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Design, Testing, Analysis, and Material Properties of Carbon Fiber Reinforced Polymers

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Design, Testing, Analysis, and Material Properties of Carbon Fiber Reinforced Polymers

By

Andrew Miner

&

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May 30th, 2016

Abstract:

Rose-Hulman Institute of Technology excels in many fields, however in the field of Carbon Fiber Reinforced Polymers (CFRPs) there is a significant lack of knowledge. Over the 2015 summer I started accumulating and building a knowledge base for the institute to help future students who have interest in this ever expanding field. This report covers many of the learnings I found in the structures of fiber reinforced polymers, manufacturing processes and controls, testing procedures and standards, important considerations in the design process of CFRPs, and analysis capabilities and methods. This report is organized as a series of short guides to assist students with the individual subject matters at hand. While many of these are bolstered by the knowledge provided in other parts of the document, due to the multifaceted approach to the problem, this is a much easier way to communicate the information to undergraduate science and engineering students trying to work reliably with CFRPs or other composite materials. Special thanks to the Rose-Hulman Institute of Technology Mechanical Engineering Department for supporting this project.

Material Properties and Design Considerations of Carbon Fiber Reinforced Materials

Introduction:

Carbon fiber reinforced polymers (CFRPs), or more commonly referred to as just carbon fiber is a rapidly expanding field in the engineering design world, being used everywhere from the structures of spacecraft down to high end sporting equipment such as cycling. CFRPs have incredibly high strength to weight ratios, very high stiffness, and many other interesting properties that have caused it to take over the market for high-performance structures.

Carbon Fiber structure is very unlike that of typical monolithic[1] materials, especially considering that when looking at a material for design consideration the only first consideration is how it behaves on a macro scale. Metals for example are classified as isotropic materials, meaning that regardless of the direction of the material, it acts the same. CFRPs are structured in an interesting way because it is actually a combination of 2 different materials. The first material is the reinforcement, long thin fibers of carbon which individually are a thread several times thinner than a human hair. A few thousands of these threads are grouped together in what is called a tow, a few millimeters wide, and this is the most basic way you can purchase carbon fibers. These tows are often woven together as fabrics which give CFRPs the dark checkered pattern they are often known for. However these are loose fabrics, which are very flexible and provides no strength in any direction other than a tensile force in plane with the fabric. They are purchased in large rolls similar to any fabric purchased from a craft store.

The second part of a CFRP is the matrix, in this case a polymer. This is typically a thermoset plastic such as epoxy or polyester. Epoxy for example is typically a two part liquid system which cures to form a solid polymer material. The final product of a CFRP is comprised of the polymer matrix with many individual fibers running throughout it. The polymer provides the shape and holds the fibers in place relative to each other, transferring loads the very short distance between fibers. The fibers provide most of the strength and stiffness to the material, although this only exists in the direction that fibers are running.

This is what provides the most significant challenge when working with carbon fiber materials. Any loads applied that are not in a direction that the fibers travel, would be relying on the matrix material properties, which are much weaker than the reinforcement. This means that when designing, you require a much better understanding of the loading that will be experience by the structure, because improper loading can cause stresses in the wrong direction, failing at a much lower equivalent stress than expected. This same reason is why carbon fiber is an amazing material for designing complex structures. With a good understanding of the loading, reinforcement can be only where is it need and only in the important direction.

General Properties:

CFRPs are well known for their high strength, high stiffness, and low weight. Additionally carbon fiber has many other interesting properties that make it suitable for complex applications. Most solid materials will expand when they increase in temperature, for structures such as

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[1] Monolithic: Consisting of one piece; solid or unbroken.

spacecraft which experience both intense thermal gradients and a wide range of temperatures, this poses a problem as a change in shape causes undue stress in the structure and at joints. This expansion is characterized by the coefficient of thermal expansion, just like any other material property. The polymer matrix has a positive coefficient of thermal expansion, like most materials, meaning that it expands with increased temperatures. Carbon fibers on the other hand have a negative coefficient, actually becoming shorter as they are heated. This means that if the carbon to epoxy ratio is closely controlled in the material, it can have a zero coefficient of thermal expansion, or any other within a certain range. This design capability is massively useful when working in extreme environments. It will build up residual stress in the material due to the conflicting material expansions but

CFRPs are also very chemically stable. This allows it to withstand extreme temperatures and harsh environments. Unlike metallic structures it has no melting temperatures and the temperature does not affect the yielding stress in the material. If the polymer matrix was a thermoplastic it would melt in a high temperature environment, however this is not nearly as common to use as a thermoset[2].

CFRPs are known to have high fatigue lives as well, and tend not to experience material nonlinearities. They are classified as a brittle material which does mean that special precautions have to be taken in the use and manufacturing of composite parts. If handled improperly, large fractures can occur or the layers of reinforcement can separate from each other, called delamination. Additionally this brittleness is a concern for when they do fail. Generally a metallic structure or beam will be subject to strain hardening[3] when it is loaded past its yield value, showing clear signs of failure before it actually stops supporting the load. A brittle material, such as CFRPs, do not do this. They reach an ultimate load and then immediately snap, which is exciting in a testing scenario, but potentially dangerous in operation because there is no chance to prepare for the failure.

Design Considerations:

When designing for CFRPs, understanding the manufacturing process is very important. Layers of fabric reinforcement are first impregnated and laid up onto the surface of a mold. Pressure is applied on the surface of the carbon to press the many layers of material together and squeeze out excess epoxy from the material. After this cures, there is often excess material that needs to be trimmed, or you may be working with a flat panel that will have complex geometries cut out of it. Either way this is an area where the brittleness of the material is an important concern. Using the proper tooling and running them at the proper speeds is very important, because failure to do so can easily cause irreparable cracks through the structure, or cause delamination. Many good process and tools have been developed for the machining of brittle materials but it is important to ensure these are researched and followed closely.

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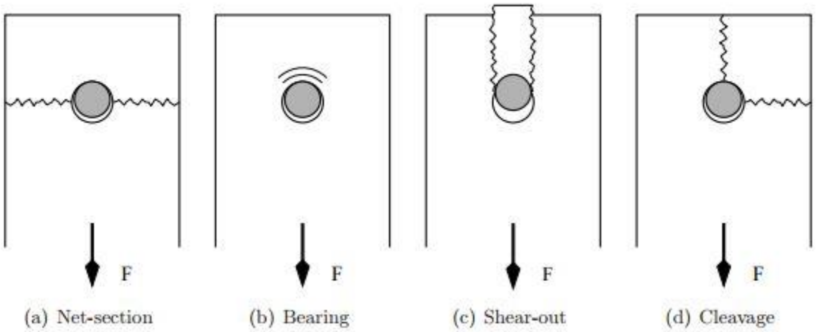
[2] Thermoplastic vs Thermoset: Thermosets harden by an irreversible chemical process which forms a plastic, thermoplastics melt at high temperatures and are formed by melting and letting cool in a mold

[3] The strengthening of a metal by plastic deformation. This occurs due to the change in the crystal structure of the material

The layup process is very important consideration when designing with complex geometries. You need to ensure that it will be possible for reinforcement to be laid across the surface. For deep groves it may be hard to get carbon fabric to lay properly when manufacturing. The easier the surface is to access the, more accurately and easily the part will be to manufacture.

Another important aspect of the design, is the reinforcement type, orientation, and layering. The three main types of reinforcement to consider are weave, unidirectional, and tows. Tows are typically used when wrapping a cylindrical or spherical mold. Unidirectional is a wide strip of fabric that can be laid onto a surface, with all of the fibers running parallel to each other. This has the highest strength to weight in the fiber direction. Weave has fibers running in perpendicular directions, interwoven into a fabric. Weave is slightly weaker than unidirectional due since the fibers don't not lay as flat, but is typically easier to work with as it stays together better. With weave you can get fabrics that have different patterns in the weave. The tighter the weave the more stiff it is as a fabric, meaning that will be easier to work with, but slightly harder to conform to tight corners or complex geometries.

When building with composite parts, joining is an important consideration. Typical methods for joining structures include bolts, rivets, welding and adhesives. Up until recently adhesive bonding was not nearly as prevalent in frames since adding a series of rivets or bolts can be performed so easily by both human and robotic assembly lines. For metallic structures that require a more consistent and permeant attachment method then riveting a multitude of welding methods have been developed, which unfortunately are entirely ineffective with carbon fiber parts. Additionally bolts and rivets run into problems when used in carbon fiber components, raising concerns of galvanic corrosion and problems with brittle material failure, seen in figure 1. A metal component would be more likely to yield slowly versus fracturing quickly at its failure limit as carbon fiber does.



(a) Net-section (b) Bearing (c) Shear-out (d) Cleavage

Figure 1. Basic failure methods of carbon fiber around a bolt-like load

With all these concerns adhesive bonding has become a prevalent method for joining composite structures together. As a designer it's important to think of what process will used to join the parts together, and plan these joints accordingly.

Manufacturing guide for test coupons, made from a flat plate.

Introduction:

This guide is to manufacture testing specimens by laying up a flat plate and cutting specimens out from it. This is an abridged and modified version of ASTM D5687, *Standard Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation*, designed for the use of science and engineering students looking for an introduction into experimentally determining material properties and manufacturing standards. It is highly recommended that you read through this entire guide before you start testing, referencing this or ASTM D5687 as needed. This guide assumes the use of pre-impregnated carbon fiber which needs to cure at an elevated temperature

Materials:

Base Plate: the base plate should be made of aluminum and milled flat to ensure proper flatness tolerances. This will be the surface that the laminate is prepared on.

Breather: A loose, randomly spun material that allows airflow through it.

Caul plate: the caul plate should be made of aluminum and milled flat to ensure proper flatness tolerances. This will sandwich the laminate with the base plate to ensure constant thickness and flatness tolerances.

High Temperature Tape: Polyester film tape that is resilient to high temperatures.

Peel Ply: a fabric designed to act as a release from a resin composite, leaving a textured surface that is good for secondary bonding

Release (TFE) film: a thin plastic film that is specifically designed to act as a release from a resin composite, leaving a smooth surface

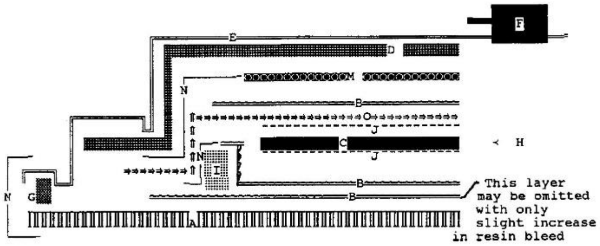
Resin dam: This can be made out of a cork tape, as long as it can withstand the temperatures experienced in the curing process

Vacuum Bag: Thin plastic designed to hold vacuum pressure on the mold surface.

Vacuum Bag Sealant tape: A gummy tape to make a seal between the vacuum bag and the base plate

Process:

The area being used for the layup on the base plate should be bordered with the damming material. The caul plate should be the exact size of the layup area so it can be used as a guide to attach the cork tape around. Adding the rest of the layers as depicted in figure 1 building from the bottom up. Ensuring that the caul plate fits securely after adding each layer of material can help to compress the stack up and ensure everything is in properly.



Key

A	Base Plate	J	Peel Ply (used on panels that undergo secondary bonding
B	TFE Film	K	Bleeder cloth (may be several plies)
C	Laminate	L	Release Fabric
D	Air Breather	M	Caul Plate
E	Vacuum Bag	N	High Temperature Tape
F	Vacuum Coupling	O	Breather string (optional along non 0° edges of laminate to provide a path for volatile escape. String must contact air breather).
G	Sealant		
H	Thermocouple		
I	Dam	P	25 mm (1 in.) wide bleeder cloth

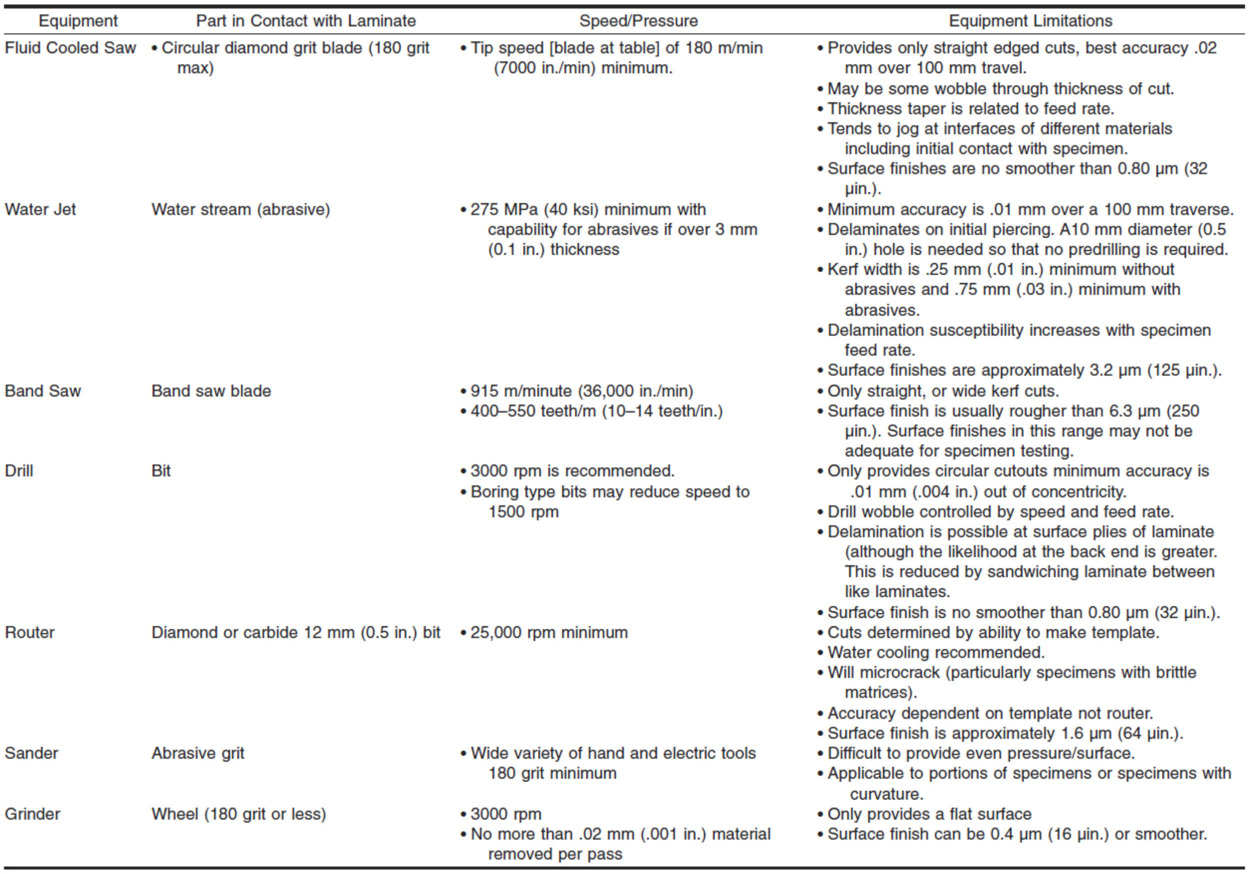
Figure 1. Layup procedure

When pulling a vacuum on the layup, a venturi will often pull enough pressure but a vacuum pump can be used to get higher pressure if desirable. Always be sure to test the vacuum to make sure that there are no leaks as these can lead to poor result during the layup. This mold should then be placed into an electronically controlled oven programmed to the desired curing temperature. In order to prevent damage from thermal strains, the temperature ramp up and down rates should be set to 3 degrees F per minute.

After demolding the films, tapes, and peel ply should all be discarded. Assuming no resin cured in the breather, that can be reused and if there is no visible damage to the resin dams they are okay to be reused.

Machining the composite specimens from the flat composite plate produced needs to done carefully. Using a water jet, you can cut out the profiles of the specimens, with about 0.040 in of excess material on each side to be machined off later. Additionally ensure that a 2 inch radius around the location of piercing is discarded in a later operation because the piercing operation tends to cause delamination in the specimen. ASTM recommendations for other machining operations can be seen in table 1. Use of abrasive diamond grit cutting wheels is highly recommended as these tend to be very clean cuts without damaging the material. Using a CNC mill for the final cutting of the material will provide clean cuts, and a precise geometry to the final specimen. Ensure that the CNC is using a sharp bit, and that you are cutting with a 0.020 in depth of cut and a maximum chip size of 0.006 in.

Table 1. Recommend tooling and specifications for composites



Equipment	Part in Contact with Laminate	Speed/Pressure	Equipment Limitations
Fluid Cooled Saw	• Circular diamond grit blade (180 grit max)	• Tip speed [blade at table] of 180 m/min (7000 in./min) minimum.	• Provides only straight edged cuts, best accuracy .02 mm over 100 mm travel. • May be some wobble through thickness of cut. • Thickness taper is related to feed rate. • Tends to jog at interfaces of different materials including initial contact with specimen. • Surface finishes are no smoother than 0.80 μm (32 μin.).
Water Jet	Water stream (abrasive)	• 275 MPa (40 ksi) minimum with capability for abrasives if over 3 mm (0.1 in.) thickness	• Minimum accuracy is .01 mm over a 100 mm traverse. • Delaminates on initial piercing. A10 mm diameter (0.5 in.) hole is needed so that no predrilling is required. • Kerf width is .25 mm (.01 in.) minimum without abrasives and .75 mm (.03 in.) minimum with abrasives. • Delamination susceptibility increases with specimen feed rate. • Surface finishes are approximately 3.2 μm (125 μin.).
Band Saw	Band saw blade	• 915 m/minute (36,000 in./min) • 400–550 teeth/m (10–14 teeth/in.)	• Only straight, or wide kerf cuts. • Surface finish is usually rougher than 6.3 μm (250 μin.). Surface finishes in this range may not be adequate for specimen testing.
Drill	Bit	• 3000 rpm is recommended. • Boring type bits may reduce speed to 1500 rpm	• Only provides circular cutouts minimum accuracy is .01 mm (.004 in.) out of concentricity. • Drill wobble controlled by speed and feed rate. • Delamination is possible at surface plies of laminate (although the likelihood at the back end is greater. This is reduced by sandwiching laminate between like laminates. • Surface finish is no smoother than 0.80 μm (32 μin.).
Router	Diamond or carbide 12 mm (0.5 in.) bit	• 25,000 rpm minimum	• Cuts determined by ability to make template. • Water cooling recommended. • Will microcrack (particularly specimens with brittle matrices). • Accuracy dependent on template not router. • Surface finish is approximately 1.6 μm (64 μin.).
Sander	Abrasive grit	• Wide variety of hand and electric tools 180 grit minimum	• Difficult to provide even pressure/surface. • Applicable to portions of specimens or specimens with curvature.
Grinder	Wheel (180 grit or less)	• 3000 rpm • No more than .02 mm (.001 in.) material removed per pass	• Only provides a flat surface • Surface finish can be 0.4 μm (16 μin.) or smoother.

If need be, these specimens can have steel tabs attached to them with little surface preparation other than cleaning with alcohol or acetone. The tabs should be manufactured to the same width as the specimens being tested and applied with a strong adhesive, following the instructions of the manufacture for mix, cure, and surface preparations. Armstrong A-20 epoxy has been shown to work well for tensile testing with steel tabs using recommend specimen dimensions in ASTM D3039.

Testing Guide for In-Plane shear strength of a fiber reinforced polymer:

Introduction:

This guide is to determine the in plane shear strength of a fiber reinforced polymer being tested on a tensile testing machine. This is an abridged and modified version of ASTM D3518, *Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45,* designed for the use of science and engineering students looking for an introduction into experimentally determining material properties. It is highly recommended that you read through this entire guide before you start testing, referencing this or ASTM D3518 as needed.

Definitions:

ASTM: American standard for testing and materials

Fiber Orientation: This refers to the angle of the fiber reinforcement relative to the axis that load is being applied on. For reference 0 deg would mean the fibers are aligned in the same axis as the tensile load is being applied. 90 degree would be fibers perpendicular to the loading axis.

Jaws: The part of the testing equipment that grips the samples

Lamina: A sample with a single ply of material

Laminate: A sample with multiple plies of material

Ply: A layer of fiber reinforce material. A final structure can be described through the orientation and material type of the plies

Stack up: How a group of fiber reinforcement is oriented and the order that it is placed in.

Specimen: A sample of the material of interest for testing purposes

Tows: A grouping of a few thousand carbon fibers into a string a few millimeters wide

Unidirectional: All the fibers are oriented in a single direction, they are all running parallel to each other. This can refer to a single ply of material or to an entire laminate.

Test Specimen Preparation:

Testing should be done on a specimen of constant rectangular cross section with small tolerances in its dimensions and a specific material stack up of unidirectional reinforcement following $[45/-45]_{ns}$ where $4 \leq n \leq 6$[4]. Width and thickness tolerances are 1% and 4%. Recommended specimen width is 25 mm [1.0 in]. Recommend specimen length is from 200 to 300 mm [8 to 12 in], inclusive.

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[4] The subscript s means that this stack up should be symmetric and n tells you how many times this pattern should be repeated. For n = 4 the stack up $[45/-45]_{ns}$ would have 16 plies in the order [45/-45/-45/45/45/-45/-45/45/45/-45/-45/45/45/-45/-45/45]

When manufacturing the test specimens, it's important to have a few extras in order to test the experimental set up before you start gathering data. Depending on your testing setup you will likely need tabs attached to the ends of your specimens in order to grip properly, and protect the composite from being damaged by the grips. Seen in figure 1, tabs sandwich the composite and give the grips a non-brittle surface to dig into tightly. Steel is a very good tab material since it is easy for the jaws to make a purchase on. If specimens without tabs are breaking inside the jaws of the tester, tabs should help to solve this issue.

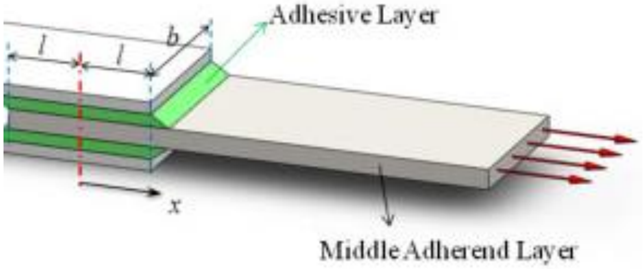

Figure 1. Diagram of tabs attached to testing specimen

Tabs should be the same width as the testing specimen and at least as long as they are wide as a rule of thumb. This can be ignored if you are testing specimens that are very wide relative to their length. Tabs should be attached with a strong adhesive, ensuring that the adhesive can withstand the expected shear loading, a 2 part epoxy works well. Follow any guidelines for surface preparation of the tabs and the test specimen as supplied by the manufacturer. The main considerations tend to be ensuring the surfaces are clear of any debris or oils, and that the surfaces are adequately rough for good adhesion. Specifically if the test specimen has a smooth shiny surface, it should be roughed up with sandpaper.

After attaching the tabs, any adhesive on the outside surface of the tabs should be cleaned of with a knife or sandpaper, being careful not to damage the testing specimen. If there is excess epoxy on the gripping surface of the tabs, it can cause the jaws to slip while testing. After tabs are attached, assuming the testing is not contingent on environmental factors, then testing is ready to commence.

Testing Procedures:

In order to have statistical significance a minimum of 5 samples should be tested, excluding any samples that fail at a material flaw for a reason other than that of interest in the test, such as tab failure. If the testing apparatus supports strain controlled testing, then testing should occur at a rate of 0.01 strain/min. Otherwise testing should be controlled so that failure occurs between 1 and 10 minutes, of testing. If an approximated time or breaking strain is unknown then testing can be performed at a constant head speed of 2 mm/min [0.05 in/min] can be used. This head speed should be adjusted based on the testing to comply with the time restrictions specified previously.

It is important to note that the difference between strain controlled testing and displacement controlled testing, mainly caused by the compliance in the testing equipment. Especially when using tabs and using a wedge grip system, the head can be moving 10 to 50 times faster than the testing specimen. This is both caused by the shear deformation in the tab, which typically has a lower shear modulus then the young’s modulus, and the compliance of the testing equipment. This unfortunately means that the head displacement cannot be used to accurately calculate the strain in the specimens.

In order to calculate a strain from this testing, strain gauges must be applied to the specimens. Take care researching the strain measurement system and if it is compatible, as typical strain gauges and adhesives designed for metallic test specimens may not adhere to the surface of a composite surface. When applying strain gauges, it is important to ensure that the gauge is larger than the characteristic length of the reinforcement pattern in the test specimen. For example if working with a weave that has 1 mm wide tows, the strain gauge should be at least 1 mm long. Alternatively an optical strain measurement system may be used, which can provide more comprehensive data on the behavior across the entire test specimen.

Data Processing

In order to calculate the ultimate shear strength of the material, use equation 1 or to calculate the stress at any data point use equation 2.

$$\tau_{max} = F_{max}/2A \qquad (1)$$

$$\tau_i = F_i/2A \qquad (2)$$

Ultimate Shear Strength: τ_{max}
Maximum Force: F_{max}
Shear Stress at ith data point: τ_i
Force at ith data point: F_i
Average cross sectional area: A

An example of the testing data can be seen in figure 2.

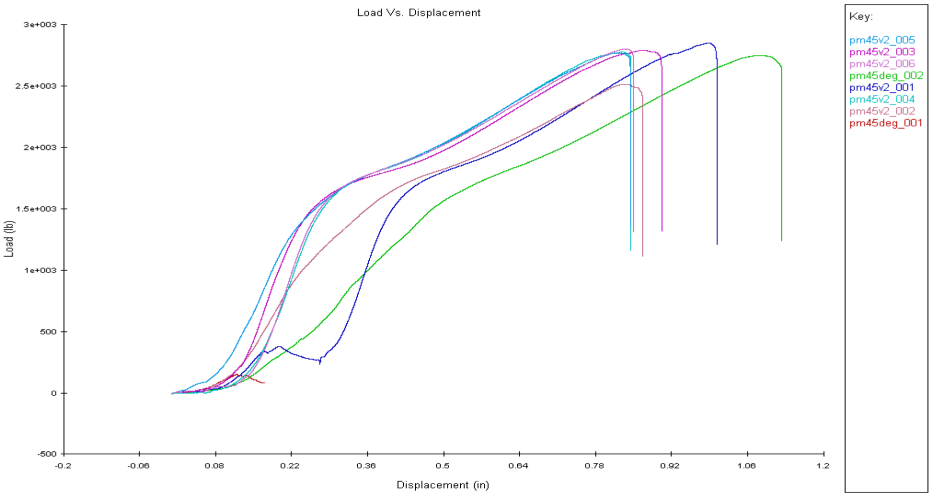

Figure 2. Example test data for in plane shear testing.

Testing Guide for tensile strength:

Introduction:

This guide is to determine the tensile strength of a fiber reinforced polymer being tested on a tensile testing machine. This is an abridged and modified version of ASTM D3039, *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, designed for the use of science and engineering students looking for an introduction into experimentally determining material properties. It is highly recommended that you read through this entire guide before you start testing, referencing this or ASTM D3039 as needed.

Definitions:

ASTM: American standard for testing and materials

Fiber Orientation: This refers to the angle of the fiber reinforcement relative to the axis that load is being applied on. For reference 0 deg would mean the fibers are aligned in the same axis as the tensile load is being applied. 90 degree would be fibers perpendicular to the loading axis.

Jaws: The part of the testing equipment that grips the samples

Lamina: A sample with a single ply of material

Laminate: A sample with multiple plies of material

Ply: A layer of fiber reinforce material. A final structure can be described through the orientation and material type of the plies

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Tows: A grouping of a few thousand carbon fibers into a string a few millimeters wide

Unidirectional: All the fibers are oriented in a single direction, they are all running parallel to each other. This can refer to a single ply of material or to an entire laminate.

Test Specimen Preparation:

ASTM D3039 requires that testing be done on a specimen of constant rectangular cross section with small tolerances in its dimensions. Width and thickness tolerances are 1% and 4% respectively. This standard also recommends the geometries in table 1 for the testing of strength based on fiber orientation. These are only recommendations and can be modified as the testing requires.

Fiber orientation	Width, mm [in]	Length, mm [in]	Thickness, mm [in]
0 deg Unidirectional	15 [0.5]	250 [10.0]	1.0 [0.040]
90 deg Unidirectional	25 [1.0]	175 [7.0]	2.0 [0.080]
Balanced and symmetric	25 [1.0]	250 [10.0]	2.5 [0.100]
Random and discontinuous	25 [1.0]	250 [10.0]	2.5 [0.100]

When manufacturing the test specimens, it's important to have a few extras in order to test the experimental set up before you start gathering data. Depending on your testing setup you will likely need tabs attached to the ends of your specimens in order to grip properly, and protect the composite from being damaged by the grips. Seen in figure 1, tabs sandwich the composite and give the grips a non-brittle surface to dig into tightly. Steel is a very good tab material since it is easy for the jaws to make a purchase on. If specimens without tabs are breaking inside the jaws of the tester, tabs should help to solve this issue.

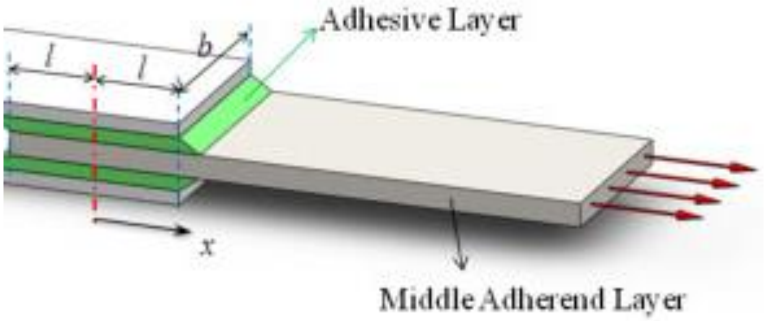

Figure 1. Diagram of tabs attached to testing specimen

Tabs should be the same width as the testing specimen and at least as long as they are wide as a rule of thumb. This can be ignored if you are testing specimens that are very wide relative to their length. Tabs should be attached with a strong adhesive, ensuring that the adhesive can withstand the expected shear loading, a 2 part epoxy works well. Follow any guidelines for surface preparation of the tabs and the test specimen as supplied by the manufacturer. The main considerations tend to be ensuring the surfaces are clear of any debris or oils, and that the surfaces are adequately rough for good adhesion. Specifically if the test specimen has a smooth shiny surface, it should be roughed up with sandpaper.

After attaching the tabs, any adhesive on the outside surface of the tabs should be cleaned of with a knife or sandpaper, being careful not to damage the testing specimen. If there is excess epoxy on the gripping surface of the tabs, it can cause the jaws to slip while testing. After tabs are attached, assuming the testing is not contingent on environmental factors, then testing is ready to commence.

Testing Procedures:

In order to have statistical significance a minimum of 5 samples should be tested, excluding any samples that fail at a material flaw for a reason other than that of interest in the test, such as tab failure. If the testing apparatus supports strain controlled testing, then testing should occur at a rate of 0.01 strain/min. Otherwise testing should be controlled so that failure occurs between 1 and 10 minutes, of testing. If an approximated time or breaking strain is unknown then testing can be performed at a constant head speed of 2 mm/min [0.05 in/min] can be used. This head speed should be adjusted based on the testing to comply with the time restrictions specified previously.

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In order to calculate a strain from this testing, strain gauges must be applied to the specimens. Take care researching the strain measurement system and if it is compatible, as typical strain gauges and adhesives designed for metallic test specimens may not adhere to the surface of a composite surface. When applying strain gauges, it is important to ensure that the gauge is larger than the characteristic length of the reinforcement pattern in the test specimen. For example if working with a weave that has 1 mm wide tows, the strain gauge should be at least 1 mm long. Alternatively an optical strain measurement system may be used, which can provide more comprehensive data on the behavior across the entire test specimen.

Data Processing

In order to calculate the ultimate strength of the material, use equation 1. To calculate the stress at any data point use equation 2.

$$\sigma_{max} = F_{max}/A \qquad (1)$$

$$\sigma_i = F_i/A \qquad (2)$$

Ultimate Strength: σ_{max}
Maximum Force: F_{max}
Stress at ith data point: σ_i
Force at ith data point: F_i
Average cross sectional area: A

Example data:

Figure 2 you can see the testing results of 6 samples of 0deg unidirectional test specimens. 0deg_6 had a crack in it before testing began so those results were discarded for the analysis. This testing resulted in an average ultimate strength of 287700 psi and a standard deviation of 32500 psi.

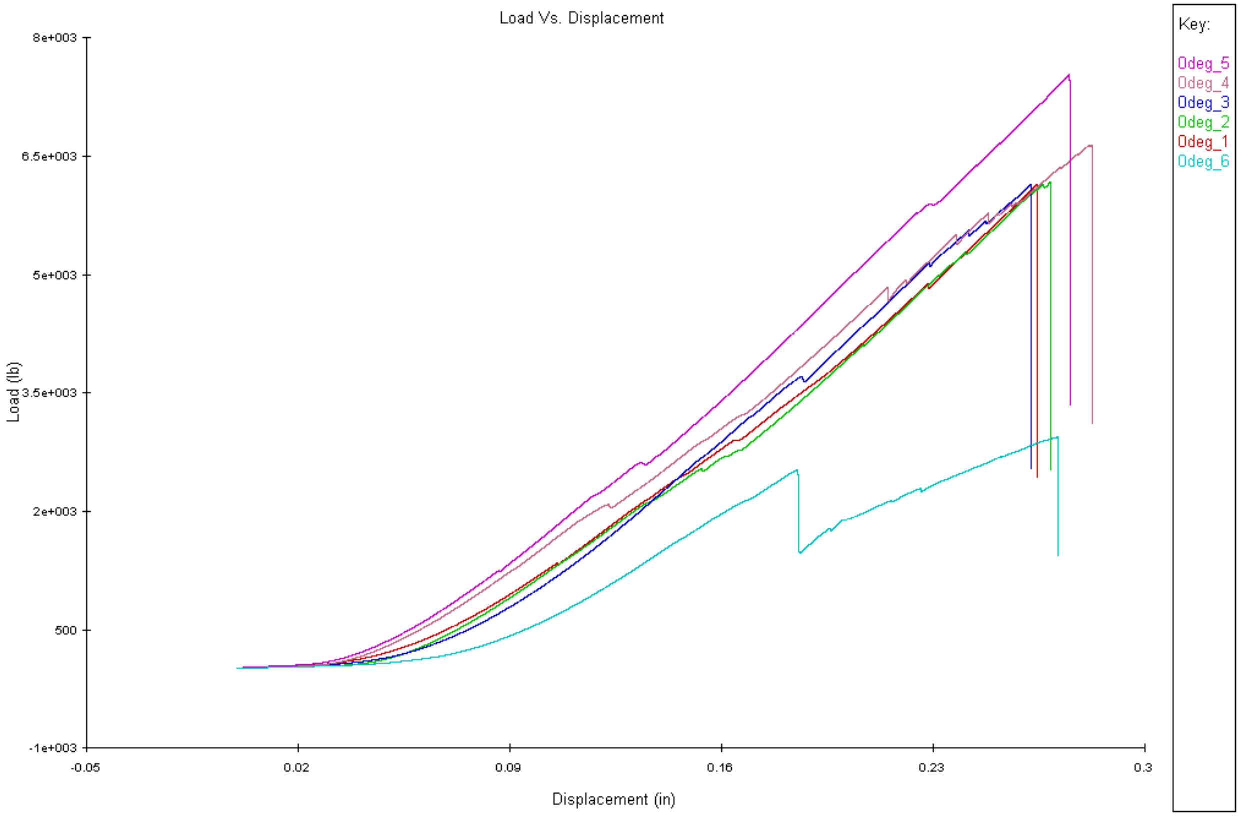

Figure 2. Example Tensile testing results

Table 2. Example Tensile testing calculations

Sample	Max force (lbf)	Area (in^2)	Ultimate Strength (PSI)
01	6135	0.0231	265300
02	6165	0.0233	264500
03	6128	0.0225	272200
04	6634	0.0225	295100
05	7522	0.0220	341600

Guide to Analysis of Carbon fiber reinforced polymers

Introduction:

This guide is intended for the use of science and engineering student interested in building accurate finite element models by providing steps for simple models and validations that can be performed.

Tensile Model:

The first testing was a tensile test of unidirectional carbon fiber samples. These samples were carefully manufactured with simple rectangular geometries to ensure simple modeling. 6 samples, seen in figure 1, were tested on a tensile testing machine recording force and displacement at the head. These samples had an average ultimate strength of 298 ksi with a standard deviation of 34 ksi. All samples were tested to failure, and failed in a very consistent way. Looking at figure 2, it is obvious the location of failure on the sample was very close to where the tabs were located in, shown by the intact center fibers.

Figure 1. Unidirectional tensile samples during testing

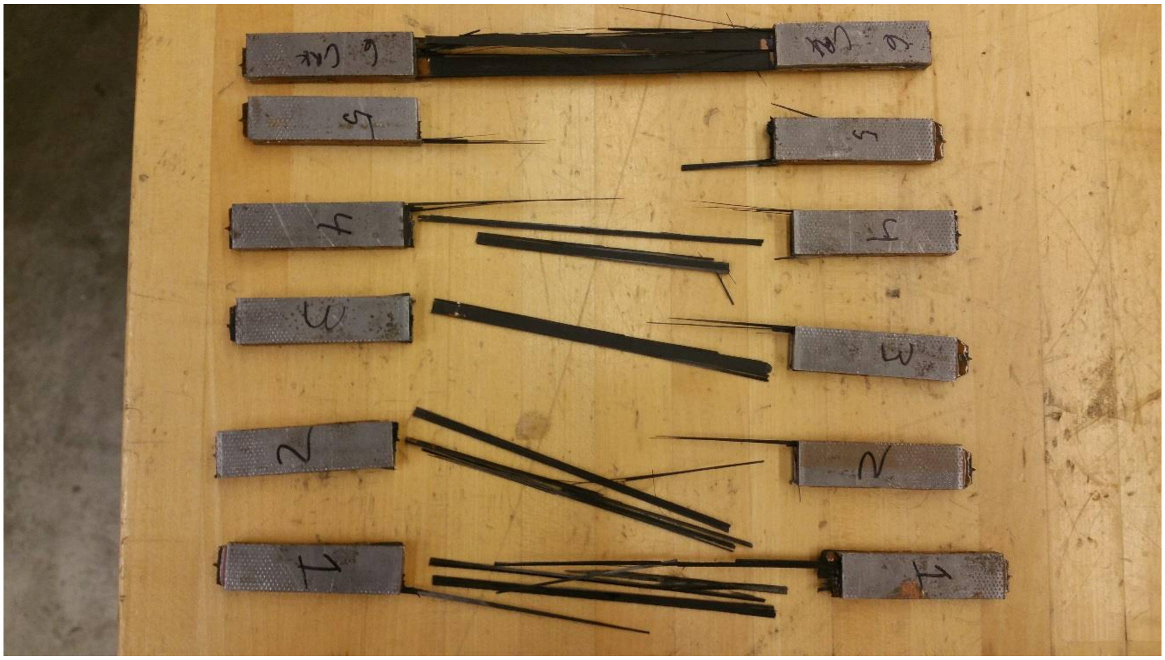

Figure 2. Failed Unidirectional tensile samples

These samples each had a test section about 10 in. long and measured a head displacement of 0.27 in. at failure. However the displacement of the head can be up to 50 times greater than that of the actual carbon specimen[i].

Tensile Finite Element Model:

The geometry was analyzed using shell elements in ANSYS 16.1 ACP Pre-Post processor on the static structural solver. A zero displacement constrain was put on the end of the model in the direction of pulling, and a 298 ksi pressure was applied to the free end. A single point was constrained in the non-testing directions to prevent any chance of the part attempting to move through space. Analysis found mesh convergence with a 5.0% threshold with 0.1 in. elements. Failure analysis, seen in figure 3, matched the failure locations of the test specimens supporting the accuracy of stress, strain, and Langley Research Center (LaRC) failure criteria.

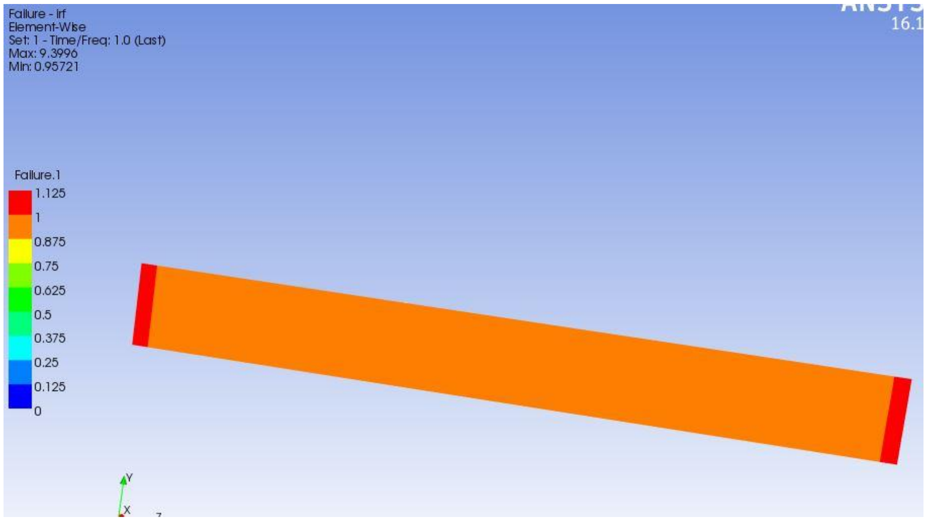

Figure 3. Failure analysis of tensile specimen

It is worth noting that the displacement from the finite element model with failure loading is 0.091 in., approximately a thirtieth of the measured displacement of the head. This is however well within the up to 50 times displacement measured at the head. This complication prevents any validation on the material stiffness from this model.

4 Point bend Model:

Using the layup materials that will be used for the final vehicle, 20, 15 in. rib samples were made and tested in 4-point bending. The ribs are simply supported over a 8.0 in. span with a 2 point top load applied across 4.0 in., centered between the simple supports. These ribs were constructed out of 0.25 in. nomex honeycomb with a 0.0182 in. layer of unidirectional carbon and a 0.0182 in. layer of weave on either side of it. A test rib can be seen in figure 4. Testing found an average failure force of 247 lbf. With a standard deviation of 53.1 lbf. Average failure deformation of these ribs was 0.189 in. with a standard deviation of 0.066 in. Since these samples were not being tested in the fiber direction, the steel testing rig is assumed to deform a negligible amount compared to the ribs and the value of head displacement is used for deformation.

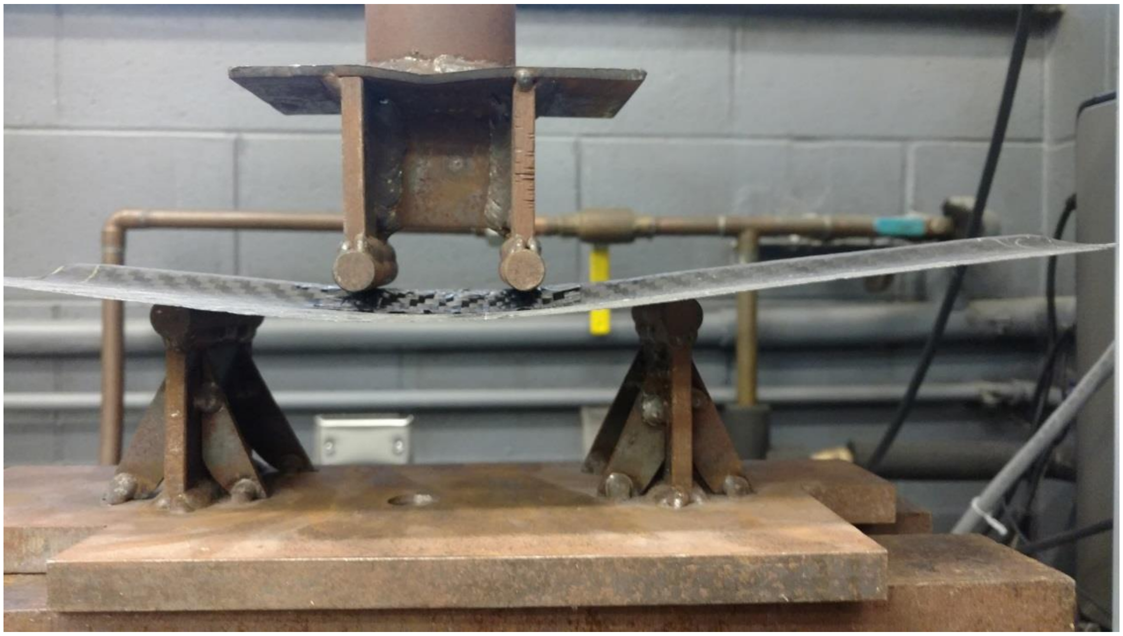

Figure 4. 0.25 in. 4 Point Bend test specimen

4 Point bend Finite Element Model:

The ribs were modeled with a stack up matching that in the previous section. The edges of the core material were originally chamfered at 45 degrees to match the physical geometry of the core material in the test samples. This was later removed as it didn't have a significant effect on the results and is a feature of manufacturing the ribs. These samples were simply supported in ANSYS and had a 247 lbf load applied across two lines where the 4 point tester would have rested. The default material properties provided by ANSYS for our manufacturing method and material was used originally, however this was found to make the ribs much stiffer than testing showed. This analysis was used to determine the stiffness of our materials, which was found to be approximately 22% of full material strength. Mesh convergence was found within a 5.0% threshold with a 0.1 in. mesh sizing. This resulted in a deformation of the loaded area of 0.183 in, only 4.2% away from the physical testing.

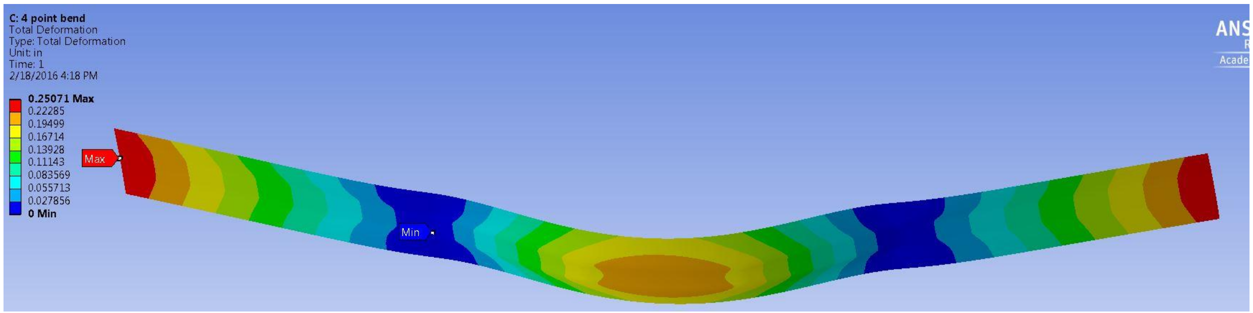

Figure 5: Deformation in 4 point bending analysis

Looking at the deformations of this rib, seen in figure 5, originally seemed very peculiar. The rib has a tendency to return closer to the horizontal plane after it passes the supports. Looking at a simply supported beam of an isotropic material, figure 6, this is very unlike the expected deformation. However this was found to be a characteristic of sandwich construction composites since the core material is unable to carry any significant shear loading through the material.

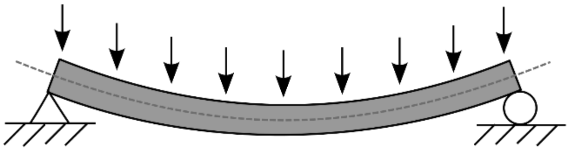

Figure 6: Simply Supported Isotropic beam

Summary:

While the linear analysis calculates the deformations very well, the validation of the failure criteria is not as strong as it should be and requires further work before it should be trusted fully.

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[i] Value from ASTM D3039 Testing standard