

AE 461 Full Engineering Report for Experiment #1, 6

Composite Laminates Manufacturing and Testing

by

Declan Fisher, Michael Haas, Patrick Hillgardner, Zayna Khan, Eugene Lim, Amber Miller

TA: Kathiresan Karunakaran

Section AB2, Group J, Tuesday 3:30 - 5:30pm

April 22, 2025

ABSTRACT

This research use two consecutive experimental procedures to investigate the making and tensile testing of composite laminates. Three different composite structures were created using graphite/epoxy prepreg sheets, with 0° , $\pm 45^\circ$, and 90° ply orientations. The final specimens for mechanical testing were created by carefully stacking, molding, and thermally curing the plies. Important physical characteristics, such as thickness, width, and length, were measured after curing. Each specimen's stress-strain response was then evaluated using tensile tests, recording force, strain, displacement, and time until material failure. Mechanical properties including ultimate strength and elastic modulus were calculated from the experimental data and compared these values to values to data obtained from theoretical micro-mechanical models.

1 INTRODUCTION

In recent years, composite materials have grown in popularity and utilization in aerospace applications because of their unique mechanical and physical properties. Composite materials weigh less than alternatives and offer high strength properties, which is critical in the aerospace sector. Through the studies presented in this paper, the group will learn more about the behavior, manufacturing, modeling, and testing of composites. Over the course of two experiments, we fabricated three different composite specimens and tested them under uniaxial tension. In experiment 1, we used various stacking configurations of a graphite/epoxy composite lamina and produced three specimens for the first experiment, which we then turned over to the lab teaching assistants to cure.

In the second phase of the experiment, known as Laboratory Experiment 6, the specimens from Experiment 1 were tested using a tension and compression equipment that could record and evaluate the pressures and strains experienced by the composites. The team examined a number of the composite's characteristics throughout this experiment, including weight and size. Analyses were conducted to determine the theoretical characteristics of the materials before the tests. Theoretical predictions were used to compare and validate material properties after the experiments.

2 THEORY AND ANALYSIS

2.1 Experimental material property determination

Tensile stress σ can be calculated by taking the force applied parallel to the stress direction divided by the cross-sectional area of the object:

$$\sigma = \frac{F}{A} \quad (1)$$

where F is the applied force [N] and A is the original cross-sectional area [mm^2].

Tensile strain ϵ is calculated as the change in length divided by the original length:

$$\epsilon = \frac{\Delta L}{L_0} \quad (2)$$

where ΔL is the change in length [mm] and L_0 is the original gauge length [mm].

The tensile modulus E (also called Young's modulus) is defined as the slope of the linear (elastic) region of the stress-strain curve:

$$E = \frac{\sigma}{\epsilon} \quad (3)$$

(where E is in units of [MPa] or [GPa].)

The elastic limit is the maximum stress at which the material still behaves elastically, which means that it returns to its original shape upon unloading. It can be found from the stress-strain curve as the point where the curve begins to deviate from linearity. Alternately, in cases where the linearity divergence point cannot be accurately found, a 0.2% strain offset may be used, as shown in Figure 16b.

The ultimate strength, or maximum stress before fracture, is determined by finding the peak value of the stress-strain curve:

$$\sigma_{\text{ult}} = \max(\sigma) \quad (4)$$

The ultimate strain is the strain corresponding to the ultimate strength:

$$\epsilon_{\text{ult}} = \text{strain at } \sigma_{\text{ult}} \quad (5)$$

2.2 Assumptions for Theoretical Analysis

Several assumptions are made in deriving and interpreting the mechanical properties of composite laminates.

- The specimens are assumed to have a uniform cross-sectional area along the gauge length.
- The material behaves in a linear elastic manner up to the elastic limit.
- The composite behaves as a homogeneous material on the laminate scale (even though microscopically it is heterogeneous).
- The deformations are small (the engineering strain approximation is valid).
- The plane sections remain plane and normal to the axis of loading (classical beam theory assumption).
- The effects of temperature and humidity are negligible during the short duration of tensile testing.

These assumptions allow for the use of simplified theoretical models, such as the Rule of Mixtures and classical lamination theory, to predict laminate properties.

2.3 Significance of Stress-Strain Behavior in Composites

The stress-strain behavior provides crucial information on how composite laminates perform under mechanical loads. For fiber-reinforced composites:

- The tensile modulus E represents stiffness, a key parameter in structural applications where deformation must be minimized.

- The ultimate strength σ_{ult} indicates the maximum load that the laminate can support before failure.
- The difference in behavior between 0° , $\pm 45^\circ$, and 90° fiber orientations highlights the anisotropic nature of composite materials.

Understanding these properties is essential for the safe and efficient design of aerospace structures, where weight, strength, and stiffness are critical performance metrics.

3 APPARATUS

The primary material used in this experiment was DA 409U/G35 150, a graphite/epoxy composite prepreg made of carbon fibres that had been partially cured with epoxy resin. Prior to specimen preparation, the prepreg was kept in a freezer at -70°F to avoid unintended sticking or premature curing. Upon reaching workable temperature, the strips were cut to 1.0 in. by 7.0 in. dimensions at specified fibre orientations of 0° , $\pm 45^\circ$, and 90° .



Figure 1: Roll of DA 409U/G35 150 graphite/epoxy composite

Following that, these strips were stacked in various ways and put into aluminium moulds that could accommodate three specimens at once. During the curing period, each mould produced a consistent compression boundary.



Figure 2: Aluminum Mold

In the lay-up process, supporting materials like bleeder cloth, peel ply, and release film were utilised to help the resin flow, keep it from sticking, and enable clean separation after curing.

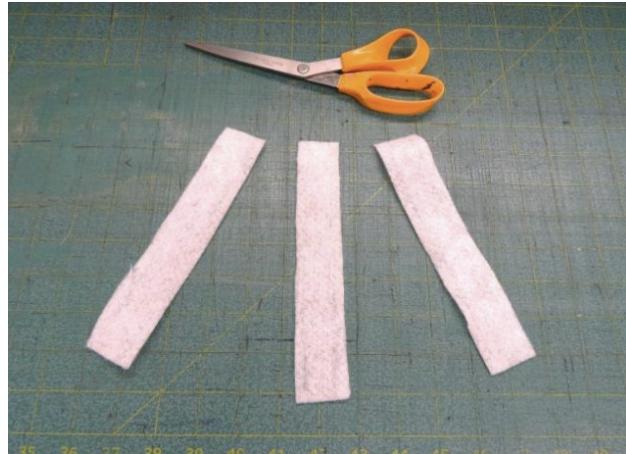


Figure 3: Bleeder Cloth - AirTech N10

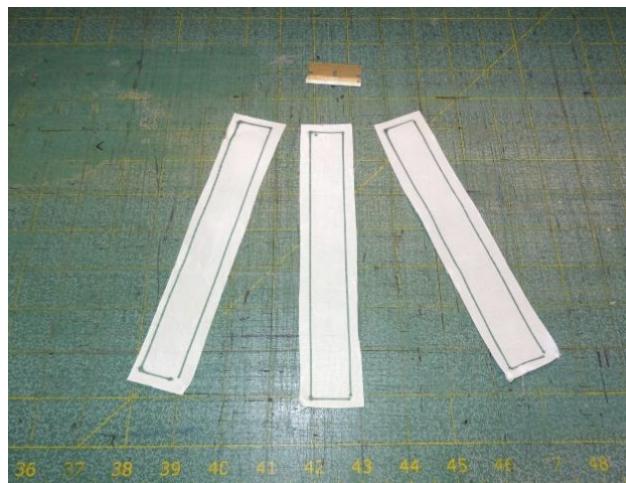


Figure 4: Peel Ply - Airtech 234 TFP

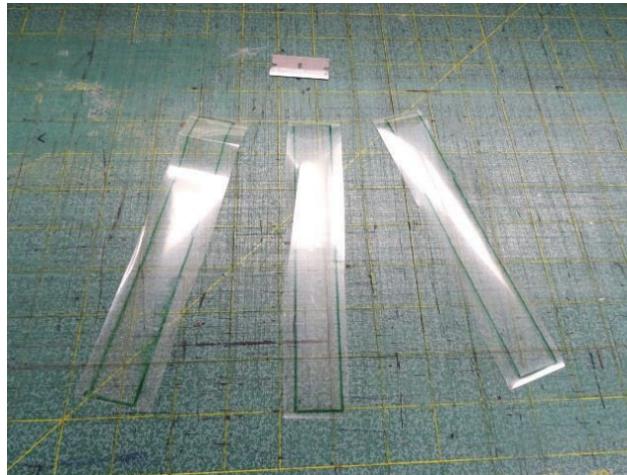


Figure 5: Release Film- Airtech A4000R

An analogue hygrometer and a digital thermometer were used to track the environmental conditions throughout lay-up. This was done to make sure that the temperature and humidity remained within reasonable bounds, as these changes could affect the behaviour of the resin and the quality of the finished product. The thermometer recorded temperatures between 23.0°F and 131.0°F with an accuracy of 1.5°F, and the hygrometer had a 2.5



Figure 6: Hygrometer and Digital Thermometer

In order to calculate density and fibre volume fraction, specimen mass was measured with 0.001 g precision using an electronic scale both before and after curing.



Figure 7: Electronic Balance

Following lay-ups, specimens were cured in a hot press that could apply up to 24 tonnes of load and achieve 850°F. This guaranteed the epoxy matrix's complete cross-linking and consolidation.



Figure 8: Hot Press

The Instron Model 4483 tension/compression machine was used to evaluate the specimens under axial tension after they had been cured. Tensile forces were applied to the specimens using this screw-driven device, which had a maximum load capacity of 20 kips. Applied force and displacement data from the machine was recorded for material property analysis and post-processing.

An extensometer was used to measure the strain on each composite specimen while they were under load. Each end would clamp down on either side of a specimen, and the displacement of the ends from rest would be measured. A 1.0 inch gage length meant that the displacement output from the extensometer equaled the strain in the specimen.

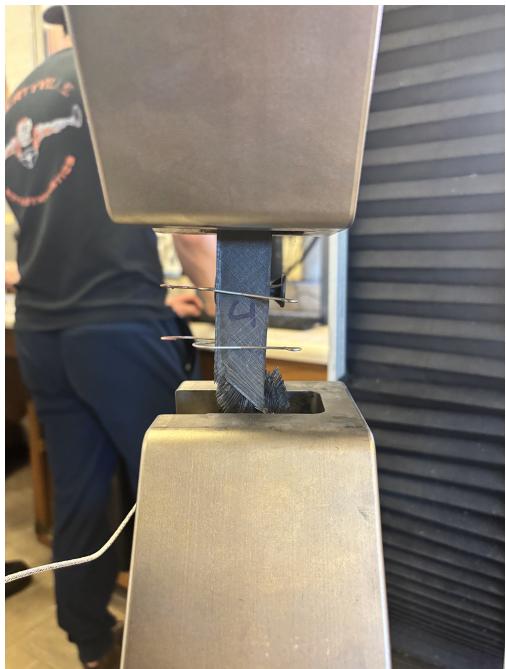


Figure 9: Extensometer

Table 1: Equipment and Specifications for the Composites Lab [1][2].

No.	Item	Specifications	Accuracy	Use In Experiment
1	Composite Prepeg	N/A	N/A	Material used for mechanical testing
2	Aluminum Mold	N/A	0-100%	Composites are put into molds to be compressed
3	Analog Hygrometer	N/A	1.0 in. × 7.0 in. 2.5% relative humidity accuracy, 1.0% resolution	Monitors humidity levels
4	Digital thermometer	23.0°F-131.0°F	1.5°F	Monitors temperature within the lab environment
5	Electronic balance	100g	0.001g	Used for weighing the composite specimens
6	Hot Press	850°F max temperature, max load=24 tonnes	N/A	Used for curing composite material
7	Instron Model 4483 Ten-sion/Compression Machine	20 kips (20,000 lb.) max load	Four significant figures	Used for loading the composite specimens for testing
8	Extensometer	1.0 inch gauge length	Four significant figures	Measured strain in composite specimens

4 PROCEDURE

4.1 Composite Manufacturing

The experiment's initial phase centred around creating composite laminates from prepreg graphite/epoxy material. The pre-made sheets were meticulously cut into 1.0-inch by 7.0-inch strips at different angles, such as 0°, ±45°, and 90°, based on the lay-up arrangement. The design for each stacking sequence was as follows: eight plies at 0°, sixteen at 90°, and for the ±45° laminate, an alternating

stack of eight $+45^\circ$ and eight -45° plies.

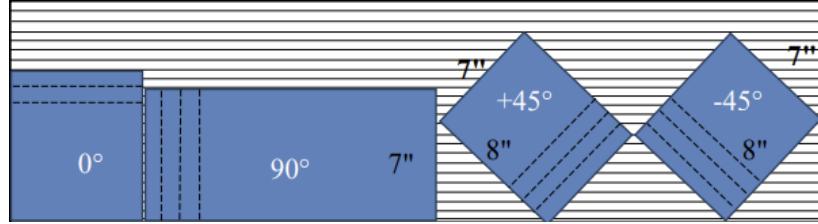


Figure 10: Prepeg Cutting Guide

After the individual plies were ready, they were stacked using release film, bleeder cloth, and peel ply. In addition to preventing adhesion to the mould and allowing excess resin to escape, these components guaranteed a clean finish following curing. Each specimen's specified ply orientations were followed when assembling the lay-ups.

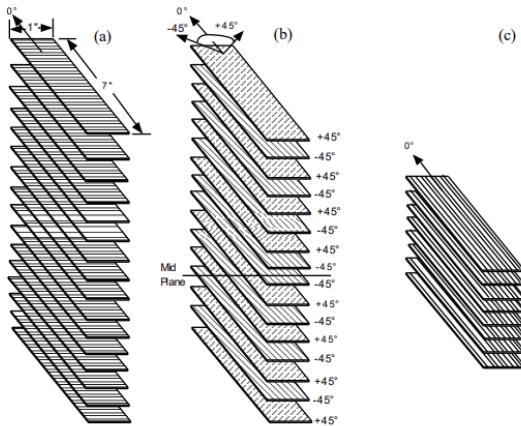


Figure 11: Specimen Configurations

Each composite specimen was prepared, weighed, and its thickness, width, and length were noted. As a way to ensure ideal environmental conditions for lay-up, the room's temperature and humidity were also recorded at this point. Once, all steps are completed, the stacking begins.

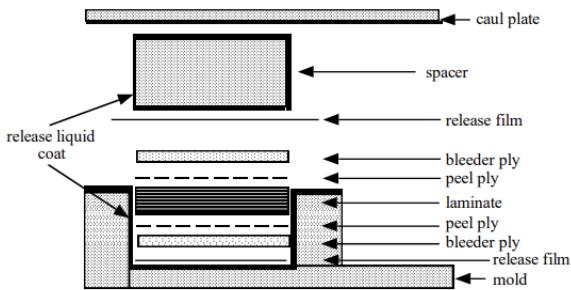


Figure 12: Stacking Sequence

When the stacking up was completed, it was put into the aluminium mould and then transferred to the hot press. In order to solidify the laminate, the lab staff used pressure and heat for four hours during the curing cycle. Following curing, the specimens were removed from the mold and their properties such as mass and thickness were measured to assess the percentage of fiber volume and shrinkage.

4.2 Composite Testing

After the composite specimens were fully cured and trimmed, mechanical testing was conducted in the second phase of this experiment using a universal testing machine. Each specimen was measured five times along its length before testing began in order to determine its average width and thickness, which were then used to determine the cross-sectional area.



Figure 13: Instron Model 4483

The specimens were subsequently put into the tension/compression machine, Instron Model 4483. The machine's upper grip applied gradually increasing tensile force until it failed, while the lower grip stayed motionless. To document strain throughout the test, an extensometer was fastened to the specimen.

5 EXPERIMENTAL UNCERTAINTY

5.1 Manufacturing error

Manufacturing composites can introduce error that causes the experimental results of strength testing to deviate from expected theoretical values. These sources of error include voids and porosity in the composite layups, contamination from oils or dust, and improper curing time, temperature, or pressure. The ambient temperature, pressure, and humidity during layup and cure can also have a large effect on the actual strength of the composite. All of these sources of error can reduce the strength of the composite specimens and introduces large amounts of uncertainty in the exper-

imental results. These sources of error also add large amounts of uncertainty to the other values calculated in the report which explains the extreme values obtained. Additionally, misalignment of layers may cause instances of missing material and unexpected loading as in Figure 14. To correct these errors, a few precautionary steps could be taken. These include performing the layup and cure in a clean room to avoid contaminants and using a layup and cure procedure that eliminates the introduction of voids or fiber misalignment.

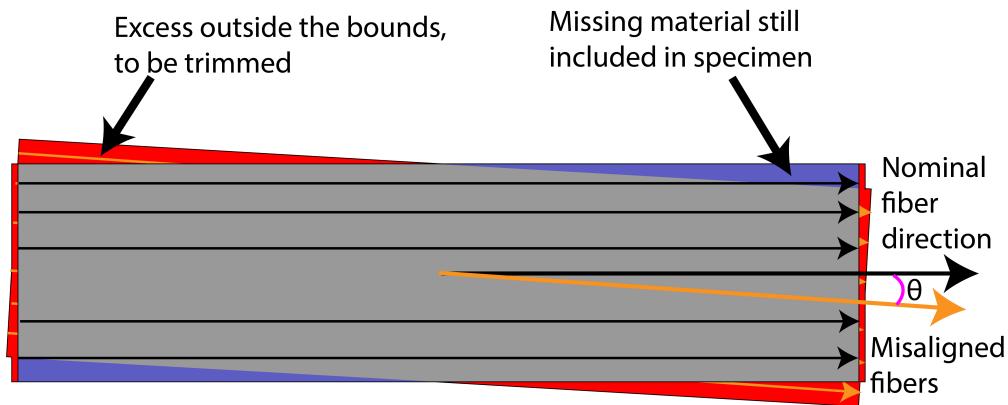


Figure 14: Composite fiber misalignment for a 0 degree case

5.2 Measurement error

Force and strain were both measured to within four significant figures; the lowest force and strain measured was within 10^{-2} and 10^{-6} , respectively. Thus, the force and strain measurements are accurate enough to draw conclusions from.

During the 0 degree test, the extensometer was observed slipping, forming a broken trend-line of stress and strain data. While the extensometer was slipping, the strain could have increased during that time, meaning that it would have not captured that data. In post processing, the lab data to be shifted in strain to form an unbroken line, also potentially causing distortion of the data from the real trend.

The scale used to measure the mass of the specimens has an accuracy of 0.001 grams, which is less than the difference between the pre-cure and post-cure samples. This indicates that the measurement error probably does not affect the overall volume fraction calculation, and that

deeper procedural errors are in play.

5.3 Procedural error

The dimensions of each specimen were measured with digital calipers; improper usage such as not zeroing the calipers or measuring at an angle may have introduced error in the analysis of the composite laminates. Additionally, when loading the 90 degree laminate, the group had to be cautious in clamping the upper and lower grips to the specimen as tight clamps could have caused material failure. The strain gauge may have also posed a source of error in experimental data for all three laminates due to potential misalignment along the composite, or due to slipping.

6 RESULTS AND DISCUSSION

6.1 Lab 1 Write-up Questions

6.1.1 *Tabulated Data*

Table 2 and 3 list the dimensions for each specimen before and after cure. The measurements taken were close to nominal expected measurements and the trends observed indicate shrinkage after cure.

Table 2: Tabulated data for all specimens before curing.

Before Cure			
Specimen	0 degree	45 degree	90 degree
Thickness 1	1.778	3.302	2.24
Thickness 2	1.778	3.302	2.44
Thickness 3	1.778	3.302	2.28
Average Thickness (mm)	1.78	3.30	2.32
Width 1	24.45	25.4	24.28
Width 2	24.45	25.654	24.64
Width 3	24.45	25.4	25.21
Average Width (mm)	24.45	25.48	24.71
Length 1	176.2125	175.768	175.75
Length 2	176.2125	175.768	175.61
Length 3	176.2125	175.768	176.45
Average Length (mm)	176.21	175.77	175.94
Mass of Specimen (g)	9.4	19.0	19.2

Table 3: Tabulated data for all specimens after curing.

After Cure			
Specimen	0 degree	45 degree	90 degree
Thickness 1	1.7	2.26	2.27
Thickness 2	1.48	2.24	2.07
Thickness 3	1.61	2.37	2.46
Average Thickness (mm)	1.60	2.29	2.27
Width 1	24.39	25.81	25.63
Width 2	24.55	25.57	25.32
Width 3	24.17	25.71	25.29
Average Width (mm)	24.37	25.70	25.41
Length 1	104.08	94.56	96.63
Length 2	103.98	95	96.69
Length 3	103.68	94.06	96.34
Average Length (mm)	103.91	94.54	96.55
Mass of Specimen (g)	7	13	13

6.1.2 Composite Density

Table 4 shows the composite densities and ply thickness for each specimen before and after cure. It generally shows a decrease in density and ply thickness after cure. The standard deviation are also shown and are not extremely high indicating relative accuracy and agreement between

specimens. Table 1.2 [1] gives the cured density as 1.53 g/cm^3 and cured ply thickness as 0.006 in which is equal to 0.1524 mm. The experimental data calculated shows a slightly lower cured density and a slightly higher cured ply thickness. This is likely due to voids in the composite or imperfect layup and curing procedures.

Table 4: Average composite density, standard deviation, and ply thickness for cured and uncured specimens.

Specimen	0 degree	45 degree	90 degree	Average	Standard Deviation
Uncured Composite Density (g/cm^3)	1.22	1.28	1.90	1.47	0.31
Cured Composite Density (g/cm^3)	1.00	1.29	1.31	1.20	0.14
Uncured Ply Thickness (mm)	0.22	0.21	0.15	0.19	0.03
Cured Ply Thickness (mm)	0.20	0.14	0.14	0.16	0.03

6.1.3 Fiber Volume Fraction

Table 5 shows the calculated fiber volume fraction for the composite specimens before and after cure. The fiber volume fractions were calculated using equation 1.4 and 1.5 and table 1.2 in the lab manual [1]. There is severe discrepancy between the calculated values and the expected values which indicates several sources of error. A fiber volume fraction of approximately 55% is expected; the actual values ranged from -22% to 110%, of which both extremes are unrealistic. The likely sources of error include significant voids present in the specimens due to improper compression during the curing process, improper measurements, or a mistake in the recording of measurements. Additionally, it is possible foreign material was trapped in the specimen during layup or the incorrect number of plies were used; however, this was not observed in the manufacturing lab. This experiment should be repeated with higher accuracy and precision to achieve better results.

Table 5: Fiber volume fraction for cured and uncured specimens.

Specimen	0 degree	45 degree	90 degree	Average
Uncured Fiber Volume Fraction	10.54%	19.06%	109.33%	46.31%
Cured Fiber Volume Fraction	-21.91%	20.85%	22.66%	7.20%

6.1.4 Volumetric Shrinkage

Table 6 shows the calculated volumetric shrinkage for each specimen after curing. The values were found by using equation 1.6 in the lab manual [1]. The values calculated vary from 1% to 32% and the expected value is 7%. Although the calculated value for the 0 degree specimen is similar to the expected value given in table 1.2 in the lab manual [1], the others vary significantly. The largest source of error for these values is likely inaccurate measurements of dimensions of the uncured and cured specimens or inaccurate recording of measurements. The curing process and presence of voids could also contribute to this error.

Table 6: Volumetric shrinkage for all specimens after cure.

Specimen	0 degree	45 degree	90 degree	Average
Volumetric Shrinkage	8.51%	32.07%	1.34%	13.97%

6.1.5 Hot Press Force

Table 7 shows the calculated force needed to be applied to each specimen by the hot press plates to achieve 150 psi. These values are calculated by finding the face area of each specimen in square inches and multiplying by 150. The values for each specimen are approximately the same and average 1,018 pounds.

Table 7: Hot press force required for all specimens to achieve 150 psi.

Specimen	0 degree	45 degree	90 degree	Average
Hot Press Force (lb)	1,002	1,041	1,011	1,018

6.1.6 Manufacturing Quality

The manufactured specimens were constructed as the lab manual instructed and there were no apparent severe defects or lack in quality. Some of the specimens had air bubbles trapped between the plies as they were stacked which would likely lead to voids and decreased strength. Additionally, some of the edges folded a little bit which may affect the strength of the specimen. The plies were put in the freezer after cutting to help with the removal of the protective layers but some of them were still sticky and hard to remove which led to the folded edges and fingerprints which may have caused foreign materials to be trapped between the plies and affect the strength of the specimen. The cure process was performed by the TAs and it was not observed by the group. Visually, the quality of the manufactured specimens was good before and after cure.

6.1.7 Cure Temperature Affects

If the cure temperature was raised to a higher temperature, it could have detrimental affects on the specimen quality and strength. The higher temperature could degrade the matrix or fibers or introduce voids if the high temperature causes bubbling, both of which would reduce strength. If the cure temperature was lowered, this would lead to lack of crosslinking and an incomplete cure. Also, the lower temperature may not allow volatiles to escape. Both of these could lead to reduced strength and quality of the cured specimen.

6.1.8 Cure Pressure Affects

If the applied pressure during cure was raised to a higher pressure it could have detrimental effects on the cured specimen. The pressure applied is unique to the material used and a higher pressure may squeeze out too much of the matrix or damage the fibers, both of which will reduce the quality and strength of the composite specimen. A lower pressure during cure will also have a detrimental affect on the cured specimen. The lower pressure will not squeeze out the appropriate amount of matrix and will leave voids in the cured specimen, leading to reduced strength.

6.1.9 Room Temperature and Humidity During Lay-up

The room temperature and humidity during lay-up is assumed to be standard room conditions of 72°F and 40% humidity. Additionally, the plies were stored in the freezer before layup to ensure premature curing was not taking place and to make the separation of the protective paper easier. The temperature and humidity during layup will have a large effect on the final quality of the composite specimen. As stated, higher temperatures can cause premature curing which will reduce quality and introduce voids or other defects. If the humidity is too high, there will be moisture introduced in the material and between the plies which again will cause voids and other defects, reducing quality of the composite specimen.

6.1.10 Temperature and Pressure History of the Cure Cycle

A typical temperature and pressure history of the cure cycle is shown in 15. As can be seen from the figure, the pressure is constant at approximately 80 psi and the temperature is ramped up from room temperature to approximately 180°C over the course of an hour, held constant for 2 hours, and then ramped back down to room temperature over the course of an hour. As discussed above, the specific cure cycle can have an impact on the strength and quality of the cured specimen.

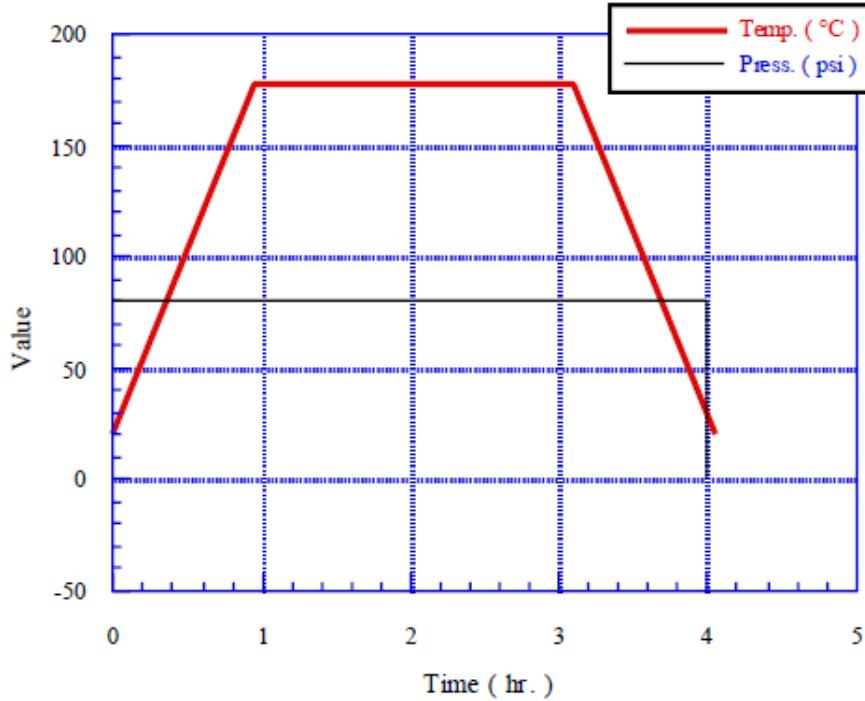


Figure 15: Typical cure cycle for the prepreg specimens [1].

6.2 Lab 6 Write-up Questions

6.2.1 Stress-Strain Curves

Figure 16 shows the stress-strain curves for the composite samples. As expected, the stress-strain curves for the 0 degree and 90 degree samples appear to be relatively brittle with a sharp peak where the sample breaks, while the 45 degree sample appears ductile with a smooth plastic deformation and eventual breaking.

A regression line was plotted through Microsoft Excel's built-in linear trendline function. The line was fit to the most linear portions of the data. For Figures 16a and 16c, the elastic limit was determined at the point where the slope of the data visibly changes. Since the stress-strain curve gradually changes for the 45 degree sample, the elastic limit was determined at the 0.2% strain offset.

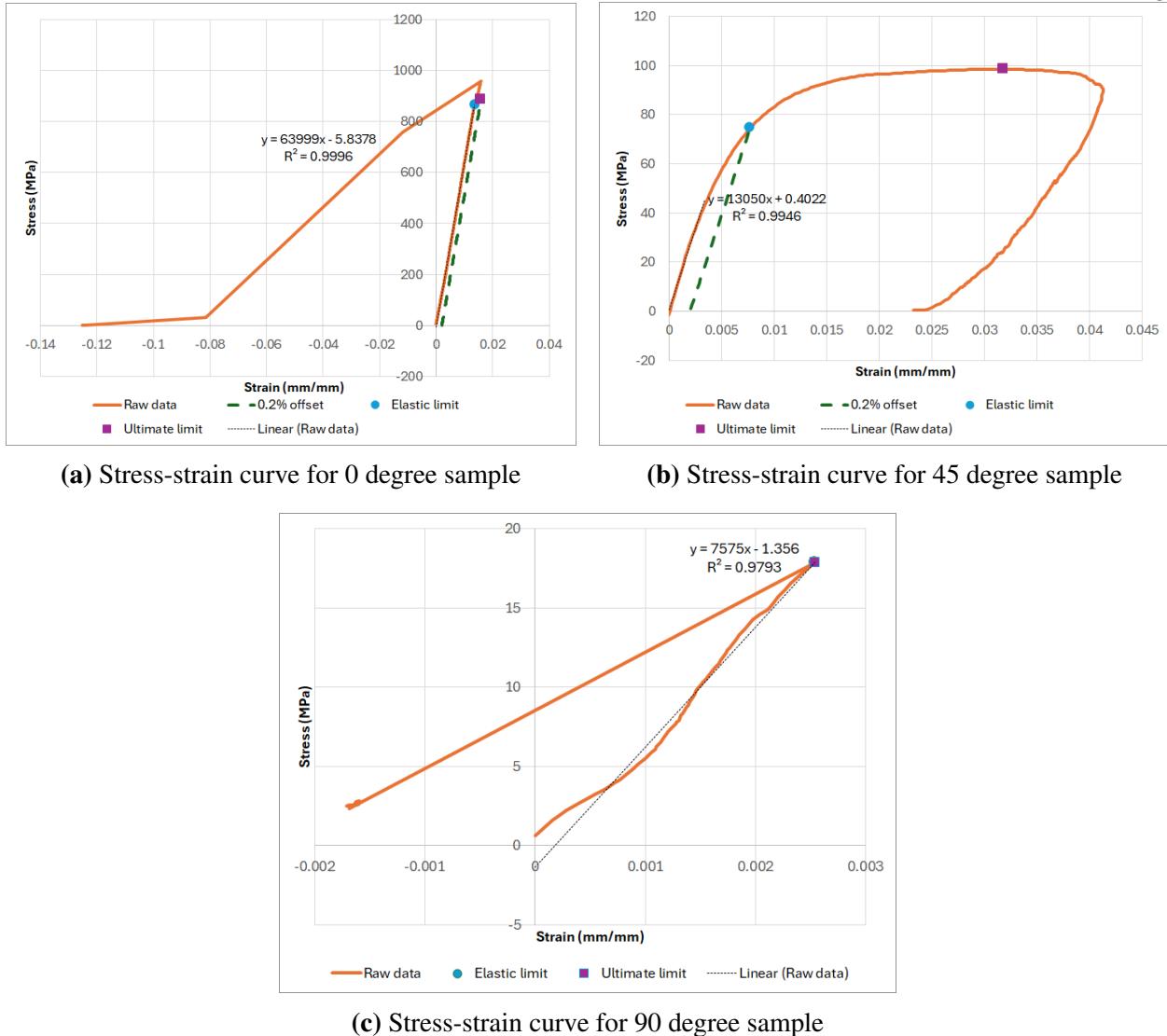


Figure 16: Stress-strain curves for 0, 45, and 90 degree composite tensile testing

6.2.2 Experimental values for elastic modulus, elastic limit, ultimate strength, and ultimate strain

Table 8 shows the elastic limit and ultimate stresses and strains, along with the tensile modulus E .

Table 8: Experimental properties for composite samples with different ply angles

Ply, deg	E , MPa	Elastic strain, %	Elastic stress, MPa	Ultimate strain, %	Ultimate stress, MPa
0	64,000	0.01360	867.7	0.01585	886.6
45	13,050	0.007732	74.80	0.03177	98.53
90	7,575	0.002538	17.86	0.002538	17.86

6.2.3 On-Axis and Off-Axis Composite Properties

Using the micromechanics models described in equations (6.8)–(6.11), (6.23)–(6.27), and (6.28)–(6.33) from the experiment 6 lab manual [2], as well as the mechanical properties of carbon fiber, 8551-7A resin, and DA 409U/G35 150 composite shown in Table 6.1 of the lab 6 manual, the on-axis and off-axis properties of the unidirectional composite laminate were computed. Table 9 shows the material properties E_1 , E_2 , ν_{12} , and G_{12} calculated from the rule-of-mixutres theory, and 10 shows the resulting stiffness properties of the zero and 90 degree laminate.

Table 9: Micromechanical Properties from Rule-of-Mixtures

Material Property	Value
E_1	130.38 GPa
E_2	5.48 GPa
G_{12}	2.04 GPa
ν_{12}	0.2225

Table 10: On-Axis Properties

Stiffness Term	0° Value [GPa]	90° Value [GPa]
Q_{11}	130.65	5.50
Q_{22}	5.50	130.65
Q_{12}	1.22	1.22
Q_{66}	2.04	2.04

Since the lamina are oriented at 90 degrees, the stiffness matrices in the 1-direction and 2-direction are flipped in comparison to the zero degree laminate.

Using the transformation equations for stiffness matrices in the lab 6 manual [2], the off-axis stiffness values were calculated at 45 degrees. Table 11 shows the corresponding stiffness values.

Table 11: Off-Axis Properties at 45 degrees

Stiffness Term	Value [GPa]
Q_{11}	36.69
Q_{22}	36.69
Q_{12}	32.60
Q_{66}	33.42
Q_{16}	30.30
Q_{26}	30.30

The values for Q_{11} and Q_{22} are equal, which indicates that the off-axis stiffness is more isotropic than the on-axis values. The equality in Q_{16} and Q_{26} further exemplifies the isotropic properties of the 45 degree composite. Q_{12} is also calculated to be less than Q_{11} , Q_{22} and Q_{66} , which showcases how the orientation of composite layers influences the laminate mechanical properties.

6.2.4 Theoretical Material Properties for Composite Specimens

To calculate the elastic constants E_1^o , E_2^o , ν_{12}^o , and G_6^o , the micromechanical models derived from equations (6.20) and (6.34)–(6.38) of the experiment 6 lab manual [2] were used. First, the laminate stiffness matrices were computed using equation (6.20) by using lamina dimensions and summing the mechanical properties of each lamina over the entire laminate. Then, the constants were derived using equations (6.34)–(6.38). Table 12 shows the elastic constants for all three composite orientations.

Table 12: Theoretical Laminate Properties

Orientation (degrees)	E_1^o [GPa]	E_2^o [GPa]	ν_{12}^o [GPa]	G_6^o [GPa]
0	130.65	5.50	0.2225	2.04
90	5.50	130.65	0.0094	2.04
45	36.69	36.69	0.8886	33.42

6.2.5 Experimental vs. Theoretical Modulus Comparison

Table 13 shows the theoretical values for elastic modulus calculated in the previous section as well as the empirical values obtained from the experimental procedure.

Table 13: Theoretical vs. Experimental Elastic Modulus

Orientation (degrees)	Theoretical E_1 [GPa]	Experimental E_1 [GPa]
0	130.65	64.0
90	5.50	7.58
45	36.69	13.05

There data shows a prominent discrepancy between the experimental and theoretical elastic modulus values. For the 0 degree and 45 degree laminates, the experimentally measured modulus is lower than the theoretical prediction, suggesting errors in the manufacturing process. For the 90 degree composite, the experimental modulus is greater than the calculated value from the micromechanics model, which suggests inaccuracy in the theory used to derive the models. Since there most likely exists errors in the construction of the composites, it is difficult to determine the failure in the rule-of-mixtures theory.

6.2.6 Comparison of Theoretical and Experimental Failure Loads

To calculate the theoretical failure loads of the various composite specimens, Values for material tension and compression strength were taken from the lab manual and experimental values were found throughout lab 6 and recorded in Table 8. The material's theoretical failure load can be calculated with equations 6.54 - 6.56 in the lab manual. The theoretical and experimental values are shown in Table 14. It can be seen that for the 0 and 90 degree samples, the theoretical values were much larger than the experimental values, however for the 45 degree sample the theoretical value is smaller than the experimental one.

Table 14: Experimental vs. Theoretical Failure Load

Orientation (degrees)	$\sigma_{failure}$ Theoretical [MPa]	$\sigma_{failure}$ Experimental [MPa]
0	1930.0	886.6
90	40.0	17.86
45	66.8	98.53

6.2.7 Comparison of Specific Elastic Modulus and Specific Strength of Specimens

Using the composite density data for each cured composite found from Table 3, the Elastic Modulus values from Table 13, and composite strength values from the lab manual, the specific elastic modulus and specific strength were calculated and tabulated in Table 15. The variations in specific strength of each composite specimen shows that there is variation in material strength depending on manufacturing quality, which is a function of density. Theoretically these strength values should be the same for each orientation, but because of the density variation between samples, its found the the 0 degree composite has the highest specific strength properties, while the 90 degree composite has the lowest.

Table 15: Specific Elastic Modulus and Specific Strength

Orientation (degrees)	E/ρ [MPa]	X/ρ [MPa]	X'/ρ [MPa]	Y/ρ [MPa]	Y'/ρ [MPa]	S/ρ
0	64.0	1.93	1.73	0.04	0.23	0.15
45	10.12	1.50	1.34	0.03	0.17	0.12
90	5.78	1.47	1.32	0.03	0.17	0.11

6.2.8 Model Predictions vs. Experimental Results

The theoretical model mostly over-predicted various properties of the composites, generally over-predicting Elastic modulus and Failure loads, except in the case of the 45 degree sample's failure load and the 90 degree sample's' elastic modulus. These variations between the model predictions and experimental results is likely a cause of manufacturing error or possibly but less likely, measurement errors.

7 CONCLUSION

In this laboratory experiment, the differences between theoretical and empirical mechanical properties of composite laminates were investigated through the creation of samples and then tensile testing. Composite specimens included 0° , $\pm 45^\circ$, and 90° orientations that were manufactured with graphite and epoxy sheets, cured om a hot press, then tested under uniaxial tension. Key

properties of these specimens such as; density, fiber volume fraction, elastic modulus, and ultimate strength, were measured and compared against models.

While some trends were consistent between theoretical and experimental results, the experimental results deviated from predicted values, particularly density fiber volume fraction, and elastic modulus. These discrepancies were probably caused by the laying process, voids created during curing, and measurement inaccuracies.

This laboratory exercise provided hands-on experience in composite laminate manufacturing, quality control, and mechanical characterization. It highlighted the importance of precision during preparation of the specimens and other environmental controls during creation to ensure reliability of material properties. To improve future results, greater care can be taken to remove air trapped between sheets and ensuring consistent pressure application during curing.

8 REFERENCES

References

- [1] Ioannis Chasiotis, "Experiment 1 Manufacturing of Composite Laminates", AE 461 Structures and Control Lab, University of Illinois at Urbana-Champaign, 2025.
- [2] Ioannis Chasiotis, "Experiment 6 Mechanical Testing of Composite Materials", AE 461 Structures and Control Lab, University of Illinois at Urbana-Champaign, 2025.
- [3] Ioannis Chasiotis, "Appendix F: Material Properties of Common Plastics, Metals, and Composites", AE 461 Structures and Control Lab, University of Illinois at Urbana-Champaign, 2025.

9 APPENDIX A: SAMPLE CALCULATIONS

9.1 Composite Density

$$\rho = m/V$$

$$\rho = m/(l \times w \times t) \times 1000$$

ρ = Composite Density [g/cm³]

V = volume [cm³]

m = mass [g]

l = length [mm]

w = width [mm]

t = thickness [mm]

$$\rho = 9.4/(176.21 \times 24.45 \times 1.78) \times 1000 = 1.22 \text{ g/cm}^3$$

9.2 Standard Deviation

$$\sigma = \sqrt{\frac{(x_1 - \bar{x})^2 + \dots + (x_n - \bar{x})^2}{n}}$$

x_i = individual measurement [g/cm³]

\bar{x} = mean of measurements [g/cm³]

n = number of samples

$$\sigma = \sqrt{\frac{(1.22 - 1.47)^2 + (1.28 - 1.47)^2 + (1.90 - 1.47)^2}{3}} = 0.31 \text{ g/cm}^3$$

9.3 Ply Thickness

$$t_{\text{ply}} = t/N$$

t_{ply} = Ply thickness [mm]

t = Total thickness [mm]

N = Number of plies

$$t_{\text{ply}} = (1.78/8) = 0.22 \text{ mm}$$

9.4 Fiber Volume Fraction

$$\rho = \rho_f v_f + \rho_m v_m$$

$$\rho = \rho_f v_f + \rho_m (1 - v_f)$$

$$v_f = (\rho - \rho_m)/(\rho_f - \rho_m)$$

ρ = Composite Density [g/cm³]

ρ_f = Fiber density [g/cm³]

ρ_m = Matrix density [g/cm³]

v_f = Fiber volume fraction

v_m = Matrix volume fraction

$$(1.22 - 1.15)/(1.84 - 1.15) = .105 = 10\%$$

9.5 Volumetric Shrinkage

$$\%Shrinkage = \frac{V_{\text{uncured}} - V_{\text{cured}}}{V_{\text{uncured}}} \times 100\%$$

V_{uncured} = Volume before curing [mm³]

V_{cured} = Volume after curing [mm³]

$$\%Shrinkage = \frac{7660 - 7008}{7660} \times 100\% = 8.5\%$$

9.6 Hot Press Force

$$F = P \times A$$

F = Force [lbf]

P = Pressure [psi]

A = Area [in^2]

$$F = (150 \text{ psi}) \times (6.94 \text{ in} \times 0.96 \text{ in}) = 1002 \text{ lbf}$$

9.7 Tensile Modulus

$$E = \frac{\sigma}{\epsilon}$$

E = Tensile modulus [GPa]

σ = Tensile stress [MPa]

ϵ = Strain [mm/mm]

$$E = \frac{50 \text{ MPa}}{0.002 \text{ mm/mm}} = 25,000 \text{ MPa} = 25 \text{ GPa}$$

9.8 Tensile Stress

$$\sigma = \frac{F}{A}$$

σ = Tensile stress [MPa]

F = Force [N]

A = Cross-sectional area [mm^2]

$$\sigma = \frac{50 \text{ N}}{25 \text{ mm}^2} = 2 \text{ MPa}$$

9.9 On-Axis and Off-Axis Composite Properties

$$E_x = v_f E_f + v_m E_m$$

$$\nu_{xy} = v_f \nu_f + v_m \nu_m$$

$$\frac{1}{E_y} = \frac{v_f}{E_f} + \frac{v_m}{E_m}$$

$$\frac{1}{G_{xy}} = \frac{v_f}{G_f} + \frac{v_m}{G_m}$$

v_f = volume fraction of fiber

v_m = volume fraction of matrix

E_f = Young's Modulus of fiber

E_m = Young's Modulus of matrix

E_x = Young's Modulus of composite

G_f = Shear Modulus of fiber

G_m = Shear Modulus of matrix

G_{xy} = Shear Modulus of composite

$$E_1 = 0.55 * 235 + 0.45 * 2.5 = 130.38 \text{ GPa}$$

$$\nu_{12} = 0.55 * 0.2 + 0.2 * 0.45 = 0.225$$

$$E_2 = 1 / ((0.55/235) + (0.45/2.5)) = 5.48 \text{ GPa}$$

$$G_{12} = 1 / ((0.55/14) + (0.45/1)) = 2.04 \text{ GPa}$$

$$c = \left[1 - \nu_{xy}^2 \frac{E_y}{E_x} \right]^{-1}$$

$$c = [1 - 0.2225^2 * \frac{5.48}{130.38}]^{-1} = 1.002$$

$$\bar{Q}_{11} = cE_x = 1.002 * 130.38 = 130.65 \text{ GPa}$$

$$Q_{11} = m^4 \bar{Q}_{11} + n^4 \bar{Q}_{22} + 2m^2 n^2 \bar{Q}_{12} + 4m^2 n^2 \bar{Q}_{66}$$

$$Q_{11} = 1 * 130.65 + 0 + 0 + 0 = 130.65 \text{ GPa}$$

where $n^4 = \cos^4(0)$, $m^4 = \sin^4(0)$ for the 0 degree laminate

9.10 Laminate Theoretical Properties

$$A_{ij} = \sum_{k=1}^N (Q_{ij})_k (z_k - z_{k-1})$$

$$A_{ij} = \sum_{k=1}^8 (130.65)_k (0.22225)$$

$$A_{ij} = 232.3 \text{ GPa}$$

$$a_{ij} = [A_{ij}]^{-1}$$

$$a_{ij} = 0.0043$$

$$E_1^o = 1/(a_{11}h) = 1/(0.0043 * 1.778) = 130.65 \text{ GPa}$$

9.11 Stress Failure

Given:

$$X = 1930$$

$$X' = 1724$$

$$Y = 40$$

$$Y' = 225$$

$$S = 150$$

$$\theta = 0$$

35

$$\begin{aligned}\bar{F}_{11} &= \frac{1}{X \cdot X'} = \frac{1}{1930 \cdot 1724} = 3E - 7 \\ \bar{F}_{22} &= \frac{1}{Y \cdot Y'} = \frac{1}{40 \cdot 225} = 1.1E - 4 \\ \bar{F}_{66} &= \frac{1}{S^2} = \frac{1}{150^2} = 4.4E - 5 \\ \bar{F}_{12} &= -\frac{1}{2}\sqrt{\bar{F}_{11} \cdot \bar{F}_{22}} = -2.9E - 6 \\ \bar{F}_1 &= \frac{1}{X} - \frac{1}{X'} = -6.2E - 5 \\ \bar{F}_2 &= \frac{1}{Y} - \frac{1}{Y'} = 0.02\end{aligned}$$

$$m=\cos(\theta)=1.0$$

$$n=\sin(\theta)=0.0$$

$$F_{11}=m^4\bar{F}_{11}+n^4\bar{F}_{22}+2m^2n^2\bar{F}_{12}+4m^2n^2\bar{F}_{66}=3.0E-7$$

$$F_1=m^2\bar{F}_1+n^2\bar{F}_2=-6.2E-5$$

$$F_{11} \cdot \sigma_{\text{failure}}^2 + F_1 \cdot \sigma_{\text{failure}} = 1$$

$$\sigma_{\text{failure}} = \frac{-F_1 + \sqrt{F_1^2 + 4F_{11} \cdot 1}}{2F_{11}} = 1930$$

9.12 Specific Elastic Modulus

$$E = 64000$$

$$\rho = 1000$$

$$\theta = 0$$

$$E/\rho = 64.0$$

10 APPENDIX B: RAW DATA

10.1 Raw Data Figures

Before Cure			
Specimen	0 degree	45 degree	90 degree
Thickness 1	1.778	3.302	2.24
Thickness 2	1.778	3.302	2.44
Thickness 3	1.778	3.302	2.28
Average Thickness (mm)	1.78	3.30	2.32
Width 1	24.45	25.4	24.28
Width 2	24.45	25.654	24.64
Width 3	24.45	25.4	25.21
Average Width (mm)	24.45	25.48	24.71
Length 1	176.2125	175.768	175.75
Length 2	176.2125	175.768	175.61
Length 3	176.2125	175.768	176.45
Average Length (mm)	176.21	175.77	175.94
Mass of Specimen (g)	9.4	19.0	19.2
After Cure			
Specimen	0 degree	45 degree	90 degree
Thickness 1	1.7	2.26	2.27
Thickness 2	1.48	2.24	2.07
Thickness 3	1.61	2.37	2.46
Average Thickness (mm)	1.60	2.29	2.27
Width 1	24.39	25.81	25.63
Width 2	24.55	25.57	25.32
Width 3	24.17	25.71	25.29
Average Width (mm)	24.37	25.70	25.41
Length 1	180.28	170.76	172.83
Length 2	180.18	171.2	172.89
Length 3	179.88	170.26	172.54
Average Length (mm)	180.11	170.74	172.75
Mass of Specimen (g)	7	13	13
Max Force (kN)	55.26	5.799	1.03

Figure B1: Raw measurements of each specimen taken before and after cure.



Figure B2: 0, 90, and 45 degree specimens after failure.

11 APPENDIX C: GROUP MEMBER CONTRIBUTIONS

11.1 Contribution of Individual Group Members

AE 461 Full Engineering Report	
Group Member	Contribution
Declan	Theory and Analysis, Conclusion
Michael	6.1 and associated sample calcs
Patrick	6.2.3, 6.2.4, 6.2.5
Zayna	Abstract, Introduction, 3, 4.1, and 4.2 Procedure
Eugene	6.2.1, 6.2.2, and associated sample calcs
Amber	6.2.6, 6.2.7, 6.2.8, and associated sample calcs