds. However, to be cost effective, spray layup is limited to simple panel like shapes. Resin density is also likely to be higher to ensure proper fiber wet out, thus increasing the component's weight.[11] Because Pratt & Miller is looking to use this method for affordably making body panels for their cars, neither of these disadvantages outweighs the advantages.

1.2.6 Three Point Bend Testing

Three-point bend testing was preformed on a number of samples to determine the flexural modulus, or stiffness, of the sprayed up composite. In 3-point bending, a single loading nose is lowered onto the material between two support noses (Figure 8). The upper loading nose is continually lowered, causing an increasing bending moment in the sample until it fails. The stiffness of the material is then found using the equation:

$$E_f = \frac{L^3 m}{4bd^3}$$

Where L is the support span of the sample, m is the slope of the linear section of the stress-strain curve (obtained during bend testing), b is the width of the sample, and b is the thickness of the sample.[7] All tests were conducted according to ATSM D790 for thin sheet composites.[11] Examples of the bend test samples can be seen below in Figure 9.

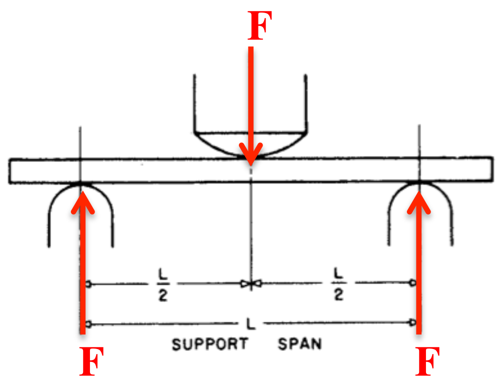

Figure 8. Three point bending schematic showing upper loading nose, lower support noses, and sample support span. Load is applied where the force marked F touches the sample.[7]

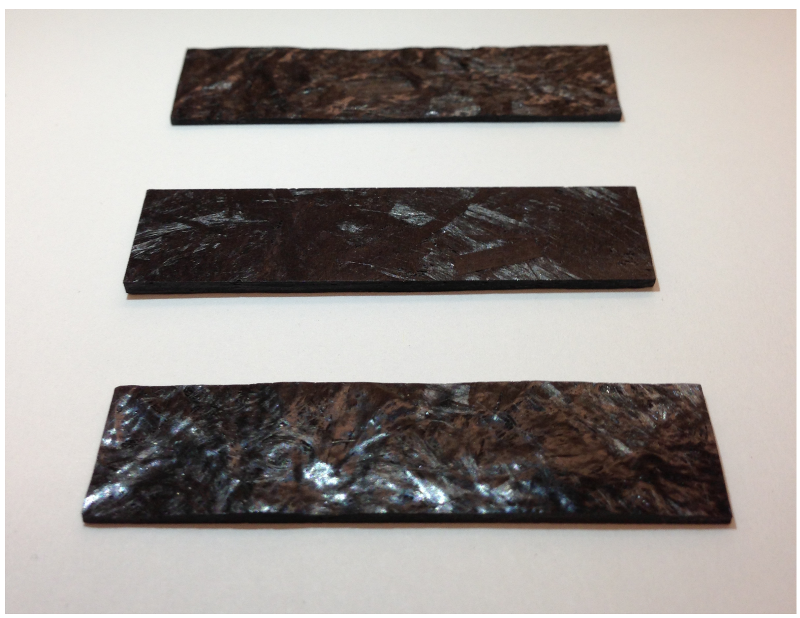

Figure 9. Three examples of bend test samples. They are 2 inches long by 0.5 inch wide and have a thickness of around 1.4 mm.

1.3 Problem Statement and Realistic Constraints

The primary reason in collecting data for this report is to help Pratt & Miller determine if a carbon fiber composite made using the spray layup method both stiff and strong enough to be used for low load bearing body panels for race applications. Three-point bend testing will be conducted on samples of varying fiber length to help characterize the mechanical properties of this new discontinuous carbon fiber composite. In addition to having the mechanical properties needed for the application, the process must lower the economic impact of production and increase manufacturability when compered to the hand layup and autoclave cure process.[12] Ideally, data found from this project will aid other individuals or companies in choosing a carbon fiber processing method that can save them time and money if their target materials properties are met using spray layup.

2. Experimental Procedure

2.1 Composite Samples

The composite laminate made by Pratt & Miller using Toho Tenax G30-700 carbon fibers in a Resin Services epoxy matrix. The fibers have an ultimate tensile strength of 4830 MPa.[13] Exact values for the mechanical properties of the epoxy matrix is unknown, however the tensile strength of typical epoxies ranges from 10-100 MPa with flexural stiffness ranging from about 1 to 4 GPa.[13] Because Pratt & Miller is interested in the affect of fiber length on the mechanical properties of the composite, two large panels were made with different average fiber lengths. The panels initially had dimensions of 3 ft. by 2ft. The first panel had an average fiber length of 1 inch while the other panel had an average fiber length of 0.75 inches. Bend test samples had to be cut from these panels.

2.2 Sample Preparation

The panels were cut using a water lubricated tile saw into samples measuring 50.8 mm by 12.7 mm. The edges of the samples were then lightly sanded to ensure safe handling. Initial tests were performed on samples cut directly from the larger panel without extra processing, however a few rounds of testing showed that there was too much scatter in

data present likely due to the uneven side of the composite causing to up to 40% thickness variation in some of the samples.

In an effort to lower the scatter and make the samples have more uniform in thickness, the uneven sides of the samples were sanded down in two steps. The samples were first belt sanded to achieve a roughly flat surface. Five thickness measurements were then taken and recorded across the width of each sample to determine a baseline average thickness and where additional sanding was necessary. The samples were then wet sanded by hand using 240 grit abrasive paper to within ±0.1 mm of their respective average thickness values. The average thickness of the samples ranged from 0.80 mm to 1.50 mm. Samples from the 0.75 inch fiber length composite received a more rigorous hand sanding procedure after testing of the 1 inch fiber length composite proved that flatter samples led to lower variation in mechanical properties. Samples from the 0.75 inch panel contained no more than ±0.05 mm deviation from their average thickness.

2.3 Flexure Testing

Once the samples were cut and flattened, they were then tested in 3-point bending using an Instron 3369 tensile testing system equipped with 3-point bending fixtures (Figure 10). The samples were tested using a 25.4 mm support span and a crosshead movement speed of 1 mm/min. Five samples were used in each round of testing as per the ASTM 790-03 spec for 3-point bend testing.[11] Instron's Bluehill 2 software was used to control the loading noses and capture data during the tests. An external Epsilon 3540-006M deflectometer was used to measure strain in the samples under the upper loading nose. The deflectometer was placed so that the measurement arm was in the middle of its travel to ensure accurate measurements (Figure 10). Samples were loaded into the fixture with the flattest side of the sample facing down. This orientation was chosen so that the deflectometer had a smooth and flat surface to rest against for accurate measurement.

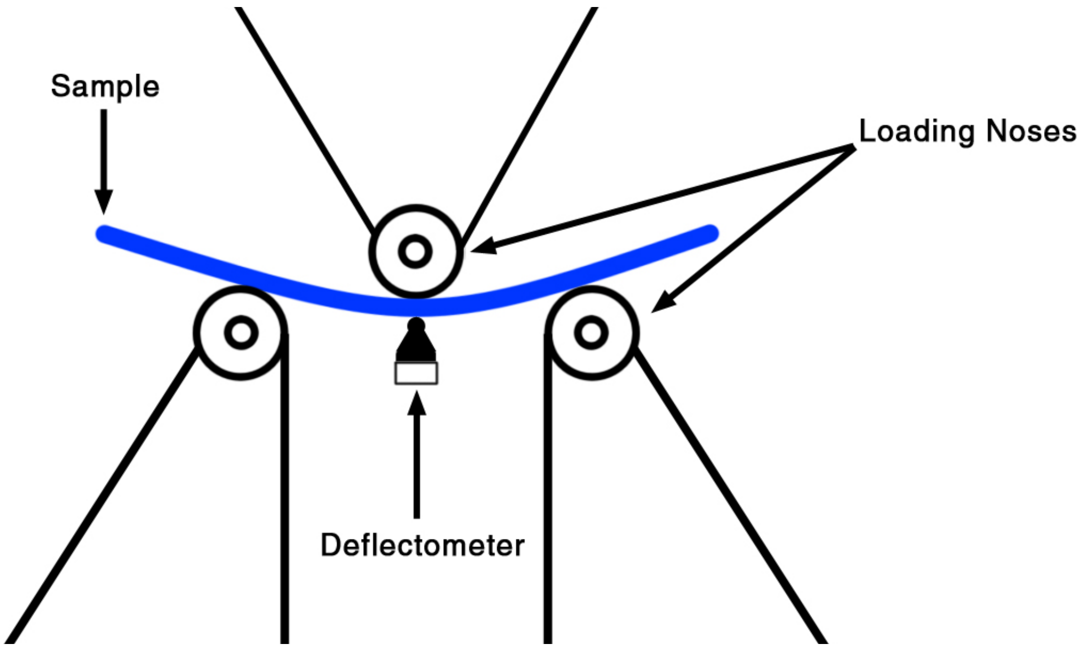

Figure 10. Diagram of experimental test setup. A bending moment is applied to the sample via forces applied through the loading noses. The position of the Epsilon deflectometer can be seen in contact with the sample directly under the loading nose.

3. Results

After testing the composite samples the raw data from the tests were imported into Excel to help calculate the mechanical properties. The first tests of the composite without the sanding process yielded a large amount of variance in both flexural strength and stiffness. In these first tests the material exhibited flexural stiffness values from 22 - 64 GPa and flexural strength values from 130 - 410 MPa with a standard deviation of around 40% of the average value for both properties.

Causes for the large range of values from first tests was likely due to the variations in thickness within each sample as well as possible voids or perforations caused by the thinness of the panel. After discovering that the large panel contained some visible holes through the composite, care was taken in cutting samples where no visible voids were present. Another problem with the non-uniform thickness of the samples occurred when the thickness gradually increased from one side of the sample to the other, causing a slight wedge shape. If the sample showed any signs of being wedge shaped, the point of

maximum flexure almost always happened offset from directly under the upper loading nose and the results from that test had to be nullified (Figure 11).

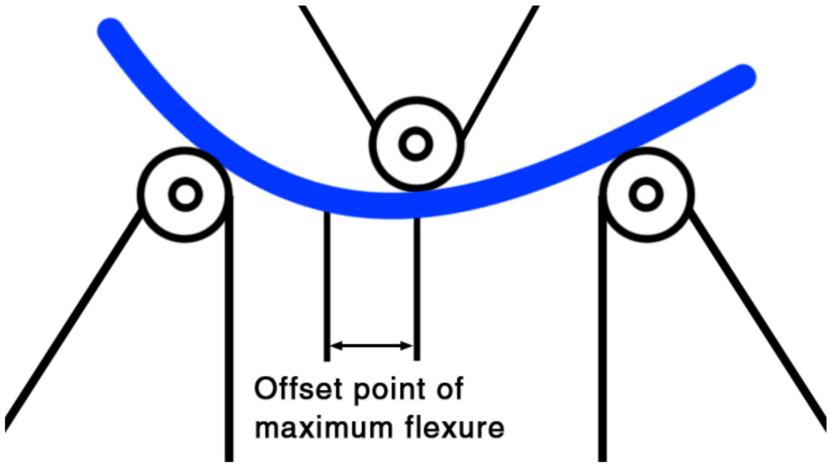

Figure 11. Example of offset bending. Amount of bending is exaggerated to better highlight the problem. Data collected from samples that showed offset bending during testing was not used in mechanical property calculations.

Results from the second round of testing can be seen below in the stress vs strain graphs of Figures 12 and 13. This last round contained the flattest samples and best represented the true properties of the material. The greatly lowered overall scatter in both properties gives more credibility to the average values shown in the table. The composite seemed to have a flexural stiffness of around 28 GPa and flexural strength of around 400 MPa. There still was a fair bit of scatter with stiffness ranging from 22 GPa to 32 GPa and strength ranging from 315 MPa to 517 MPa (Table I).

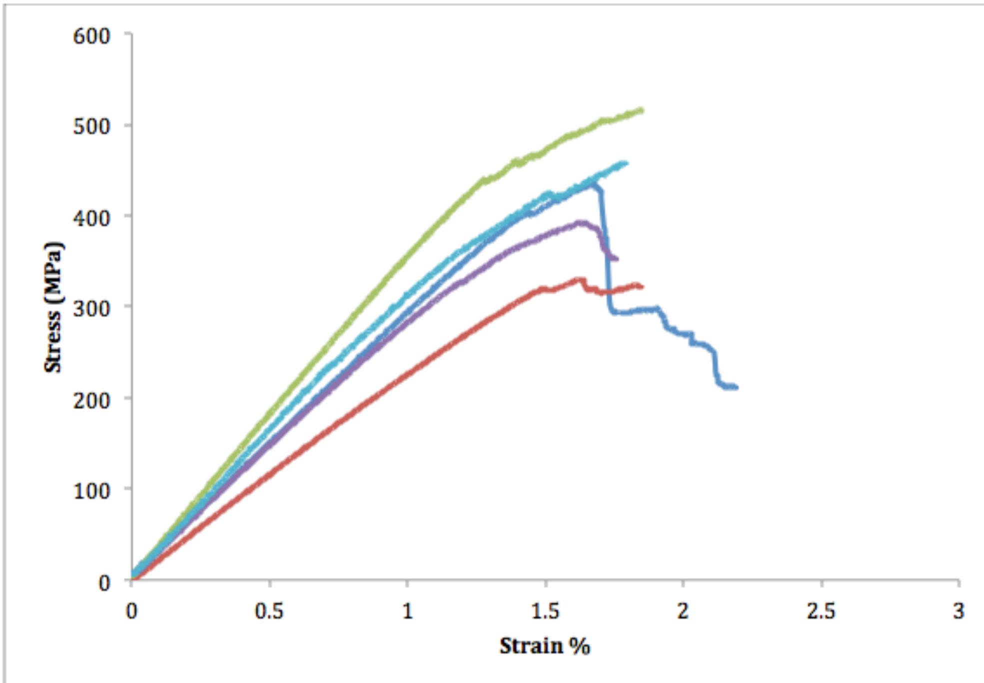

Figure 12. Stress vs strain results of 1 inch fiber length composite. Flexural strength is determined by the amount of stress the sample receives before critical failure. Flexural stiffness is calculated from the slope of the initial linear section of each sample.

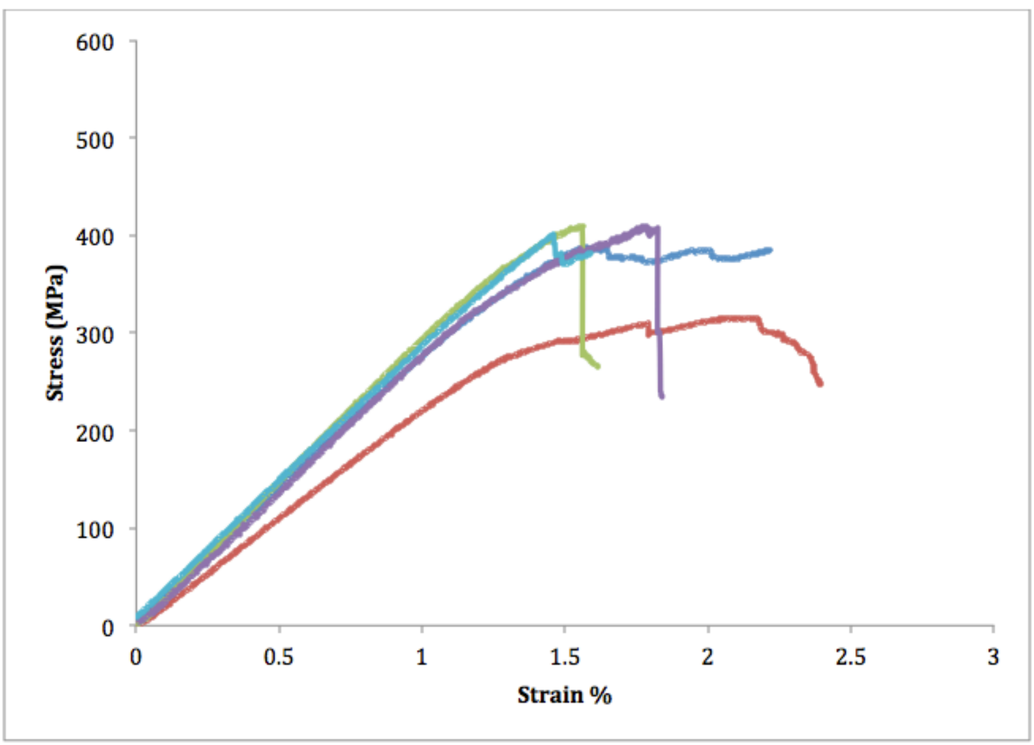

Figure 13. Stress vs strain results of 0.75 inch fiber length composite. Flexural stiffness and flexural strength is determined from this data using the same method as figure 12.

Table I. Recorded Flexural Stiffness and Flexural strength Values for Both 1 inch and 0.75 inch Fiber Length Composite Panels

	1 Inch Ave. Fiber Length		0.75 Inch Ave. Fiber Length	
Sample	Stiffness (GPa)	Strength (MPa)	Stiffness (GPa)	Strength (MPa)
1	28.8	435.9	27.7	387.7
2	22.0	330.3	22.6	315.8
3	35.1	517.1	29.6	409.6
4	28.2	392.9	28.1	409.5
5	31.7	458.6	27.7	401.5
Average	29.2	427.0	27.1	384.8
Standard Deviation	4.8	70.2	2.7	39.6

A one way analysis of variance was run on both stiffness and strength between the two average fiber lengths tested. Although the 0.75 inch fiber length composite seemed to have slightly lower stiffness and strength, there was no statistical difference found between the two composites tested for either property. To better illustrate the differences in the values found between the composites, refer to the boxplots of Figures 14 and 15. The effect of the additional flattening to the 0.75 inch fiber length composite can be seen in the lower overall variation in both mechanical properties compared to the 1 inch fiber length composite (Figures 14 and 15).

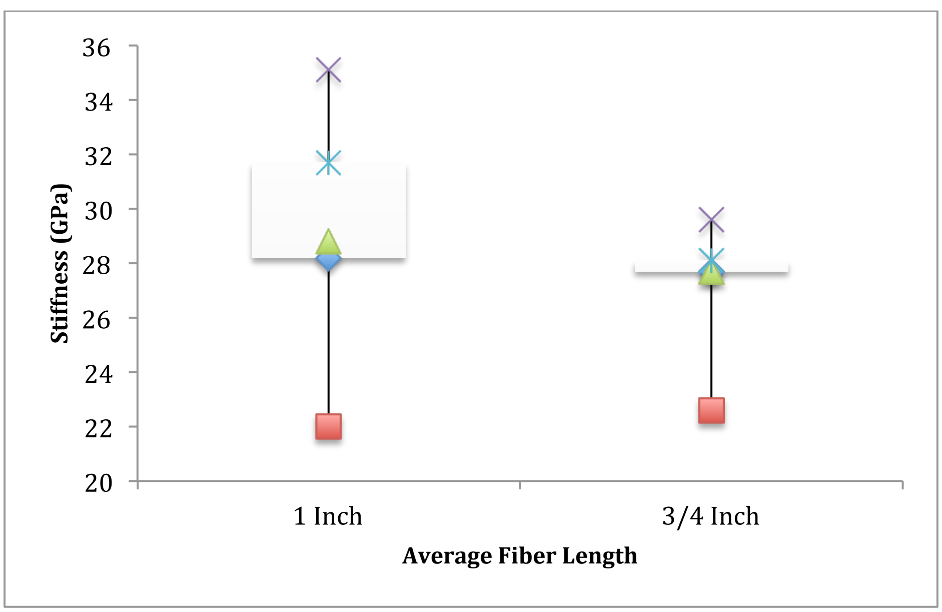

Figure 14. Boxplot of recorded stiffness values for both fiber length composites tested. The difference in variation between the two fiber lengths tested is likely attributed to the additional flattening of the ¾ inch fiber length samples.

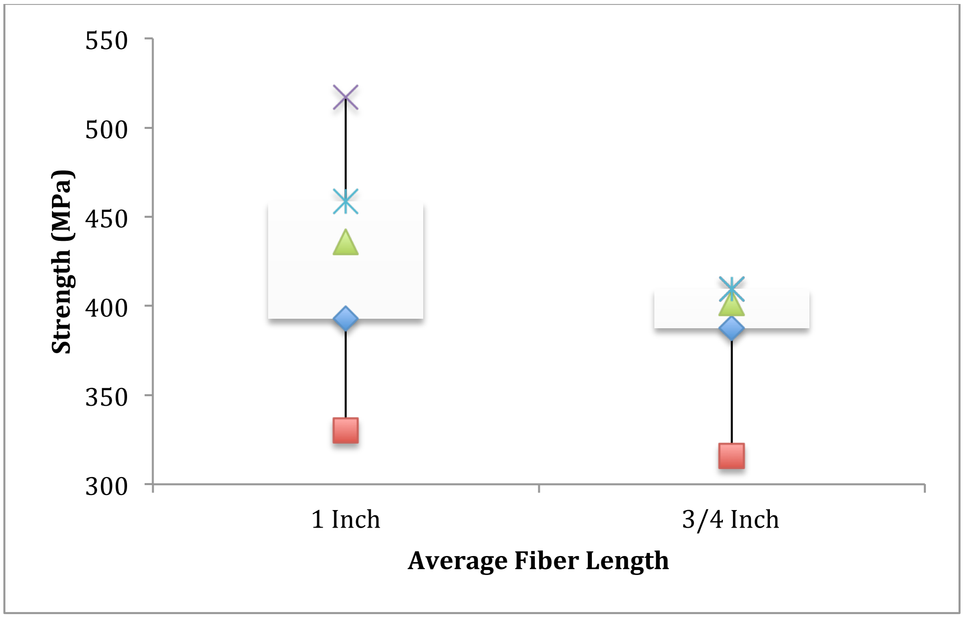

Figure 15. Boxplot of flexural strength values for both fiber length composites. As in the previous figure, the decreased variance in the ¾ inch samples being more flat.

4. Discussion

Since carbon fiber composites derive much of their strength by their ability to share loads along the lengths of the fibers it is expected that the discontinuous composite panels tested for this project do not compare to the flexural strength and flexural stiffness possible with hand laid-up continuous carbon fiber composites. According to MatWeb, a materials property archive, continuous carbon fiber and epoxy composites can reach a stiffness of 200 GPa and flexural yield strength of 2000 MPa,[13] which is much higher than the 28 GPa flexural stiffness and 400 MPa flexural strength of the sprayed up composite. Despite this disadvantage, the sprayed up composite performed relatively well after flattening the samples and exhibited a greater flexural strength and half the stiffness of 6061-T6 aluminum,[13] an alloy commonly used for decades as lightweight automotive body panels.[14] It should be noted however, that the average mechanical properties of the sprayed up composite almost exactly matches the mechanical properties given by HexCel for their discontinuous carbon fiber SMC's adding to the validity of the data collected.

While the upper range of values for the 0.75 inch sample were reduced with additional sanding, the composite still achieves nearly the same minimum property values as the 1

inch fiber length composite. Although the epoxy is not likely to have a flexural stiffness more than 6 GPa or flexural strength higher than 100 MPa, the fact that both composites reached similar minimum values suggests excessive epoxy leading to increased influence over the mechanical properties of the composite. This is likely due to the low thickness of the samples, which may mean that there are some areas in the sample where the fiber/resin mixture was unable to combine properly and fully wet the fibers.

Another issue with the thickness of the samples occurred in early tests where the thickness of some of the samples resembled a wedge shape, as mentioned earlier. When tested, the samples would sometimes experience maximum flexure offset from the upper loading nose and lead to bad data (Figure 11). While the sanding greatly helped this problem, there were still some sample tests that had to be thrown out due to improper bending. This suggests that other factors such as internal voids or nonhomogeneous distribution of resin may be the cause of this issue. These small inconsistencies are difficult to avoid using spray layup when making a thin sheet panel due to the way the fiber/resin mixture is deposited onto the mold. Because the resin and fiber mixture are mixed as they travel from the chop gun to the mold surface, the fibers may have a chance of clumping up and causing a non-homogeneous structure. While the vacuum bagging step help to redistribute the resin more uniformly, there is always the possibility of heterogeneous sections. Producing a thicker panel would allow for a longer vacuum bagging step, but more uniform resin distribution.[15]

Even though Pratt & Miller did not disclose any information regarding target flexural stiffness or flexural strength values required for automotive body panels; with some refinement to the process, spray layup seems to be a viable option for body panel manufacture. The most important of the refinements is to make the mold side surface of the composite smoother. The automotive world demands a surface finish of AAA rating and although the flat side of the composite is relatively smooth, as it is now it would require additional wet sanding before being painted.[10] The use of a higher quality mold may solve this issue so the composite part can be painted right out of the mold. Even at its lowest recorded strength the composite is still stronger than 6061-T6 aluminum that

has been used for automotive body panels for many years. While the stiffness is about half that of aluminum, the tested composite is still much more stiff than spray laid-up fiberglass that has been used on the first Corvette since 1954 that has flexural stiffness of around only 2-6 GPa.[15]

5. Conclusions

1. The composite exhibited a flexural stiffness an average of 28 GPa and a flexural strength of 406 MPa, which is comparable to mechanical properties of other discontinuous carbon fiber composites. However due the variation in the data, minimum values of 22 GPa for flexural stiffness and 300 MPa for flexural strength should be used for safety reasons.
2. There was no statistical difference found between the two average fiber lengths tested.
3. The spray lay up process seems to be viable in the creation of low load nonstructural automotive body panels.

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