Investigation of the Effects of Cladding Layers on Longitudinal and Transverse Mechanical Properties in Composite Laminates

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By

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Abstract

The addition of cladding layers to composite laminates is used in industry to improve bond adhesion and the ease of manufacturing. However, there is no public data on the effects of cladding layers on the mechanical properties of composite components. To directly observe how cladding layers affect mechanical properties, four laminates with zero, one, two, and three cladding layers of twill fabric were added symmetrically to a biased core. The mechanical testing performed was tensile, short beam strength, and compression testing in the longitudinal and transverse directions. The measured strengths were related to the longitudinal properties of the core, and this was done to model the trends beyond this specific laminate. Second, third, and fourth order polynomials were tested for all testing methods and directions. The polynomial with the highest R^2 value above 0.90 was selected to model a trend if it was observed for the method-direction groupings. If a trend was not observed, adding a cladding layer does not need to be considered for that grouping. The significant trends can be described as a decrease in the longitudinal tensile strength, an increase in the transverse tensile strength and short beam strength, and the other test conditions did not yield a significant and meaningful correlation.

Keywords

Composites, carbon fiber, pre-preg, cladding, two-twill, mechanical testing, tensile testing, ASTM D3039, short beam strength, ASTM D2344, combined load compression, ASTM D6641, flatwise tensile, ASTM D7291, Cal Poly Materials Engineering

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1. Composites General Information

Composite materials have been around society dating back to ancient times [1]. In function, a composite material is a combination of at least two materials that are used to obtain properties that cannot be obtained from the individual materials themselves [2]. The composites that will be discussed in this paper are fiber reinforced polymers (FRP). The fiber that is used in a FRP is usually dependent on the industry, but some of the most widely used include carbon, fiberglass, and Kevlar. For example, carbon fiber reinforced polymers (CFRP) are attractive to industries in the modern day because of their high strength and low weight as. CFRPs can have a strength 10 times greater than steel or aluminum, but weight up to 5 times less than the metals alternatives [3]. Additionally, carbon fiber alternatives are resistant to fatigue, corrosion, and high temperatures. As a whole, variations of composites that use carbon fiber held within a polymer matrix have undergone exponential growth since its technology was developed in the 1960s. Furthermore, composite technology is specific and unique to itself, there is no other industry quite like it. Because of this, composites have a certain set of terminology that one should know when discussing the field.

1.1 Industry Trends and Demand

Ever since the 1960s, the carbon fiber industry has grown as a result of the demand for them in aerospace and defense applications [3]. From 1971 to 2015, the annual usage of CFRPs grew from 2 metric tons to 83,000 metric tons. Even though the aerospace and defense industries were at the forefront of the expansion of the carbon fiber industry, recently other industries have joined in the expansion. These include recreational products such as bicycles and industrial applications such as the automotive. Starting in 2015, predictions were made into the demand that CFRP composites would have on the automotive, pressure vessel, wind energy, and aerospace industries. This demand, in terms of metric tons, can be seen in graphical and table form below in Figure 1 and Table I respectively.

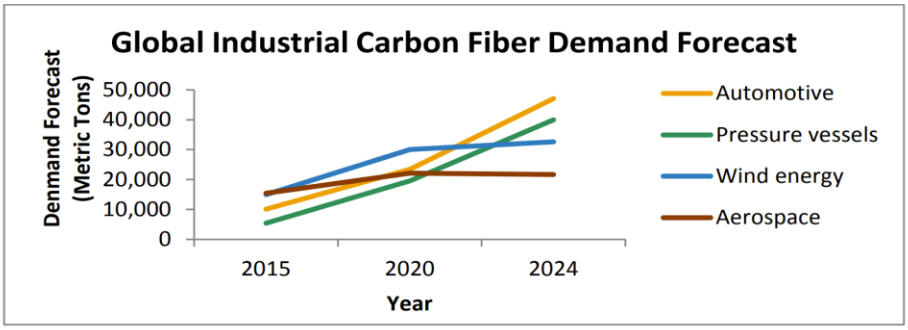


Figure 1. The demand of carbon fiber in respective industries [3].

Table I: Global Carbon Fiber Demand Forecast in Metric Tons [3]

Market	2015	2020	2024	CAGR
Recreational	14,830	16,740	18,620	**2.30%**
Aerospace	15,460	22,100	21,650	**3.40%**
Industrial	52,800	118,490	178,920	**13%**
Total	**83,090**	**157,320**	**219,200**	**10.20%**

CAGR stands for compound annual average growth rate.

1.2 Terminology

There is a unique set of terminology when talking about composites, and it is important to know these terms in order to communicate composite knowledge accurately. Most of this terminology is best understood through an understanding of how a composite material goes from a fiber, to a fabric, to a usable part called a laminate. The steps and meaning of these will be investigated through the rest of this section. The scope of this project encompasses carbon fiber, so all of these steps will be written in terms of carbon fiber.

1.2.1 Fibers

To begin with, carbon fiber starts as small individual fibers, around 5-10 μm in diameter [4]. These small fibers are made from a polyacrylonitrile (PAN) precursor [5]. The filaments from the PAN are stretched out at a higher temperature of 200^{o}C to 300^{o}C where some oxidation also occurs [6]. Later, the PAN is heated between 1000^{o}C and 2000^{o}C to undergo a carbonization process. This process transforms the fiber into a chain of only carbon atoms by eliminating the oxygen and nitrogen. The molecular structure also changes taking on a more graphitic form, which increases properties such as the tensile modulus.

Once the properties are increased, the individual fibers can be moved on to the next stage in the process. Here, different amounts of fibers can be put into a bundle. Each of these bundles is referred to as a tow, and they are defined by the number of fibers in each bundle [5]. Commonly found tow ratings include 3k, 6k, and 12k. This means for every one tow, there are 3,000, 6,000, and 12,000 fibers respectively in that one tow. Tows are mainly important because they influence the price of the fabric, and smaller tow fabrics are typically more expensive as a result of manufacturing challenges [6].

1.2.2 Fabrics

After the carbon is made into the fiber form, it goes into the next stage of manufacturing where the fibers are formed into flat fabric sheets or woven fabrics. These fabrics are made into long sheets that are put on rolls which are later used to make a composite part. There are several different types of fabrics known in the composite industry. One common fabric type is unidirectional (UD), where all of the fibers are oriented in the same direction (Figure 2). UD is held together by small amounts of glass and polyethylene fibers to prevent this sheet from falling apart [4]. UD is well known for producing parts with a higher strength and stiffness [5]. Despite all of the strength benefits of UD, there are some major drawbacks when it comes to manufacturing various parts. For instance, it can be difficult to place on complex contours.

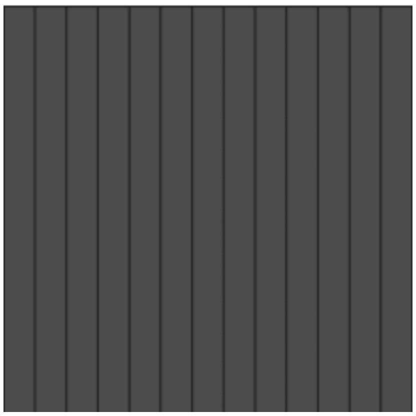


Figure 2. Example of a unidirectional fabric [5].

Another category of fabrics is weaves, the first being plain weave. Plain weave fabric is highly identifiable with its chess board, symmetrical appearance (Figure 3). This is a result of the tows being woven under and over for every tow. However, since the fiber is woven with this frequency, the fiber crimp is sharp (Figure 4). A fiber crimp is where the fiber bends at an angle in a woven fabric [5]. This means that there is a stress concentration at this location in the fabric, and these stress concentrations could become failure points over time. There is a benefit to having these crimps, as they do provide extra stability to the fabric.

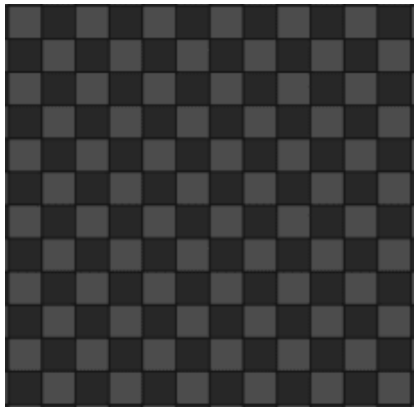


Figure 3. Example of a plain weave fabric [5].

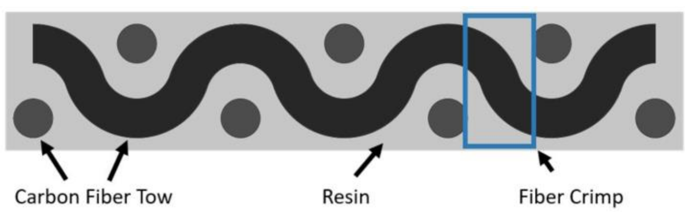


Figure 4. Diagram of a woven fabric that shows the locations of crimps. The crimp is the bend of the fiber in the blue box [5].

Twill weave has a fish-bone-like appearance and can be used in both functional and cosmetic applications (Figure 5) [5]. Some more common twill weaves are 2x2 twill and 4x4 twill, and these can be interpreted as the number of tows crossed over followed by the number of plies crossed under. So a 2x2 twill will cross over 2 tows and under 2 tows over, and the 4x4 crosses over 4 tows and under 4 tows respectively. The fiber crimp is similar to that of plain weave in regard to sharpness, but they occur less frequently over the weave. In consequence, there are less stress concentrations. One of the benefits of twill weaves is that they are easier to form over contours as compared to plain weave or UD.

The harness satin weave pattern is one of the most common weave patterns, and its use dates back thousands of years originating from silk fabrics [5]. Similar to silk fabrics back in the day, composite harness satin weaves are drapable. This makes it the ideal weave when making complex parts. However, when putting harness satin over complex contours there are several voids that form between the fibers, which impacts the quality of the part. One of the most common harness satin weaves is four harness satin (4HS), meaning that the fiber goes over three tows and then under one tow (Figure 6).

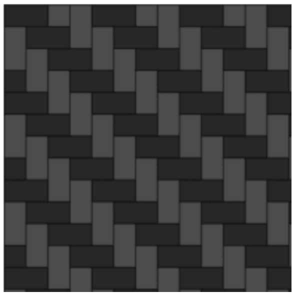


Figure 5. Example of a 2x2 twill weave fabric [5].

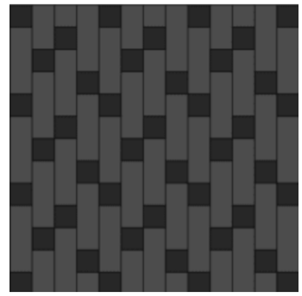


Figure 6. Example of a four-harness satin weave (4HS) fabric [5].

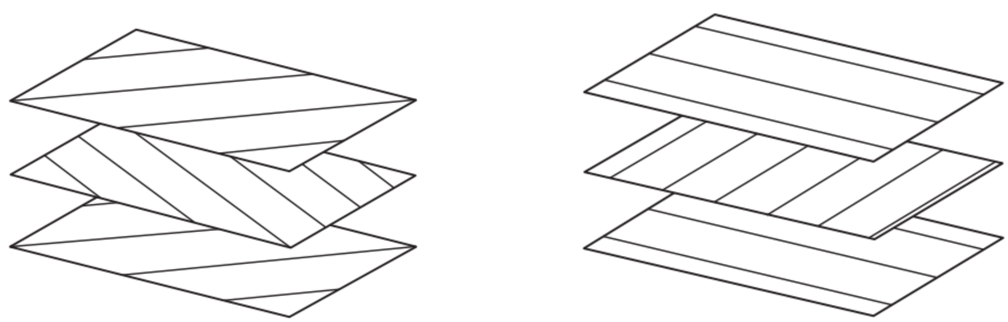
1.2.3 Plies and Laminates

Each individual layer of composite fabric is referred to as one ply (or one lamina). A laminate is a fully processed composite part that is composed of several plies. It is important to note that plies within a laminate do not need to be the same material, fabric pattern, or orientation, and there can be a lot of variation in these aspects when designing a part [7]. The ply orientation is important because the values of the fiber properties are significantly larger in the longitudinal direction (along the length) when compared to the transverse properties (through the cross section) [6]. This directional dependence of material properties is known as anisotropy. UD fabric in particular is considered to be rather anisotropic, and the strength of these fabrics are greatly reduced if loaded in the transverse direction [4]. Woven fabrics tend to be less anisotropic and more orthotropic (having consistent properties along symmetrical planes) [6]. Whether the plies are considered anisotropic or orthotropic, it is important to take note of the orientations of each individual ply and fabric type so that it will be manufactured correctly. As such, short-hand notation has been developed to help communicate the stacking sequence (or schedule) of ply orientations. This code involves using several rules, and examples of the rules are shown in Table II.

The ply orientation and weaves of a laminate will depend on the applications of the part, such as load structure and strength requirements of the design [6]. There are also several general types of laminates that new designs can build off pre-existing laminate layups. These laminates include unidirectional, angle-ply, cross-ply, symmetric, and quasi-isotropic (QI) laminates. A unidirectional laminate has all of the plies in the same direction, which is typically noted as 0^o. An angle-ply laminate has alternating layers of fibers oriented in θ and $-\theta$, where θ is not 0^o or 90^o (Figure 7a). A cross ply laminate alternates between 0^o and 90^o layers (Figure 7b).

Table II. Ply Orientation Code [6]

Ply Count [Ply Orientation]	Code	Explanation of Rule Used
1 2 3 4 5 6 [0 /+45 /90 /90 /+45 /0]	$[0/45/90]_S$	Subscript S in the code indicates symmetry about the midplane.
1 2 3 4 5 [0 /+45 /90 /+45 /0]	$[0/45/\overline{90}]_S$	The bar over 90 indicates that the plane of symmetry passes midway through the thickness of the 90° ply.
1 2 3 4 [0 /+45 /-45 /90]	$[0/\pm45/90]$	Adjacent +45° and -45° plies are grouped as ±45°.
1 2 3 4 [0 /0 /0 /0]	$[0_4]$	Four adjacent 0° plies are grouped together as 0_4.
1 2 3 4 [+45 /-45 /+45 /-45]	$[(\pm45)_2]$	Two adjacent ±45° plies are grouped as $(\pm45)_2$.



(a) (b)

Figure 7. Diagram showing an example of (a) an angle-ply laminate and (b) a cross-ply laminate [6].

A symmetric laminate is symmetric about the centerline of the laminate, but the orientation of the fibers is not important beyond the symmetry [6]. One of the benefits of a symmetric laminate is that it more evenly distributes forces, and that simplifies the design process. Because of this, symmetric laminates are often used paired with other types of laminates. QI laminates need to have at least three plies of identical thickness, and the angles between the ply orientations should be equal. This results in a laminate that acts more isotropically (similarly in all directions), which can allow composite laminates to be used in a wider variety of loading conditions. An example of a quasi-isotropic laminate uses the schedule of $[0/90/\pm45]_S$ (Figure 8), but quasi-isotropic laminates are also commonly made using combinations of $[0/\pm60]$.

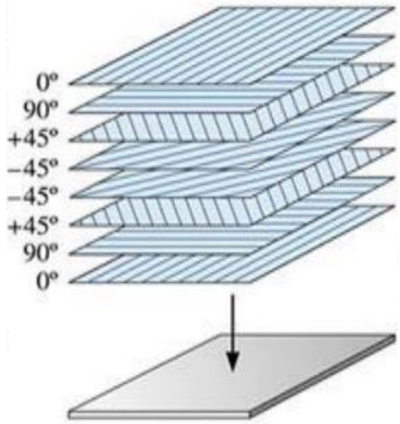


Figure 8. Example of a symmetric quasi-isotropic laminate with the stacking sequence of $[0/90/\pm45]_S$ [8].

1.3 Matrices in Laminates

Thus far, the discussion has been around the fiber portion of a composite. However, fibers are not the only factor that makes up a composite laminate. Another component is the matrix, which acts as a reinforcement for the fibers [4]. Similar to fiber types, there are different categories of matrices including thermosets and thermoplastics which break down further into other sub-categories. In modern day, thermosets are more commonly used [6]. Thermoplastics are becoming more attractive as they are significantly less expensive than thermosets, but these resins produce parts with more defects in their current state. The focus will be on thermoset resins for this project, and specifically epoxy resins.

1.3.1 Epoxies

Among the thermoset resins, epoxy resins are favorable for many industries due to their mechanical properties. Epoxy resins have high strength, high rigidity, and high hot service temperatures [9]. Additionally, they provide low shrinkage after cure, superior fiber-matrix adhesion, are moisture resistant, and are chemical resistant. When using resins with carbon fiber, it is important to consider the post-cure effects and the fact that carbon fiber is often sized specifically to be compatible with epoxy resins.

1.3.2 Introducing a Matrix into a Laminate

There are many ways in which a matrix is introduced into a laminate. The three most common ways for this is with a wet layup, resin transfer, or prepreg. A wet layup involves applying resin by hand to dry fibers followed by removing any excess resin [10]. This method is typically inexpensive because it requires less equipment than the other methods, but it can only be used in low volume applications and is difficult to get a uniform resin distribution. Resin transfer methods can be described as infusing resin into dry fibers that are already in a closed environment [11]. There are many different types of resin transfer systems, and several companies have their own versions. Prepreg methods utilize fabrics that are impregnated with a predetermined ratio of polymer matrix [6]. The impregnation of the resin results in a process that saves time and provides quality assurance. For these reasons, prepreg is the most commonly used method, even if the equipment is more expensive.

1.4 Manufacturing

There are two main methods for manufacturing prepreg laminates: autoclave and out of autoclave (OoA). In both methods, prepreg plies are layered onto a mold along with other layers to aid in manufacturing.

The assembly is then placed into a vacuum bag, and a vacuum is applied. By doing this, the vacuum removes entrapped air that could become defects if left inside the laminate.

1.4.1 Autoclave

The autoclave is a piece of equipment where temperature and pressure can be controlled (Figure 9). The autoclave is beneficial for multiple reasons. The first is that the autoclave can uniformly and effectively distribute the matrix within the laminate, which allows for better interlayer adhesion [12]. Second, components have a high degree of uniformity. Third, more of the fibers can be impregnated with resin in autoclave processes when compared to OoA methods, and this helps decrease the number of voids.

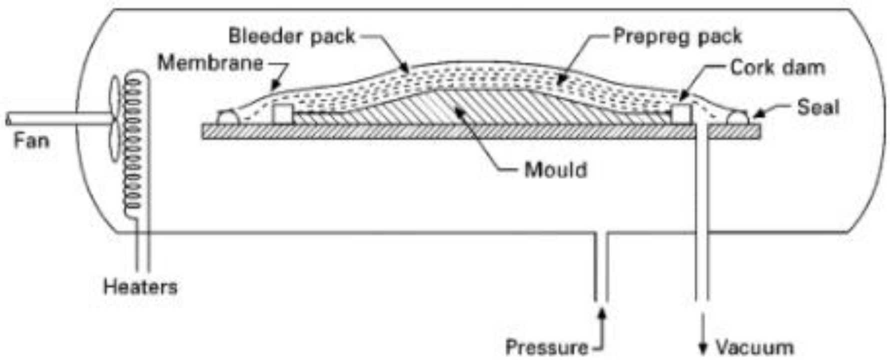


Figure 9. Schematic of an autoclave with a component inside [12].

Despite the benefits of an autoclave, there are several downsides. The autoclave limits the amount and size of a component [12]. Autoclave methods also have lower production rates when compared to OoA. Lastly, using an autoclave is more expensive as it requires a company to purchase the specific equipment.

1.4.2 Out of Autoclave

The OoA method is a less expensive alternative to the autoclave process. Rather than using an autoclave, the OoA process relies on an oven to control temperature, but not pressure [13]. Compared to prepregs designed for autoclaves, OoA prepregs are formulated specifically to provide air channels to help remove the air entrapped during the lay-up stage (Figure 10).

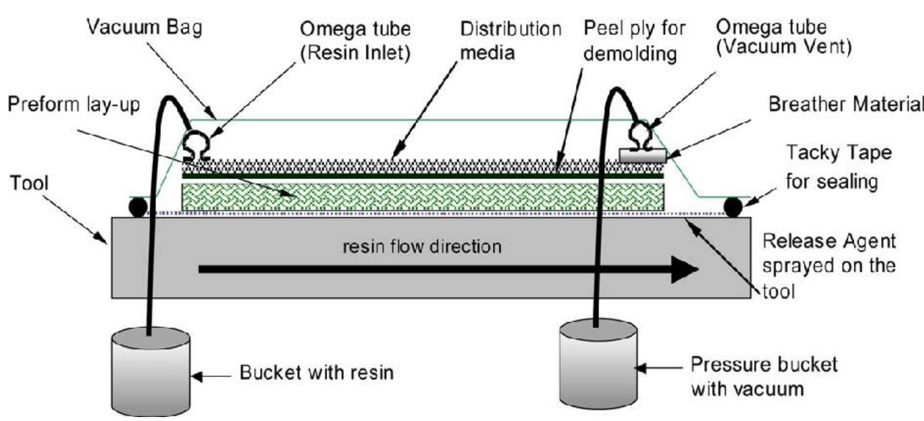


Figure 10. Schematic of the out of autoclave method [14].

2. Mechanical Testing of Composite Laminates

Mechanical testing of materials is necessary for a number of reasons. Baseline data on the material properties is required in order for engineers to have confidence in their designs. Additionally, testing of the manufactured parts is important to ensure both the safety of the consumer and the quality of the part. Furthermore, comparative testing (under similar conditions) is required in order to prove that one material outperforms another in a specific application. The testing of composite materials is generally more difficult than other material systems. This is because composite materials contain more than one material type and are often anisotropic [15]. Because of this, there are many challenges in the process of obtaining useful and consistent data from testing composite panels.

In order to help address some of these challenges, several international organizations have published standards for these test methods. ASTM International is one of these groups, and they have published a number of standards for a variety of testing such as: in-plane tensile testing, flatwise tensile testing, compression testing, and shear testing. These standards focus on allowing the testing conditions to be as consistent and reproducible as possible, but the publishers acknowledge the need for flexibility in order to produce meaningful results. As a result, these standards acknowledge that performing these tests is more of an art, rather than a science [16].

2.1 Tensile Testing

The general method of performing a tensile test involves slowly pulling a sample coupon at a constant rate until failure. Tensile testing usually refers to in-plane tensile (IPT) tests, which yield some of the most commonly reported properties about composite materials including the ultimate tensile strength, ultimate tensile strain, modulus of elasticity, and Poisson's ratio [17]. Unfortunately, quality data is rather difficult to acquire in practice since it is challenging to induce desirable failure. Premature failure in this test is commonly a result of a few factors, most notably as a result of excessive bending or issues with gripping [16]. ASTM D3039 mentions that an excessive amount of bending can cause erroneous results, especially in the calculated values for modulus of elasticity. To recognize this error, the standard recommends checking for alignment during the test by using tools to measure displacement (most commonly strain gauges or extensometers) on both sides of the coupon.

Most of the challenges involving gripping are a direct result of the large tensile loads required to break composite materials. The coupon will slip out if the grip strength is too low, but the coupon can also be damaged or gain stress concentrations if the grip strength is too high. The coupons of other material systems often have a "dog-bone" shape to them, and this shape allows the stress in the gauge length to be higher than the stresses in the grips. This method is unavailable to composite materials because axial splitting (between the fibers) prevents the width tapering from being effective in most composite panels [17]. The solution to many of the problems with gripping comes in the form of bonding end tabs to the coupon (Figure 11). These tabs allow for larger gripping forces to be applied without damaging the test laminate. Fiberglass composites are often used for these tabs because they are inexpensive, have a relatively high strength, and have a relatively low elastic modulus. The high strength and low elastic modulus are desirable because that allows the tab material to have minimal effect on the test, which could occur by inducing stress concentrations or premature fracture.

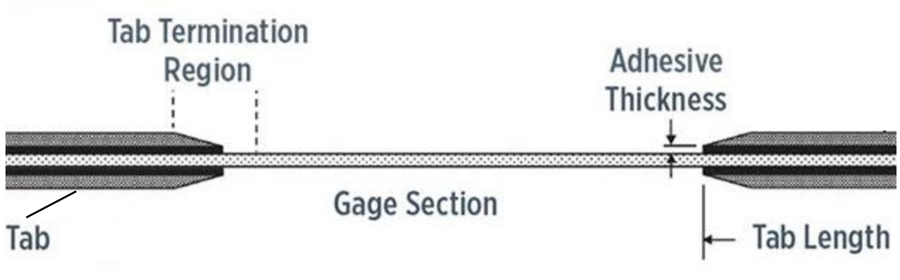


Figure 11. Example of an IPT coupon with tabs on the ends [17].

2.1.1 Flatwise Tensile Testing

Another subset of tensile testing that is specifically applicable to composite materials is flatwise tensile (FwT) testing. The way that this method differs from the IPT testing is that FwT measures the out-of-plane and interlaminar (between plies) tensile properties [18]. It does this by adhering tab blocks to the flat faces of laminate and slowly pulling these tab blocks apart (Figure 12). FwT testing is often viewed as being less significant than in-plane tensile testing, but the results from FwT are necessary to predict the separation of plies known as delamination. ASTM D7291 is the method mainly used to investigate delamination failure between the core material and surface plies in sandwich panels [19]. Sandwich panels are made by using surface plies as the "sandwich bread" for a core material (commonly made of a foam or honeycomb structure) [6]. These sandwiches are often used because they help increase the stiffness-weight ratio. Because of the wide use of this panel type, it is important to be able to predict delamination failure since it is one of the primary failure modes seen by the aircraft industry [20].

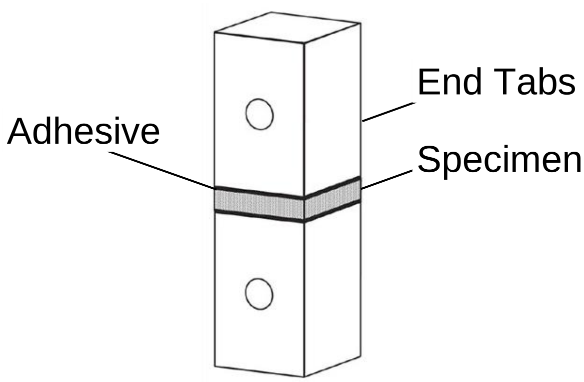


Figure 12. Drawing of a FwT sample prepared with end tabs [18].

2.2 Compression Testing

While the tensile test methods pull the test coupon apart to induce fracture, compression testing crushes the sample. These compressive loads can be applied through end loading, shear loading, or the combination of end and shear loading [21]. This combination loading compression (CLC) method has become "the most-used compression test method for composite materials" as a result of its simplicity and efficiency. To use this method, the sample is loaded into a fixture of four blocks which act to load the sample and help control buckling (Figure 13). Buckling failure is a major concern during compression testing, and ASTM D6641 specifically says that "the occurrence of Euler buckling invalidates the test" [22]. The design of the testing fixture also acts to mitigate bending, and this is useful since error can appear in the results when the bending is over 10%. The last major benefit of the CLC method is that the combination of shear and edge loading help prevent edge crushing [21], which is another source of error called out in ASTM D6641 [22].

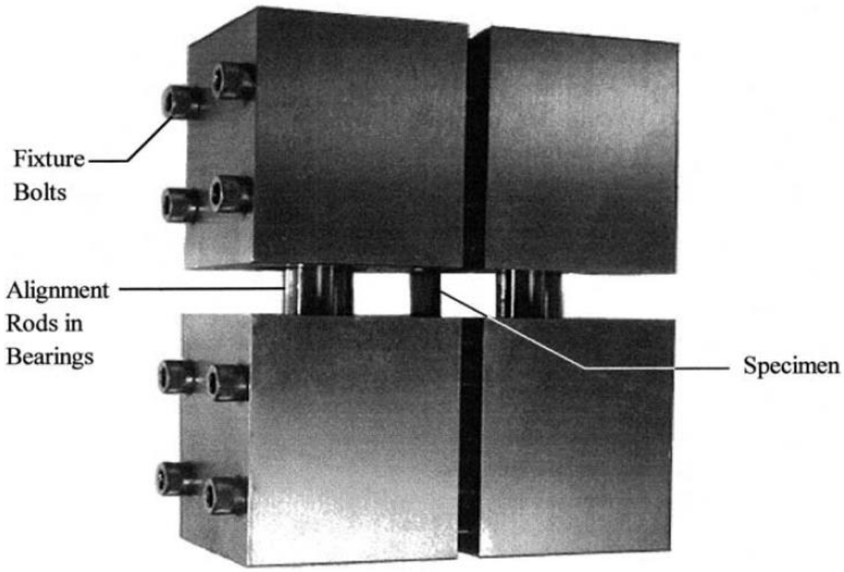


Figure 13. Fixture blocks for CLC testing [18].

Similar in the way that tensile testing was able to provide material properties, the CLC method can be used to determine the ultimate compressive strength, ultimate compressive strain, the compressive modulus of elasticity, and the Poisson's ratio in compression.

2.3 Shear Testing

Shear testing is a lot simpler compared to tensile testing or compressive testing, but the results are also more limited as they do not yield the value of any true material property [15]. Shear methods, such as the short-beam strength (SBS) method, instead yield an apparent strength value. These apparent strengths are still useful in quality control, process control, and comparative testing as a result of the ease of this test method [23]. The reason why the SBS method is so simple is related to the small size of the test coupons and the lack of a complex gripping situation. The fixtures involved with ASTM D2344 involve the test coupon sitting freely on two support beams, and a nose cylinder (equidistance between the two) loads the sample from above (Figure 14).

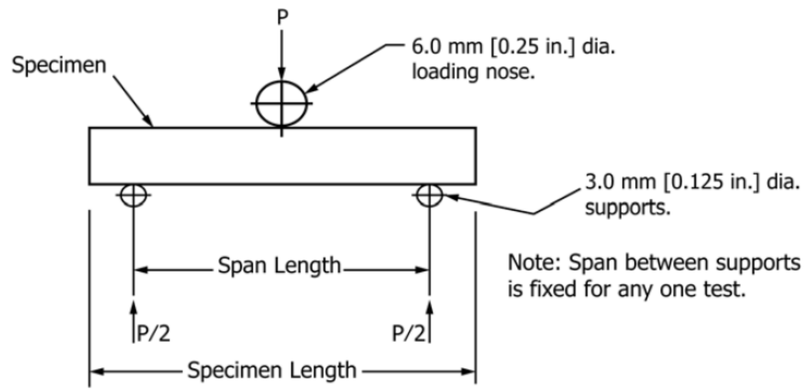


Figure 14. Schematic of the SBS test fixture [23].

Even though the benefits and limitations of the SBS method are widely recognized, it still meets criticism from some in the composite materials testing community [24]. The main arguments of the criticism is that the stress concentrations from the support points are not negligible as a result of the small dimensions of the beam. As a result of this less than ideal stress state, ASTM chose to name this method short-beam "strength" rather than short-beam "shear" despite the fact that SBS is often used as a comparative shear method.

3. Project Overview

3.1 Sponsor

The Toray Group focuses on five different segments of business: fibers & textiles, performance chemicals, carbon fiber composite materials, environment & engineering, and life science [25]. This project is partnered with Toray Advanced Composites which is a subsidiary of the Toray Group. Toray Advanced Composites develops carbon fiber composite materials and is contracted to make parts for companies.

As the applications of composite materials continue to develop, so must the manufacturing methods continue to innovate. The technical challenge that the company presented for this project is to investigate the use of cladding layers, which are surface plies with a different weave pattern.

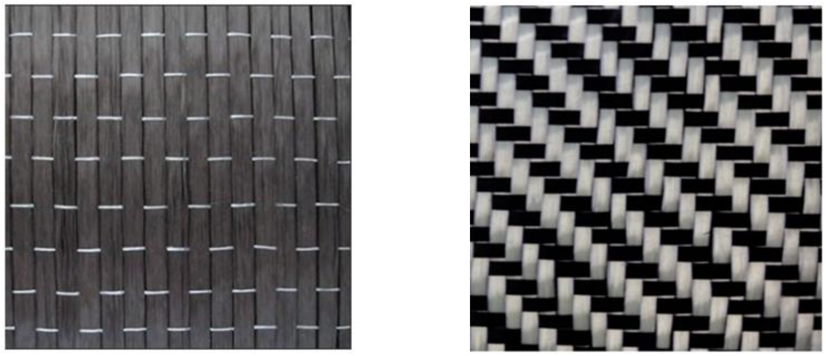
3.2 Problem Statement

This project will compare the effects of adding woven cladding layers (up to three per surface) to determine the effects on the tensile strength, compression strength, and short beam strength in the longitudinal direction and the transverse direction of composite laminates.

4. Experimental Design

4.1 Materials Used

There are two different composite fiber forms that are used in this project, one for the base core and one for the cladding layers (Figure 15). The base core uses a unidirectional carbon prepreg, meaning that all fibers are aligned in the same direction for a single layer. The fiber aerial weight for a ply is 150 grams per square meter (gsm) and the prepreg aerial weight of 224 gsm. The cladding layers are made with 2x2 twill carbon prepreg. This is a type of weave where there are fibers going in the 0° and 90° directions, going under two tows and then over two tows, repeating throughout the layer. The fiber aerial weight for a ply is 195 gsm and the prepreg aerial weight of 325 gsm. A more detailed representation of the fiber types of the properties acquired from a technical data sheet can be seen in Table III.



[A] [B]

Figure 15. Images representative of the fiber types used in tested samples. **[A]** Unidirectional Carbon, TC380 Resin/T800GC Fiber used to make the core of the laminates and **[B]** TC380 Resin/IM7 Fiber used for the cladding layers in the laminate.

Table III: Mechanical Properties of Materials Used from Technical Data Sheet

Property		Tensile (ksi)		SBS (ksi)		Compressive (ksi)	
		Long.	Trans.	Long.	Trans.	Long.	Trans.
T800GC (UD)*	[26]	477	11	-	-	216	-
IM7 (Clad)	[27]	152	154	10.6	10.6	117	122

**Properties were acquired from the technical data sheet for T800S since it was comparable to T800GC [28]*

4.2 Testing Groups and Specimen Notation

The laminates used in this project are comprised of a 16 layer (ply) core, where the number of cladding layers added to this core varied from zero to three layers. When cladding layers are added to the core, it is done symmetrically meaning that if one cladding layer is added on one side of the laminate, it is done on the other side as well. In Figure 16, the diagram shows the unidirectional core at the center, with the 2x2 twill cladding layer added on both sides of the laminate. Figure 17 shows the four different variations of cladding tested in this project with respect to the core at the center. These variations include zero, one, two, and three cladding layers.

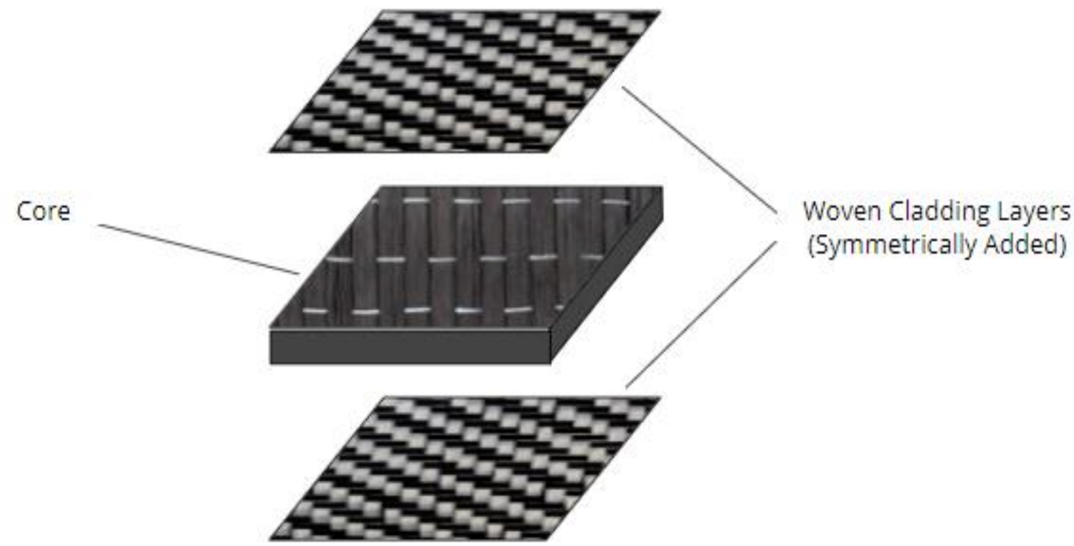


Figure 16. Woven cladding layers added to core.

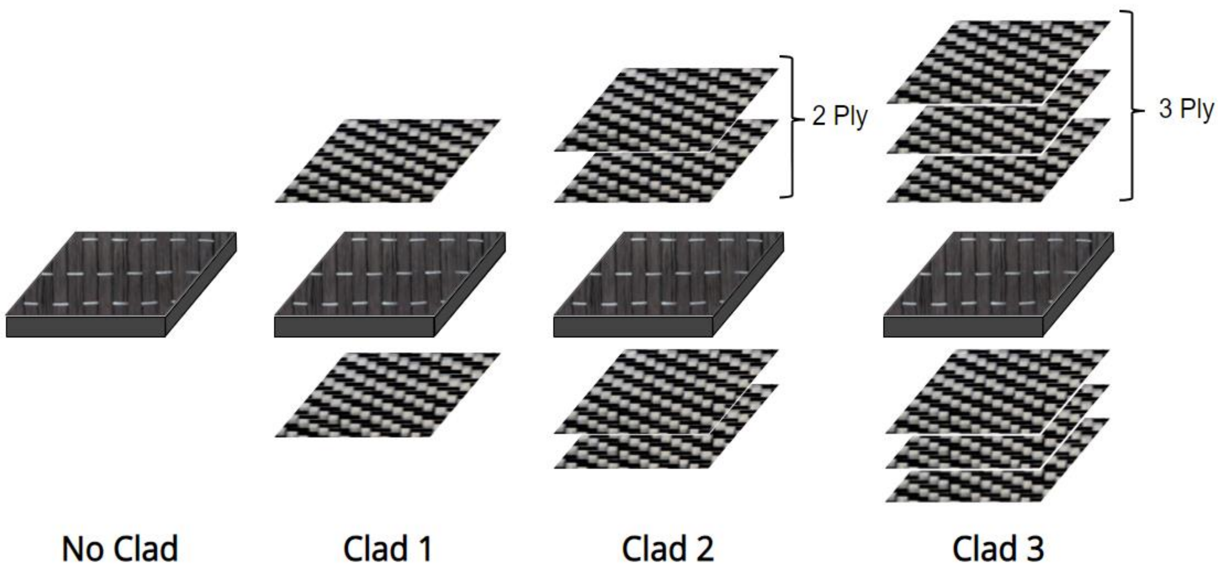


Figure 17. All variations of cladding.

4.3 Laminate Schedules

To better understand what changes are happening, the different laminate schedules should be discussed. Table IV contains all of the laminates produced for testing. All of these schedules are symmetrical, as denoted by the schedule notation. Starting with the quasi-isotropic laminate, there are fibers in four different orientations and multiplied four times for a total of 16 plies in the laminate. A quasi-isotropic laminate was initially designed to be used as a baseline before further testing could take place. This quasi-isotropic laminate was modified to be used as the axial asymmetric core in the cladding laminates. The difference between a quasi-isotropic and the axial asymmetric core used in this project is one ply oriented in a different way. In the axial asymmetric schedule, the 90º unidirectional ply from the quasi-isotropic is replaced by a 0° ply. Figure 18 shows each ply in the repeating unit and the simplified notation that can represent the laminate. This way, it can be directly seen what a cladding layer will do mechanically to a laminate oriented in longitudinal and transverse directions.

Table IV: Laminate Names and Schedules

Name	Schedule
Quasi-Isotropic	$[(0/+45/90/-45)_2]_S$
Axial Asymmetric (Core)	$[(0/+45/0/-45)_2]_S$
Clad 1	$[(Fabric)/(0/+45/0/-45)_2]_S$
Clad 2	$[(Fabric)_2/(0/+45/0/-45)_2]_S$
Clad 3	$[(Fabric)_3/(0/+45/0/-45)_2]_S$

The axial asymmetric cores were cut in different directions to test the different orientations, the individual unidirectional plies are shown with the associated orientation (Figure 19). These four unidirectional plies can be represented in a simplified symbol on the right. When there are two plies going in the testing direction, it is a longitudinal core laminate, when perpendicular, it is a transverse core.

Keeping the schedules and orientations in mind and the laminate schedules, there are a total of nine different types of laminates being tested. Table V shows a summary of all these testing groups, the name of each group, if the laminate has a longitudinal or transverse core (written and base schedule visual), and the number of cladding layers.

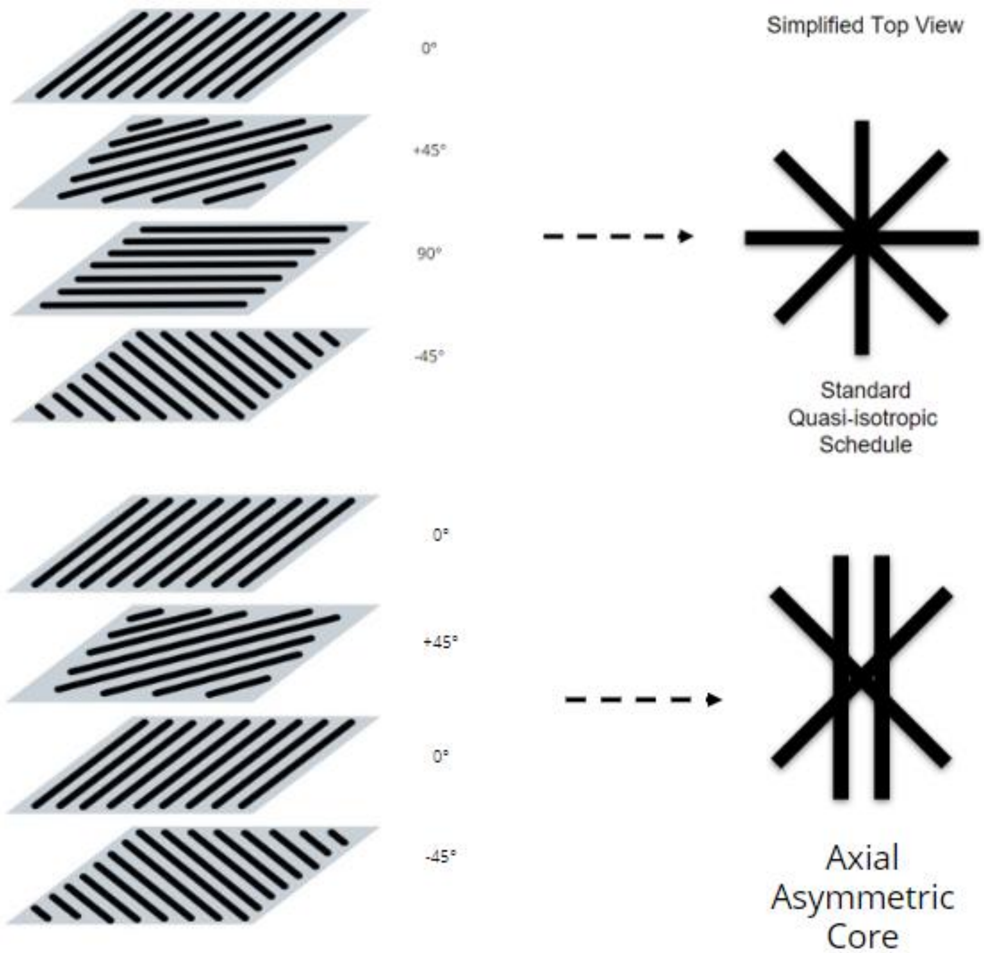
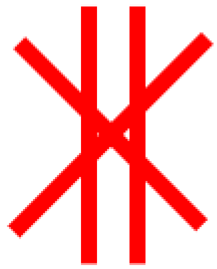
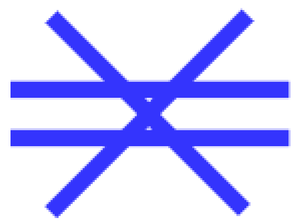


Figure 18. Simplified top view symbol explanation. On the left, four unidirectional plies can be denoted with the overhead view on the right. The top shows a standard quasi-isotropic laminate, and the bottom shows the modified axial asymmetric laminate.



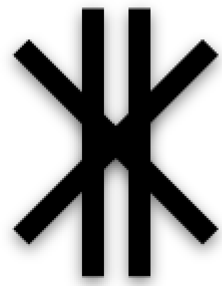
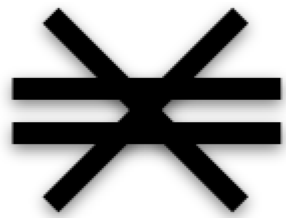
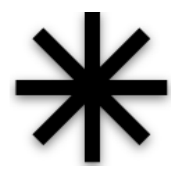
[A]



[B]

Figure 19. The two laminate orientations. **[A]** Longitudinal laminate orientation, **[B]** transverse laminate orientation.

Table V: Summary Table of All Testing Groups

Group #	Sample Group Name	Base Schedule	# of Cladding Layers (Symmetric)
1	Axial Asym., Longitudinal		0
2	Clad 1, Longitudinal		1
3	Clad 2, Longitudinal		2
4	Clad 3, Longitudinal		3
5	Axial Asym., Transverse		0
6	Clad 1, Transverse		1
7	Clad 2, Transverse		2
8	Clad 3, Transverse		3
9	Quasi Isotropic		0

4.4 Test Methods

Each of these nine groups underwent four different types of mechanical tests to evaluate the effects of adding a cladding layer. These tests included tensile strength, combined load compression (CLC) strength, short beam strength (SBS), and flatwise tensile (FWT). Tensile, SBS, and FWT tests were performed on the Instron of the Cal Poly Materials Engineering Department. The compression strength tests were done by Toray (our sponsor) as the Cal Poly Materials Engineering Department did not have the correct fixtures. All mechanical tests followed the ASTM standards: ASTM D3039 – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials [16], ASTM D6641 – Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture [22], ASTM D2344 – Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates [23], and ASTM D7291 – Standard Test Method for Through-Thickness “Flatwise” Tensile Strength and Elastic Modulus of a Fiber-Reinforced Polymer Matrix Composite Material [19].

Test methods were set up with the Instron to perform these tests. An extensometer was not used in the methods because precision in elongation for the final analysis is not necessary. For the tensile, SBS, and CLC methods a constant cross-head-speed of 0.05 in/min was used. Tensile testing pulled the sample apart whereas the SBS and CLC pushed the sample together. The flatwise tensile used a slower testing rate at 0.005 in/min. Considering the limitations of Cal Poly's Instron, sample dimensions were designing as to not exceed these limitations. The dimensions in association with the method and testing rate can be seen in Table VI.

Table VI: ASTM Standards, Sample Dimensions, and Testing Rates Used

Test Method	ASTM Standard	Designed Sample Dimensions		Testing Rate (in/min)
		Length (in)	Width (in)	
Tensile	ASTM D3039 [16]	5.0	0.50	0.05
Short Beam Strength	ASTM D2344 [22]	1.0	0.25	0.05
Combined Load Compression	ASTM D6641 [23]	-	0.50	0.05
Flatwise Tensile	ASTM D7291 [19]	2.0	2.0	0.005

In total, 509 coupons were received from Toray and accordingly measured. Each sample are measured nine times: three times for the length, three times for the width, and three times for the thickness. The total number of samples we used for our results was 369 samples, 88 tensile, 202 SBS, and 79 CLC (Table VII). There were a greater number of SBS samples tested as these were fast and easy to conduct. There were no usable samples from FWT, this will be discussed later in the results section.

Table VII. Number of Tested Samples

Testing Type	Number Tested
Tensile	88
SBS	202
CLC	79

Figures 20, 21, 22 show the tensile, SBS, and FWT samples in Cal Poly's Instron respectively. Note that each sample requires the use of a different fixture. In Figure 20, the tensile sample can be loaded directly into the grips of the Instron. In Figure 21, the SBS sample uses a three-point bend test fixture on a small, 1 inch scale. The SBS sample is small, an inch in length, so the two bottom points of the three points of contact are close together per ASTM standards. In Figure 22, the FWT fixture takes up the majority of the Instron frame. This fixture was needed to test our sample due to the adhesive blocks attached at 90-degree orientations to one another (Figure 23). It is difficult to see the sample in Figure 22 because the thickness of our laminates varied from around 0.09 to 0.14 inches.

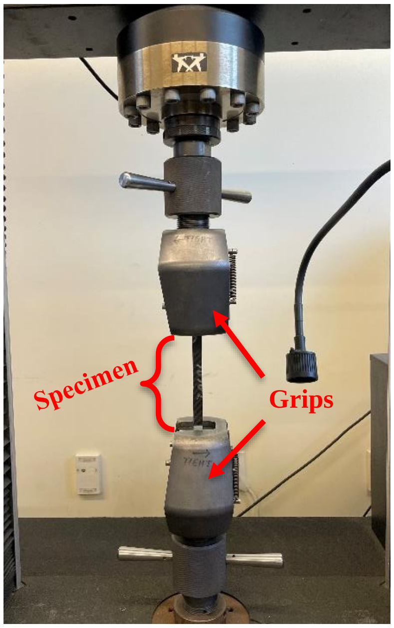


Figure 20. Tensile sample ready for testing. ASTM D3039.

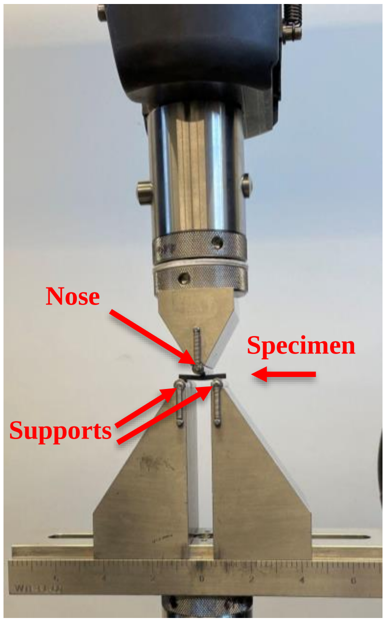


Figure 21. Short Beam Strength test fixture. ASTM D2344.

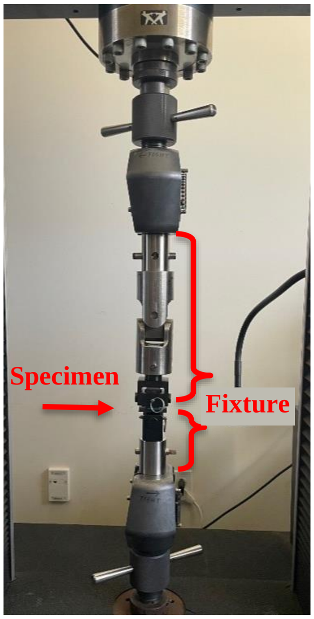


Figure 22. Fixture that allows for testing at 90 degree orientation, provided by Toray. ASTM D7291.

Figure 23. Flatwise sample bonded to the blocks before loading it into the FWT fixture.

5. Results

5.1 Tensile Results

At least five test samples were tested for each of the eight testing groups. Samples tested within the same groups all fractured at or around the same tensile stress (Figure 24). Notably, in Figure 24, the tensile stress is greater in the 90° when compared to the 0°, which is due to the test orientation. Table VIII shows a summary for the mean strength. For the longitudinal orientation, as the number of cladding increased, the strength would decrease. However, for the transverse orientation, the strength increases with the number of cladding.

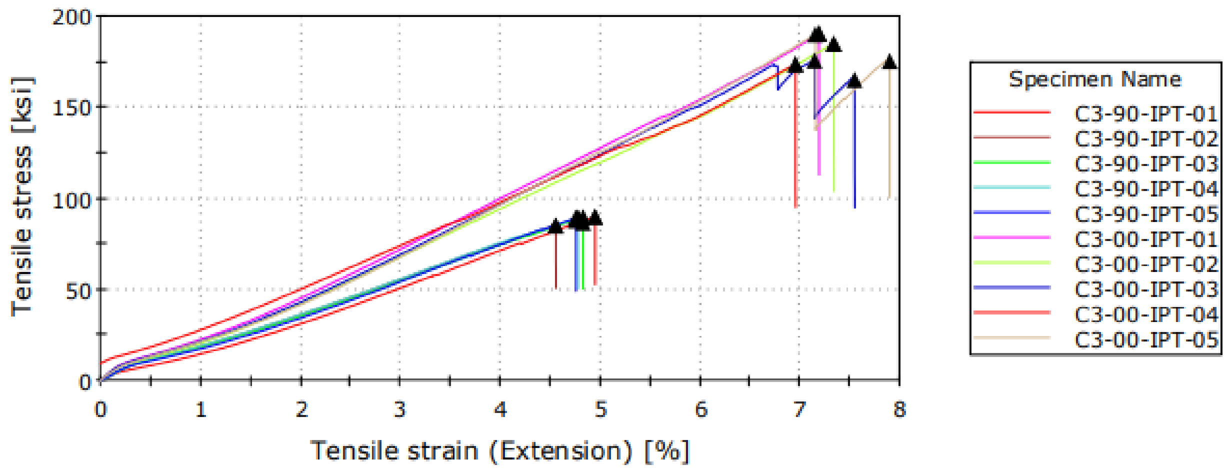


Figure 24. Example of load vs extension for tensile samples.

Table VIII: Summarized Results of the Tensile Testing

Testing Groups		Number of Samples	Mean Strength (ksi)	Standard Deviation	95% Confidence Interval
Longitudinal	Axial Asymmetric	10	242.46	9.99	(235.64, 249.28)
	Clad 1	10	202.37	11.44	(195.55, 209.19)
	Clad 2	10	188.54	11.27	(181.72, 195.36)
	Clad 3	5	182.80	7.88	(173.16, 192.45)
Transverse	Axial Asymmetric	10	38.65	1.69	(37.05, 40.25)
	Clad 1	9	59.65	3.43	(57.96, 61.33)
	Clad 2	9	75.746	2.29	(74.06, 77.43)
	Clad 3	5	88.96	1.99	(86.697, 91.23)

A trend occurred for the failure modes. All samples fractured at multiple sites – at the tabs, in the middle, or near the edge of the top and bottom tabs. Some samples had longitudinal splitting, similar to Figure 25. Other samples were explosive such as Figure 26, where splitting and delamination of the cladding layer occurred. Lastly, there were also samples that had angular and perpendicular splitting such as Figure 27.

Figure 25. Longitudinal splitting failure located within the tab.

Figure 26. Explosive splitting and delamination failure in the middle and at the tab.

Figure 27. Angled and perpendicular splitting.

5.2 Short Beam Strength Results

Thirty test samples were tested for each of the eight testing groups. Qualitatively, the most common failure seen was flexural and interlaminar shear (Figure 28).

Figure 28. Interlaminar shear of a sample for short beam strength.

For the short beam strength tests, samples tested within the same groups all fractured at or around the same load (Figure 29). From the load data the strength was calculated using Equation 1. The results are summarized in Table IX. For both orientations, as the number of cladding increases, the strength would increase.

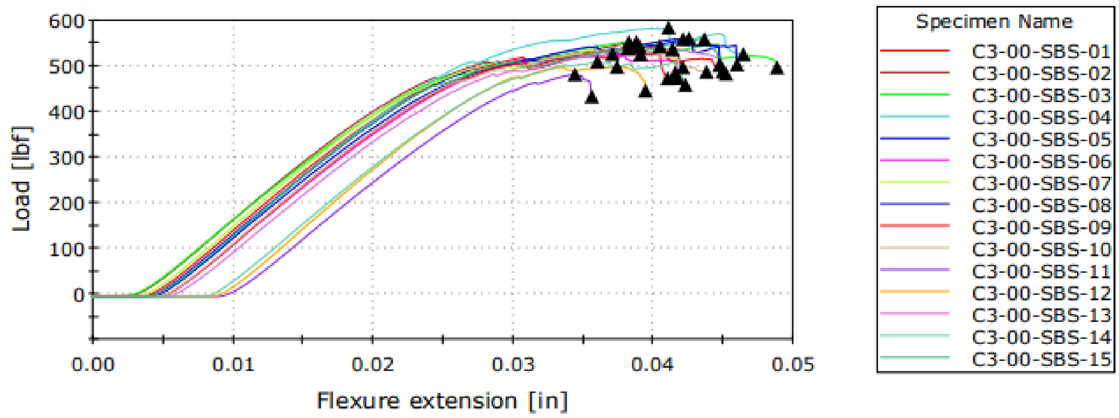


Figure 29. Example of load vs extension for longitudinal short beam shear samples.

Equation 1 $$[\boldsymbol{Short\ Beam\ Strength}] = \mathbf{0.75}\frac{[\boldsymbol{Load\ at\ Failure}]}{[\boldsymbol{Width}] \times [\boldsymbol{Thickness}]}$$

Table IX: Summarized Results of the Short Beam Strength Testing

Testing Groups		Number of Samples	Mean Strength (ksi)	Standard Deviation	95% Confidence Interval
Longitudinal	Axial Asymmetric	30	10.25	0.48	(10.06, 10.44)
	Clad 1	28	10.30	0.75	(10.10, 10.50)
	Clad 2	30	10.80	0.35	(10.61, 10.99)
	Clad 3	15	11.13	0.40	(10.87, 11.40)
Transverse	Axial Asymmetric	12	4.26	0.21	(4.06, 4.46)
	Clad 1	27	7.13	0.36	(8.48, 8.76)
	Clad 2	25	8.62	0.41	(8.48, 8.76)
	Clad 3	15	9.57	0.30	(9.40, 9.75)

5.3 Combined Load Compression Results

The combined load compression testing was conducted at the sponsoring company, Toray, as the Cal Poly Materials Engineering department did not have the proper fixture. Ten test samples were tested for each of the testing groups. As summarized in Table X, for the longitudinal orientation, adding one layer of cladding to the axial asymmetric core will marginally increase the strength. However, when two layers of cladding are added, the strength will decrease. For the transverse direction, adding one cladding layer to the axial asymmetric core will decrease the strength. On the other hand, adding two layers will increase the strength. For the combined load testing, qualitatively, the most common failures seen are transverse shear (Figure 30) and through thickness (Figure 31).

Table X: Summarized Results of the Combined Load Compression Testing

Testing Groups		Number of Samples	Mean Strength (ksi)	Standard Deviation	95% Confidence Interval
Longitudinal	Axial Asymmetric	9	107.02	3.14	(102.26, 111.79)
	Clad 1	10	108.11	4.11	(103.59, 112.63)
	Clad 2	10	103.65	10.68	(99.13, 108.17)
Transverse	Axial Asymmetric	10	60.88	3.18	(58.98, 62.79)
	Clad 1	10	49.83	1.02	(47.93, 51.74)
	Clad 2	10	51.49	3.84	(49.59, 53.40)

Figure 30. Transverse shear failure for combined load compression.

Figure 31. Through thickness failure for combined load compression.

5.4 Flatwise Tensile Results

Results were inconclusive. Three samples - one with two cladding layers, one with one cladding layer, and one with no cladding layer - were tested. Each sample had an adhesive failure between the metal fixture and the sample (Figure 32). None of the samples had failures between the layers. In order to have a valid result, failure must occur between layers. Due to the lack of time, more samples were unable to be prepped and tested.

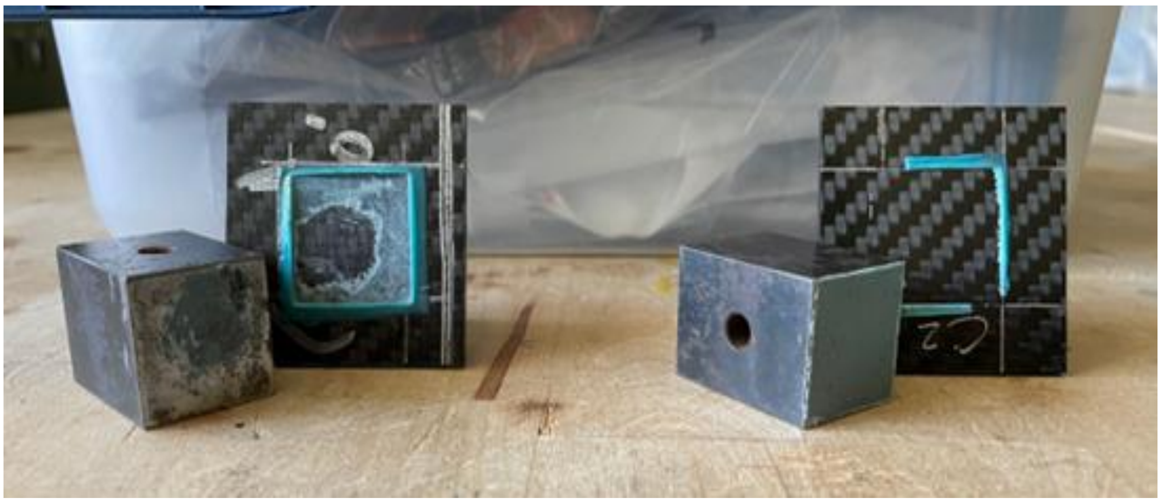


Figure 32. Adhesive failure between the block fixture and composite laminate.

5.5 Excluded Data

Attached to this report are 63 samples that were tested but their results were not analyzed, and these can be found in Appendix A, Table A.VII. A few of the excluded samples had issues during the testing or were used to establish the test methods. Most of these excluded samples are using the quasi-isotropic laminate schedule. It was determined that the quasi-isotropic laminate would not be a true representation of the isotropic response from the cladding. Instead, the cladding fabric properties (from Table III) were used to represent these trends.

6. Discussion

6.1 Relative Data

In order to make broader conclusions, all of the data was relativized to the axial asymmetric strengths in the longitudinal direction using Equation 2. These relative strengths were compared to the fiber weight percent clad (FWPC), which was found using Equation 3. The FWPC for each of the laminates tested were as follows: 0% for Axial Asymmetric, 14% for Clad 1, 25% for Clad 2, and 33% for Clad 3. Using these values, trends were observed in the data.

Equation 2 $$[\boldsymbol{Relative\ Strength}] = \frac{[\boldsymbol{Strength}]}{[\boldsymbol{Axial\ Asym.,Longitudinal}]_{\boldsymbol{Avg}}}$$

Equation 3 $$\boldsymbol{FWPC} = \frac{[\boldsymbol{\#\ of\ clad\ ply}] * [\boldsymbol{gsm}]_{\boldsymbol{clad}}}{[\boldsymbol{\#\ of\ clad\ ply}] * [\boldsymbol{gsm}]_{\boldsymbol{clad}} + [\boldsymbol{\#\ of\ core\ ply}] * [\boldsymbol{gsm}]_{\boldsymbol{core}}}$$

Since no models had publicly been established for these trends, four different trend types were tested: a 2nd degree polynomial, a 3rd degree polynomial, a 4th degree polynomial, and an exponential function. The trend lines were all found using the FIT() function in MATLAB (Appendix B). The R^2 values of each of these fits were then compared in Table XI. This showed that the highest R^2 value for the tensile results (in both directions) occurred with the exponential function. The highest R^2 value for the transverse SBS was the 4th degree polynomial, but the exponential function was also fairly high and only 0.0027 less than the value from the 4th degree polynomial. Because the exponential function was consistently producing high R^2 values, it was chosen to be the formula for the model. It should be noted that the other three orientation-method categories have no correlation between the relative strength values and the FWPC also had low R^2 values, with the highest only having an R^2 value of 0.2373.

Table XI: R^2 Values Using Different Fitting Models

Orientation and Test Method	Polynomial			Exponential Function
	2nd Order	3rd Order	4th Order	
Longitudinal Tensile	0.8643	0.9147	0.8996	**0.9203**
Transverse Tensile	0.9748	0.8526	0.6653	**0.9971**
Longitudinal SBS	0.0364	0.0578	0.0763	**0.0138**
Transverse SBS	0.7701	0.9121	0.9672	**0.9645**
Longitudinal CLC	0.2372	0.1291	0.0148	**0.0169**
Transverse CLC	-11.27	-20.95	-31.67	**0.0000**

6.2 Trends That Decrease as a Result of Cladding

Figure 33 shows the results of the longitudinal relative tensile strength versus FWPC. The data and trends suggest that the longitudinal tensile properties will decrease as a function of FWPC. This most likely occurs because of the changes in the cross-sectional area and the maximum load. Adding cladding layers increases the thickness of the cross-section, but the cladding plies cannot bear as much of a load as the longitudinal plies in the core. The decrease in tensile strength can be explained since the increase in cross-sectional area is more significant than the increase in maximum load.

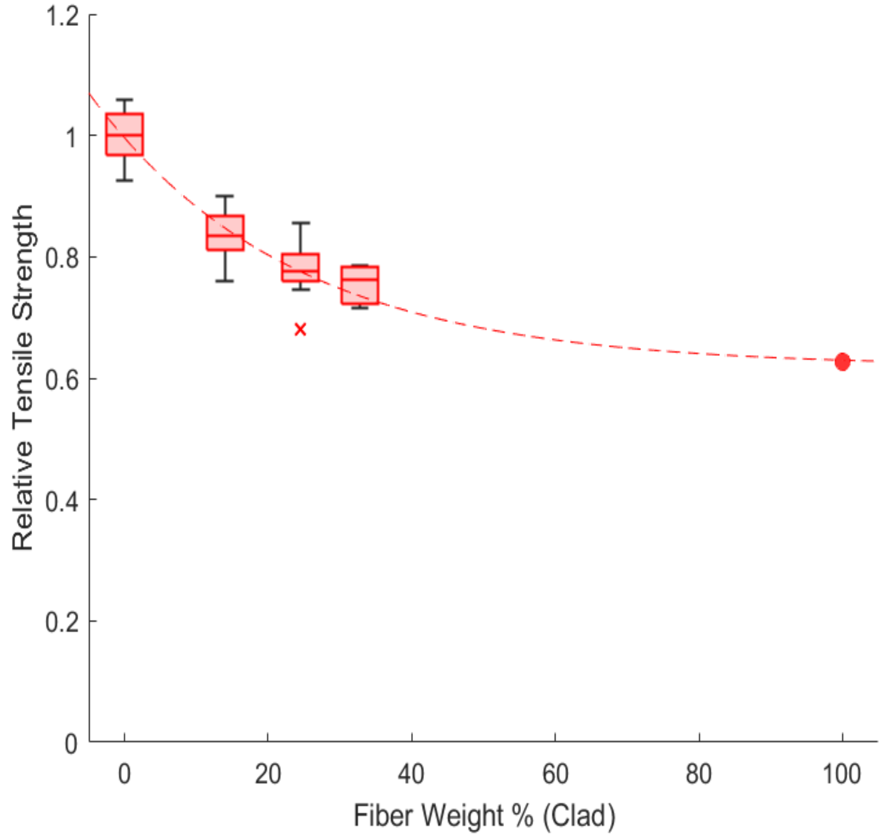


Figure 33. Plotted results of the relative tensile strength vs FWPC. Only the longitudinal results are plotted, and they are shown in red. The boxes show the quartiles of the data by laminate group. The x's represent data that was marked as an outlier by the BOXCHART() function in MATLAB. The red dot at 100 FWPC represents the clad fabric property (as acquired from the technical data sheet). The dashed line is plotted using the trend line found from the FIT() command in MATLAB, and it follow the equation y = 0.365e^(-0.036x + 0.031) + 0.0619.

6.3 Trends That Increase as a Result of Cladding

The transverse relative strengths versus FWPC plots for the tensile results and short beam strength results are shown in Figure 34 and Figure 35. These plots suggest that the transverse tensile properties and transverse short beam strength will decrease as a function of FWPC. This trend is most likely occurring for the same reason that the longitudinal tensile properties decrease with FWPC, but acting in reverse. Adding cladding layers increases the thickness of the cross-section, but the cladding plies can bear more load than the transverse plies in the core. The increase in tensile strength can be explained using Equation 4 since the increase in the maximum load is more significant than the increase in cross-sectional area.

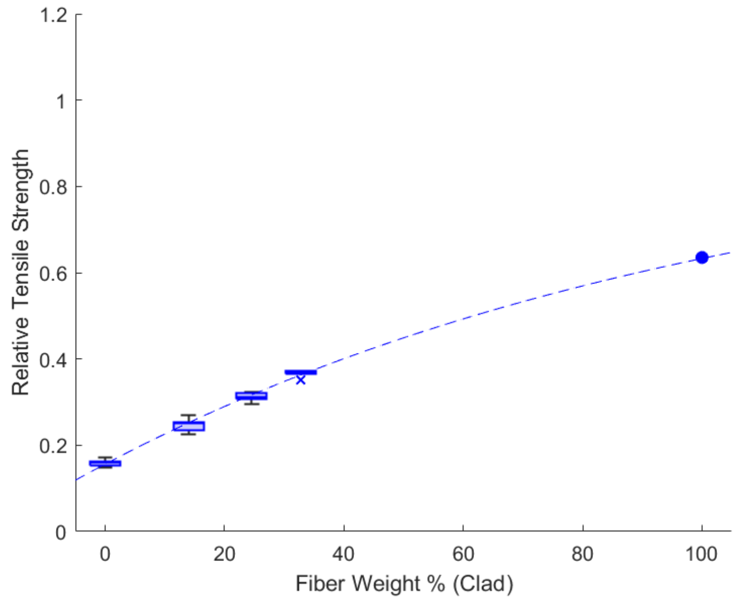


Figure 34. Plotted results of the relative tensile strength vs FWPC. Only the transverse results are plotted, and they are shown in blue. The boxes show the quartiles of the data by laminate group. The x's represent data that was marked as an outlier by the BOXCHART() function in MATLAB. The blue dot at 100 FWPC represents the clad fabric property (as acquired from the technical data sheet). The dashed line is plotted using the trend line found from the FIT() command in MATLAB, and it follow the equation y = -0.376e^(-0.009x + 0.755) + 0.954.

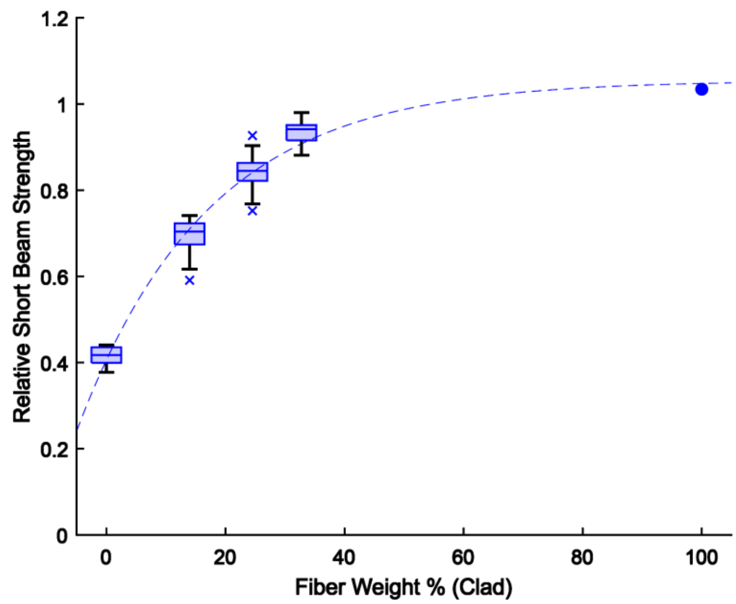


Figure 35. Plotted results of the relative short beam strength (SBS) vs FWPC. Only the transverse results are plotted, and they are shown in blue. The boxes show the quartiles of the data by laminate group. The x's represent data that was marked as an outlier by the BOXCHART() function in MATLAB. The blue dot at 100 FWPC represents the clad fabric property (as acquired from the technical data sheet). The dashed line is plotted using the trend line found from the FIT() command in MATLAB, and it follow the equation y = -0.140e^(-0.045x + 1.532) + 1.055.

6.4 Trends That Did Not Change as a Result of Cladding

Unlike the previous groups, there were a few test method-orientation pairings that did not show a correlative trend as a result of the cladding. These pairings included the short beam strength in the longitudinal direction (Figure 36) and the combined load compressive strength in both directions (Figure 37). Referring to Table XI, the R^2 values of these groups were all below 0.2373. In the case of the transverse CLC results, the R^2 values were negative, which signifies that plotting a horizontal line would be more representative.

Since no correlations presented itself in the models, additional analysis was performed on these groups to determine if there was any statistical difference between the laminates. This analysis used one-way ANOVA and Tukey comparison (in Minitab) to compare the relative strengths. These results were then condensed into Tables XII, XIII, Table XIV. The relative cladding strengths were added to the table as a reference value, and this was done in order to show how it compares to the other groups. Most of the letter groupings used the results of the Tukey test, but the letter groupings of the reference value were based on the other groups' 95% confidence intervals.

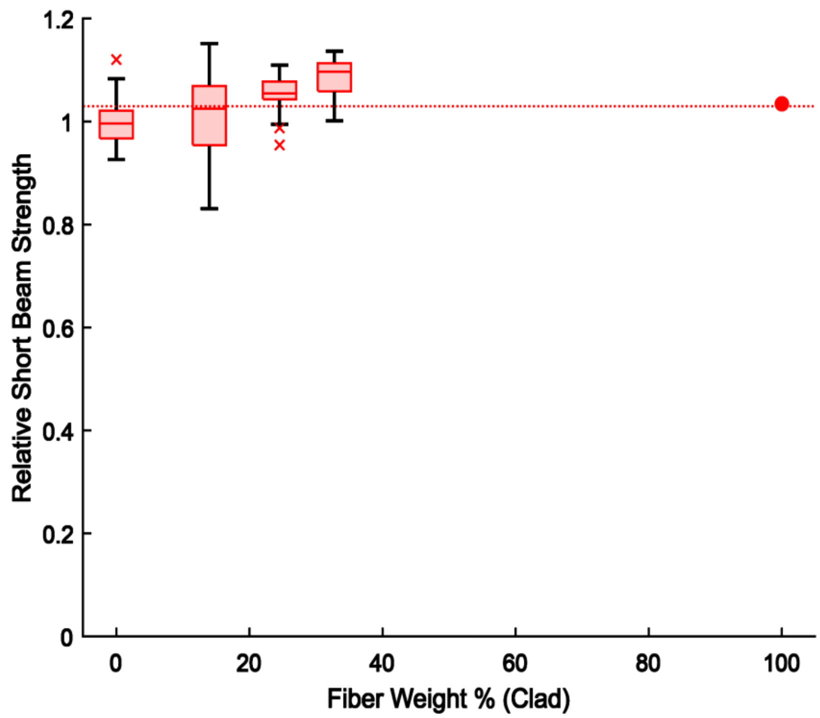


Figure 36. Plotted results of the relative short beam strength (SBS) vs FWPC. Only the longitudinal results are plotted, and they are shown in red. The boxes show the quartiles of the data by laminate group. The x's represent data that was marked as an outlier by the BOXCHART() function in MATLAB. The red dot at 100 FWPC represents the clad fabric property (as acquired from the technical data sheet). The dotted horizontal line is plotted at the average strength value for all of the samples in the testing direction. This horizontal line was plotted instead of trend line because no trend was able to fit the data set.

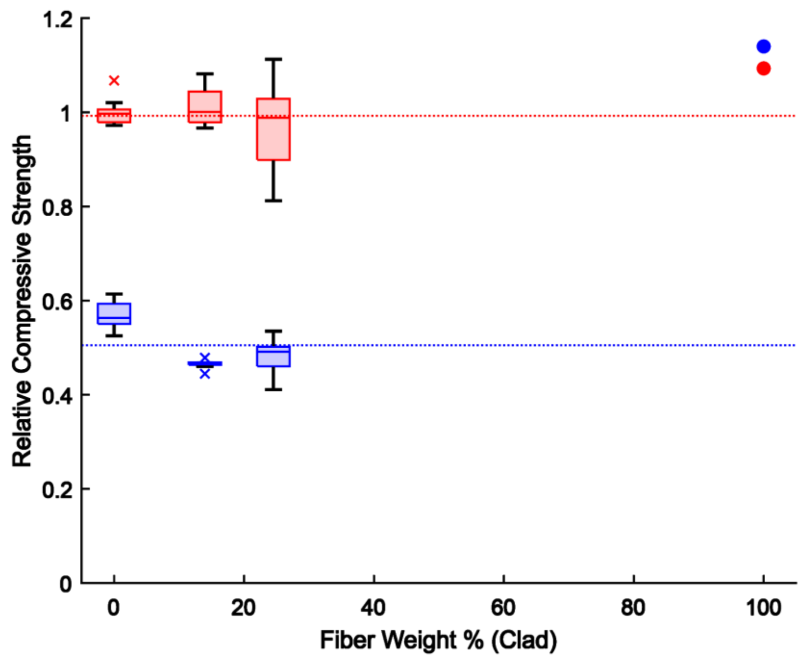


Figure 37. Plotted results of the relative combined load compression (CLC) vs FWPC. Longitudinal results are shown in red and the transverse results are shown in blue. The boxes show the quartiles of the data by laminate group. The x's represent data that was marked as an outlier by the BOXCHART() function in MATLAB. The red and blue dots at 100 FWPC represent the clad fabric properties (as acquired from the technical data sheet). The dotted horizontal lines are plotted at the average strength value for all of the samples in the testing direction. These horizontal lines were plotted instead of trend lines because no trend was able to fit the data set.

Regarding the relative longitudinal SBS (Table XII), there is a statistically significant difference between some of the groups. The letter groupings for [A], [B], and [C] can be interpreted as showing a strength increase from the additional cladding layers, but this interpretation is misguided. Letter grouping [D] represents the fully cladded laminate, but [D] does not follow the trend of increasing strength with cladding. Instead, [D] occurs between [A] and [B]. While the measurements in this report (and the literature investigated) do not suggest any reasons for this trend, a possible hypothesis is suggested. The SBS method is intended to cause interlaminar shear as the failure mode. While ideally this failure mode will engage the entire specimen prior to failure, internal forces may not always be entirely homogenous in composite laminates. Adding the cladding layers may help homogenize the load across the entire specimen, and this would decrease the likelihood of premature failure at a stress concentration. The necessary measurements to prove or disprove this hypothesis were not in the scope of this investigation, so no conclusions can be made about the validity of this hypothesis.

Table XII: 95% Confidence Intervals and Letter Groupings for Longitudinal SBS

Group	N	Mean	Std. Dev.	95% CI	Letter Groupings			
AA-00-SBS	30	0.999	0.045	(0.981, 1.017)	A			
C1-00-SBS	30	0.995	0.081	(0.977, 1.013)	A			
C2-00-SBS	30	1.053	0.034	(1.040, 1.066)			B	
C3-00-SBS	15	1.087	0.037	(1.069, 1.105)				C
Clad Fabric Property	-	1.034	-	-		D		

The results of the relative longitudinal CLC testing (Table XIII) differs from that of the longitudinal SBS, and there was no significant difference between the groups. This can be seen by the fact that all of the testing groups are in group [J]. The only value that was statistically different than the rest in this category was the reference value (which was in group [K]). This does not imply much on its own, but a completely different result was seen in transverse CLC groupings. Rather than the increase in the longitudinal SBS or the unchanged longitudinal CLC, the transverse CLC results (Table XIV) showed that non-cladded group was stronger than the cladded groups. This was further complicated by the fact that the reference value (group [Z]) was much stronger than the non-cladded group (group [X]) or the cladded groups (group [Y]). The outsourcing of the CLC testing makes it difficult to form any meaningful conclusions to explain the differences in the CLC results, but manufacturing defects can be ruled out of consideration. The reason this is unlikely is because all the CLC specimens were cut from the same panel of each laminate.

Table XIII: 95% Confidence Intervals and Letter Groupings for Longitudinal CLC

Group	N	Mean	Std. Dev.	95% CI	Letter Groupings	
AA-00-CLC	9	1.001	0.029	(0.957, 1.045)	J	
C1-00-CLC	10	1.010	0.038	(0.968, 1.052)	J	
C2-00-CLC	10	0.968	0.099	(0.926, 1.010	J	
Clad Fabric Property	-	1.093	-	-		K

Table XIV: 95% Confidence Intervals and Letter Groupings for Transverse CLC

Group	N	Mean	Std. Dev.	95% CI	Letter Groupings		
AA-90-CLC	10	0.567	0.028	(0.549, 0.585)		X	
C1-90-CLC	10	0.465	0.012	(0.447, 0.483)	Y		
C2-90-CLC	10	0.484	0.037	(0.464, 0.500)	Y		
Clad Fabric Property	-	1.140	-	-			Z

7. Conclusions

7.1 Longitudinal tensile strength decreases as a result of cladding.

Longitudinal tensile strength is often a design criteria in composite components. This trend should be considered when designing components with cladding layers in order to prevent premature failure.

7.2 Transverse tensile strength and transverse SBS increase as a result of cladding.

Cladded models will yield a design with a higher factor of safety than models without the cladding effects, so it is not critical to model the effects of cladding for these properties.

7.3 Compressive strength and longitudinal SBS do not change as a result of cladding.

It is not critical to model the effects of cladding for these properties since it will not have much effect on the design.

8. Recommendations

8.1 Develop a model by altering the cladding laminate.

Some of these alterations could include changing the core schedule, changing the core material, changing the cladding weave pattern, changing the cladding material, changing the FWPC, or changing the total ply count.

8.2 Repeat testing with calibrated equipment to increase the accuracy of the data.

One of the limitations this senior project had was that the testing apparatuses used were not in calibration. In order to overcome this limitation, the quality of these trends should be reinforced before it is used in design.

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Appendix A. Raw Data

Table A.I: Specimen Label Key

Pattern: [Direction Identifier] - [Orientation Identifier] - [Test Method Identifier] - [Sample Number]					
Direction Identifier		**Orientation Identifier**		**Test Method Identifier**	
AA	Axial Asymmetric	00	Longitudinal	Ten	Tensile Testing
C1	Clad 1	90	Transverse	SBS	Short Beam Strength
C2	Clad 2			CLC	Combined Load Compression
C3	Clad 3			FWT	Flatwise Tensile
QI	Quasi-Isotropic				

Table A.II: Group Summary Information

Coupon ID Group	Ply Count		% Clad		QTY Tested	Strength (ksi)		Relative Strength	
	Total	Clad	Ply	Fiber Weight		Mean	Std Dev	Mean	Std Dev
AA-00-Ten	16	0	0.0	0.0	10	242.5	9.99	1.00	0.04
AA-90-Ten	16	0	0.0	0.0	10	38.6	1.69	0.16	0.01
C1-00-Ten	18	2	11.1	14.0	10	202.4	11.44	0.83	0.05
C1-90-Ten	18	2	11.1	14.0	10	54.3	17.25	0.25	0.01
C2-00-Ten	20	4	20.0	24.5	10	188.2	13.47	0.78	0.06
C2-90-Ten	20	4	20.0	24.5	10	69.1	21.06	0.31	0.01
C3-00-Ten	22	6	27.3	32.8	5	182.8	7.89	0.75	0.03
C3-90-Ten	22	6	27.3	32.8	5	89.0	1.99	0.37	0.01
AA-00-SBS	16	0	0.0	0.0	31	10.2	0.46	1.00	0.05
AA-90-SBS	16	0	0.0	0.0	31	4.3	0.18	0.42	0.02
C1-00-SBS	18	2	11.1	14.0	31	10.2	0.84	0.99	0.08
C1-90-SBS	18	2	11.1	14.0	32	7.1	0.39	0.70	0.03
C2-00-SBS	20	4	20.0	24.5	30	10.8	0.35	1.05	0.03
C2-90-SBS	20	4	20.0	24.5	31	8.7	0.39	0.85	0.04
C3-00-SBS	22	6	27.3	32.8	15	11.1	0.40	1.09	0.04
C3-90-SBS	22	6	27.3	32.8	15	9.6	0.30	0.93	0.03
AA-00-CLC	16	0	0.0	0.0	9	107.0	3.14	1.00	0.03
AA-90-CLC	16	0	0.0	0.0	10	60.9	3.18	0.57	0.03
C1-00-CLC	18	2	11.1	14.0	10	108.1	4.11	1.01	0.04
C1-90-CLC	18	2	11.1	14.0	10	49.8	1.02	0.47	0.01
C2-00-CLC	20	4	20.0	24.5	10	103.7	10.68	0.97	0.10
C2-90-CLC	20	4	20.0	24.5	10	51.5	3.84	0.48	0.04

Table A.III: Full Tensile Testing Results Included in Data Analysis

Coupon ID	Average Length (in)	Average Width (in)	Average Thickness (in)	Peak Load (lb)	Peak Stress (ksi)	Relative Stress
AA-00-Ten-01	5.017	0.5033	0.0900	10167.19	224.46	0.93
AA-00-Ten-02	5.023	0.5000	0.0907	10514.76	231.86	0.96
AA-00-Ten-03	5.023	0.5003	0.0913	11400.55	253.35	1.04
AA-00-Ten-04	5.027	0.5013	0.0913	11051.78	245.60	1.01
AA-00-Ten-05	5.010	0.4993	0.0917	10903.92	242.31	1.00
AA-00-Ten-06	5.023	0.4997	0.0913	10567.43	234.83	0.97
AA-00-Ten-07	5.023	0.5003	0.0907	10898.39	242.19	1.00
AA-00-Ten-08	5.020	0.4990	0.0900	10900.66	242.24	1.00
AA-00-Ten-09	5.027	0.4990	0.0910	11544.52	256.54	1.06
AA-00-Ten-10	5.027	0.5000	0.0907	11303.55	251.19	1.04
AA-90-Ten-01	5.013	0.4997	0.0877	1726.88	39.41	0.16
AA-90-Ten-02	5.017	0.5007	0.0860	1790.84	41.59	0.17
AA-90-Ten-03	5.000	0.5000	0.0887	1808.73	40.19	0.17
AA-90-Ten-04	5.007	0.4990	0.0887	1607.90	35.73	0.15
AA-90-Ten-05	5.010	0.4997	0.0877	1725.95	38.35	0.16
AA-90-Ten-06	5.020	0.4993	0.0883	1671.66	37.15	0.15
AA-90-Ten-07	5.020	0.4990	0.0893	1764.92	39.22	0.16
AA-90-Ten-08	5.017	0.4990	0.0887	1665.27	37.01	0.15
AA-90-Ten-09	5.013	0.5007	0.0873	1741.93	38.71	0.16
AA-90-Ten-10	5.020	0.4987	0.0880	1761.18	39.14	0.16
C1-00-Ten-01	5.014	0.5003	0.1050	10851.15	217.02	0.90
C1-00-Ten-02	5.020	0.4987	0.1060	11509.88	218.04	0.90
C1-00-Ten-03	5.027	0.4993	0.1063	11387.80	207.05	0.85
C1-00-Ten-04	5.023	0.4993	0.1080	11571.74	210.40	0.87
C1-00-Ten-05	5.023	0.4983	0.1097	11161.49	202.94	0.84
C1-00-Ten-06	5.026	0.5020	0.1077	10260.32	186.55	0.77
C1-00-Ten-07	5.027	0.5063	0.1080	11020.73	196.45	0.81
C1-00-Ten-08	5.024	0.5053	0.1077	11303.57	201.49	0.83
C1-00-Ten-09	5.028	0.5050	0.1110	10322.38	184.00	0.76
C1-00-Ten-10	5.023	0.5047	0.1113	10986.99	199.76	0.82
C1-90-Ten-02	5.023	0.4983	0.1053	3200.21	62.53	0.26
C1-90-Ten-03	5.007	0.4997	0.1050	3031.04	55.11	0.23
C1-90-Ten-04	5.027	0.4983	0.1053	3256.38	59.21	0.24
C1-90-Ten-05	5.027	0.4990	0.1043	3034.44	60.69	0.25
C1-90-Ten-06	5.023	0.4980	0.1057	3001.97	54.58	0.23
C1-90-Ten-07	5.013	0.4993	0.1057	3176.38	57.75	0.24
C1-90-Ten-08	5.027	0.4980	0.1063	3334.69	60.63	0.25

C1-90-Ten-09	5.020	0.4993	0.1047	3050.52	61.01	0.25
C1-90-Ten-10	5.020	0.5017	0.1027	3265.37	65.31	0.27
C2-00-Ten-01	5.014	0.5008	1.0000	11982.44	193.27	0.80
C2-00-Ten-02	5.008	0.5013	0.1281	11799.01	183.99	0.76
C2-00-Ten-03	5.013	0.5010	0.1237	11810.86	196.85	0.81
C2-00-Ten-04	5.038	0.5011	0.1265	11759.35	180.91	0.75
C2-00-Ten-05	5.019	0.5038	0.1196	12436.42	207.27	0.85
C2-00-Ten-06	5.030	0.5012	0.1266	10710.29	164.77	0.68
C2-00-Ten-07	5.024	0.5008	0.1280	12365.11	190.23	0.78
C2-90-Ten-01	5.027	0.5027	0.1230	4416.11	71.81	0.30
C2-90-Ten-02	5.033	0.5023	0.1197	4696.19	78.61	0.32
C2-90-Ten-03	5.030	0.5023	0.1237	4557.71	75.96	0.31
C2-90-Ten-04	5.027	0.5013	0.1237	4497.98	74.97	0.31
C2-90-Ten-06	5.047	0.5017	0.1240	4544.13	75.74	0.31
C2-90-Ten-07	5.030	0.5020	0.1243	4719.33	78.66	0.32
C2-90-Ten-08	5.027	0.5023	0.1240	4539.04	75.65	0.31
C2-90-Ten-09	5.027	0.5017	0.1247	4632.17	77.20	0.32
C2-90-Ten-10	5.040	0.5027	0.1190	4386.73	73.11	0.30
C3-00-Ten-01	5.027	0.5010	0.1321	12559.16	190.29	0.78
C3-00-Ten-02	5.020	0.5017	0.1367	12574.87	184.92	0.76
C3-00-Ten-03	5.020	0.5017	0.1357	11908.76	175.52	0.72
C3-00-Ten-04	5.023	0.5013	0.1400	12145.93	173.51	0.72
C3-00-Ten-05	5.027	0.5027	0.1327	12335.98	189.78	0.78
C3-90-Ten-01	5.043	0.5003	0.1353	5858.45	90.13	0.37
C3-90-Ten-02	5.033	0.5010	0.1397	5980.04	85.43	0.35
C3-90-Ten-03	5.033	0.5007	0.1403	6299.50	89.99	0.37
C3-90-Ten-04	5.033	0.5013	0.1400	6280.77	89.73	0.37
C3-90-Ten-05	5.043	0.5030	0.1340	5998.31	89.53	0.37

Table A.IV: Full Short Beam Strength Testing Results Included in Data Analysis

Coupon ID	Average Length (in)	Average Width (in)	Average Thickness (in)	Peak Load (lb)	Peak Stress (ksi)	Relative Stress
AA-00-SBS-01	1.003	0.2530	0.0880	320.11	10.78	1.05
AA-00-SBS-02	1.001	0.2520	0.0870	297.66	10.18	0.99
AA-00-SBS-03	1.006	0.2520	0.0870	308.37	10.55	1.03
AA-00-SBS-04	1.001	0.2520	0.0870	335.61	11.48	1.12
AA-00-SBS-05	1.004	0.2510	0.0890	287.21	9.64	0.94
AA-00-SBS-06	1.002	0.2500	0.0890	295.88	9.97	0.97
AA-00-SBS-07	1.003	0.2510	0.0870	287.71	9.88	0.96

AA-00-SBS-08	1.003	0.2540	0.0880	296.60	9.95	0.97
AA-00-SBS-09	1.003	0.2520	0.0880	305.53	10.33	1.01
AA-00-SBS-10	1.002	0.2520	0.0850	310.40	10.87	1.06
AA-00-SBS-11	1.003	0.2510	0.0900	291.32	9.67	0.94
AA-00-SBS-12	1.001	0.2510	0.0890	309.48	10.39	1.01
AA-00-SBS-13	1.003	0.2460	0.0880	293.94	10.18	0.99
AA-00-SBS-14	1.003	0.2500	0.0880	300.27	10.24	1.00
AA-00-SBS-15	1.003	0.2530	0.0890	319.20	10.63	1.04
AA-00-SBS-16	1.008	0.2530	0.0890	292.48	9.74	0.95
AA-00-SBS-17	1.004	0.2520	0.0870	317.99	10.88	1.06
AA-00-SBS-18	1.006	0.2510	0.0890	282.75	9.49	0.93
AA-00-SBS-19	1.004	0.2530	0.0890	311.77	10.38	1.01
AA-00-SBS-20	0.998	0.2560	0.0860	293.15	9.99	0.97
AA-00-SBS-21	1.004	0.2510	0.0900	298.49	9.91	0.97
AA-00-SBS-22	1.005	0.2520	0.0900	311.67	10.31	1.01
AA-00-SBS-23	1.003	0.2480	0.0890	286.74	9.74	0.95
AA-00-SBS-24	1.003	0.2490	0.0890	296.57	10.04	0.98
AA-00-SBS-25	1.003	0.2520	0.0880	328.14	11.10	1.08
AA-00-SBS-26	1.003	0.2530	0.0870	297.08	10.12	0.99
AA-00-SBS-27	1.004	0.2520	0.0900	314.25	10.39	1.01
AA-00-SBS-28	1.006	0.2520	0.0900	316.41	10.46	1.02
AA-00-SBS-29	1.013	0.2530	0.0890	291.49	9.71	0.95
AA-00-SBS-30	1.004	0.2510	0.0870	303.35	10.42	1.02
AA-90-SBS-01	1.002	0.2560	0.0890	123.62	4.07	0.40
AA-90-SBS-02	1.003	0.2550	0.0890	130.95	4.33	0.42
AA-90-SBS-03	1.003	0.2550	0.0890	135.22	4.47	0.44
AA-90-SBS-04	1.002	0.2540	0.0890	130.77	4.34	0.42
AA-90-SBS-05	1.005	0.2550	0.0850	117.13	4.05	0.40
AA-90-SBS-06	1.006	0.2550	0.0870	133.70	4.52	0.44
AA-90-SBS-07	1.004	0.2550	0.0900	130.94	4.28	0.42
AA-90-SBS-08	1.004	0.2520	0.0850	117.53	4.12	0.40
AA-90-SBS-09	1.005	0.2560	0.0880	134.70	4.48	0.44
AA-90-SBS-10	1.005	0.2560	0.0880	127.16	4.23	0.41
AA-90-SBS-11	1.000	0.2550	0.0840	120.39	4.22	0.41
AA-90-SBS-12	1.004	0.2560	0.0880	127.54	4.25	0.41
AA-90-SBS-13	1.004	0.2560	0.0890	135.44	4.46	0.44
AA-90-SBS-14	1.004	0.2550	0.0880	119.90	4.01	0.39
AA-90-SBS-15	1.004	0.2550	0.0880	127.21	4.25	0.41
AA-90-SBS-16	1.003	0.2570	0.0870	126.04	4.23	0.41

AA-90-SBS-17	1.001	0.2550	0.0840	119.33	4.18	0.41
AA-90-SBS-18	1.005	0.2560	0.0900	130.38	4.24	0.41
AA-90-SBS-19	1.004	0.2550	0.0880	133.56	4.46	0.44
AA-90-SBS-20	1.003	0.2550	0.0880	134.46	4.49	0.44
AA-90-SBS-21	1.088	0.2550	0.0870	126.50	4.28	0.42
AA-90-SBS-22	1.005	0.2520	0.0860	128.83	4.46	0.44
AA-90-SBS-23	1.002	0.2560	0.0860	118.36	4.03	0.39
AA-90-SBS-24	1.005	0.2550	0.0880	134.82	4.51	0.44
AA-90-SBS-25	1.003	0.2560	0.0880	116.20	3.87	0.38
AA-90-SBS-26	1.000	0.2530	0.0830	121.69	4.35	0.42
AA-90-SBS-27	1.003	0.2550	0.0880	131.85	4.41	0.43
AA-90-SBS-28	1.006	0.2560	0.0890	140.41	4.62	0.45
AA-90-SBS-29	1.005	0.2570	0.0890	134.38	4.41	0.43
AA-90-SBS-30	1.005	0.2540	0.0880	131.28	4.40	0.43
C1-00-SBS-01	1.002	0.2540	0.1050	419.61	11.80	1.15
C1-00-SBS-02	1.003	0.2560	0.1040	389.90	10.98	1.07
C1-00-SBS-03	1.003	0.2540	0.1050	389.56	10.96	1.07
C1-00-SBS-04	1.004	0.2560	0.1030	347.77	9.89	0.97
C1-00-SBS-05	1.002	0.2530	0.1070	382.41	10.59	1.03
C1-00-SBS-06	1.001	0.2530	0.1030	290.23	8.35	0.82
C1-00-SBS-07	1.002	0.2540	0.1030	323.69	9.28	0.91
C1-00-SBS-08	1.003	0.2540	0.1040	374.10	10.62	1.04
C1-00-SBS-09	1.004	0.2540	0.1070	400.60	11.05	1.08
C1-00-SBS-10	1.005	0.2570	0.1080	363.92	9.83	0.96
C1-00-SBS-11	1.004	0.2520	0.1060	362.92	10.19	0.99
C1-00-SBS-12	1.005	0.2550	0.1050	375.99	10.53	1.03
C1-00-SBS-13	1.004	0.2540	0.1050	346.95	9.76	0.95
C1-00-SBS-14	1.003	0.2560	0.1070	385.94	10.57	1.03
C1-00-SBS-15	1.003	0.2550	0.1030	335.76	9.59	0.94
C1-00-SBS-16	1.004	0.2510	0.1060	346.74	9.77	0.95
C1-00-SBS-17	1.001	0.2560	0.1050	305.13	8.51	0.83
C1-00-SBS-18	1.003	0.2540	0.1050	347.73	9.78	0.95
C1-00-SBS-19	1.001	0.2540	0.1030	385.50	11.05	1.08
C1-00-SBS-20	1.004	0.2550	0.1040	385.88	10.91	1.07
C1-00-SBS-21	1.006	0.2560	0.1080	344.13	9.34	0.91
C1-00-SBS-22	1.004	0.2550	0.1030	383.44	10.95	1.07
C1-00-SBS-23	1.004	0.2550	0.1060	396.27	11.00	1.07
C1-00-SBS-24	1.004	0.2550	0.1050	395.14	11.07	1.08
C1-00-SBS-25	1.005	0.2530	0.1060	382.61	10.70	1.04

C1-00-SBS-26	1.004	0.2550	0.1060	377.49	10.47	1.02
C1-00-SBS-27	1.001	0.2550	0.1030	319.90	9.13	0.89
C1-00-SBS-28	1.004	0.2530	0.1060	360.02	10.07	0.98
C1-00-SBS-29	1.005	0.2560	0.1050	358.48	10.00	0.98
C1-00-SBS-30	1.001	0.2520	0.1040	313.69	8.98	0.88
C1-90-SBS-03	1.003	0.2560	0.1040	269.57	7.59	0.74
C1-90-SBS-04	1.001	0.2530	0.1010	253.40	7.44	0.73
C1-90-SBS-05	1.001	0.2540	0.1070	257.65	7.11	0.69
C1-90-SBS-06	1.001	0.2550	0.1030	252.67	7.22	0.70
C1-90-SBS-07	1.001	0.2520	0.1000	229.76	6.84	0.67
C1-90-SBS-08	1.002	0.2530	0.1020	238.61	6.93	0.68
C1-90-SBS-09	1.002	0.2530	0.1040	241.43	6.88	0.67
C1-90-SBS-10	1.001	0.2560	0.1070	259.13	7.10	0.69
C1-90-SBS-11	1.001	0.2530	0.1070	263.62	7.30	0.71
C1-90-SBS-12	1.003	0.2540	0.1040	255.29	7.25	0.71
C1-90-SBS-13	1.005	0.2530	0.1060	269.86	7.55	0.74
C1-90-SBS-14	1.003	0.2520	0.1070	267.44	7.44	0.73
C1-90-SBS-15	1.002	0.2520	0.1030	218.69	6.32	0.62
C1-90-SBS-16	1.001	0.2540	0.1050	244.34	6.87	0.67
C1-90-SBS-17	0.998	0.2540	0.0980	228.90	6.90	0.67
C1-90-SBS-18	1.003	0.2530	0.1070	263.80	7.31	0.71
C1-90-SBS-19	1.000	0.2540	0.1020	209.26	6.06	0.59
C1-90-SBS-20	1.004	0.2550	0.1050	248.20	6.95	0.68
C1-90-SBS-21	1.002	0.2540	0.1040	261.26	7.42	0.72
C1-90-SBS-22	1.003	0.2540	0.1070	261.77	7.22	0.71
C1-90-SBS-23	1.004	0.2540	0.1010	253.54	7.41	0.72
C1-90-SBS-24	1.002	0.2540	0.1060	258.72	7.21	0.70
C1-90-SBS-25	1.002	0.2530	0.1050	259.30	7.32	0.71
C1-90-SBS-26	1.004	0.2540	0.1040	241.11	6.85	0.67
C1-90-SBS-27	1.001	0.2540	0.1010	253.17	7.40	0.72
C1-90-SBS-28	1.005	0.2530	0.1050	264.99	7.48	0.73
C1-90-SBS-29	1.004	0.2540	0.1060	257.93	7.18	0.70
C1-90-SBS-30	1.002	0.2540	0.1050	245.15	6.89	0.67
C2-00-SBS-01	1.001	0.2560	0.1220	442.49	10.63	1.04
C2-00-SBS-02	1.006	0.2550	0.1230	457.65	10.94	1.07
C2-00-SBS-03	1.007	0.2550	0.1240	455.24	10.80	1.05
C2-00-SBS-04	1.010	0.2550	0.1180	440.98	10.99	1.07
C2-00-SBS-05	1.006	0.2540	0.1220	448.88	10.86	1.06
C2-00-SBS-06	1.009	0.2560	0.1190	436.91	10.76	1.05

C2-00-SBS-07	1.007	0.2540	0.1230	456.65	10.96	1.07
C2-00-SBS-08	1.010	0.2540	0.1210	426.78	10.41	1.02
C2-00-SBS-09	1.011	0.2560	0.1190	461.81	11.37	1.11
C2-00-SBS-10	1.008	0.2550	0.1240	441.51	10.47	1.02
C2-00-SBS-11	1.009	0.2550	0.1170	429.14	10.79	1.05
C2-00-SBS-12	1.006	0.2540	0.1230	460.08	11.04	1.08
C2-00-SBS-13	1.009	0.2560	0.1190	426.84	10.51	1.03
C2-00-SBS-14	1.007	0.2560	0.1240	468.21	11.06	1.08
C2-00-SBS-15	1.007	0.2520	0.1230	446.70	10.81	1.05
C2-00-SBS-16	1.010	0.2560	0.1170	442.81	11.09	1.08
C2-00-SBS-17	1.006	0.2550	0.1180	406.01	10.12	0.99
C2-00-SBS-18	1.008	0.2550	0.1190	436.32	10.78	1.05
C2-00-SBS-19	1.009	0.2560	0.1230	470.52	11.21	1.09
C2-00-SBS-20	1.006	0.2560	0.1240	454.14	10.73	1.05
C2-00-SBS-21	1.008	0.2540	0.1180	438.20	10.97	1.07
C2-00-SBS-22	1.006	0.2550	0.1190	456.64	11.29	1.10
C2-00-SBS-23	1.011	0.2550	0.1200	451.99	11.08	1.08
C2-00-SBS-24	1.006	0.2560	0.1220	445.11	10.69	1.04
C2-00-SBS-25	1.008	0.2560	0.1170	441.49	11.05	1.08
C2-00-SBS-26	1.006	0.2560	0.1240	413.95	9.78	0.95
C2-00-SBS-27	1.009	0.2560	0.1170	440.80	11.04	1.08
C2-00-SBS-28	1.009	0.2570	0.1190	438.53	10.75	1.05
C2-00-SBS-29	1.009	0.2560	0.1200	442.54	10.80	1.05
C2-00-SBS-30	1.011	0.2590	0.1200	422.39	10.19	0.99
C2-90-SBS-01	1.002	0.2510	0.1240	373.34	9.00	0.88
C2-90-SBS-02	0.999	0.2520	0.1210	323.29	7.95	0.78
C2-90-SBS-03	1.003	0.2520	0.1200	317.39	7.87	0.77
C2-90-SBS-04	1.004	0.2510	0.1200	340.21	8.47	0.83
C2-90-SBS-05	1.002	0.2500	0.1160	333.99	8.64	0.84
C2-90-SBS-06	0.999	0.2540	0.1160	356.85	9.08	0.89
C2-90-SBS-07	1.001	0.2520	0.1160	335.75	8.61	0.84
C2-90-SBS-08	1.002	0.2520	0.1130	345.63	9.10	0.89
C2-90-SBS-09	1.002	0.2530	0.1210	353.37	8.66	0.84
C2-90-SBS-10	1.005	0.2520	0.1240	343.70	8.25	0.81
C2-90-SBS-11	1.004	0.2520	0.1120	348.39	9.26	0.90
C2-90-SBS-12	1.005	0.2540	0.1250	373.90	8.83	0.86
C2-90-SBS-13	1.006	0.2530	0.1200	355.41	8.78	0.86
C2-90-SBS-14	1.004	0.2530	0.1170	374.82	9.50	0.93
C2-90-SBS-15	1.002	0.2530	0.1180	350.65	8.81	0.86

C2-90-SBS-16	1.005	0.2520	0.1170	333.08	8.47	0.83
C2-90-SBS-17	1.004	0.2530	0.1230	352.75	8.50	0.83
C2-90-SBS-18	1.006	0.2540	0.1250	366.69	8.66	0.85
C2-90-SBS-19	1.004	0.2520	0.1160	331.85	8.51	0.83
C2-90-SBS-20	1.002	0.2550	0.1250	372.96	8.78	0.86
C2-90-SBS-21	1.005	0.2520	0.1210	367.63	9.04	0.88
C2-90-SBS-22	1.006	0.2540	0.1250	326.30	7.71	0.75
C2-90-SBS-23	1.005	0.2520	0.1220	357.50	8.72	0.85
C2-90-SBS-24	1.005	0.2540	0.1250	379.11	8.96	0.87
C2-90-SBS-25	1.006	0.2550	0.1260	360.68	8.42	0.82
C2-90-SBS-26	1.005	0.2540	0.1260	377.32	8.84	0.86
C2-90-SBS-27	1.004	0.2540	0.1260	378.39	8.87	0.87
C2-90-SBS-28	1.004	0.2520	0.1240	377.04	9.05	0.88
C2-90-SBS-29	1.002	0.2540	0.1150	327.96	8.42	0.82
C2-90-SBS-30	1.006	0.2550	0.1230	352.07	8.42	0.82
C3-00-SBS-01	1.002	0.2540	0.1420	525.22	10.92	1.07
C3-00-SBS-02	1.003	0.2560	0.1430	552.23	11.31	1.10
C3-00-SBS-03	1.003	0.2540	0.1430	551.80	11.39	1.11
C3-00-SBS-04	1.003	0.2720	0.1410	583.63	11.41	1.11
C3-00-SBS-05	1.003	0.2580	0.1420	559.48	11.45	1.12
C3-00-SBS-06	1.004	0.2620	0.1420	526.29	10.61	1.04
C3-00-SBS-07	1.004	0.2540	0.1410	539.59	11.30	1.10
C3-00-SBS-08	1.002	0.2540	0.1420	558.72	11.62	1.13
C3-00-SBS-09	1.003	0.2560	0.1420	542.77	11.20	1.09
C3-00-SBS-10	1.004	0.2550	0.1420	541.34	11.21	1.09
C3-00-SBS-11	1.004	0.2550	0.1380	481.54	10.26	1.00
C3-00-SBS-12	1.002	0.2550	0.1380	498.04	10.61	1.04
C3-00-SBS-13	1.003	0.2540	0.1410	536.67	11.24	1.10
C3-00-SBS-14	1.003	0.2540	0.1390	509.60	10.83	1.06
C3-00-SBS-15	1.002	0.2550	0.1410	558.36	11.65	1.14
C3-90-SBS-01	1.005	0.2530	0.1390	470.90	10.04	0.98
C3-90-SBS-02	1.003	0.2540	0.1350	455.70	9.97	0.97
C3-90-SBS-03	1.007	0.2540	0.1380	422.10	9.03	0.88
C3-90-SBS-04	1.002	0.2540	0.1360	436.63	9.48	0.93
C3-90-SBS-05	1.005	0.2540	0.1390	454.28	9.65	0.94
C3-90-SBS-06	1.004	0.2540	0.1340	424.22	9.35	0.91
C3-90-SBS-07	1.002	0.2710	0.1350	446.56	9.15	0.89
C3-90-SBS-08	1.004	0.2540	0.1410	472.98	9.90	0.97
C3-90-SBS-09	1.003	0.2530	0.1410	458.89	9.65	0.94

C3-90-SBS-10	1.004	0.2530	0.1330	427.24	9.52	0.93
C3-90-SBS-11	1.005	0.2520	0.1380	448.39	9.67	0.94
C3-90-SBS-12	1.005	0.2630	0.1410	482.13	9.75	0.95
C3-90-SBS-13	1.005	0.2560	0.1410	460.43	9.57	0.93
C3-90-SBS-14	1.002	0.2590	0.1420	477.83	9.74	0.95
C3-90-SBS-15	1.004	0.2540	0.1380	428.28	9.16	0.89

Table A.V: Full Combined Load Compression Testing Results Included in Data Analysis

Coupon ID	Average Length (in)	Average Width (in)	Average Thickness (in)	Peak Load (lb)	Peak Stress (ksi)	Relative Stress
AA-00-CLC-01	-	0.5030	0.0898	4735.39	104.84	0.98
AA-00-CLC-02	-	0.5030	0.0900	4789.67	105.80	0.99
AA-00-CLC-03	-	0.5030	0.0899	4825.44	106.71	1.00
AA-00-CLC-04	-	0.5030	0.0897	4814.44	106.71	1.00
AA-00-CLC-05	-	0.5030	0.0898	5161.15	114.26	1.07
AA-00-CLC-06	-	0.5030	0.0896	4829.66	107.16	1.00
AA-00-CLC-07	-	0.5030	0.0894	4698.27	104.48	0.98
AA-00-CLC-08	-	0.5030	0.0893	4673.78	104.05	0.97
AA-00-CLC-09	-	0.5030	0.0898	4932.93	109.21	1.02
AA-90-CLC-01	-	0.5010	0.0872	2573.62	58.91	0.55
AA-90-CLC-02	-	0.5010	0.0833	2742.73	65.72	0.61
AA-90-CLC-03	-	0.5010	0.0853	2806.60	65.67	0.61
AA-90-CLC-04	-	0.5000	0.0874	2668.32	61.06	0.57
AA-90-CLC-05	-	0.5020	0.0872	2460.39	56.21	0.53
AA-90-CLC-06	-	0.5030	0.0878	2662.64	60.29	0.56
AA-90-CLC-07	-	0.5020	0.0878	2549.29	57.85	0.54
AA-90-CLC-08	-	0.5010	0.0891	2610.29	60.28	0.56
AA-90-CLC-09	-	0.5010	0.0878	2549.99	59.34	0.55
AA-90-CLC-10	-	0.4950	0.0856	2690.86	63.51	0.59
C1-00-CLC-01	-	0.5060	0.1055	5726.36	107.27	1.00
C1-00-CLC-02	-	0.5070	0.1073	5627.47	103.44	0.97
C1-00-CLC-03	-	0.5060	0.1037	5467.68	104.20	0.97
C1-00-CLC-04	-	0.5070	0.1072	5691.50	104.72	0.98
C1-00-CLC-05	-	0.5070	0.1074	5821.68	106.91	1.00
C1-00-CLC-06	-	0.5070	0.1068	6050.04	111.73	1.04
C1-00-CLC-07	-	0.5070	0.1022	5615.42	108.37	1.01
C1-00-CLC-08	-	0.5060	0.1075	6297.38	115.77	1.08
C1-00-CLC-09	-	0.5060	0.1074	5744.02	105.70	0.99
C1-00-CLC-10	-	0.5060	0.1057	6042.10	112.97	1.06

C1-90-CLC-01	-	0.5060	0.1070	2696.48	49.80	0.47
C1-90-CLC-02	-	0.5060	0.1080	2719.21	49.76	0.46
C1-90-CLC-03	-	0.5070	0.1082	2610.58	47.59	0.44
C1-90-CLC-04	-	0.5060	0.1051	2646.51	49.76	0.46
C1-90-CLC-05	-	0.5060	0.1032	2607.73	49.94	0.47
C1-90-CLC-06	-	0.5070	0.1061	2755.42	51.22	0.48
C1-90-CLC-07	-	0.5070	0.1082	2702.94	49.27	0.46
C1-90-CLC-08	-	0.5060	0.1088	2820.11	51.23	0.48
C1-90-CLC-09	-	0.5060	0.1090	2767.30	50.17	0.47
C1-90-CLC-10	-	0.5060	0.1080	2710.31	49.60	0.46
C2-00-CLC-01	-	0.5070	0.1236	5561.48	88.75	0.83
C2-00-CLC-02	-	0.5070	0.1251	6100.68	96.19	0.90
C2-00-CLC-03	-	0.5070	0.1244	5481.16	86.90	0.81
C2-00-CLC-04	-	0.5070	0.1244	6425.65	101.88	0.95
C2-00-CLC-05	-	0.5070	0.1244	6335.56	100.45	0.94
C2-00-CLC-06	-	0.5060	0.1244	7162.36	113.79	1.06
C2-00-CLC-07	-	0.5070	0.1241	7491.13	119.06	1.11
C2-00-CLC-08	-	0.5060	0.1244	6910.10	109.78	1.03
C2-00-CLC-09	-	0.5070	0.1236	6898.45	110.08	1.03
C2-00-CLC-10	-	0.5070	0.1238	6882.57	109.65	1.02
C2-90-CLC-01	-	0.5070	0.1175	3201.81	53.75	0.50
C2-90-CLC-02	-	0.5060	0.1267	2819.09	43.97	0.41
C2-90-CLC-03	-	0.5050	0.1196	3239.08	53.63	0.50
C2-90-CLC-04	-	0.5060	0.1268	3173.37	49.46	0.46
C2-90-CLC-05	-	0.5060	0.1270	3083.40	47.98	0.45
C2-90-CLC-06	-	0.5060	0.1264	3480.37	54.42	0.51
C2-90-CLC-07	-	0.5060	0.1232	3070.88	49.26	0.46
C2-90-CLC-08	-	0.5060	0.1267	3671.74	57.27	0.54
C2-90-CLC-09	-	0.5060	0.1272	3348.70	52.03	0.49
C2-90-CLC-10	-	0.5060	0.1261	3392.84	53.17	0.50

Table A.VI: Excluded Group Summary Information

Coupon ID Group	Ply Count		% Clad		QTY Tested	Strength (ksi)	
	Total	Clad	Ply	Fiber Weight		Mean	Std Dev
QI-00-SBS	16	0	0.0	0.0	10	152.8	10.77
QI-00-SBS	16	0	0.0	0.0	31	9.4	1.15
QI-00-CLC	16	0	0.0	0.0	11	84.6	1.87

Table A.VII: Testing Results Excluded From Data Analysis

Coupon ID	Average Length (in)	Average Width (in)	Average Thickness (in)	Peak Load (lb)	Peak Stress (ksi)
C1-90-Ten-01	5.017	0.4993	0.1027	3107.62	6.06
C2-90-Ten-05	5.033	0.5027	0.1230	570.34	9.51
AA-00-SBS-74	1.004	0.2516	0.0883	301.22	10.17
AA-90-SBS-43	1.006	0.2551	0.0875	133.09	4.47
C1-00-SBS-43	1.003	0.2544	0.1050	395.87	11.11
C1-90-SBS-01	1.002	0.2540	0.1030	257.93	7.39
C1-90-SBS-02	1.003	0.2540	0.1040	222.23	6.31
C1-90-SBS-36	1.002	0.2537	0.1041	221.49	6.29
C1-90-SBS-37	1.002	0.2537	0.1041	240.04	6.81
C2-90-SBS-37	1.004	0.2529	0.1207	355.30	8.73
QI-00-Ten-01	5.040	0.5050	0.0920	6424.45	138.28
QI-00-Ten-02	5.033	0.5053	0.0897	7227.75	160.81
QI-00-Ten-03	5.037	0.5063	0.0913	7628.75	166.20
QI-00-Ten-04	5.037	0.5037	0.0903	7309.97	162.44
QI-00-Ten-05	5.027	0.5040	0.0913	6571.18	146.03
QI-00-Ten-06	5.037	0.5003	0.0887	7396.66	164.37
QI-00-Ten-07	5.035	0.5033	0.0890	7293.01	145.86
QI-00-Ten-08	5.036	0.5037	0.0890	6191.83	137.60
QI-00-Ten-09	5.041	0.5027	0.0883	7095.09	157.67
QI-00-Ten-10	5.036	0.5037	0.0890	6711.40	149.14
QI-00-SBS-01	1.000	0.2550	0.0890	285.02	9.42
QI-00-SBS-02	1.000	0.2510	0.0860	274.86	9.55
QI-00-SBS-03	1.004	0.2510	0.0860	299.52	10.41
QI-00-SBS-04	1.003	0.2520	0.0880	293.46	9.92
QI-00-SBS-05	1.003	0.2500	0.0870	233.98	8.07
QI-00-SBS-06	1.004	0.2540	0.0900	298.86	9.81
QI-00-SBS-07	1.004	0.2530	0.0870	292.53	9.97
QI-00-SBS-08	1.006	0.2530	0.0880	267.88	9.02
QI-00-SBS-09	1.007	0.2540	0.0900	291.50	9.56
QI-00-SBS-10	1.004	0.2520	0.0890	289.79	9.69
QI-00-SBS-11	1.005	0.2530	0.0900	280.74	9.25
QI-00-SBS-12	1.005	0.2530	0.0890	302.55	10.08
QI-00-SBS-13	1.004	0.2540	0.0890	241.36	8.01
QI-00-SBS-14	1.004	0.2510	0.0910	260.77	8.56
QI-00-SBS-15	1.003	0.2520	0.0900	305.37	10.10
QI-00-SBS-16	1.005	0.2530	0.0910	294.51	9.59
QI-00-SBS-17	1.004	0.2520	0.0900	295.22	9.76

QI-00-SBS-18	1.004	0.2520	0.0880	298.84	10.11
QI-00-SBS-19	1.005	0.2530	0.0890	391.60	13.04
QI-00-SBS-20	1.005	0.2530	0.0860	273.54	9.43
QI-00-SBS-21	1.002	0.2530	0.0900	281.22	9.26
QI-00-SBS-22	1.003	0.2530	0.0890	288.81	9.62
QI-00-SBS-23	1.003	0.2540	0.0850	257.01	8.93
QI-00-SBS-24	1.004	0.2510	0.0890	284.83	9.56
QI-00-SBS-25	1.004	0.2520	0.0900	240.64	7.96
QI-00-SBS-26	1.001	0.2520	0.0900	252.66	8.36
QI-00-SBS-27	1.002	0.2550	0.0900	283.47	9.26
QI-00-SBS-28	1.002	0.2540	0.0900	288.12	9.45
QI-00-SBS-29	1.004	0.2500	0.0910	298.32	9.83
QI-00-SBS-30	1.004	0.2490	0.0900	274.04	9.17
QI-00-SBS-74	1.004	0.2525	0.0889	168.38	5.63
QI-00-CLC-01	-	0.5050	0.0894	3920.93	86.85
QI-00-CLC-02	-	0.5050	0.0903	3911.52	85.78
QI-00-CLC-03	-	0.5050	0.0905	3781.57	82.74
QI-00-CLC-04	-	0.5050	0.0905	3984.36	87.18
QI-00-CLC-05	-	0.5050	0.0883	-	-
QI-00-CLC-06	-	0.5050	0.0902	3768.86	82.74
QI-00-CLC-07	-	0.5050	0.0899	3871.08	85.27
QI-00-CLC-08	-	0.5050	0.0904	3835.16	84.01
QI-00-CLC-09	-	0.5050	0.0902	3925.90	86.19
QI-00-CLC-10	-	0.5050	0.0900	3772.98	83.01
QI-00-CLC-11	-	0.5050	0.0901	3740.81	82.21

Appendix B. MATLAB Code

```
%% Data Entry
   % Fitting Data
            % Format = [Ply %, Weight %, Strength, Relative Strength]
            % Clad fabric properties are included
L_Ten = [];  % This was the array containing the Longitudinal tensile data.
T_Ten = [];  % This was the array containing the transverse tensile data.
L_SBS = [];  % This was the array containing the Longitudinal SBS data.
T_SBS = [];  % This was the array containing the transverse SBS data.
L_CLC = [];  % This was the array containing the Longitudinal CLC data.
T_CLC = [];  % This was the array containing the transverse CLC data.


   % Adapted Data
            % Format = [Ply %, Weight %, Strength, Relative Strength]
            % Clad fabric properties are not included
AL_Ten = []; % This was the array containing the Longitudinal tensile data.
AT_Ten = []; % This was the array containing the transverse tensile data.
AL_SBS = []; % This was the array containing the Longitudinal SBS data.
AT_SBS = []; % This was the array containing the transverse SBS data.
AL_CLC = []; % This was the array containing the Longitudinal CLC data.
AT_CLC = []; % This was the array containing the transverse CLC data.


   % Fiber Properties
            % These lines pull the fabric properties, which were included at the
            % end of the Fitting Data
FL_Ten = L_Ten(length(L_Ten),:);
FT_Ten = T_Ten(length(T_Ten),:);
FL_SBS = L_SBS(length(L_SBS),:);
FT_SBS = T_SBS(length(T_SBS),:);
FL_CLC = L_CLC(length(L_CLC),:);
FT_CLC = T_CLC(length(T_CLC),:);


   % Loop Variables
i = 2;                  % i was a variable to define what column the was
                        % being plotted as the x variable.

B = 2;                  % B was a variable to allow easy manipulation of
                        % trend fitting for loop. B is the initial variable.

E = 5;                  % E was a variable to allow easy manipulation of
                        % trend fitting for loop. E is the final variable.

if i == 2
       A = 'Weight %';
   else
       A = 'Ply %';
end
```

```
%% Loop
for n = B:E

   %% Data ID Loop
           % The IF statements in this FOR loop all are to select
           % which of the 6 data sets are being analyzed.

   for m = 1:6
       if m == 1
           X = L_Ten;
           if n > B
               R_Square = R_LT;
               Trend_Line = TL_LT;
           end

       elseif m == 2
           X = T_Ten;
           if n > B
               R_Square = R_TT;
               Trend_Line = TL_TT;
           end

       elseif m == 3
           X = L_SBS;
           if n > B
               R_Square = R_LS;
               Trend_Line = TL_LS;
           end
       elseif m == 4
           X = T_SBS;
       if n > B
           R_Square = R_TS;
           Trend_Line = TL_TS;
       end
       elseif m == 5
           X = L_CLC;
           if n > B
               R_Square = R_LC;
               Trend_Line = TL_LC;
           end
       elseif m == 6
           X = T_CLC;
           if n > B
               R_Square = R_TC;
               Trend_Line = TL_TC;
           end
       end


       %% Fit Type Loop
               % n is running on a FOR loop between variables B and E
               % n = 1 tests a first degree polynomial
               % 2 <= n <= 4 tests polynomials of the n degree
               % n = 5 tests an exponential function
```

```
if n == 1
    ft = fittype('poly1');
elseif n == 5
    ft = fittype('-a*exp(-b*x+c)+d');
else
    ft = fittype(['a*(x-100)^',num2str(n),'+',num2str(X(length(X),4))]);
end


%% Trend Fit
        % These commands fit the trend. The WARNING() are there
        % because FIT wants a starting point, but it can operate
        % without one. It got annoying and was thus muted. The IF
        % statement compares the R^2 values, and keeps the FIT
        % results with the higher R^2 value.

warning('off');
[T, R] = fit(X(:,i),X(:,4),ft);
warning('on');

if      n == B
    Trend_Line = T;
    R_Square = R;
elseif      R_Square.rsquare < R.rsquare
    Trend_Line = T;
    R_Square = R;
end


%% Trend Fit Export
        % These IF statements are only to store the results of the
        % Trend Fit section so that they can be recalled after the
        % loops are over

if m == 1
    R_LT = R_Square;
    warning('off');
    Rs_LT(n) = R.rsquare;
    Es_LT(n) = R.sse;
    warning('on');
    TL_LT = Trend_Line;

elseif m == 2
    R_TT = R_Square;
    warning('off');
    Rs_TT(n) = R.rsquare;
    Es_TT(n) = R.sse;
    warning('on');
    TL_TT = Trend_Line;
```

```
        elseif m == 3
            R_LS = R_Square;
            warning('off');
            Rs_LS(n) = R.rsquare;
            Es_LS(n) = R.sse;
            warning('on');
            TL_LS = Trend_Line;

        elseif m == 4
            R_TS = R_Square;
            warning('off');
            Rs_TS(n) = R.rsquare;
            Es_TS(n) = R.sse;
            warning('on');
            TL_TS = Trend_Line;

        elseif m == 5
            R_LC = R_Square;
            warning('off');
            Rs_LC(n) = R.rsquare;
            Es_LC(n) = R.sse;
            warning('on');
            TL_LC = Trend_Line;

        elseif m == 6
            R_TC = R_Square;
            warning('off');
            Rs_TC(n) = R.rsquare;
            Es_TC(n) = R.sse;
            warning('on');
            TL_TC = Trend_Line;
        end
    end
end


%% Tensile
        % This section is just plotting and formatting the tensile graphs

figure;
hold on

    % Longitudinal Tensile
boxchart(AL_Ten(:,i),AL_Ten(:,4),'BoxWidth',5,'BoxFaceColor','r','MarkerStyle','x',
'MarkerColor','r')
plot(TL_LT,'--r')                               % Experimental Trend Line

    % Transverse Tensile
boxchart(AT_Ten(:,i),AT_Ten(:,4),'BoxWidth',5,'BoxFaceColor','b','MarkerStyle','x',
'MarkerColor','b')
plot(TL_TT,'--b')                               % Experimental Trend Line

plot(FL_Ten(i),FL_Ten(4),'or')                  % Plots the Fiber Properties
plot(FT_Ten(i),FT_Ten(4),'ob')                  % Plots the Fiber Properties
```

```
xlim([-5 100])
ylim([0,1.2])
ylabel('Relative Tensile Strength')
xlabel('Fiber Weight % (Clad)')
legend({'Longitudinal Data','Longitudinal Fit','Transverse Data','Transverse
Fit'},'Location','southeast')

%% SBS
       % This section is just plotting and formatting the SBS graphs.
       % The longitudinal SBS plots a horizontal line at the average
       % value rather than the trend line since no meaningful correlation
       % was observed.

figure;
hold on

   % Longitudinal SBS
boxchart(AL_SBS(:,i),AL_SBS(:,4),'BoxWidth',5,'BoxFaceColor','r','MarkerStyle','x',
'MarkerColor','r')
plot([-50 150],mean(AL_SBS(:,4))*[1 1],':r')    % Horizontal Line at Average

   % Transverse SBS
boxchart(AT_SBS(:,i),AT_SBS(:,4),'BoxWidth',5,'BoxFaceColor','b','MarkerStyle','x',
'MarkerColor','b')
plot(TL_TS,'--b')                               % Experimental Trend Line

plot(FL_SBS(i),FL_SBS(4),'or')                  % Plots the Fiber Properties
plot(FT_SBS(i),FT_SBS(4),'ob')                  % Plots the Fiber Properties

xlim([-5 100])
ylim([0,1.2])
ylabel('Relative SBS')
xlabel('Fiber Weight % (Clad)')
legend({'Longitudinal Data','Longitudinal Fit','Transverse Data','Transverse
Fit'},'Location','southeast')

%% CLC
       % This section is just plotting and formatting the CLC graphs. Both
       % plots use a horizontal line at the average value rather than the
       % trend line since no meaningful correlation was observed.

figure;
hold on

   % Longitudinal CLC
boxchart(AL_CLC(:,i),AL_CLC(:,4),'BoxWidth',5,'BoxFaceColor','r','MarkerStyle','x',
'MarkerColor','r')
plot([-50 150],mean(AL_CLC(:,4))*[1 1],':r')    % Horizontal Line at Average

   % Transverse CLC
boxchart(AT_CLC(:,i),AT_CLC(:,4),'BoxWidth',5,'BoxFaceColor','b','MarkerStyle','x',
'MarkerColor','b')
plot([-50 150],mean(AT_CLC(:,4))*[1 1],':b')    % Horizontal Line at Average
```

```
plot(FL_CLC(i),FL_CLC(4),'or')                    % Plots the Fiber Properties
plot(FT_CLC(i),FT_CLC(4),'ob')                    % Plots the Fiber Properties

xlim([-5 100])
ylim([0,1.2])
ylabel('Relative Compressive Strength')
xlabel('Fiber Weight % (Clad)')
legend({'Longitudinal Data','Longitudinal Fit','Transverse Data','Transverse
Fit'},'Location','southeast')
```