**Static and Fatigue Failure Response of Woven
Carbon Fiber Specimens with Double-Edge Notches**

A Thesis

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California Polytechnic State University, San Luis Obispo

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of the Requirements for the Degree
Master of Science in Aerospace Engineering

by

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Abstract

Static and Fatigue Characteristics of Woven Carbon Fiber

Specimens with Double-Edge Notches

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Carbon fiber composites are continually seeing increased use in aerospace applications. It is necessary to understand their failure modes in order to properly design and perform analysis on structures constructed primarily from them. This thesis studies woven carbon fiber composites with and without double-edge notches in a series of static and fatigue tests performed on an Instron 8801 servo-hydraulic testing system.

Specimens were constructed of Advanced Composites Group product # LTM45EL woven carbon fiber pre-preg/epoxy and were cut to approximately 9-inch in length and 1-inch in width. Notches were cut into some of the specimens using a slitting saw blade of 0.006-in. thickness.

Ultimate strength, Young's modulus and Poisson's ratio for specimens were determined to be 119,418 psi, 7,149,000 psi and 0.05, respectively. Fracture stress for specimens with notch depths of 0.10, 0.15, 0.20, 0.25, 0.30 and 0.35 was determined to be 93,481 psi, 88,193 psi, 86,968 psi, 81,112 psi, 84,197 psi and 81,955 psi, respectively. The results from these tests showed that the specimens followed Griffith's model for brittle failure.

Average number of cycles to failure was determined to be 6,600, 37,200, 94,300 and 293,400 for fatigue tests with maximum stresses of 72.5%, 75%, 77.5% and 80% of the ultimate strength. Fatigue tests performed on notched specimens produced data that was too scattered from which to draw a statistically significant result. Numerical modeling in Abacus showed comparable results to experimental tests for stress and strain.

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Nomenclature

English Letters

A	Area (in ²)
E	Young's modulus (lb/in ²)
G	Shear modulus (e+03 lb/in ²)
L	Length (in)
N	Number of cycles to failure
P	Load (lb)
a	Notch depth (in)
t	Thickness (in)
w	Width (in)

Greek Letters

ε	Strain (in/in)
σ	Stress (lb/in ²)
τ	Shear strength (lb/in ²)
ν	Poisson's Ratio

Subscripts

f	Fracture
max	Maximum
min	Minimum
ult	Ultimate
y	Yield

1 INTRODUCTION

1.1 Review of Fracture Mechanics and Failure Prediction

The field of fracture mechanics has existed for roughly one century. During the first World War Alan Griffith developed a concept to deal with stress analysis of structures containing cracks.¹ The United States Naval Research Laboratory continued this research after no explanation could be found for the catastrophic failure of the liberty ships during World War II.² It was from this continued research that the concept of fracture toughness emerged, as well as structural failure due to fatigue. Structural designers now had an additional tool at their disposal to predict failure and a new field for research emerged.

The ability to accurately predict failure in structures is a relatively young concept compared to basic structural analysis. The desire to predict failure, however, is as old as Galileo's attempt to solve for the failure of a cantilever beam. Multiple theories have been introduced, such as the maximum principle stress theory, maximum shear stress theory, and maximum strain energy theory to name a few among many. While Griffith's work is claimed to be reasonable at predicting the fracture of brittle materials, further work has been done on the subject involving ductile materials and composite materials. Some of the most critical progress has been made in predicting failure using Finite Element Analysis (FEA) models alongside validation models used in early stages of design and analysis, lowering the design cost of many structures.

1.2 Literature Review

A composite material is one that is comprised of two or more distinct constituent materials. While many metals have impurities (natural or introduced) they are generally not considered composite materials from the view of analysis.³ Composite materials for

analysis purposes are generally considered those consisting of two or more distinct materials with a distinct interface that separates them.⁴ Generally, the materials can be seen on a macroscopic scale and identified by the naked eye.

The mechanical properties of composite materials are determined by the properties of the constituent materials, their arrangement and their interaction. Thus, the geometry of the reinforcing carbon fibers in an epoxy matrix would determine the mechanical properties of the composite material. A lamina with unidirectional fibers would have different properties than a lamina with woven fibers running in perpendicular directions.

Some recognizable advantages to composite materials are increased strength and stiffness per weight when compared to conventional materials. Composite materials can be produced that have the same strength and stiffness as steel, but are 70% lighter.⁵ Composites can also be tailored to meet special design requirements for load bearing capability or stiffness in various directions.

This increased strength-to-weight advantage of composite materials is partially due to the ability of fibers in a composite material to limit the size of initial flaws. Generally, the strength of a material is limited by flaws that are always present. The measured strength of most materials is often smaller than the theoretical strength due to these inherent flaws. The strength of a material can be enhanced by reducing flaws such as cracks that are perpendicular to the direction of loading.

Galileo Galilei observed while attempting to answer the question “why do bodies break?” that workers would pay significantly more attention when constructing large ships than small ships. He discovered that the larger ships displayed more brittleness than the smaller ships.⁶ This was due to larger flaws that could be accommodated. The nature of fibers is that they have a small cross-section area. This limits flaw size, which results in higher strength being achieved along the fiber direction.⁷

Embedding these fibers in a matrix material, such as epoxy, is necessary to bind fibers together to create a useful product. Other purposes of the matrix material include transferring loads between broken fibers, protecting fibers from damage through handling and protecting fibers from damage from the environment.⁸

Flaws cannot be entirely eliminated and imperfections in a composite material can include voids, irregularities in fiber packing, fiber ends or some other preexisting flaw.⁹ These flaws lead to the generation of a micro-crack, which represents the first stage of fracture in composite materials. Next the micro-crack grows into a macro-crack that propagates in an unstable fashion at a critical stress level. This critical stress level is dependent on crack size and geometry.¹⁰

Materials also fail in conditions where they are subject to repeated fluctuating loads even though the maximum stress never exceeds the critical stress level. This makes the fatigue life of any material a significant design parameter. Unlike ductile materials such as metals which propagate damage at single crack front, composites can display multiple damage modes during fatigue including matrix cracking, fiber breaking, delamination and fracture of the entire material.¹¹ This results in notable scatter among fatigue test results.

This scatter in fatigue results for composite materials partially accounts for the considerable experimental efforts devoted to fatigue behavior of composite materials. The change in fiber geometry or different materials used from one composite to another is also reason for experimental research. Damage laws that have been formulated for unidirectional boron fibers in an epoxy matrix may not apply to woven glass fibers in an epoxy of different chemical make up.⁴

1.3 Current Research

The research discussed in this paper includes static testing on unnotched and notched woven carbon fiber specimens. These tests will determine ultimate strength, Young's modulus and Poisson's ratio of the unnotched specimens and the fracture stress of the notched specimens.

Notches of varying depths will be cut into woven carbon fiber specimens to simulate macroscopic cracks that can be expected in practical structures due to manufacturing processes or damage accrued during service. This research will determine the fracture stress for double-edge notched woven carbon fiber specimens with various notch depths. This data will then be used to determine the fracture toughness of double-edge notched woven carbon fiber specimens.

Fatigue testing will also be performed to define an S-N relation for unnotched woven carbon fiber specimens. The tests will determine the fatigue life of the unnotched specimens under different maximum stress levels. The specimens are always under tension as the cyclic stress is applied around a mean stress that is half of the ultimate strength of the unnotched specimens. Notched specimens with notch depth of $a/w = 0.20$ will be subject to fatigue testing to observe the effect of the notch on fatigue life.

1.4 Scope of this Thesis

This thesis discusses the manufacturing and testing of unnotched and notched woven carbon fiber specimens and creating a numerical model from the results of the experimental tests. Manufacturing and testing of all specimens is conducted in the CalPoly Aerospace Structure and Composites Laboratory. The manufacturing procedure used to create specimens is discussed and includes composite plate assembly and specimen preparation.

All tests are performed on an Instron 8801 servo-hydraulic testing system. The test procedures used include static and fatigue tests on unnotched and notched woven carbon fiber specimens.

Unnotched specimens are subject to static tests for ultimate strength, Young's modulus and Poisson's ratio. Unnotched specimens are also subject to a series of fatigue tests with increasing maximum stress. Notched specimens with increasing notch depths are subject to static tests for fracture stress. Notched specimens with notch depth of $a/w = 0.20$ are subject to a series of fatigue tests with increasing maximum stress. Results are discussed and compared to a numerical model generated in Abaqus.

2 MANUFACTURING PROCESS

2.1 Woven Carbon Fiber Laminate Plate Assembly

Carbon fiber plates were cured using the Aerospace Engineering Structure/Composite Laboratory's Tetrahedron plate press. The material used was woven, pre-impregnated with epoxy (prepreg) carbon fiber manufactured by Advanced Composites Group (ACG). The model number of the carbon fiber used is LTM45EL.

Carbon fiber rolls were removed from the Aerospace Engineering department's composite materials freezer. Prepreg carbon fiber is kept in the freezer at a temperature of 8°F to keep the epoxy from curing prematurely.

Ten-inch squares of carbon fiber were cut from the rolls to create the layers for the carbon fiber laminate plates. Six layers of carbon fiber were placed on top of each other to create the composite plates. After three layers were laid down, a rolling pin was run over the unfinished plate to remove trapped air between layers. The same was done when all six layers were stacked.

Figure 1 shows the setup used in the Tetrahedron plate press to cure the carbon fiber plates. The carbon fiber plates were placed on top of and underneath a non-stick, porous material, in this case perforated Teflon. On one side of the porous material was a layer of thin cotton to absorb additional epoxy that would run off during the curing cycle. Non-porous Teflon sheets were placed above and below to keep epoxy from reaching the steel plates, the plate press and other carbon fiber plates. These Teflon sheets kept carbon fiber plates from sticking to each other and the steel plates. Four carbon fiber plates were cured at once while Figure 1 shows a diagram with only single carbon fiber plate for simplicity.

Figure 1 - Plate press setup diagram for a single carbon fiber plate.

Figure 2 shows the Tetrahedron plate press in use on a different plate with a similar cure cycle, where the applied heat can be clearly read as 150°F. The black steel plates sandwich non-porous Teflon sheets which insulate the steel plates from epoxy run off.

Figure 2 - Plate press during cure cycle.

Four carbon fiber plates were cured simultaneously using the curing cycle shown below in Figure 3. The load placed on the plates was raised to 300 lb and maintained during the entirety of the cure cycle. Phase I of the cure cycle raised the temperature of the plate press from room temperature to 150°F at a rate of 4°F per minute. Phase II of the cure cycle maintained this temperature for 16 hours. Phase III of the cure cycle reduced the temperature from 150°F to 70°F at a rate of 4°F per minute. Phase IV maintained this temperature for two hours.¹²

Figure 3 - Cure cycle for pre-preg carbon fiber plates.

2.2 Woven Carbon Fiber Test Specimen Preparation

The edges of the carbon fiber plates that come out of the plate press are normally covered in excess epoxy and not straight. A wet tile saw is used to cut the plates into squares and then into 1-inch wide carbon fiber test specimens. Figure 4 shows a carbon fiber plate that has been made square. It was cut into 1-inch wide specimens on the same tile saw used to clean the plate.

Figure 4 - Square carbon fiber plate. Distortion is from the wide angle lens.

Lines are drawn with marker on the carbon fiber plates along the fiber directions. These are used as guides to make cuts using the tile saw to cut finished carbon fiber square plates from unfinished carbon fiber plates. The wet tile saw used to cut the squares was also used to cut the specimens to their final dimensions. Specimens were approximately 9-inches long, 1-inch wide and 0.1-inch thick. The length of the specimens was regulated by the dimensions of the carbon fiber plates after they were cut and made square.

After being dried and checked for splinters and burrs the specimens were cleaned and sanded so aluminum tabs could be applied to each end. Aluminum tabs were attached to the ends of the carbon fiber test specimens to avoid damage from the wedge grips in the Instron 8801 servo-hydraulic test machine. The ends of the carbon fiber specimens were roughed using 80-grit sandpaper. Figure 5 shows the end of a specimen after sanding and before further cleaning. The epoxy has been scratched and the fibers have been left alone to avoid structural damage to the specimens.

Figure 5 - Carbon fiber specimen with sanded end.

Aluminum tabs were cut from a sheet of super-corrosion-resistant Aluminum alloy 5086 of thickness 0.063 inch. Tabs were cut to 1.5 x 1 inch using the Aerospace Engineering department's shear. A deburring tool was used to remove burrs from both. Tabs were initially created at 1-inch in length. These tabs did not have enough bonding are between the aluminum and carbon fiber and slipped off in static testing. This effect was not seen with tabs that are 1.5-inch in length.

It was calculated that the aluminum tabs would not have any appreciable effect on test results. The aluminum used was ordered from McMaster-Carr and is alloy 5086-H32. Shear modulus, G , of this aluminum is 3,830 ksi and shear strength, τ , is 25,400 psi.¹³ The aluminum tabs are 0.063-inch thick and are cut to 1.5-inch length and 1-inch width. Woven carbon fiber specimens failed at an average load, P , of 10,760 lb. Equation 1 shows the relation between shear modulus, tab dimensions, load placed on the tab and the amount of tab deflection. This can be rearranged to calculate Δx , the deflection of the aluminum tab at a particular load.

$$G = \frac{Pt}{A\Delta x}$$

1

Figure 6 shows a diagram of the aluminum tab in shear and displays Equation 1 rearranged to calculate for the deflection of the aluminum tab. The load, P, used in the calculation is one-half of the ultimate load placed on the test specimen. This is because there are two aluminum tabs and each tab transfers one-half of the load to the woven carbon fiber specimen.

Figure 6 - Diagram of aluminum tab in shear.

The following variables were used in the calculation of the deflection of the aluminum tab. The deflection is calculated to be 5.9 e-05 in. This is four orders of magnitude lower than the deflection measured in the woven carbon fiber specimens and is considered negligible.

$$P = \frac{1}{2} * (10,760 \text{ lb})$$

$$t = 0.09 \text{ in}$$

$$A = 1.5 \text{ in}^2$$

$$G = 3,830 \text{ e}+03 \text{ psi}$$

$$\Delta x = 5.9 \text{ e-}05 \text{ in}$$

To ensure a good bond in the epoxy between the aluminum tabs and woven carbon fiber specimens, tabs were then roughed with sandpaper in a similar manner as the carbon fiber. Figure 7 shows a carbon fiber specimen with sanded end and a sanded aluminum tab that is ready to be applied.

Figure 7 - Carbon fiber specimen with sanded aluminum tab ready to be applied.

Aluminum tabs and carbon fiber specimens were wiped with a paper towel dampened with acetone to remove particles left over from sanding and to clean off the surfaces before applying epoxy. The standard safety procedure for using acetone in the lab is to wear goggles and gloves and to apply acetone in the fume hood with the safety shield at the recommended height.

Scotch Weld DP-460NS epoxy was used to bond the aluminum to the carbon fiber. A small amount was placed on the carbon fiber specimen on the sanded ends of

one surface where the aluminum would be. Figure 8 shows the Scotch Weld epoxy, the applicator and mixing nozzle used.

Figure 8 - Scotch Weld DP-460NS with applicator and mixing nozzle.

A popsicle stick was used to spread the adhesive over the area on both ends of one surface. Aluminum tabs were then applied to the ends of the carbon fiber specimens. The specimens were turned over and the process repeated so that both ends on each surface had aluminum tabs attached. A sheet of non-adhesive vacuum bagging material was laid over the finished tabs. Steel plates and then weights were laid on top of the specimens to apply pressure during the 24-hour curing cycle of the Scotch Weld adhesive. Figure 9 shows the weights placed on the curing pieces. The steel plates distribute the weight and a layer of vacuum bagging material keeps excess epoxy off of the table and the plates.

Figure 9 - Weights used to provide pressure to cure Scotch Weld.

2.3 Strain Gage Set-up

Poisson's ratio was determined using strain gages attached to a P-3500 Strain Indicator. The Strain Indicator was connected to a National Instrument BNC-2111 External Connector box attached to a data acquisition PC running Bluehill 2. Figure 10 shows strain gages that were placed parallel and perpendicular to the length of the specimen. The gage aligned in the parallel direction is said to be in the longitudinal direction. The gage aligned in the perpendicular direction is said to be in the lateral direction. Each gage is attached to two lead wires that keep the weight of the connecting wires from affecting the gage readings.

The strain gage and a pad containing two copper leads are positioned on the specimen. The copper leads on the pad are connected to the strain gage leads by two small, lightweight wires as shown above in Figure 10. For a Poisson's ratio one gage is applied in the longitudinal direction and one in the lateral direction. Each gage has its own pad with copper leads close to it.

Figure 10 - Strain gages applied in the longitudinal and lateral directions.

The strain gages used in this research are Vishay Micromeritics 120 Ω resistance gages. The model number is EA-13-125AD-120. Strain gages were applied following the technique outlined in the Student Strain Gage Application Manual as written by Vishay. A summary of that process is given below.

The area where the strain gage are going to be applied was cleaned using acetone then the alkaline base cleaner provided by Vishay Micromeritics. A paper towel was dampened with acetone and used to clean the surface of the specimens. Next, a few drops of cleaner are applied to cotton swabs which are then used to finish cleaning the surface of the specimen. The swabs are run in a single direction to avoid picking up debris and re-depositing it in the application area.

M-Bond 200 adhesive is used to apply strain gages to the test specimens. The adhesive consists of a two-part epoxy and is shown in Figure 11.

Figure 11 - M-Bond 200 Adhesive Kit.

The gage and copper lead are positioned on the surface of the cleaned specimen where they will be applied. Scotch tape is placed on the specimen and pressed down on top of the strain gage and copper lead. The tape is peeled back and fastened so it doesn't fall back down. Blue M-Bond 200 Catalyst C is applied to the underside of the strain gage and copper lead.

After the catalyst has dried, clear M-Bond 200 Adhesive is applied in front of the area where the tape is attached to the specimen. The tape is pressed down in a single sweeping motion forcing the adhesive outward in a thin layer. Pressure is applied on the strain gage and copper lead for approximately one minute. The tape is then completely removed in a careful manner as to not dislodge the strain gage.

Two small lead wires are soldered between the strain gage to the copper leads. This is followed by soldering two wires that are approximately 3-inch in length to the copper leads. These wires are used to connect to the P-3500 Strain Indicator. Figure 12 shows a photo of these wires on sample 9-5. The main purpose of these wires is to reduce the risk of damage to the strain gage, so that multiple static tests may be performed on a sample.

Figure 12 - Sample 9-5 with longitudinal and lateral strain gages attached.

2.3.1 Calibrating Strain Gages

Strain gages were calibrated before use in a static test for Poisson's ratio on unnotched, woven carbon fiber specimens. Specimens were placed vertically in the Instron 8801 wedge grips and the attached controller and data acquisition PC was used to ensure no load was being applied.

Strain gages were attached to a P-3500 Strain Indicator in a quarter bridge circuit. A BNC-to-BNC cable was used to connect the Strain Indicator to a National Instruments BNC-2111 External Connector box. The BNC-2111 is directly attached to the controller and data acquisition PC that operates the Instron 8801.

Instron's Bluehill 2 software is used to operate static tests and record data from the Instron. The VersaChannel option is enabled in Bluehill 2 to record external data channels from the BNC-2111. Once enabled, a VersaChannel tab appears in the software's Options menu that is used to add two external data channels.

These channels can be given any discrete name. For the experiments discussed in this report they are labeled Longitudinal Strain and Lateral Strain in reference to the longitudinal and lateral strain gages, respectively. They must be assigned a voltage range for their data collection. The options include the default ± 10 Volts and the ± 5 and

± 1 settings. The closer the voltage range option is set to the voltage range of the external data channel the higher the accuracy of the data collection.

The maximum output voltage for the Strain Indicators is recorded using a digital multimeter. First press the CAL button on the Strain Indicator, which creates a shunt, or bypass, around the strain gage. This causes the Strain Indicator to display the maximum reading it can register on its display screen and output via its BNC output. This voltage determines the voltage range option in Bluehill 2.

The external data channels in Bluehill 2 that are used through the VersaChannel option must be calibrated with full-scale, gage length and calibration point values. The values initially used were taken from notes recorded during a demonstration by an Instron representative describing the use of the VersaChannel option with the National Instruments BNC-2111. These data recorded through the strain gages appeared to be approximately 240-times greater than what would be expected. This discrepancy was not discovered for some time since the data showed the expected trends, but not the correct values.

The following series of loading tests were performed on specimens with strain gages to determine the proper full-scale, gage length and calibration point settings for the strain gages in use. Bluehill 2 was used to record longitudinal and lateral strain gage data and these values were compared to the Strain Indicator display readings taken at the same loading in the same tests.

Specimens were brought to an initial setting with no load applied to them. The value on the Strain Indicator readout was set a convenient tare value of zero using a dial on the Strain Indicator. This would be compared to the initial value recorded in Bluehill 2. The load on the specimen was brought to 100lb over five seconds and kept there. The value on the Strain Indicator display was recorded and compared to the value recorded by Bluehill 2. Loads were brought to between 400lb in 100lb increments, with each

increment taking 5 seconds to apply the load and a pause between increments of 30 seconds. Values were recorded from the Strain Indicator display and compared to data recorded Bluehill 2. Calibration data is given in Table 1.

Table 1 - Strain gage calibration data.

Load (lb)	Strain Indicator		Bluehill	
	ϵ_{lat} ($\mu\epsilon$)	ϵ_{long} ($\mu\epsilon$)	ϵ_{lat} ($\mu\epsilon$)	ϵ_{long} ($\mu\epsilon$)
100	-6	120	-6	125
200	-13	247	-13	257
300	-19	382	-20	396
400	-25	515	-25	534

The proper values for the calibration settings were arrived at after a series of tests were performed. During testing, a discovery was made using 5% total elongation measureable by the strain gages and multiplying this by the 125mil gage length and using the product as the full-scale and calibration point values. Using 6.25mil for these settings the results were 10-times greater than what they were supposed to be.

Full-scale and calibration point values were reduced by a factor of ten to 0.625mil and gage length left at 125mil. The results of these tests showed agreement between the data recorded by Bluehill 2 and the readings from the Strain Indicator.

2.4 Creating a Notch in the Carbon Fiber Specimens

The Aerospace Engineering department's Haas vertical mill was used to make the cuts to the depths shown in Table 2. Cut depths were set as a ratio of the width of the part and were made to equal depths on opposite sides of the specimens. Cuts were made at the mid-section of the specimens and were perpendicular to the length of the specimen. Table 2 shows notch depths for a specimen exactly 1.000 in wide. The

example notch depth shown in Table 2 is for a specimen that measured 0.983 in wide. The accuracy of the vertical Haas mill is 0.0001 in, which governs the notch depth accuracy for all real cuts and the example notch depths given in Table 2.

Table 2 - Notch depths for 0.983-in wide specimen

Notch Size a/w	Ideal Notch Depth (inch)	Example Notch Depth (inch)
0.10	0.050	0.0492
0.15	0.075	0.0737
0.20	0.100	0.0983
0.25	0.125	0.1229
0.30	0.150	0.1475
0.35	0.175	0.1720

2.4.1 Design and Manufacturing the Arbor for Cutting Notches

Notches were cut using a stainless steel slitting saw blade with a blade-width of 0.006-in, otherwise referred to as the saw blade's kerf, and 2-in diameter. The original arbor used to hold the slitting saw blade is shown below in Figure 13. This arbor was initially used for creating notches, but was inadequate for notch sizes of $a/w > 0.20$.

Figure 13 - Long reach arbor for saw blade with 1/2-in hole.

The arbor shown in Figure 13 was not long enough for the notch sizes above $a/w = 0.20$. The diagram in Figure 14 shows the limited use the original long-reach arbor provided. The tool housing contacts the carbon fiber specimen when trying to make a cut deeper than 0.1 inch.

Figure 14 - Diagram showing limited use of original long-reach arbor.

A replacement arbor was constructed from spare rod stock and is shown in Figure 15. This arbor was long enough to avoid contact between specimens being cut and the tool housing on the mill. This first replacement arbor was non-uniform in density which caused a wobble when it was placed in the mill. A second arbor was constructed to increase the accuracy of cutting.

Figure 15 - First replacement arbor.

A second replacement arbor was machined from a dual-diameter ultra-precision shaft ordered from McMaster-Carr. Overall length of the Type 303 stainless steel shaft is 9-inch and the diameter steps up from $\frac{1}{2}$ - to $\frac{3}{4}$ -inch. Figure 16 shows the arbor with the bolt and cap from the original long-reach arbor which were used to hold the slitting saw blade on this arbor as well.

Figure 16 - Second replacement arbor.

2.4.2 Cutting notches using Haas Vertical Mill

Notches were cut using a stainless steel slitting saw of 0.006-inch kerf and 2-inch diameter that was obtained from McMaster-Carr. Accuracy of the cuts is determined by the ability of the mill to control the table movement in increments of 0.0001-inch in all three axes.

The carbon fiber specimens are held by two wooden blocks in a vice on the table of the mill as shown in Figure 17. They are aligned vertically using a right angle level that is placed against one side of the specimen when the vice is being tightened. As the wood blocks begin to grip the specimen it is aligned vertically, then the vise is tightened fully and the specimen alignment checked again. Figure 17 also shows the second replacement arbor and the slitting saw blade used to cut the notches.

Figure 17 - Carbon fiber specimens in vice in Haas vertical mill.

Figure 18 shows a notch cut into a carbon fiber specimen with notch size $a/w = 0.20$. The width of the cut is determined by the slitting saw blade kerf of 0.006-in.

Figure 18 – Photo of a notch in a carbon fiber specimen.

The diagram in Figure 19 shows the process used in the mill to create notches. The first step involves moving the mill table forward or backward in the table's y-direction so that the specimen is aligned with the axis of the arbor and slitting saw. The y-axis position field in the mill's control panel is set to zero so that the blade can be brought around to both sides of the specimen without having to re-align the specimen manually. The second step involves moving the table up or down so that the blade is in approximately at the mid-section of the specimen. A mark is made with a sharpie ahead of time that is at the mid-section as measured by a ruler with 0.01-inch accuracy. The z-axis position field in the mill's control panel is set to zero so it can be brought back to the same height in case it is moved.

Step 1: Align y-axis
Jog the table in y-axis to align specimen to center of arbor/blade.

Step 2: Align z-axis
Jog the table in z-axis to align blade to mark on specimen where cut will be made

Step 3: Align x-axis
Jog the table x-axis in 0.0001-in increments until noise is heard

Step 4: Create cuts
Jog the table in x-axis to notch depth. Pull blade out, and repeat **Step 3** on other side

Figure 19 - Diagram showing notch cutting procedure.

The spinning blade is very slowly against the side of the specimen. A pinging sound is heard when carbon fiber is cut. It is the sound of the saw blade tearing through fibers and is very distinct and high pitched. This sound is notification that the saw blade has begun cutting the carbon fiber specimen. The blade is stopped at this point and the x-axis position field in the mill's control panel is set to zero. The cut is made to a measured depth then the blade is backed out and brought around to the other side of the specimen to the same y-axis position. The same procedure using the sound of the saw blade to mark the x-axis position of the saw blade is used on the second side.

3 TEST PROCEDURES

The experimental tests performed for this research can be separated into two different categories. They are static testing and fatigue testing. Table 3 gives a list of tests performed in this research.

All static tests are performed on an Instron 8801 servohydraulic testing system and controlled by Instron's Bluehill 2 software on an attached controller and data acquisition PC. The static tests performed on unnotched specimens will determine the material properties for woven carbon fiber specimens such as Young's modulus, Poisson's ratio and ultimate strength. Experimental tests for Poisson's ratio include the use of strain gages and an extensometer is used for calibration purposes. Static tests are performed on notched specimens to determine the fracture strength of woven carbon fiber specimens with double-edge notches of increasing depth.

The second category of tests includes fatigue testing. Fatigue tests are performed on an Instron 8801 servo-hydraulic testing system controlled by Instron's WaveMatrix software that is being run on an attached controller and data acquisition PC. Fatigue tests performed will determine the number of loading cycles a woven carbon fiber specimen can withstand before failure. The amplitude of the load applied is varied and the number of cycles until failure is recorded for unnotched specimens. Fatigue tests are performed on woven carbon fiber specimens with double-edge notches of notch size $a/w = 0.20$.

Table 3 - Tests performed.

	Test Procedure	Specimen Destroyed?	Software Used	Data Gathered
Static	Ultimate Strength	Yes	Bluehill 2	σ_{ult} , E
	Poisson's Ratio	No	Bluehill 2	ν
	Fracture Stress	Yes	Bluehill 2	σ_f

Fatigue	Fatigue Life for Unnotched Specimen	Yes	WaveMatrix	N_f
	Fatigue Life for Notched Specimen	Yes	WaveMatrix	N_f

3.1 Static Test Procedures

Static tests were performed on an Instron 8801 servo-hydraulic testing system. Figure 20 shows the Aerospace Engineering Department's Instron 8801 setup. The PC shown is used to control the tests with Instron's Bluehill 2 software. Data is also recorded by the PC using the same software. The procedure used for creating the tests in Bluehill 2 is described in Appendix A.

Figure 20 - Instron 8801 servo-hydraulic testing machine.

3.1.1 Procedure to Determine Ultimate Strength of Unnotched Specimens

A series of ultimate strength tests were performed on the Instron 8801 servohydraulic testing system. Unnotched woven carbon fiber specimen dimensions are measured using dial calipers and a metal ruler. The caliper's least scale reading is 0.001-inch and the ruler's least scale reading is 0.01-inch. The specimen dimensions and sample name are entered into Bluehill 2 before each test.

Specimens are then placed in the wedge grips of the Instron 8801 and aligned vertically using a bubble level. Figure 21 shows a specimen that has been placed in the grips and is being checked with a level.

Figure 21 – Test specimen placed vertically in Instron 8801 grips.

Bluehill 2 is used to operate the Instron 8801 for an ultimate strength test. The entered dimensions are used by Bluehill 2 to automatically calculate stress and strain for test specimens from the load and extension data it records from the Instron 8801. Load is recorded from the load cell located above the upper wedge grip and extension is recorded from the displacement of the piston attached to the lower wedge grip.

The ultimate strength test involves subjecting the specimen to a constant extension rate of 0.05 in/min and recording the resulting load. The extension rate used simulates a quasi-static load scenario. The test ends when the recorded load drops by 40% of the peak measured load.

Figure 22 shows a diagram of the response of a brittle and ductile material. The response of the brittle material, represented by the blue line, shows that once the material reaches some critical stress level it fails and can no longer carry load. For the woven carbon fiber specimens in this test, that point is marked by failure in a brittle manner and the specimen breaking into two or more pieces.

Figure 22 - Diagram showing stress-strain curves for brittle and ductile materials.

The highest load recorded for brittle specimens is nominally the point of failure. The ultimate strength of the part is calculated as the recorded failure load divided by the measured cross-section area. Ultimate strength is automatically calculated by Bluehill 2 and recorded in a results file for each test. Table 4 displays a standard results file for a series of ultimate strength test performed on a random sampling unnotched specimens.

Table 4 – Ultimate strength test results for random sampling of unnotched specimens.

Specimen Label	Maximum Load	Stress at Maximum Load	Length	Thickness	Width	Area
	(lbf)	(psi)	(in)	(in)	(in)	(in ²)
Sample 7-8	11159.0	124389.6	6.10	0.089	1.008	0.08971
Sample 8-5	10894.0	125912.7	6.07	0.086	1.006	0.08652
Sample 7-7	10924.9	126022.6	6.05	0.086	1.008	0.08669
Sample 6-4	10239.8	110533.6	7.05	0.092	1.007	0.09264

3.1.2 Procedure to Determine Young's Modulus of Unnotched Specimens

A series of tests were performed on an Instron 8801 servo-hydraulic testing system to determine Young's modulus for unnotched, woven carbon fiber specimens. Young's modulus for a specimen was determined from data recorded by Bluehill 2 during an ultimate strength test. As the part is extended at 0.05 in/min the strain is calculated by dividing the recorded piston displacement, and therefore the specimen extension, by the measured length of the specimen. Stress is calculated in a similar manner as for an ultimate strength test. The load recorded by the load cell is divided by the measured cross-section area of the test specimen.

Data is recorded by Bluehill 2 approximately every 0.1 second in an ultimate strength and Young's modulus test. Calculations for stress and strain are performed automatically for each data point. All data points and automatically calculated values are recorded to a RAW data file with no formatting.

This file will be opened in Microsoft Excel and organized from text into columns. A chart is generated using stress and strain data calculated by Bluehill 2. A linear trend line will be fit to this data and the slope of the equation will be the value of Young's modulus for the specimen.

Young's modulus, E , is defined as the relation between uniaxial stress and strain and is also sometimes called the tensile modulus. Stress is defined in Figure 23 as the uniaxial load, P , being applied divided by the area, A , of the example material. Strain is defined in Figure 23 as the change in length, ΔL , of the material when placed under load

divided by the original length, L , of the material. Young's modulus, E , does not predict the nature of failure, but the relation between stress and strain of a material before an elastic limit is reached as seen in Figure 23.

Figure 23 shows a diagram displaying two different material responses to a uniaxial loading. The red line displays the material response of a ductile material. Steel is an example of a metal that displays this sort of behavior. The initial response of steel to loading is a linear relation between loading and strain, or elongation, of the part. After the elastic limit, the yielding stress, has been reached the material response enters a region of plasticity that includes strain hardening until the second peak in stress is reached and then necking until failure. The woven carbon fiber specimens in this experiment show a brittle failure and do not have any plastic region in their material response. They can be represented by the blue line in Figure 23 since they display a linear strain response to loading up until failure. The elastic limit for brittle materials is also the point of failure since there is no plastic response region.

Figure 23 - Diagram showing Young's modulus.

3.1.3 Procedure to Determine Poisson's Ratio of Unnotched Specimens

A series of tests will be performed on an Instron 8801 servo-hydraulic testing system to determine Poisson's ratio of unnotched, woven carbon fiber test specimens. Tests are controlled by Bluehill 2 software on an attached controller and data collection PC. Poisson's ratio is defined as the negative of the transverse strain divided by the axial strain of a material under an applied load and is given in Equation 2.

$$\nu = -\frac{\epsilon_{transverse}}{\epsilon_{axial}} \quad 2$$

FIGURE, displays a diagram of a rectangular material with loads applied in the x-direction. The dashed outline shows an exaggerated deformation with the material stretching in the direction of the applied load, P, and contracting in the perpendicular direction to the load. The changes in dimensions, ΔL and ΔW , are the results of the applied load, P, and are used to calculate Poisson's ratio. ΔL and ΔW are measured by strain gages in this test and the results recorded by Bluehill and are referred to as longitudinal and lateral strain, respectively.

Figure 24 - Diagram showing Poisson's ratio.

The test setup used to record strain gage data is shown below in Figure 25. A strain gage is connected to the P-3500 Strain Indicator. A National Instruments BNC-2111 External Connector box is used to attach the Strain Indicator to a data acquisition PC. The VersaChannel option in Bluehill 2 is used to record external data.

Figure 25 - Diagram of data acquisition system used to record strain gage data.

Unnotched woven carbon fiber specimens with strain gages attached to their surfaces are placed vertically in the Instron 8801 wedge grips. Strain gages are then connected directly to a P-3500 Strain Indicator. The P-3500 Strain Indicator contains a screen that displays the microstrain readings from the strain gage as well as a BNC output for an external data recorder.

Each P-3500 Strain Indicator is attached with 24-gage wire to a strain gage in a quarter bridge circuit as described by a diagram printed on the inside the lid of the strain indicators. Once attached to the strain gage, the strain indicators are powered on by pressing the AMP ZERO button. The operational amplifier is then balanced by a metal dial to a value of zero.

Next, the gage factor is set to the value of the attached strain gage as given by the manufacture. To do this, the GAGE FACTOR button is pressed to display the current value of the gage factor on the display screen. A dial located above the GAGE FACTOR button is rotated to bring the value to 2.110, the value given by Vishay Micro-Measurements as the gage factor of the strain gages used in this research.

The RUN button is pressed next, which sets the display screen to show the microstrain reading from the strain gage. The microstrain value reading on the display screen is brought to a tare value of zero using a second dial that is to the right of the dial used to set the gage factor. Setting this value to zero also sets the output voltage at the BNC output to zero.

A cable with a BNC connector at one end and alligator clips at the other is attached to the P-3500 Strain Indicator. The leads from a digital multimeter are attached to the alligator clips and the multimeter set to record voltage. The CAL button on the Strain Indicator is pressed and the calibration voltage recorded. This voltage is the maximum voltage the Strain Indicator can output and will be used with setting up external data channels in Bluehill 2.

The National Instruments (N.I.) BNC-2111 External Connector box, shown below in Figure 26, is then connected to the P-3500 Strain Indicator via a BNC cable. The N.I. External Connector box is used with the VersaChannel option in Bluehill 2 to record data from the Strain Indicator.

Figure 26 - National Instruments BNC-2111 used to record P-3500 output to PC.

Bluehill 2 is used at this point to operate the test and record data. Bluehill 2 is opened and the VersaChannel option is enabled in the system options menu. This opens a new menu where the number of external data channels will be set to two – one for each strain gage on the unnotched, woven carbon fiber specimen being tested. The calibration voltage from each strain indicator is used to determine the voltage range of the external data channel in Bluehill 2. The default value for voltage range of external data channels is ± 10 Volts, but can be changed to ± 5 or ± 1 Volts. The Strain Indicators have a maximum output voltage of 2.3 Volts. Output voltage can be changed on the Strain Indicator using a dial labeled OUTPUT next to the BNC connector and is normally in the 0-1 Volt range. The value for the voltage range of the external data channels in Bluehill 2 is set to closest range that encompasses the Strain Indicator maximum output voltage.

Bluehill 2 must be closed and reopened after the external data channels have been included. Once reopened the strain gage data channels are calibrated. A series of experiments has been performed to determine proper calibration values for strain gages in Bluehill 2 and is discussed in Section 2.3.1. The full-scale and calibration point values used are 0.625-mil and the gage length value is 125-mil.

Once these values are entered the strain gage channels can be calibrated. Beginning the calibration in Bluehill 2 the user is prompted to set the strain gage to a tare value with no load. After a few seconds the user is prompted to set the strain indicator to the calibration voltage. Finally, the user is prompted to return the voltage to the tare value. The strain gage external data channels are now calibrated and data can be recorded in Bluehill 2.

The unnotched, woven carbon fiber specimens are subject to an extension of 0.05 in/min. Longitudinal and lateral strains are recorded by the strain gage external data channels. Data is output from Bluehill 2 into a RAW data file. This is opened in Microsoft Excel and data is organized from text into columns. A chart is generated that contains the longitudinal and lateral strain gage data. A linear trend line is fit to the data and the slope is Poisson's ratio.

3.1.4 Procedure to Determine Fracture Stress of Notched Specimens

A series of fracture stress tests will be performed on the Instron 8801 servohydraulic testing system. Tests are controlled by Bluehill 2 on an attached controller and data acquisition PC. Notched, woven carbon fiber specimen dimensions are measured using dial calipers and a metal ruler. The caliper's least scale reading is 0.001-inch and the ruler's least scale reading is 0.01-inch. Specimen dimensions and sample name are entered into Bluehill 2 before each test.

Specimens are then placed vertically in the Instron 8801's wedge grips. Bluehill 2 is used to control the test and to record data. Specimens are subject to extension at a rate of 0.05 in/min. The test ends when the load recorded by Bluehill drops by 40% from the peak load recorded. The highest load recorded in the test is divided by the measured cross-section area to calculate the highest stress experienced by the notched specimen

before failure. This value is recorded as the failure stress in a results file output automatically by Bluehill 2 for each test.

3.2 Fatigue Test Procedures

Fatigue tests are performed on an Instron 8801 servo-hydraulic testing system. Tests are controlled with Instron's WaveMatrix software. Data is also recorded by the PC using the same software. The procedure used for creating the tests in WaveMatrix, is described below in Appendix B.

3.2.1 Procedure for Determining Fatigue Life of Unnotched Specimens

A series of fatigue tests will be performed on an Instron 8801 servo-hydraulic testing system. Tests are controlled by WaveMatrix on an attached controller and data acquisition PC. Unnotched woven carbon fiber specimen dimensions are measured before testing by a dial caliper with least scale reading of 0.001-inch and a metal ruler with least scale reading of 0.01-inch. The dimensions are used to calculate the cross-section area, which is used to determine the mean load and amplitude of the cyclic load applied to the specimen.

Figure 27 shows a diagram explaining the parameters used in a fatigue test. Unnotched, woven carbon fiber specimens are brought to a mean stress and then subject to a cyclic loading at a constant amplitude and frequency.

Figure 27 – Diagram showing fatigue test parameters.

The mean stress used for all fatigue tests in this research is half of the ultimate strength. The amplitude of the cyclic loading waveform applied is increased in increments of 2.5% from 22.5% of the ultimate strength to 30% of the ultimate strength. Table 5 lists these parameters. All cyclic loading is performed at a constant frequency of 20 Hz.

Table 5 - Fatigue test parameters.

	σ_{mean} (% σ_{ult})	$\sigma_{\text{amplitude}}$ (% σ_{ult})
		22.5%
Fatigue Tests for Unnotched		25%
Woven Carbon Fiber Specimens	50%	27.5%
		30%

WaveMatrix controls the Instron 8801 using load, not stress, as the variable which controls the test. The measured cross-sectional area of the individual test specimens are used to determine the mean load and amplitude of the cyclic loading that will be applied during the tests. These values are calculated by multiplying the cross-

sectional area of the specimen by the mean stress and amplitude of the stress that is to be applied. These are entered into WaveMatrix as the mean load and load amplitude, respectively.

After WaveMatrix has been set to the correct values for mean load and load amplitude, an unnotched, woven carbon fiber specimen is placed vertically in the Instron 8801 wedge grips. The position of the lower wedge grip is observed and a position limit is placed in the software controlling the Instron 8801. The position limit is necessary to avoid damage to the Instron 8801 during a fatigue test. The limit is normally 0.5-inch in either direction of where the grip is located when the unloaded specimen is installed in the grips.

The test is started in WaveMatrix after the position limits are enabled. The tests continue until the specimen fails, which is recorded by a 15% drop in either load carrying capability or extension of the specimen during loading. The 15% drop is in comparison to the extension and load results at the 500th cycle. Extension and load results are monitored at the maximum and minimum of the loading cycle. Data is recorded at these peaks for maximum and minimum loading and extension. Data is recorded at every 10th cycle up to 100 cycles, every 1,000th cycle up to 10,000 cycles, and every 100,000th cycle up to 1,000,000 cycles. Data for the most recent 500 cycles is also recorded and saved to an output file when the part fails.

3.2.2 Procedure for Determining Fatigue Life of Notched Specimens

A series of fatigue tests were performed on an Instron 8801 servo-hydraulic testing system. Tests are controlled by WaveMatrix on an attached controller and data

acquisition PC. The fatigue test for notched specimens is similar to the test for unnotched specimens except for the following changes.

Notched specimens tested in fatigue all contain notches of size $a/w = 0.20$. Notched woven carbon fiber specimen dimensions were measured before testing by a dial caliper with least scale reading of 0.001-inch and a metal ruler with least scale reading of 0.01-inch. The caliper was used to measure the width and thickness of the specimen and the metal ruler was used to measure the length of the specimen.

The ultimate stress for notched specimens is lower due to the reduced area and the introduced stress concentrations at the ends of the notches. All references to the ultimate strength of the specimens refer to the fracture stress of the notched specimens.

Results from a series of initial fatigue tests on notched specimens that were performed at the same stress amplitudes as unnotched specimens showed that notched specimens were being tested below their endurance limit. The amplitude of the applied cyclic loading was increased until tests showed specimens failing in fatigue. The amplitude of the stresses used on notched specimens is given in Table 6.

Table 6 - Fatigue test parameters for notched specimens.

	σ_{mean} (% σ_{ult})	$\sigma_{\text{amplitude}}$ (% σ_{ult})
		35%
		36.25%
Fatigue Tests for Notched		37.5%
Woven Carbon Fiber Specimens	50%	40%
		42.5%

4 Results and Discussion

Unnotched, woven carbon fiber specimens were tested for their material properties in a series of static tests. Test results were separated into the ultimate strength, Young's modulus and Poisson's ratio of the specimens. Notched woven carbon fiber specimens were then tested for fracture stress in a series of tests on specimens with increasing notch depth.

Data for static tests was automatically recorded by Bluehill 2. This program is run on a PC attached to an Instron 8801 servo-hydraulic testing system. Besides recording data Bluehill 2 also operates the static tests performed by the Instron 8801.

A series of fatigue tests were performed on unnotched woven carbon fiber specimens with test parameters listed in Table 5. Tests were performed in which the amplitude of the cyclic load applied to the unnotched specimens was increased from 22.5% to 30% of the ultimate strength of the unnotched specimens. The amplitude was increased in increments of 2.5% of the ultimate strength of the specimens.

A series of fatigue tests were performed on notched woven carbon fiber specimens with test parameters listed in Table 6. The mean load for all fatigue tests was 50% of the ultimate strength of the unnotched specimens. Notched specimens were also tested in fatigue. Notch depth on all specimens tested in fatigue was $a/w = 0.20$. The mean load for all fatigue tests on notched specimens was 50% of the fracture stress of the notched specimens. The different amplitudes of the cyclic load applied to the notched specimens are 35%, 36.25%, 37.5%, 40% and 42.5% of the fracture stress of the notched specimens.

Data for fatigue tests was automatically recorded by WaveMatrix. This program is run on a PC attached to an Instron 8801 servo-hydraulic testing system. Besides

recording data WaveMatrix also operates the fatigue tests performed by the Instron 8801.

Post processing of all data is performed in Microsoft Excel. Comma-separated variable (.CSV) and raw data files (.RAW) in text format are converted to Excel .XLS spreadsheet files. All charts are generated using Microsoft Excel.

4.1 Static Test Results for Unnotched Specimens

Unnotched woven carbon fiber specimens were tested on an Instron 8801 servo-hydraulic testing system. Tests were performed to determine the material properties of the specimens.

Ultimate strength and Young's modulus were determined in static tests which subjected specimens to an extension rate of 0.05 in/min until the specimen failed. Tests were controlled and data collected by Bluehill 2 on a PC attached to the Instron 8801.

A results file automatically generated by Bluehill 2 contained ultimate strength for each specimen. A raw data output file automatically generated by Bluehill 2 contained stress and strain values for each specimen. These values are used to generate a graph in Microsoft Excel to which a linear trend line is fit that gives the value for Young's modulus as its slope.

Poisson's ratio was calculated from data in a static test in which specimens were subject to an extension rate of 0.05 in/min until a load of 3,000 lb was reached. Strain gages were attached to unnotched woven carbon fiber specimens and data collected by Bluehill 2 through the use of a P-3500 Strain Indicator and National Instruments BNC-2111 External Connector box. Strain gage readings were used to generate a graph in Microsoft Excel to which a linear trend line is fit that gives the value for Poisson's ratio as its slope.

4.1.1 Ultimate Strength Test Results for Unnotched Specimens

Bluehill 2 calculates the ultimate strength of specimens by dividing the load at failure by the cross-sectional area of the specimen. This data is output to a results file. Table 7 shows the results for the 21 tests performed to determine ultimate strength of unnotched woven carbon fiber specimens used in this research. Results from tests 1, 3 and 7 are considered invalid and are highlighted in red in Table 7. During these tests, the epoxy holding aluminum tabs to the ends of the carbon fiber specimens failed. This can be seen in the specimens themselves and in the plotting of their stress vs. strain responses as is seen in Figure 28.

Table 7 - Test results for ultimate strength.

Test #	Sample #	Max Load (lb)	Width (in)	Thickness (in)	Ultimate Strength (psi)
1	6-1	9304	1.008	0.092	100,328
2	2-2	10726	1.01	0.091	116,701
3	6-8	6949	1.01	0.091	75,607
4	2-3	10081	1.007	0.092	108,814
5	6-6	10570	0.992	0.090	118,392
6	6-5	10562	1.011	0.091	114,803
7	6-7	9945	0.958	0.092	112,837
8	2-7	11520	1.004	0.092	124,719
9	2-8	10586	1.015	0.091	114,611
10	6-2	11163	1.011	0.091	121,336
11	6-3	11088	1.011	0.092	119,209
12	2-4	10154	0.998	0.093	109,399
13	2-5	11312	1.008	0.092	121,978
14	7-1	11040	1.013	0.086	126,722
15	7-2	10843	1.013	0.086	124,461
16	8-1	10634	0.986	0.086	125,409
17	8-2	10182	1.008	0.087	116,106
18	7-8	11159	1.008	0.089	124,387
19	8-5	10894	1.006	0.086	125,919
20	7-7	10925	1.008	0.086	126,026
21	6-4	10240	1.007	0.092	110,529

Average	119,418
Standard Deviation	6,036

Figure 28 shows the results from all ultimate strength tests on unnotched woven carbon fiber specimens, including the three excluded tests highlighted in Table 7.

Samples 6-1 and 6-8 show the most apparent epoxy slipping. Results from sample 6-8 might lead one to believe a ductile material, such as steel, was tested if the failure at the epoxy was not noticed. Unnotched, woven carbon fiber specimens nominally fail in a brittle manner as is shown by the majority of results given by Figure 28.

Figure 28 - Stress vs. strain for unnotched, woven carbon fiber specimens.

Figure 29 shows the results from ultimate strength tests and their diversion from the average. The average ultimate strength of the unnotched woven carbon fiber specimens is calculated to be 119,418 psi. The standard deviation of 6,036 psi is shown on Figure 29 as the set of error bars from the average value. The red X markers are the excluded tests which failed at the epoxy bond between the aluminum tabs and carbon

fiber specimens. The black triangles represent tests which are within one standard deviation from the average and the blue triangles represent tests which are outside one standard deviation from the average.

Figure 29 - Ultimate strength test results.

4.1.2 Young's Modulus Test Results for Unnotched Specimens

Bluehill 2 records data throughout a static test and writes it to a raw data file when the test is completed. Data recorded includes stress and strain as calculated by Bluehill 2. Stress is calculated by dividing the load cell reading by the cross-section area as measured before the test. Strain is calculated as the displacement of the piston divided by the length of the specimen as measured before the test.

Figure 30 through Figure 50 show the stress vs. strain results gathered for all Young's modulus tests for unnotched, woven carbon fiber specimens. A data region in the response of the sample is highlighted in red in the figures and a linear trend line is fit to this data. The equation of the linear trend line is given on each figure and the value of the slope is the Young's modulus as calculated for each specimen in units of ksi/(in/in), or just ksi.

Figure 30 - Stress vs. strain for sample 6-1.

Figure 31 - Stress vs. strain for sample 2-2.

Figure 32 - Stress vs. strain for sample 6-8.

Figure 33 - Stress vs. strain for sample 2-3.

Figure 34 - Stress vs. strain for sample 6-6.

Figure 35 - Stress vs. strain for sample 6-5.

Figure 36 - Stress vs. strain for sample 6-7.

Figure 37 - Stress vs. strain for sample 2-7.

Figure 38 - Stress vs. strain for sample 2-8.

Figure 39 - Stress vs. strain for sample 6-2.

Figure 40 - Stress vs. strain for sample 6-3.

Figure 41 - Stress vs. strain for sample 2-4.

Figure 42 - Stress vs. strain for sample 2-5.

Figure 43 - Stress vs. strain for sample 7-1.

Figure 44 - Stress vs. strain for sample 7-2.

Figure 45 - Stress vs. strain for sample 8-1.

Figure 46 - Stress vs. strain for sample 8-2.

Figure 47 - Stress vs. strain for sample 7-8.

Figure 48 - Stress vs. strain for sample 8-5

Figure 49 - Stress vs. strain for sample 7-7.

Figure 50 - Stress vs. strain for sample 6-4.

The results for Young's modulus for unnotched specimens as determined in Figure 30 through Figure 50 are given in Table 8. Tests 1, 3 and 7 are highlighted in red. These are the three tests that failed at the epoxy holding aluminum tabs to the carbon fiber specimens. Data from these three tests are excluded from the calculation for the average Young's modulus of the unnotched, woven carbon fiber specimens. The remaining 18 tests are used to calculate an average Young's modulus of 7,149 ksi/(in/in). The standard deviation is 247 ksi/(in/in).

Table 8 - Test results for Young's modulus.

Test #	Sample #	Young's Modulus (ksi/in/in)
1	6-1	7,033
2	2-2	6,861
3	6-8	6,362
4	2-3	6,747
5	6-6	6,815

6	6-5	6,909
7	6-7	6,911
8	2-7	7,009
9	2-8	7,071
10	6-2	7,466
11	6-3	7,150
12	2-4	7,358
13	2-5	7,264
14	7-1	7,373
15	7-2	7,425
16	8-1	7,255
17	8-2	7,498
18	7-8	6,767
19	8-5	7,312
20	7-7	7,146
21	6-4	7,247
Average		7,149
Standard Deviation		247

Figure 51 shows the Young's modulus test results for unnotched, woven carbon fiber specimens as they relate to the average Young's modulus. Tests which failed and are excluded from the data set are represented by a red X. Black triangles represent specimens with test results within one standard deviation, 247 ksi, from the average Young's modulus of 7,149 ksi. Blue triangles represent specimens with results outside of one standard deviation from the average. The average Young's modulus is represented by the red line and the error bars show one standard deviation above and below.

Figure 51 - Young's modulus results for tests.

4.1.3 Poisson's Ratio Test Results for Unnotched Specimens

Bluehill 2 records data throughout a static test and writes it to a raw data file when the test is completed. Strain gage data is recorded as an external data channel through the VersaChannel option in Bluehill 2. A National Instruments BNC-2111 External Connector box is attached to the data acquisition PC and is used to record data from a P-3500 Strain Indicator. Strain gages were calibrated before tests were performed. Figure 52 shows the placement of the lateral and longitudinal strain gages.

Figure 52 - Longitudinal and lateral strain gages.

Reading data from strain gages involves the use of a P-3500 Strain Indicator as a signal amplifier and conditioner. This is necessary since the change in electrical resistance that is being measured is very small. The P-3500 Strain Indicators are used to generate an amplified output signal that can be recorded by Bluehill 2. The National Instruments BNC-2111 External Connector box is shielded to prevent external electromagnetic (EM) interference, but the wiring from the strain gage to the P-3500 strain indicator was not.

Figure 53 shows data recorded from the lateral single strain gage during the course of a test on sample 9-5. The sample was subject to extension at a rate of 0.05 in/min and the test stopped when a load of 3,000 lb was reached. The black line shows the strain signal that is influenced by EM interference from lighting in the room, active computers and electronics, etc. The red line is a linear fit to the oscillating strain data and is considered the strain gage output for calculating Poisson's ratio.

Figure 53 – Lateral strain gage data recorded by Bluehill 2.

Figure 54 shows the longitudinal strain gage data from the test performed on sample 9-5. Noise is not seen since it is on a smaller scale than the longitudinal strain gage data. Once again a linear trend line is fit to the data.

Figure 54 - Longitudinal strain gage data.

Poisson's ratio is calculated as the negative of the lateral strain divided by longitudinal strain as given by equation 3. This can be measured as the slope of the line of the lateral strain plotted against the longitudinal strain.

$$\nu = - \frac{\epsilon_{lateral}}{\epsilon_{longitudinal}} \quad 3$$

Figure 55 shows the lateral vs. longitudinal strain gage data for sample 9-5. The slope of the line is approximated with a linear regression and is shown as -0.05. The definition of Poisson's ratio is the negative of the lateral strain value divided by the

longitudinal strain value so the sign on the slope value is switched from negative to positive and Poisson's ratio is determined to be 0.05.

Figure 55 - Poisson's ratio for sample 9-5.

Figure 57 shows the lateral strain gage data for sample 5-6. Strain gage data for this sample showed noise similar to sample 9-5. The data had a linear trend line fit to it to remove noise. The black line in Figure 57 shows the strain gage data with noise. The red line shows the linear trend line that was fit to the data to remove noise.

Figure 56 - Lateral strain gage data for sample 5-6.

Figure 57 shows the lateral vs. longitudinal strain gage data for sample 5-6. A linear trend line is fit to the data and its equation is shown on the graph. The value for the slope of the trend line is the negative of Poisson's ratio. Poisson's ratio is shown on the graph as being 0.05 for sample 5-6, similar to Poisson's ratio of 0.05 for sample 9-5.

Figure 57 - Poisson's ratio for sample 5-6.

4.1.4 Discussion of Static Test Results for Unnotched Specimens

Figure 58 shows the failure of test sample 2-4 in an ultimate strength test. Two horizontal tearing sections are seen, one on each surface. A delamination range can be seen between them. Also, near the lower horizontal tear a small section of the surface layer delaminated at the time of failure. The popping sounds of individual fibers tearing were heard before the part failed; however, all visible damage seen in Figure 58 appeared at the moment of failure. Sample 2-4 failed instantly as is characteristic for a brittle material.

Figure 58 – (left) Photograph of sample 2-4. (right) Opposite side of sample 2-4.

Figure 59 shows the failure of sample 6-2 in an ultimate strength test. Multiple horizontal tears are visible that pass through all layers of the sample. The horizontal tear toward the bottom of sample 6-2 is the only one that spans across the width of the part. A section of the surface near the horizontal tear across the part shows damage that appears similar to the delamination in Figure 58. All visible damage to sample 6-2 occurred at the moment of failure.

Figure 59 - (left) Photograph of sample 6-2 after failure. (right) Close up on horizontal tear.

As Figure 58 and Figure 59 display, delamination and multiple instances of horizontal tearing are common during failure of unnotched woven carbon fiber specimens. This is further evidenced in Figure 60, which shows sample 16-6 after failure in an ultimate strength test. The horizontal tearing of the sample is due to a local material imperfection such as a broken fiber, void in epoxy matrix, a fiber not aligned perfectly in the local region, localized micro-delamination due to machining, etc. This material imperfection formed a stress concentration that caused a microcrack. Under continued loading this microcrack then passed some critical size and caused brittle failure of the specimen.

Cracks in carbon fiber propagate at super-sonic speeds¹⁸ so there is no photo from this research of these parts in the process of failing. The horizontal face cracking that can be seen above the horizontal tearing in Figure 60 did not appear until the part

failed. It is likely that during failure and crack propagation a stress wave emanating from the crack front caused localized failure in the form of horizontal face cracking.

Figure 60 – Photograph of sample 16-6 after failure.

Figure 61 shows a photograph of sample 16-6 after failure from a different angle than the one seen in Figure 60. Delamination is seen in some test specimens and appears to originate at the location where horizontal tearing occurs. This is possibly due to a localized stress concentration that is the result of a material deformity. Another possibility is that during the formation of the crack front, as one layer of carbon fiber tears before another, the strain gradient between the damaged and undamaged layer is great enough to encourage a second interlaminar crack front.

Delamination may have originated at the same location where horizontal tearing began. A shear wave may be responsible for this second failure that appears at the same time as the horizontal tearing.

Delamination between layers appears during same moment as horizontal tearing.

Figure 61 – A different view of sample 16-6 after failure.

Figure 62 shows the failure of sample 2-8 in ultimate strength test. Sample 2-8 failed with horizontal tearing along one surface, delamination along most of the length of the part and tearing on the other surface that follows an arbitrary path. All three failures appeared at the moment of failure.

Figure 62 – (left) Photograph of sample 2-8 after failure. (right) Close up on tearing.

Figure 63 shows the failure of sample 8-2 in an ultimate strength test. Similar to the results seen in previous examples this sample shows multiple simultaneous failures. Unlike the previous examples, this sample's failure shows two distinct horizontal tears that both pass through all layers and both span the sample. All specimens showed damage at multiple locations after failure, a few like sample 8-2 showed tearing across the entire part in multiple locations.

Multiple simultaneous failures in the form of horizontal tears through all layers and across sample

Figure 63 - Photograph of sample 8-2 after failure.

Having multiple horizontal tears that spanned the sample was not a failure that was particular to sample 8-2 or an uncommon failure among unnotched woven carbon fiber specimens. Figure 64 shows the failure of sample 19-7 in an ultimate strength test. Simultaneous failures are seen as horizontal tearing toward the top and bottom of the specimen. Tears pass through all layers and across the specimen. Sample 19-7 was tested for ultimate strength as part of a quality assurance check. It was not one of the original 21 tests used to calculate the average for ultimate strength. Sample 19-7 showed an ultimate strength of 113,890 psi. This is within one standard deviation of 6,036 psi of the average ultimate strength of 119,418 psi.

Figure 64 – Photograph of sample 19-7 after failure.

4.2 Static Test Results for Notched Specimens

Notched woven carbon fiber specimens were tested on an Instron 8801 servo-hydraulic testing system. Tests were controlled and data collected by Bluehill 2 on a PC attached to the Instron 8801.

Tests were performed to determine the fracture stress of the specimens. Fracture stress was determined in static tests which subjected specimens to an extension rate of 0.05 in/min until the specimen failed.

A results file automatically generated by Bluehill 2 contained failure stress results for each specimen. A raw data output file is also automatically generated by Bluehill 2 that contains the stress vs. strain response for individual specimens.

4.2.1 Fracture Stress Test Results for Notched Specimens

Table 9 shows the results from the 7 tests performed for notched specimens with notch size $a/w = 0.10$. Test 4 was excluded since it appeared to be an outlier in its response as compared to the other specimens of notch size $a/w = 0.10$. The average fracture stress for specimens with notch size $a/w = 0.10$ is 93,481.4 psi and the standard deviation for this calculation is 5,902.9 psi.

Table 9 - Fracture stress test results for specimens with notch size $a/w = 0.10$.

Test #	Specimen label	Maximum Load (lbf)	Thickness (in)	Width (in)	Stress at Maximum Load (ksi)
1	Coupon 4-1	7183.9	0.091	1.008	86942.8
2	Coupon 4-2	7312.0	0.093	1.012	86210.6
3	Coupon 4-4	7755.4	0.09	1.01	94693.4
4	Coupon 4-8	7935.6	0.091	1.008	96040.1
6	Coupon 7-3	7689.9	0.084	1.013	100269.7
7	Coupon 8-6	7726.0	0.086	1.007	99048.4
8	Coupon 8-9	7439.4	0.088	1.002	93723.6
Average		7,517.8			93,481.4
Standard Deviation		240.6			5,902.9

Figure 65 shows the stress vs. strain responses recorded during static tests on notched, woven carbon fiber specimens with notch size $a/w = 0.10$. Sample 4-8 shows a markedly different response from the other tests. The most likely explanation for this is that the notch was cut to the wrong size on this specimen or that it was mislabeled as being of notch size $a/w = 0.10$.

Figure 65 - Stress vs. Strain data for specimens with notch size $a/w = 0.10$.

Figure 66 displays the fracture stress results for specimens with notch size $a/w = 0.10$ as they relate to the average fracture stress. The average fracture stress for specimens with notch size $a/w = 0.10$ is shown as a red line. Error bars are displayed that represent one standard deviation above and below the average. The red X marker represents sample 4-8 which is removed from consideration toward the average. Black triangle markers represent data points that lie within one standard deviation from the average. Blue triangle markers represent data points that lie outside one standard deviation from the average.

Figure 66 - Fracture stress for notched specimens with notch size $a/w = 0.10$.

Table 10 gives the results from the 6 tests performed for notched specimens with notch size $a/w = 0.15$. The average fracture stress for specimens with notch size $a/w = 0.15$ is 88,192.7 psi and the standard deviation for this calculation is 5,135.4 psi.

Table 10 - Fracture stress test results for specimens with notch size $a/w = 0.15$.

Test #	Specimen label	Maximum Load (lbf)	Thickness (in)	Width (in)	Stress at Maximum Load (psi)
1	Coupon 3-1	6818.4	0.085	1.007	93601.1
2	Coupon 3-2	6686.7	0.085	1.009	91579.5
3	Coupon 4-3	7048.2	0.09	1.009	91167.7
4	Coupon 4-5	6588.3	0.091	1.01	84184.7
5	Coupon 4-6	6135.1	0.089	1.011	80062.9
6	Coupon 4-7	6914.6	0.091	1.008	88560.0
Mean		6,698.5			88,192.7
Standard Deviation		320.3			5,135.4

Figure 67 shows the stress vs. strain responses recorded during static tests on notched, woven carbon fiber specimens with notch size $a/w = 0.15$. All specimens show similar stress vs. strain responses for fracture stress.

Figure 67 - Stress vs. Strain for specimens with notch size $a/w = 0.15$.

Figure 68 displays the fracture stress results for specimens with notch size $a/w = 0.15$ as they relate to the average fracture stress. The average fracture stress for specimens with notch size $a/w = 0.15$ is shown as a red line. Error bars are displayed that represent one standard deviation above and below the average. Black triangle markers represent data points that lie within one standard deviation from the average. Blue triangle markers represent data points that lie outside one standard deviation from the average.

Figure 68 - Fracture stress for specimens with notch size $a/w = 0.15$.

Table 11 gives the results from the 6 tests performed for notched specimens with notch size $a/w = 0.20$. The average fracture stress for specimens with notch size $a/w = 0.20$ is 86,967.8 psi and the standard deviation for this calculation is 3,640.4 psi.

Table 11 – Fracture stress test results for specimens with notch size $a/w = 0.20$.

Test #	Specimen label	Maximum Load (lbf)	Thickness (in)	Width (in)	Stress at maximum Load (psi)
1	Coupon 3-3	6250.2	0.085	1.007	91117.4
2	Coupon 3-4	6380.1	0.086	1.013	91250.9
3	Coupon 3-5	6097.1	0.086	1.011	87418.8
4	Coupon 3-6	5878.4	0.087	1.008	83623.1
5	Coupon 8-7	5667.4	0.086	0.996	82789.6
6	Coupon 8-8	5752.8	0.084	1.000	85606.9
Average		6,004.3			86,967.8
Standard Deviation		283.9			3,640.4

Figure 69 shows the stress vs. strain responses recorded during static tests on notched, woven carbon fiber specimens with notch size $a/w = 0.20$. All specimens show similar stress vs. strain responses for fracture stress.

Figure 69 - Stress vs. strain for specimens with notch size $a/w = 0.20$.

Figure 70 displays the fracture stress results for specimens with notch size $a/w = 0.20$ as they relate to the average fracture stress. The average fracture stress for specimens with notch size $a/w = 0.20$ is shown as a red line. Error bars are displayed that represent one standard deviation above and below the average. Black triangle markers represent data points that lie within one standard deviation from the average. Blue triangle markers represent data points that lie outside one standard deviation from the average.

Figure 70 - Fracture stress for specimens with notch size $a/w = 0.20$.

Table 12 gives the results from the 6 tests performed for notched specimens with notch size $a/w = 0.25$. The average fracture stress for specimens with notch size $a/w = 0.25$ is 81,112.4 psi and the standard deviation for this calculation is 4,250.5 psi.

Table 12 - Fracture stress test results for specimens with notch size $a/w = 0.25$.

Test #	Specimen label	Maximum Load (lbf)	Thickness (in)	Width (in)	Stress at Maximum Load (psi)
1	Coupon 9-6	5360.1	0.097	0.942	79853.1
2	Coupon 9-7	5452.1	0.097	0.942	81224.0
3	Coupon 9-8	5594.0	0.097	0.935	84189.7
4	Coupon 5-5	5201.5	0.093	1.013	73303.1
5	Coupon 12-6	5613.9	0.095	0.959	83347.6
6	Coupon 12-7	5708.8	0.095	0.959	84756.9
Mean		5,488.4			81,112.4
Standard Deviation		187.4			4,250.5

Figure 71 shows the stress vs. strain responses recorded during static tests on notched, woven carbon fiber specimens with notch size $a/w = 0.25$. All specimens show

a linear stress vs. strain response until fracture. The response of sample 12-7 displays a local peak before failure. This is due to a small group of fibers breaking before the entire specimen fractured. While individual fibers were heard breaking during tests, this behavior was not seen in this scale in specimens with notch depth less than $a/w = 0.25$.

Figure 71 - Stress vs strain for specimens with notch size $a/w = 0.25$.

Figure 72 displays the fracture stress results for specimens with notch size $a/w = 0.25$ as they relate to the average fracture stress. The average fracture stress for specimens with notch size $a/w = 0.25$ is shown as a red line. Error bars are displayed that represent one standard deviation above and below the average. Black triangle markers represent data points that lie within one standard deviation from the average. Blue triangle markers represent data points that lie outside one standard deviation from the average.

Figure 72 - Fracture stress for specimens with notch size $a/w = 0.25$.

Table 13 gives the results from the 6 tests performed for notched specimens with notch size $a/w = 0.30$. The average fracture stress for specimens with notch size $a/w = 0.30$ is 84,197.1 psi and the standard deviation for this calculation is 2,688.9 psi.

Table 13 - Fracture stress test results for specimens with notch size $a/w = 0.30$.

Test #	Specimen label	Maximum Load (lbf)	Thickness (in)	Width (in)	Stress at Maximum Load (psi)
1	Coupon 13-4	5121.0	0.089	1.028	79960.4
2	Coupon 13-5	5261.7	0.086	1.024	85355.2
3	Coupon 13-6	5473.9	0.087	1.024	87776.5
4	Coupon 11-4	4949.0	0.088	0.938	85651.4
5	Coupon 11-5	4688.4	0.086	0.937	83116.6
6	Coupon 11-6	4754.7	0.087	0.937	83322.8
Mean		5,041.4			84,197.1
Standard Deviation		302.4			2,688.9

Figure 73 shows the stress vs. strain responses recorded during static tests on notched, woven carbon fiber specimens with notch size $a/w = 0.30$. All specimens show similar stress vs. strain responses until fracture. Sample 13-4 and sample 13-6 display

peaks in their response before fracture. This is due to a group of fibers breaking before the part fractured.

Figure 73 - Stress vs strain for specimens with notch size $a/w = 0.30$.

Figure 74 displays the fracture stress results for specimens with notch size $a/w = 0.30$ as they relate to the average fracture stress. The average fracture stress for specimens with notch size $a/w = 0.30$ is shown as a red line. Error bars are displayed that represent one standard deviation above and below the average. Black triangle markers represent data points that lie within one standard deviation from the average. Blue triangle markers represent data points that lie outside one standard deviation from the average.

Figure 74 - Fracture stress for specimens with notch size $a/w = 0.30$.

Table 14 gives the results from the 6 tests performed for notched specimens with notch size $a/w = 0.35$. The average fracture stress for specimens with notch size $a/w = 0.35$ is 81,954.6 psi and the standard deviation for this calculation is 2,386.8 psi.

Table 14 - Fracture stress test results for specimens with notch size $a/w = 0.35$.

Test #	Specimen label	Maximum Load (lbf)	Thickness (in)	Width (in)	Stress at Maximum Load (psi)
1	Coupon 13-1	4864.2	0.089	1.025	82032.1
2	Coupon 13-2	5148.4	0.091	1.031	84422.8
3	Coupon 13-3	4625.8	0.089	1.029	77709.2
4	Coupon 11-1	4307.0	0.087	0.939	81109.8
5	Coupon 11-2	4451.5	0.088	0.930	83681.0
6	Coupon 11-3	4553.3	0.091	0.930	82772.9
Mean		4,658.4			81,954.6
Standard Deviation		303.6			2,386.8

Figure 75 shows the stress vs. strain responses recorded during static tests on notched, woven carbon fiber specimens with notch size $a/w = 0.35$. All specimens show similar stress vs. strain responses until fracture occurs. Local peaks in the response are seen for sample 13-2, sample 13-3 and sample 11-3. These are due to a small group of fibers breaking before the specimen fractured.

Figure 75 - Stress vs strain for specimens with notchsize $a/w = 0.35$.

Figure 76 displays the fracture stress results for specimens with notch size $a/w = 0.35$ as they relate to the average fracture stress. The average fracture stress for specimens with notch size $a/w = 0.35$ is shown as a red line. Error bars are displayed that represent one standard deviation above and below the average. Black triangle markers represent data points that lie within one standard deviation from the average. Blue triangle markers represent data points that lie outside one standard deviation from the average.

Figure 76 - Fracture stress for specimens with notch size $a/w = 0.35$.

Figure 77 shows a graph of fracture stress of notched specimens vs. notch depth. The average values are shown by a red square marker that is connected by a red line. The solitary test performed on a specimen with a notch depth is of $a/w = 0.05$ is shown on Figure 77. This specimen was accidentally cut to the wrong notch depth, but test results show that its fracture stress is in an expected range.

Figure 77 - Fracture stress for all notched specimens.

4.2.2 Discussion of Static Test Results for Notched Specimens

Figure 78 shows a diagram of the three fracture modes.¹⁴ Each represents a different way of applying a load to enable a crack to grow. The results seen in this research are associated with Mode I failure due to the loading used.

Figure 78 – The three fracture modes.

Figure 79 shows a picture of failed specimen 8-6 from the $a/w = 0.10$ fracture toughness tests. The notch introduces a local stress concentration and its tip and forces a crack front to form at that location. A Mode I opening failure is seen with horizontal tearing spanning from one machined notch across the part to the other notch.

Figure 79 - Fracture of sample 8-6, $a/w = 0.10$.

Figure 80 shows a close-up photograph of the fracture seen for sample 8-6 in Figure 79. The dominant mode of failure is Mode I opening in the form of horizontal tearing across the specimen. There is also local delamination seen in the area of the notch. The area of the specimen immediately behind the notch carries no load and that may be why delamination in this part does not continue along the length of the part as it did for specimens without notches.

Figure 80 - Close up on area of fracture for $a/w = 0.10$ static test.

Figure 81 shows the results of a static test with notch size $a/w = 0.15$. Sample 4-7 shows Mode I opening as its only failure mode. Horizontal tearing appears at one notch and creates a crack front that travels across to the other notch.

Figure 81 – Fracture of sample 4-7, $a/w = 0.15$.

Figure 82 shows a close-up of the failure of sample 4-7 shown in Figure 81. Local delamination is seen in the area behind where the notch was cut. This sample only had one example of delamination around the notch area unlike the $a/w = 0.10$ fracture test.

Figure 82 - Close up on area of fracture for $a/w = 0.15$ static test.

Figure 83 shows a photograph from a static test failure for sample 3-6 with notch size $a/w = 0.20$. Mode I opening is visible in the horizontal tearing across the specimen. The tearing for sample 3-6 on this face appears to follow a jagged line instead of travelling horizontally. The internal layers and opposite face all show horizontal tearing. It appears the tearing across the surface layer followed a random pattern that travelled along fiber directions and between longitudinal fibers in the matrix whenever possible.

Figure 83 – Fracture of sample 3-6, $a/w = 0.20$.

Figure 84 shows a close-up photograph of the fracture for sample 3-6 in Figure 83. Delamination is visible in the area behind the notch. Once again the delamination is localized and does not travel beyond the area of the notch or farther down the piece. The local delamination is likely due to greater strain energy release than could be absorbed by the growing crack front that travelled across the specimen from one notch to the other.

Figure 84 - Close up on area of fracture for $a/w = 0.20$ static test.

Figure 85 shows the fracture of sample 9-7 with $a/w = 0.25$. The Mode I opening is seen as horizontal tearing from one notch across the specimen to the other notch. The waviness visible in the weave on the lower half of the specimen (below the tear) appears to have controlled the growth of the crack front on this surface. The crack followed alongside the fibers instead of travelling across them at a shallow angle. The waviness is a result of imperfect manufacturing methods.

Figure 85 - Fracture of sample 9-7, $a/w = 0.25$.

Figure 86 shows a close up photograph of sample 9-7. The $a/w = 0.20$ test piece displays the usual fibrous tearing in the section between the notch areas and a small delamination in the area behind the notch. The delamination does not continue farther into the piece.

Figure 86 - Close up on area of fracture for $a/w = 0.25$ static test.

Figure 87 displays the fracture result from sample 13-4 from a static test where the sample had a notch size of $a/w = 0.30$. Mode I opening is seen in the horizontal

tearing that starts at one notch and travels across the specimen to the other notch. The tearing across the surface appears chaotic and does not follow any sort of pattern. Fibers are beginning to 'pop-out' of the matrix in greater number at this notch size. These can be seen as the cloudy spots on the surface where carbon fibers are debonding from the surrounding matrix and tearing themselves.

Figure 87 - Fracture of sample 13-4, $a/w = 0.30$.

Figure 88 shows a close up photograph of sample 13-4. Delamination is once again visible in the area behind the notch, but does not continue farther down the piece. An example of fibers popping-out from the matrix is called out Figure 88.

Figure 88 - Close up on area of fracture for $a/w = 0.30$ static test.

Figure 89 shows a photograph of the fracture of sample 13-1 from a static test. Mode I opening is seen as the horizontal tearing that starts at one notch and tears across the specimen to the other notch. There is also some delamination of the surface layer in the area between the notches.

Figure 89 - Fracture of sample 13-1, $a/w = 0.35$.

Figure 90 shows a close-up photograph of the fracture of sample 13-1 in a static test. Delamination is seen, but it is seen in the form a void in the area behind the notch. This delamination may be the result of machining the notch. Since no other samples show delamination away from the crack front it is also possible that it is a result of imperfection during plate fabrication and not a result of machining the notch.

Void likely created
during plate
fabrication, not
machining of the notch

Figure 90 - Close up on area of fracture for $a/w = 0.35$ static test.

4.3 Fatigue Test Results for Unnotched Specimens

Results from the fatigue tests on woven carbon fiber specimens without damage are shown in Figure 91. The red line shows the average values of the tests at various amplitudes. The black line represents a logarithmic trend line and its equation and R^2 value are also shown on in the figure. The R^2 value of the trend line is $R^2 = 0.9882$. Fatigue tests were performed at maximum stress values of 72.5%, 75%, 77.5% and 80% of the ultimate stress (119,419.2 psi).

Figure 91 - S-N curve for woven carbon fiber specimens with no damage.

Fatigue results for each test shown in Figure 91 are tabulated in Table 15 and listed under percentage of ultimate stress applied during the test and number of cycles to failure. Table 15 shows fatigue test results for pieces without notches. The colors of the highlighted rows in Table 15 correspond to the colors of the markers in Figure 91. The variance in part life at similar stress levels can be mainly attributed to uncontrollable

microscopic defects of different sizes in the different test specimens. This scatter of data at similar loading is common in fatigue test results.¹⁵

Table 15 - Fatigue test results.

Specimen Name	Max Stress $\sigma_{\max}$ (% σ_{ult})	Cycles to Failure N_f (# cycles)
5-1	80.0%	1,454
3-7	80.0%	2,264
5-2	80.0%	3,129
3-8	80.0%	8,992
5-3	80.0%	5,470
5-8	80.0%	3,530
2-6	80.0%	291
9-1	80.0%	546
9-2	80.0%	12,596
9-3	80.0%	979
12-1	80.0%	7,695
12-2	80.0%	6,779
12-3	80.0%	8,821
10-4	80.0%	15,014
16-7	80.0%	3,776
17-5	80.0%	5,885
15-7	80.0%	25,762
17-3	77.5%	15,240
16-3	77.5%	8,996
15-2	77.5%	56,124
14-3	77.5%	25,192
13-7	77.5%	101,672
16-8	77.5%	15,781
15-4	77.5%	52,840
19-3	77.5%	22,135
15-8	75.0%	180,000
16-4	75.0%	31,552
17-1	75.0%	66,955
15-3	75.0%	207,172
16-2	75.0%	37,009
17-4	75.0%	58,693
15-1	75.0%	82,280
14-4	75.0%	100,981
18-7	75.0%	83,794
18-1	72.5%	369,609
19-2	72.5%	271,390
18-2	72.5%	316,429
18-5	72.5%	445,021
19-4	72.5%	240,002
19-8	72.5%	117,652

4.3.1 Discussion of Fatigue Test Results for Unnotched Specimens

The photo in Figure 92 shows sample 18-1 that failed in a fatigue test. Evident in the failure of sample 18-1 are multiple failures as expected. The fibers on the surface facing the camera popped-out well before the specimen failed at ~370,000 cycles. While popping-out was a slow process for this specimen, the catastrophic failure of the entire specimen occurred with suddenly with the sound of a fibers being torn in rapid succession in the moments before the specimen tore apart. The specimen failed as expected, suddenly and from an unseen microscopic deformation and not from slow crack growth emanating from a visible crack as could be expected in a ductile material. Delamination can be seen as well as horizontal tearing at the surface.

Figure 92 - Sample 18-1 after failure in fatigue.

Figure 93 show sample 18-5 after failure in fatigue. The specimen shows severe delamination between multiple layers and horizontal tearing on both surfaces. Also, due to the multiple delaminations the tearing of internal layers can be seen. Delamination was not a common result in fatigue tests for unnotched woven carbon fiber specimens. Delamination was seen in fatigue tests at all multiple stress levels. Sample 18-1 and sample 18-5 were both subjected to the lowest maximum stress of 72.5% of the unnotched woven carbon fiber specimen ultimate strength.

Figure 93 - Sample 18-5 after failure in fatigue.

Figure 94 shows sample 19-4 after failure in a fatigue test. Sample 19-4 was tested at a similar maximum stress as sample 18-5. Both display extensive delamination in their failure. Sample 19-4 displays delamination between multiple layers as well as horizontal tearing on the surface. All delamination and damage seen on the surface in the form tearing occurred at the moment of failure. Fibers popping out near edges on the

surface were visible before failure, but did not seem to be associated with the location or moment of failure since horizontal tearing and delamination occurred away from them.

Figure 94 - Sample 19-4 after failure in fatigue.

Figure 95 shows the failure of sample 16-7 after failure in a fatigue test. Unlike the failures seen in Figure 92 and Figure 93, little delamination is seen in the failure of this specimen. Horizontal tearing can be seen toward the top of the specimen that crosses the entire part and passes through all layers. A secondary tear is seen toward the bottom of the specimen that passes through all layers, but does not cross the width of the sample. Delamination is seen in the specimen at failure, but only in the area adjacent to the horizontal tearing at the bottom of the specimen. Sample 16-7 was subjected to a maximum stress of 80% of the ultimate strength of unnotched woven carbon fiber specimens.

Figure 95 - Sample 16-7 after failure in fatigue.

Figure 96 shows sample 15-7 after failure in a fatigue test. Tearing on the surface is seen that follows an arbitrary path. Underneath the surface layer delamination can be seen. On the opposite surface a 4-inch section of the surface layer delaminated at failure and was ejected a few feet outward. The trajectory of the ejected piece took it away from the safety shield on the front of the Instron 8801 and toward the back wall of the Aerospace Structure and Composites Laboratory. Sample 15-7 was subject to a maximum stress of 80% the ultimate strength of unnotched woven carbon fiber specimens.

Figure 96 - Sample 15-7 after failure in fatigue.

Figure 97 shows sample 16-2 after failure in a fatigue test. Delamination can be seen starting at the bottom of the specimen and traveling most of the way up the length of the specimen. Horizontal tearing is seen with delamination toward the bottom of the specimen. Horizontal tearing is also seen on the opposite face at the bottom end of the specimen and the end of where delamination occurred. Sample 16-2 was subject to a maximum stress of 75% of the ultimate strength of the unnotched woven carbon fiber specimens.

Figure 97 - Sample 16-2 after failure in fatigue.

4.4 Fatigue Test Results for Notched Specimens

A series of tests was run in order to determine fatigue properties of the test specimens with notches of notch size $a/w = 0.20$. Figure 98 shows the results of the fatigue tests. A logarithmic trend can be seen in the tests that did not fail immediately. The R^2 value is 0.5669 for the trend line that approximates the fatigue test data for specimens with notches.

Figure 98 - S-N curve for woven carbon fiber specimens with damage.

A series of tests was performed at higher stress values, but all failed almost immediately. These data points are removed from Figure 98 and from the calculation of the logarithmic trend line that describes the fatigue results of specimens with a notch size of $a/w = 0.20$. The remaining data points are given in Table 16. The percentage of maximum stress used in these tests is not the same range as used in the fatigue tests for specimens without damage due to a few tests performed at those stress levels that appeared to be below the endurance limit and lasted for more than two million cycles.

Table 16 - Fatigue test results for specimens with damage.

Specimen Name	Max Stress σ_{max} (% σ_{ult})	Cycles to Failure N_f (# cycles)
19-6	92.5%	1,020
20-1	92.5%	1,409
20-3	90.0%	1,231

19-5	90.0%	249,041
17-8	87.5%	509,377
19-1	87.5%	1,424,524
20-8	86.3%	5,106
17-7	85.0%	1,006,801
20-6	85.0%	982,995
18-6	85.0%	4,785
18-8	85.0%	2,661
20-5	85.0%	3,151

4.4.1 Discussion of Fatigue Test Results for Notched Specimens

Figure 99 shows sample 17-7 in the middle of a fatigue test. Sample 17-7 is a double-edge notched woven carbon fiber specimen with notch depth of $a/w = 0.20$.

Figure 99 shows the damage to Sample 17-7 after 500,000 cycles. Stress concentrations at the notch tips have caused longitudinal fibers in the surface to pop out of the matrix. Initial damage occurred at the notch tip and evolved outward toward the ends of the sample as the test continued.

Figure 99 - Damage to sample 17-7 during a fatigue test.

Figure 100 shows sample 17-7 after failure in fatigue. This occurred after 1,006,801 cycles with a maximum stress of 85% of the fracture stress of notched woven carbon fiber specimens with notch depth of $a/w = 0.20$. The surface seen in the photo on the left in Figure 100 is the surface on the left in Figure 99. The same is true for the photos on the right in Figure 99 and Figure 100. The damage is no longer isolated to a single bundle of longitudinal fibers that passes near the notch tip. Delamination and tearing are seen in the area between the notches. This is expected since stress is concentrated at the notch tips.

Figure 100 - Sample 17-7 after failure in fatigue.

Figure 101 shows damage sample 19-1 in the middle of a fatigue test. Sample 19-1 is a double-edge notched woven carbon fiber specimen with notch depth of $a/w = 0.20$. Figure 101 shows the damage to Sample 19-1 after 1,000,000 cycles. Stress concentrations at the notch tips have caused two sets longitudinal fibers in the surface to pop out of the matrix. Note that in the photo on the left it is visible that the longitudinal

fibers that have popped out are at a slight angle to the direction of the specimen and the loading. Similar fibers being pulled out are seen on the other side of the specimen. The photograph on the right side of Figure 101 shows a close up of the notch where multiple longitudinal fibers are being pulled out. The notch passes directly through the closest bundle being pulled out.

Figure 101 - Damage to sample 19-1 during a fatigue test.

Figure 102 shows sample 19-1 after failure in a fatigue test. This occurred after 1,424,524 cycles with a maximum stress of 87.5% of the fracture stress of notched woven carbon fiber specimens with notch depth of $a/w = 0.20$. The surfaces seen in the photos of Figure 101 are the surface seen in the left of Figure 102. The popped out longitudinal fibers of Figure 101 have become a local delamination zone that can be seen in the upper portion of the specimen in Figure 102. As expected, tearing and delamination are seen in the area between notches.

Figure 102 - Sample 19-1 after failure in fatigue.

Figure 103 shows sample 19-5 after failure in a fatigue test. This occurred after 249,041 cycles with a maximum stress of 90% of the fracture stress of notched woven carbon fiber specimens with notch depth of $a/w = 0.20$. Popped-out longitudinal fibers are seen in this test as well. Once again the damage was initially seen near the notch tips and observed to grow outward toward the ends of the specimen until the end of the test. Horizontal tearing is seen in the area between the notches with less delamination than other fatigue tests on notched specimens. Delamination is seen, but it is behind the notch area and only on one surface layer. The pulled-out longitudinal fibers create an area of delamination between themselves and the edge of the specimen, similar to damage seen in Figure 102 for sample 19-1.

Figure 103 - Sample 19-5 after failure in fatigue.

5 Theoretical Analysis for Fracture Mechanics

For elastic fracture it is assumed that when a crack grows energy is released from the material into the new surfaces formed. This energy is released at a rate, G . If the energy necessary to grow the crack is assumed to be constant, G_C , then a crack will grow when the energy being released, G , is greater as given in equation 4.¹⁶

$$G \geq G_C \quad 4$$

Crack geometry, geometry of the body and applied load define G . G_C , also known as the fracture toughness of a material, is considered a material property. For a plate with a crack through its thickness and assuming it is in a condition of plane stress we can define G as equation 5.

$$G = \frac{\sigma_{\infty}^2 \pi a}{E} \quad 5$$

In the above equation E is the Young's modulus of a material, a is the size of the crack and σ_{∞} is the stress at an area distant from the crack front. If we assume that the energy release rate, G , is greater than the critical energy release rate, G_C , we can rearrange the above equation to determine σ_{∞} for a known crack size. We will call this the fracture stress and it will be denoted as σ_f as given by equation 6.

$$\sigma_f = \sqrt{\frac{G_C E}{\pi a}} \quad 6$$

Since G_C and E are material properties and assumed to be constant a relation can be seen between σ_f and crack size, a . Equation 7 shows the relation we expect to develop and Figure 104 shows results from Griffith's tests on blown glass specimens.¹⁷

$$\sigma \propto \frac{1}{\sqrt{a}} \quad 7$$

Figure 104 – Fracture stress of Griffith's glass specimens related to notch size.

Figure 104 shows the results of Griffith's work with glass with individual data points represented by dots. The values for glass appear to align with the results predicted by theory. The notches created in Griffith's glass samples are much smaller than the ones cut into the woven carbon fiber samples used in this research. This is due

to the very small size of Griffith's glass specimens and the limited size of notches that can be created in small specimens.

Figure 105 shows the results obtained for the woven carbon fiber specimens tested with notches. A linear trend line is applied to the data that shows a decent linear fit for the woven carbon fiber test specimens to the theoretical predictions as well. One place this theory breaks down is at disappearing notch sizes where the linear relation would predict increasing fracture stress well above where the carbon fiber was breaking without visible or introduced damage (119,418 psi). The linear fit to the theoretical prediction shows that fracture at the ultimate stress of the experimental pieces without damage occurs with a notch of size of 0.011 inch.

Figure 105 – Fracture stress of woven carbon fiber specimens related to notch size.

For Mode I opening, the stress intensity factor, K_{IC} , is related to critical energy release rate by equation 8. This can be substituted into the above equation 6 to obtain a

relation between fracture stress and stress intensity factor and allows us to calculate stress intensity factor as shown in equation 9.

$$G_C = \frac{K_{IC}^2}{E} \quad 8$$

$$K_{IC} = \sigma_f \sqrt{\pi a} \quad 9$$

Fracture toughness for woven carbon fiber specimens with double-edge notches was calculated using a modified version of equation 9 as given by equation 10. The geometry correction factor, Y , is 1.35 for double-edge notched specimens.¹⁸

$$K_{IC} = Y\sigma_f \sqrt{\pi a} \quad 10$$

Woven carbon fiber test specimens with double-edge notches were tested using the same procedure used to determine ultimate strength for specimens without notches. The results for fracture toughness for all specimens are given in Figure 106. Excluding the solitary test at a notch depth of $a/w = 0.05$, the average of the remaining tests is calculated to be $53,652 \text{ psi(in)}^{1/2}$.

Figure 106 - Fracture toughness data for woven carbon fiber test specimens.

The results obtained through this study are similar to those obtained for plain-weave carbon fiber specimens with double-edge notches performed by Lee and Gowayed.¹⁹ Similar to the work by Lee and Gowayed, the fracture toughness data for woven carbon fiber specimens with double-edge notches appears to have an arbitrary relation between fracture toughness, K_{IC} , and notch size, a/w . The materials used by Lee and Gowayed are different than the materials used in this thesis and their average value for fracture toughness is understandably different. Fracture toughness recorded by Lee and Gowayed is $32.42 \text{ MPa}\cdot\text{m}^{1/2}$ for their eight-layer, plain weave carbon fiber specimens with double-edge notches.

Fracture toughness of the woven carbon fiber specimens tested in this research is compared to nominally brittle materials in Table 17. The average fracture toughness value for woven carbon fiber in this test is converted from $53,652 \text{ psi}\cdot\text{in}^{1/2}$ to $9.4 \text{ MPa}\cdot\text{m}^{1/2}$.

Table 17 - Fracture toughness values of materials.

Material	K_{IC} $\text{MPa(m)}^{1/2}$
Woven Carbon Fiber Test Specimens	9.4
Borosilicate Glass	0.8
Alumina 99% Polycrystalline	4.0
Zirconia-Toughnes Alumina	6.0
Aluminum 7075-T6	25.0
AlSiC Metal Matrix Composite	10.0
Epoxy	0.4

Fracture toughness as a material property does not describe crack growth; however, for brittle materials such as the woven carbon fiber specimens in this research it does give an indication of when fracture occurs for different notch sizes. Fracture for brittle materials is sudden and catastrophic in nature with crack growth rates that are supersonic.²⁰ Crack growth rates in brittle materials are beyond the scope of this research.

6 Finite Element Analysis Results

6.1 Equivalent Single Layer Finite Element Analysis Model

The Finite Element Analysis (FEA) model used in this study was generated using Daussalt Systemes' Abaqus FEA software. The model was generated as a planar shell model with six composite material layers. The material properties that were determined experimentally are assigned to the carbon fiber layers in the FEA model. A quasi-static test was run with the loading profile taken from one of the experiments and applied to the FEA model until the point of failure in the experiment.

6.1.1 Generating the Part

A 3-Dimensional deformable part was created with 2-D Planar qualities in Abaqus. The part is shown below in Figure 107. Sections were created on the surface of the 2-D part in order to generate a focused mesh around the crack tip and are highlighted in Figure 107.

Figure 107 - Abaqus part model with section area highlighted.

6.1.2 Assigning the Material Properties

Experimental results for material properties of the woven carbon fiber test specimens are assigned to the FEA model. The model will assume the woven carbon fiber specimens will react in an isotropic manner and will model the specimen as an

Equivalent Single Layer (ESL) model. The material properties necessary for this are Young's modulus and Poisson's ratio. These were determined through testing of the woven carbon fiber specimens.

6.1.3 Generating an Analysis Step

A single step is necessary for this analysis to apply load. A general, static step was created to model the quasi-static nature of the experimental loading procedure. The load from the experiment on sample 8-9 is used as the loading profile in this analysis. The data from Bluehill 2 that will be used includes time and load and will be applied to the FEA model to verify its ability to model the experimental tests.

6.1.4 Generating Seams and Crack Tips

The notches are generated as seams in the FEA model under the Interaction module. Cracks are also generated and assigned to the tip of the notch. Crack growth is assigned as growing toward the other crack similar to what experimental results have shown in static and fatigue situations.

Figure 108 - Generating a seam in the part to describe a notch.

6.1.5 Defining Output Variables

Abaqus default output variables include a series of metrics that are irrelevant to this analysis. The field output variables are changed in this analysis to only include stress, strain, displacement, and failure measure components. Additional variables such as contact energy are removed.

History output will be changed to include stress intensity factors as automatically calculated by Abaqus. The crack initiation criterion is selected to be maximum energy release rate, similar to what Griffith's analytical work on brittle materials has shown.

6.1.6 Generating Boundary Conditions

The FEA model is encastred at one end. This means that the nodes at this end cannot rotate or translate and are similar to the conditions on the test specimens in the upper wedge grip in the Instron machine. Load is applied to the right edge of the shell and is based on the stress recorded during the static test for sample 8-9. The stress is applied as an amplitude that controls a shell edge load with a magnitude of -1 to direct the load to be in tension.

Figure 109 - Boundary conditions and load shown on the FEA model.

6.1.7 Generating the Mesh

Nodes are seeded around the notch area as shown in the left side of Figure 110. The right side of Figure 110 shows the mesh around the same local area around the seam and the crack. Elements used are linear shell elements from the Abaqus Standard element set.

Figure 110 - (left) Nodes seeded around seam and crack. (right) Mesh around same area.

Figure 111 below shows the mesh for the entire specimen with a concentration of elements around the area of interest. The crack tips at the end of the notches are highlighted with two small yellow circles.

Figure 111 - Mesh used on $a/w = 0.10$ analytical model.

6.1.8 FEA Analysis Results for ESL Model

The ESL model results below are for the $a/w = 0.10$ analysis. The model was built around sample 8-9 and the loading used was taken from the experimental test of sample 8-9. Figure 112 shows the results from the ESL model with displacement shown on the model. It is approximately 10 times greater than the displacement shown in the experimental model.

Figure 112 - Results from FEA model. Displacement is shown in banded colors.

6.2 Quarter Model

The test specimen and FEA model are both symmetric about their length and width. This allowed a quarter of the specimen to be modeled in Abacus. The quarter model is shown in Figure 113.

Figure 113 - Symmetric quarter-model in Abacus.

The bottom of the model in Figure 113 is set to be symmetric about the horizontal x-z plane, simulating the symmetry in the model about its length. The left side of the model in Figure 113 is set to be symmetric about the vertical y-z plane, simulating the symmetry in the model about its midsection. Load is applied on the free edge (the right face) as a pressure equal to the stress the Instron 8801 applied to the test specimen the FEA model is based on.

A close up view of the mesh around the crack tip is given in Figure 114. The boundary conditions along the midsection of the specimen can be seen along a section of the model ending at the crack tip. The surface of the cut is allowed to move freely.

Figure 114 - Mesh around crack tip in Abacus model.

Figure 115 shows the FEA model after loading. Displacement is shown on the model that was based on sample 16-1 with a notch size of $a/w = 0.20$. Results for this model were within 4% of the experimental results for sample 16-1.

Figure 115 - FEA model with displacement results shown.

6.2.1 FEA Analysis Results for Quarter Model

The results for the quarter model as compared to the experimental test specimens are given below in Table 18. Except for the $a/w = 0.25$ case, the remaining models were within 5% of the experimental results.

Table 18 - Comparison between FEA and experiemental results.

Notch Size (a/w)	Extension		% Difference
	Experimental (in)	FEA Model (in)	
0.10	0.0722	0.0724	0.3%
0.15	0.0672	0.0662	1.5%
0.20	0.0614	0.0590	3.8%
0.25	0.0613	0.0562	8.3%
0.30	0.0568	0.0548	3.5%
0.35	0.0515	0.0495	4.0%

7 Comparison between FEA and Experimental Results

FEA results and experimental results are compared in this section. Stress and strain as calculated in an FEA analysis are recorded and plotted against experimental data.

7.1 Comparison of Stress vs. Strain Graphs

The results from the $a/w = 0.10$ analysis are shown compared to the experimental results for the static test in Figure 116. The experimental results showed a horizontal band in the response at very low stress. It is entirely clear where this horizontal response originates, but a possibility is that it is a result of the Instron 8801 being set up incorrectly. The proper alignment and fastening of the vice grips in the Instron 8801 is a procedure that can easily be performed incorrectly. If one of the grips is not tightened or aligned perfectly it can introduce slight movement into the test results as load is applied and the grip and test specimen shift around. This slipping would be seen as the horizontal band of data in Figure 116 near the origin where stress would show no significant increase to an increase in strain, or extension.

The extension caused by the slipping can be accounted for and removed from the response data as it has been in Figure 116 without significantly affecting results or analysis of the results. Once the grip slips into position under load it is in a static position and will not continue to move.

The slipping appears in experimental data for static tests on specimens with notches of size $a/w = 0.10$ and $a/w = 0.15$. Another possibility is that the slipping originates in the epoxy used to hold the aluminum tabs to the carbon fiber specimens. No damage was seen in any of the specimens from the experimental tests at the area where the epoxy held the aluminum tabs so it is assumed this is not the cause.

Figure 116 - Comparison between FEA and experimental results, $a/w = 0.10$.

The results from the $a/w = 0.15$ analysis are shown compared to the experimental results for the static test in Figure 117. The experimental results showed some slipping in the beginning of the test while the FEA model did not have this behavior included. This slipping data is seen in a few tests and none of the samples with these results show any damage to the bond between aluminum and carbon fiber. It is assumed the Instron 8801 was improperly setup with the vice grips not properly tightened or perfectly aligned before the test was run.

Figure 117 – Comparison between FEA and Experimental results, $a/w = 0.15$.

The results from the $a/w = 0.20$ analysis are shown compared to the experimental results for the static test in Figure 118. The data matches very well and only fails to capture the slightly shallower slope of the second half the static test.

Figure 118 - Comparison between FEA and Experimental results, $a/w = 0.20$.

The results from the $a/w = 0.25$ analysis are shown compared to the experimental results for the static test in Figure 119. The FEA data shows a higher failure stress and lower strain at failure. It doesn't appear to capture the slight tapering off the experimental stress/strain curve displays toward the end of the test.

Figure 119 – Comparison between FEA and experimental results, $a/w = 0.25$.

The results from the $a/w = 0.30$ analysis are shown compared to the experimental results for the static test in Figure 120. Once again the FEA doesn't capture the tapering off of the stress/strain curve at the end of the experimental data.

Figure 120 - Comparison between FEA and experimental results, $a/w = 0.30$.

The results from the $a/w = 0.35$ analysis are shown compared to the experimental results for the static test in Figure 121. The experimental results show a slight tapering off in stress/strain response that is not captured by the FEA model.

Figure 121 - Comparison between FEA and experimental results, $a/w = 0.35$.

8 Summary and Conclusion

This thesis involved the manufacturing of unnotched and notched woven carbon fiber specimens to study their responses to static and fatigue tests and to create a numerical model in Abaqus based on the experimental results for material properties of the unnotched specimens.

The first part of this thesis involved the fabrication of carbon fiber specimens. Woven carbon fiber specimens were prepared using a Tetrahedron plate press and cut to size on a Target wet tile saw. Aluminum tabs were applied to the ends of specimens so they could be placed in the wedge grips of an Instron 8801 servo-hydraulic testing system. Approximately 160 specimens were prepared and tested including the number of notched and unnotched specimens.

The second part of this thesis involved the testing of unnotched and notched woven carbon fiber specimens. The testing phase was split between static and fatigue tests. Static tests were performed on unnotched specimens to determine ultimate strength, Young's modulus and Poisson's ratio. Static tests were performed on notched specimens to determine fracture stress of carbon fiber specimens for a series of increasing of notch depths.

Fatigue tests were performed on unnotched specimens to determine the fatigue life at a series of increasing maximum stresses. Fatigue tests were then performed on notched specimens to determine the fatigue life of specimens with notch depth $a/w = 0.20$ for a series of increasing maximum stresses.

The third part of this thesis involved creating and testing a numerical model in Abaqus. The finite element analysis results were then compared with experimental results for notched specimens in a static test.

Material properties were determined in static tests performed on unnotched woven carbon fiber specimens and are given in Table 19. The average ultimate strength of unnotched specimens was calculated to be 119,419 psi. This was the average of 18 out of 21 tests performed. Three ultimate strength tests were excluded due to failure at the epoxy holding aluminum tabs interfering with results. The average Young's modulus of unnotched specimens was calculated to be 7,149,000 psi/(in/in). This value was calculated from the stress vs. strain responses of the same 18 tests used to calculate ultimate strength. Poisson's ratio, ν_{12} , of unnotched specimens was calculated to be 0.05. This value was calculated from calibrated strain gage data on two specimens. The material properties for the woven carbon fiber specimens (product # LTM45EL, manufactured by Advanced Composites Group) given in Table 19 can be used for further modeling and analysis as long as the curing procedure is similar to that discussed in Section 2.1.

Table 19 - Static test results for unnotched specimens.

	Ultimate Strength (psi)	Young's Modulus (psi/in/in)	Poisson's Ratio
	119,418	7,149,000	0.05
Number of Tests Performed	21	21	2

Static tests on notched woven carbon fiber specimens resulted in the following fracture stresses given in Table 20. For a notch depth of $a/w = 0.10$, seven tests were performed to determine the average value for fracture stress. This value was calculated as the average of six out of seven tests performed as one of the tests was excluded as an outlier in its response. Six tests were performed at the remaining notch sizes and no data was excluded as being an outlier.

Table 20 – Average fracture stress for notched specimens.

Notch Size a/w	Fracture Stress σ_f (psi)
0.10	93,481
0.15	88,193
0.20	86,968
0.25	81,112
0.30	84,197
0.35	81,955

The average values for fracture stress in Table 20 are shown in Figure 122, marked with red triangles. Figure 122 shows that double-edge notched, woven carbon fiber specimens follow Griffith's model for failure of brittle materials containing cracks. This is unexpected since the woven carbon fiber specimens are not homogeneous isotropic materials which Griffith crafted his model about. The response seen in Figure 122 can be used to model fracture behavior of woven carbon fiber specimens, prepared in a similar manner, for further testing or analysis.

Figure 122 – Fracture stress related to crack size for notched specimens.

The Griffith model is known to be inaccurate at vanishing notch sizes and to approximate a non-infinitesimal crack size at the ultimate strength of the material. For the woven carbon fiber specimens the approximated crack size that the Griffith model predicts is a 0.012-in. crack for the specimens to fail at ultimate stress value of 119,418 psi. No visible damage was seen on any of the specimens that were tested for ultimate strength. It appears that the Griffith model fails to predict accurate ultimate strength in woven carbon fiber specimens with no damage similar to the prediction that homogeneous, isotropic materials should have a non-infinitesimal crack size in order to fail at their tested ultimate strength. It is at this vanishing crack size that microscopic flaws in a material become the dominant failure point.

The critical stress intensity factor for double edge notched woven carbon fiber specimens appears to be independent of notch size. This

Fatigue test results, also known as an S-N curve, for unnotched woven carbon fiber specimens are shown in Figure 123. The results show some scatter among the number of cycles to failure at all maximum stress levels. This can be expected due to inherent flaws of different sizes in the various specimens. The scatter seen in the S-N curve for the woven carbon fiber specimens is typical of fatigue test results.

Figure 123 - Fatigue test results for unnotched specimens.

The S-N curve in Figure 123 shows the woven carbon fiber specimens follow a logarithmic pattern. The logarithmic trendline given in Figure 123 can be used to predict failure by fatigue for unnotched woven carbon fiber specimens in various testing conditions provided the material is prepared in a similar manner. Endurance stress for the woven carbon fiber specimens is predicted to be 83,963 psi. At this maximum stress the specimens are predicted to, on average, last for 1,000,000 cycles before failure.

Fatigue tests results for double-edge notched woven carbon fiber specimens are shown in Figure 124. The scatter that was visible in the unnotched specimens test results was amplified in the notched specimens results. The results shown in Figure 124 exclude all tests which failed at less than 100 cycles. A series of tests at all maximum stress levels failed at a few thousand cycles and are included in the graph.

Figure 124 - Fatigue test results for notched specimens.

A logarithmic trend line is fit to the remaining tests; however, predicting endurance stress wouldn't be accurate for the double-edge notched woven carbon specimens since the scatter on the data is large enough to invalidate the prediction. Also, specimens with a maximum stress of 75,336 psi and 77,552 psi passed 1,000,000 cycles to failure. The scatter of data in Figure 124 leads to the conclusion that the fatigue life of a double-edge notched woven carbon fiber sample may not be predicted accurately.

Initially, results were expected that would allow prediction of fatigue life of woven carbon fiber specimens with damage in the form of double edge notches. The failure of some test specimens at only a few thousand cycles shows that once damage has been accrued on a specimen there is a possibility of seemingly random catastrophic failure in a relatively short time span.

A few specimens lasted to around 1 million cycles in similar maximum stress levels as other specimens which failed almost instantly. This leads to the possibility that the specimens were different due to manufacturing or preparation. Specimens without

notches from all batches were randomly sampled for fatigue life and material properties and all showed similar responses without the large amount of scatter seen in Figure 124. This leaves the preparation of the samples with notches as a possible source of the scattered data.

The vice and wood blocks used to hold the specimen while creating the notch may have allowed for the specimen to vibrate and alter the finish of the notch on a specimen-by-specimen bases. Also, the notches were made by hand and the feed rate controlled manually – it is extremely unlikely the feed rate between two specimens, though close, were the same. Surface finish on the edge of the specimens may also have been slightly different due to the fact that specimens were cut from carbon fiber plates using a tile saw where the plates were manually fed to the blade. Different feed rates while cutting the specimens out from a plate may have produced different surface finishes on the edges of the specimens that only had pronounced effects while testing for fatigue life of notched specimens. The source of the scatter in the data for notched fatigue tests would need to be determined before continued testing could yield useful results and the ability to predict failure for double edge notched specimens in fatigue.

The material properties for woven carbon fiber specimens have been experimentally determined as well as the fracture stress for various notch sizes. The critical stress intensity factor for double edge notched woven carbon fiber specimens has been shown to be independent of the notch size for specimens prepared for this thesis. The S-N curve of unnotched woven carbon fiber specimens shows an expected response, but the S-N curve for notched specimens shows an unexpected amount of scatter in the data that needs to be resolved before any predictions can be made for fatigue life of double edge notched woven carbon fiber specimens.

9 Future Work

Fracture tests performed related well to Griffith's model for notched specimens, but did not show the limits of where that theory is applicable to double-edge notched, woven carbon fiber specimens. Further testing at smaller or larger notch sizes could be performed to show the limits of the theoretical predictions. At smaller notch sizes the effects of microscopic defects are expected to be dominant and at larger notch sizes the effects of interaction between both notches would alter the response.

Due to the large scatter in the data from test results for notched specimens in fatigue testing it is recommended that a procedure is developed in which this could be reduced. The possibility of using a laser cutter for more accurate cuts instead of the slitting saw blade used is one recommendation. A different type of test procedure could also be used, such as a tension-compression test or a test in which the minimum stress is zero.

The FEA model can be recreated using a Hashin damage criteria for the composite plies used in the lay-up. The values necessary to incorporate this model would need to be determined through a series of further experimental testing for failure energies and compressive strengths. Tests to determine the delamination properties of the carbon fiber specimens used in this thesis would aid in creating the FEA model to capture the delamination aspects seen in some failures.

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11 Appendix A

The following is the standard operating procedure for running Bluehill 2 in the Aerospace Structure and Composites Laboratory. It was written during the research described in this document. It describes the operation of setting up and implementing a static test in Bluehill 2 in a step-by-step manner with screen captures of each step.

1. Open **Bluehill 2** from the desktop. The start-up screen for **Bluehill 2** gives you options for beginning a test, creating and editing methods, editing report templates, editing software settings, accessing help and exiting the program.

2. Click on **Method** to get to the **Create or Modify a Test Method** screen. To create a new test method, click on the **New*** button on the right side of the screen and then click the **Create** button.

3. Bluehill 2 will prompt you for the type of method you want to create. Choose **Tension Method** from the list of options.

4. You will be in the **General >> Method** screen. Change the **System of Units** to **US Customary** from the default.

5. Go to the **Control >> Test** screen. Here you will enter the extension rate of the test.

6. Go to the **Control >> End of Test** screen. This is where you will set the parameter that specifies the end of the test.

7. Go to the **Calculations >> Setup** page. In the **Available Calculations** column select **Absolute Peak** and use the arrow next to the column to add it to the **Selected Calculations** column. The default channel is **Tensile Extension**. Change this to **Load**.

8. Go to the **Results I >> Columns** screen. In the **Available Results** column expand the **Maximum Load** field and use the arrow next to the column to add **Load**, **Extension**, **Tensile Stress** and **Tensile Strain**. Expand the **Dimensions** field and use the arrow next to the column to add **Length**, **Thickness** and **Width**.

9. Go to the **Raw Data >> Columns** screen. In the **Available Channels** column select **Tensile Strain** and use the arrow next to the column to add it to the **Selected Channels** column. Also add **Tensile Stress**.

10. Go to the **Results >> Export Results** screen. Check the box next to the **Export Results** option. Change the **Format** to **Comma Separated Variable (.CSV)**.

11. Go to the **Raw Data >> Export Raw Data** screen. Check the box next to the **Export Raw Data** option. Leave the default **Format of Classic (.RAW)**.

12. Go to the **Test Prompts >> Test Workspace** screen. In the **Available Parameters** column expand the **Text Inputs** field and select **Specimen Label**. Use the arrows Next to the column to add it to the **Selected Parameters** column. Expand the **Dimension** field and use the arrows next to the column to add **Length, Thickness** and **Width**.

13. Click on the **Save & Close** button. Save your test under a useful directory and name.

14. Go to the **Bluehill 2** start up screen using the icon in the top left of the screen that says **Bluehill** next to an image of a house. To run your test click on **Test**. This will bring you to the **Create a New Sample** screen. The default option selected on the left is **New Sample**. You should be able to find your method in the list of **Most Recently Used**

Methods. Click **Browse** to find your method if it is not listed and select it. Click **Next** when you have selected your method.

15. Now that you have selected a method you must provide a sample filename and output folder for where data should be saved. Enter a **Sample Filename** that is relevant. Click on **Browse** to change the directory where your data will be saved. If you use **Browse** to change the directory where you will save your file, then you will be taken to the **Test** screen when you are done. Otherwise click **Next**.

16. Enter the **Specimen Label** and **Length, Thickness** and **Width** dimensions. Click **Reset** to zero-out the gage length. **DO NOT CLICK RETURN** as this will likely break your test specimen or damage the Instron. When you are ready click **Start** to begin your test. Make sure the safety shield is in place before clicking **Start**.

When you are finished, please clean your workspace.

12 Appendix B

The following is the standard operating procedure for running WaveMatrix in the Aerospace Structure and Composites Laboratory. It was written during the research described in this document. It describes the operation of setting up and implementing a fatigue test in WaveMatrix in a step-by-step manner with screen captures of each step. The values used in the example below for mean and cyclic load are the values used for the fatigue test on sample 17-5.

1. Open **WaveMatrix** from the desktop. The start-up screen for **WaveMatrix** gives you options for beginning a test, creating and editing methods, editing software settings, accessing help and exiting the program.

2. Click on **Method** to get to the **Open an Existing Test Method** screen. To create a new test method, click on the **New Method** option on the left side of the screen and then

click the **Create** button.

3. The Test >> Sequence screen is where you will configure the steps and loops in your fatigue test.

4. The default test consists of three steps. These will be modeled as an initial loading, a cyclic load and finally unloading the part. The figure below shows the test and the values that will be used in **WaveMatrix**. The mean amplitude of your waveform will be determined by the mean stress and cross-sectional area of the part you are testing. The frequency of the cyclic waveform is the inverse of the period of the cyclic waveform you will be applying.

Example

Our test conditions involve loading a carbon fiber test specimen to 50% of its ultimate stress and then applying a cyclic load equivalent to 30% of the ultimate stress. This cyclic load is in the shape of a sine wave and has a frequency of 20 Hz. The rectangular carbon fiber bar has the following properties:

$$\sigma_{ult} = 119,418 \text{ psi}$$

$$w = 1.006 \text{ in}$$

$$t = 0.093 \text{ in}$$

From the information given we can determine the test specimen will be placed in tension at a loading of 59,709 psi. This will be the mean stress during the test.

Using the cross-sectional area of the rectangular specimen we can calculate the load applied to the piece to be 5,586 lb. This will be the mean load value used in

Step 5. Similarly, we can multiply the ultimate stress of the test specimen by 0.30 to arrive at the amplitude of the stress that will be applied. This can be converted to the amplitude of the load by multiplying this value by the cross-section area of the test specimen to arrive at a value of 3,352 lb. This load amplitude and the frequency given will be used in **Step 6**.

5. Click on the box with the dashed gray line under the **Step 1** heading to bring up the waveform options. Pick the **Absolute Ramp** waveform from the list of icons. Change the **Control Mode** from **Position** to **Load** and enter the mean load value for your part as the **End Point** for the waveform. You should see a red arrow in **Step 1** if you changed the **Control Mode** to load and it should be pointed slightly upwards if you entered a positive value for the **End Point** (your part will be in tension).

6. Click on the **Step 2** waveform box to bring up waveform options for **Step 2**. Choose the **Cyclic Waveform** option and change the **Control Mode** to **Load** like you did for **Step 1**. The **Enable Amplitude Control** box should be checked. Enter the **Amplitude**

and **Frequency** of your cyclic waveform. Enter the **Number of Cycles** your test encompasses.

7. Click on the waveform box for **Step 3** and then choose and **Absolute Ramp**. Make sure to change the control mode to **Load** and set the **End Point** to 0 lb.

8. Click on the **Data Processor** box under **Step 2**, and then on the **Save Peaks & Trends** tab. Check the box to enable **Save Peak & Trend Data to a File** and leave the default values.

9. Click on the **Monitor Peaks & Trends** tab and check the box for **Enable Peak & Trend Event Detector**. Leave the **reference cycle** at 100, remove the **Change Criteria** of a position change and enable the **Percent Change Criteria** for maximum and minimum loads. Leave those values at **10%**.

10. Click on the **Layout** option on the left side of the screen and go to **Layout >> Customized**. On the right side of the screen move the component **Test Inputs** up to the next fifth position using the arrow buttons next to it. Under **Pane 3** on the bottom left of the test workspace click the left-most button to **Split this Pane Horizontally**. This will create a new pane that will house the **Test Inputs** component. This will allow you to save each individual test under a specific **Test ID**, allowing use of the same test on the same specimen in multiple tests.

11. Save your test method under a useful directory and name then exit to the **WaveMatrix** start-up screen using the button on the top left of the screen that shows a house and an arrow. From the start-up screen click the **Test** button to begin a new test. The default option is to begin a new project. Enter a relevant project name. This will create a folder in the default directory (c:\Documents and Settings\All Users\Documents\Instron\WaveMatrix\Projects\[**your project name**]) with your project name and will save test data from all tests performed to this folder. Click **Next** after you have entered a project name.

12. Finish creating your new project by selecting the test method you created earlier.

The list available gives the most recently used methods. If your method is not in that list you can find it using the **Browse** button on the right. Click **Next** after you have chosen the correct method.

13. You are now ready to test and should enter a **Test ID** that is useful in describing the test.

14. Before you begin the test make sure the limits are set on the Instron machine. Using the Instron Control Panel check what the current position of the lower vise grip is **with your part installed and ready to test**. Set the upper and lower position limits to one-inch in either direction and make sure to check the **Limit Enabled** box. Now is also a great time to make sure the safety shield is installed in between you and your test piece.

15. Once you are ready to test click the **Start** button. Make sure the safety shield is in place. If you have not set limits on the Instron you will see a warning informing you. You will also see a warning that the Console version number is too low. Click **Continue** to move past the warnings and begin your test. You will be prompted at this time by pop-up window to begin the test.