Effect of Fatigue Cycle Loading Amplitude Tension-Tension on Composite Laminated
Plates with initial Delamination

A Thesis
presented to
the Faculty of California Polytechnic State University,
San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Aerospace Engineering

By

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June 2013

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ABSTRACT

Effect of Fatigue Cycle Loading Amplitude Tension-Tension on Composite Laminated Plates with Delamination

Composite materials provide many mechanical advantages; however, they are susceptible to failure or delamination due to impact, high concentrated stresses and fatigue produced by high loading and dripping weight due to poor manufacturing processes yielding to delamination. The objective of enhancing delamination in the laminated composite structural panel's elements is to control the response of the composite structures in order to prevent catastrophic failure due to excessive deformation. The main scope of this thesis is to study the effect of a different amplitude fatigue cycle in tension-tension on a carbon fiber laminated composite plates with initial delamination to determine the maximum number of loading cycles required to propagate the initial delamination and failure through the preformed delamination. The study also, will encompass the comparison with numerical analysis models using Nastran/Patran software .

The laminate composite plates were fabricated with woven prepreg carbon fiber with an initial delamination and tested under tensile and constant amplitude cycle loading. The tensile characteristics of the laminated composite plates were determined using the standard test. The number of the fatigue cyclic was determined for fatigue tests with different maximum stresses of 72.5%, 69.5%, 66.5%, 63.5%, and 60.5% from the average ultimate failure loading. A linear static numerical analysis was performed using MSC Patran/Nastran to correlate a finite element model and test data for the tensile load cases. The finite element model was validated by comparing the deformation shape and

the predicted high stress concentration areas of the test specimen during the experimental analysis with the predicted numerical analysis.

The flexural stiffness is predicted to be reduced by approximately 200% by the addition of an initial delamination. The fatigue life of the laminated composite plates tested would extend over 20000 cycles at a load rate between 55% and 60% of the ultimate failure loading if the input load drops above 10%. The numerical analysis performed showed a difference of 41% to the experimental analysis.

ACKNOWLEDGMENTS

I would like to thank my thesis advisors, Dr. Daniel Biezad and Dr. Eltahry Elghandour for providing me the opportunity to work on this project. I would like to specially thank Dr. Elghandour for all of his encouragement, understanding, support, guidance and assistance during the duration of my research.

Thanks to all of my family for your love, constant support and encouragement through this process. I would also like to thank Thomas, Mike and Eugene for their assistance and help during the instrumentation and set up of the tests in the Aerospace Structures Lab.

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CHAPTER 1: INTRODUCTION

A composite material is a material that is engineered from the combination of two materials with different mechanical and electrical properties that as end result will provide the best characteristics of both materials. The constituents of the composite material are mixed and bonded on a macroscopic scale retaining their identities and do not merge, dissolve or blend into each other but they act together to provide unique properties to the composite material. Composites are made of a matrix (or binder) and the reinforcement (usually fibers). Fillers or modifiers can be added to the composite material to smooth manufacturing process, insert special properties, and reduce cost.

The matrix is the component that surrounds and binds together a cluster of fibers or fragments of a much stronger material (the reinforcement) to form the bulk of the material. Its function is not only to hold the fibers together to form the desired shape, but also to maintain their relative positions and protects them from mechanical by transferring any stresses among them and/or environmental damage.

The basic requirement for the selection of a matrix material is that its strain at break must be larger than the fibers or reinforcement it is holding. The matrix materials can be classified as resins (plastics), metal and non-metal. Resin matrix materials can be classified as thermosetting or thermo-softening plastics.

Thermosetting plastics are polymer materials usually liquid or malleable that irreversibly cured to a stronger form. The cure can be done through heat or through a chemical reaction as they harden and become rigid when cured, so they cannot be melted or reshaped. These materials do not become soft under high temperatures and resist wear

and attack by chemicals making them very durable, even when exposed to extreme environments.

Thermo-softening plastics are hard at low temperatures but melt to a liquid when heated and freezes to a brittle state when cooled sufficiently. They can be remelted and remolded when heat is added along with greater fracture toughness, longer shelf life of the raw material and capacity for recycling.

The most common resin matrix materials include: Epoxy, Phenolic, Polyester, Polyurethane, Polyimide, Polyamide, Polypropylene, PEEK, and Vinyl Ester. Among these resin materials, polyesters are the most widely used. Epoxies are also widely used but have higher cost for their higher adhesion and less shrinkage.

Less commonly used are metal matrix and non-metal matrix materials which include aluminum, copper, lead, magnesium, nickel, silver, and titanium for metal matrix as well as ceramics and carbon for non-metal matrix. These matrices are used in applications that require higher performance at elevated temperatures.

The reinforcement is usually fibers but can also be particles, flakes, and/or fillers. It is the material impregnated in the matrix that imparts and improves the overall mechanical and physical properties to enhance the matrix properties. The primary function of the fibers is to carry the loads along their longitudinal direction. Common fiber reinforcement materials include: Aluminum, Aluminum oxide, Aluminum silica, Asbestos, Beryllium, Beryllium carbide, Beryllium oxide, Carbon (Graphite), Glass (E-glass, S-glass, D-glass), Molybdenum, Polyamide (Aromatic polyamide, Aramid), such

as Kevlar 29 and Kevlar 49, Polyester, Quartz (Fused silica), Steel, Tantalum, Titanium, Tungsten, and Tungsten mono-carbide.

The modifiers and fillers are additives whose primary function are to reduce cost, improve workability, and impart desired properties. Cost is reduced by filling up to 40% of the total weight given a low cost to weight ratio. The workability is improved by reducing shrinkage and the coefficient of friction on surfaces, helping air release, controlling emissions, decreasing viscosity, sealing molds and guiding resin flows, and by speeding or slowing the curing process. The properties enhanced by these additives include improvement of electric conductivity, fire resistance, corrosion resistance, ultraviolet resistance, surface toughness, stabilize heat transfer, reduce tendency of static electric charge and add desired colors.

The common filler materials used as additives include: Feldspar, Glass microspheres, Glass flakes, Glass fibers, Mica, Silica, Talc, and Wollastonite. Modifier material used as additives include: Organic peroxide, Benzyl peroxide, Tertiary butyl catechol (TBC), Dimethylaniline (DMA), Zinc stearate, waxes, silicones, Fumed silica, and clays.

Composite materials have an incredible design potential. It allows engineers to tailor the properties to meet specific design requirements by carefully selecting the reinforcement, the matrix and the manufacturing process.

1.0. Brief History of Composite Materials

The early use of composite materials can be dated back to biblical times when the Egyptians used bricks comprised of straw and mud for construction. Although there has

been evidence of the use of primitive composite materials like bricks and other various forms of composites throughout history, the beginning of modern composites can be traced back to the late 1940's with the discovery of Fiber Glass.

With the commercialization of fiber glass, aircraft companies such as Douglas Aircraft started using this new material to reinforce cast plastic molds that were previously made of metal. The metal molds used for their hydropress forming process were expensive and had long lead time which restricted the ability of the company to verify new designs. The benefits from the use of fiber glass in the plastic molds were translated to the use of the reinforced plastic dies for prototype parts as a standard that were initially made with Phenolic resin. Later on, the use of fiber glass for reinforcement became a standard for other manufacturing and tooling processes of jigs and fixtures for the assembling of aircraft.

The development of World War II made a huge impact in the acceleration, advancement and adoption of composite materials for the fabrication of structural and semi-structural parts in the Aircraft industry. Parts that had complex and complicated geometries started to be fabricated with composite materials which allowed for faster design validation and improved manufacturing processes. Among the first aircraft parts made during this time with composites are ducts, engine nacelles, radomes (domes to protect aircraft radar antennas) and plastic airplane seats. Other non-aircraft applications included ship bearings, switchgears, brake linings and many other applications such boat moldings.

After World War II, the space race era gave new stimulus to industry to continue research and development of new composites added to the high demand in lower weight, high strength and high rigidity materials. New materials were developed such as carbon fibers in 1961, fibers with boron filaments in 1965, aramid fibers also known as Kevlar commercialized in 1971 by DuPont, and ultra high molecular weight polyethylene fibers in the early 1970's. Moreover, new improved resins were also developed that contributed to higher temperature applications where high corrosion resistance is needed such as rocket engine applications.

1.1. Types of Composite Materials

Composite materials are classified according to the form of reinforcement used. They are categorized as particulate, fibrous, and laminate composites.

1.1.1. Particulate Composites

These are particle reinforced composites in which the filler materials are roughly round and the particles can be either metallic or non-metallic as can the matrix. The particle may be of various sizes and shapes randomly dispersed within the matrix. They are used when dispersion-strengthened composites are needed it usually containing 10-100 nm particles. In this type of composites, the matrix bears the major portion of the applied load and the small particles hinder dislocation, motion, and limit plastic deformation making them not as effective in improving fracture resistance as fibrous composites. Due to the randomness of the particle distributions, particulate composites can be regarded as quasi homogeneous on a scale larger than the particle size and spacing and quasi-

isotropic. There are four possible combinations of the constituents of a particulate composite, they are:

- Nonmetallic particles in nonmetallic matrix
- Metallic particles in nonmetallic matrix
- Metallic particles in metallic matrix
- Nonmetallic particles in metallic matrix

1.1.2. Fibrous Composites

Fibrous composites are fiber reinforced composites in which the filler material has a length to diameter ratio, l/d , greater than one and its diameter is near crystal size. They can be made of short fiber that generally have an l/d of approximate a 100 or long fiber that have an l/d greater than 100. Long fibers are intrinsically much stiffer and stronger than the same material in bulk form due to the more perfect structure of a fiber, where the crystals are aligned along the fiber axis, thus reducing internal defects.

The long and continuous fibers can be parallel (unidirectional), can be oriented at right angles to each other (crossply or woven fabric), or can be oriented along several directions (multidirectional).

Along with fibers, whiskers can be also use in fibrous composite materials. They show the same near crystal size diameter and its l/d can be in the hundreds. Whiskers show higher properties than in bulk form or fibers due to its fabrication process. They have very high strength and stiffness in the lengthwise direction. They are obtained by crystallization on a very small scale that results on an almost perfect alignment of its

crystals reducing the amount of internal defects and dislocations. However, whiskers when used for reinforcement generally have a random orientation within the reinforced material giving it isotropic properties.

None of the fibers and whiskers properties can be enhanced to direct use unless they are bonded together with a matrix material in order to take the form of a structural element that can carry loads. The matrix will then support, protect and transfer stresses between broken fibers or whiskers.

1.1.3. Laminate Composites

Laminate composite materials consist of layers of at least two different materials that are bonded together. The composites are non-homogeneous and lamination is used to combine the best properties of the constituent layers and bonding material. The enhanced properties of laminated composite materials are strength, stiffness, low weight, corrosion resistance, wear resistance, thermal insulation, and acoustical insulation among others. Types of laminate composite materials include bimetals, clad metals, laminated glass, plastic based laminates and laminated fiber reinforced composites.

1.2. Fiber Reinforced Composites

Fiber reinforced composites are the result of embedding strong and stiff fibers in a parallel array in a matrix material that has superior properties in the fiber direction. The properties in the transverse direction (perpendicular to the fiber direction) of the material are weaker than in the fiber direction. This is caused by the size of the cross sectional area of the fiber and that any load must be transferred through the matrix. Moreover, the transverse properties depend also in great part to the integrity of the bond between the

fibers and the matrix. If the bond is weak and with imperfections, the transverse properties and transverse strength of the composite material will be weak and the thermal and electric conduction resistance will be high. The direction properties are shown below in Figure 1.

Figure 1: Direction Properties of Fiber Reinforced Composites

Due to the poor transverse and shear properties, components made of fiber reinforced composites are laminated. The building block of a laminate is a lamina or ply, which is a flat arrangement of unidirectional or woven fibers in a matrix. The lamina is orthotropic with principal material axes in the direction of the fibers (longitudinal direction), normal to the fibers in the plane of the lamina (in-plane transverse direction), and normal to the plane of the lamina. For woven fabric lamina, the fill is in the longitudinal direction and warp is in the in-plane transverse direction. The types of lamina and their principal coordinate axis are shown below in Figure 2.

Figure 2: Types of Lamina and Principal Coordinate Axis

A laminate is a bonded stack made up of two or more unidirectional or woven lamina or plies stacked at various orientations. The plies are usually bonded together with the same type of matrix used to bond the fibers in the lamina and can be of different materials and/or thicknesses. The orientation of each lamina in the laminate is tailored to the directional dependence of strength and stiffness to match the loading requirements of the composite material. For example, if a laminate is subjected to some in-plane shear, the layers can be oriented at 30° , 45° , or 60° . If the laminate is subjected to both shear and tension loads, fibers may need to be oriented at 45° to react the shear load, and at 0° and/or 90° to react to the tensile load. The amount of plies used in each orientation is relative to the magnitudes of the shear and tensile loads. The orientation of a given ply is

given by the angle between the reference x -axis and the fiber orientation of the ply measured counterclockwise on the x - y plane.

The symmetry between the plies is also important since it will determine the bending properties of the composite material. For example, if a lamina is not arranged symmetrically, the result is stiffnesses that represent coupling between bending and extension. Symmetry is measured about the middle surface of the laminate and is designated according to the stacking sequence of the plies.

Some examples of fiber reinforced composites are:

- **Prepregs:** A prepreg is a resin impregnated fiber or fabric in flat form which is stored for later use in hand lay-up or molding manufacturing processes. They can be either unidirectional or woven. Woven fabric prepregs are used to make highly contoured parts.
- **Hybrid Laminates:** These are composites containing plies of two or more different types of materials. There are also intraply hybrid laminates that have different types of fibers intermingle within the same unidirectional ply.

The fiber reinforced composites are designated indicating the number, type, orientation, stacking sequence and symmetry of the plies. The following are some examples of laminate designations:

- Crossply symmetric: $[0/90/90/0] = [0/90]_s$
- Angle-ply symmetric: $[+45/-45/-45/+45] = [\pm 45]_s$
- Multidirectional: $[0/45/-45/-45/45/0] = [0/\pm 45]_s$

1.3. Composite Manufacturing Processes

Composite materials must be formed to shape and are fabricated using a variety of manufacturing processes according to the specific design requirement and the physical and mechanical characteristics of the materials to be use. The manufacturing techniques most commonly used are shown below in Figure 3.

Figure 3: Composite Manufacturing Processes

There are four basic steps involved in the fabrication of a composite part: impregnation, lay-up, consolidation, and solidification. During the impregnation step, fibers and matrix are mixed together to form the lamina. The purpose of this step is that the matrix flows entirely around all fibers. The lay-up step involves the formation of composite laminates by placing laminas or prepregs at desired angles following a design lay-up stack sequence. Following the lay-up step is the consolidation step which involves creating the contact between each layer of lamina or prepreg. During this step, it is

important to ensure that there is not entrapped air between the layers to ensure that applied pressure is shared by both the fibers and the resin. Once the excess resin flow outwards towards the boundary, compressive pressure causes the fiber to go through elastic deformation. The final step is the solidification process, which vary in length depending on the type of matrix used. If a thermoplastic matrix is used, the process may take up to a minute while for thermoset matrices the process may take up to 6 hrs. During this step a curing cycle is applied using heat and may include a constant pressure or vacuum. A typical curing cycle is shown in Figure 4 below.

Figure 4: Curing Cycle during Solidification

Among the most common composite manufacturing processes are the open mold methods that are simpler and offer the lowest cost. These methods are used for low volume production and are suited for large components. On the other hand, the closed

mold methods are mainly use for middle to high production and use faster curing cycles by placing the composite parts in a closed vessel or chamber. The hand lay-up process is an example of an open mold method and the vacuum bagging of a closed mold method.

1.3.1. Hand Lay-up Process

There are two methods associated with hand lay-up which are prepreg lay-up and wet lay-up. For this method, an open mold is used where the reinforcement material is poured or brushed with resin into the plies and entrapped air is removed using either a squeegee or a roller as shown in Figure 5 below. The curing can be done by adding heat or by using an autoclave.

Figure 5: Hand Lay-up Process

1.3.2. Vacuum Bag Molding

This process is an addition to the hand lay-up process that can improve the mechanical properties of a composite material by allowing an increase in the fiber content of a laminate up to 50% by curing the composite part in a vacuum bag. Moreover, it provides higher reinforcement concentrations, better adhesion between layers and more

controlled matrix to fiber ratios due to the force exerted by the added pressure on the composite material. Once the hand lay-up process is finished, the composite part is then placed in a vacuum bag where entrapped air and resin excess is eliminated by reducing the pressure inside the vacuum bag. The curing for this process can be at room temperature or at higher temperatures using autoclave. The basic vacuum bag configuration is shown below in Figure 6.

Figure 6: Vacuum Bag Molding

1.4. Advantages and disadvantages of composites materials

Composite materials offer a variety of advantages. Among the main advantages is the design freedom it provides the designers to produce materials that fulfill the requirements for a particular structure by carefully choosing an appropriate combination of reinforcement and matrix material. Moreover, its high strength and stiffness to weight ratio provides the greatest benefit for applications where mass constraint is the main requirement. The directional strength and/or stiffness can be tailored according the loading type that will be applied to the structure.

Other composite materials advantages include:

- **Cost:** Cost reduction is possible due to the fast fabrication of prototypes that allow for testing before mass production. Mass production of composite materials have overall reduced costs due to part consolidation and low machining features that are built in molds hence acceleration production times and the maintenance requirements.
- **Dimension:** Large parts and structures requiring special geometry can be fabricated through a variety of manufacturing processes such as hand lay-up or spray lay-up.
- **Surface Properties:** Various reinforcement materials provide corrosion resistance and weather resistance
- **Thermal Properties:** Composite materials such as sandwich composites provided low thermal conductivity and low coefficient of thermal expansion due to the mismatch in coefficient of thermal expansion between face-skins and core materials.
- **Electric Property:** Different types of composite materials provide high dielectric strength and are non magnetic. They also provide electrical insulation.

There is a great variety of advantages compare to a few disadvantages of composite materials. It can be discussed that depending on the application of the composite material the cost can be either an advantage or disadvantage but in general terms it is considered an advantage. Some disadvantages such as high manufacturing

costs due to the high cost of materials and manufacturing time can be pointed out. Moreover, there can be a lack of extensive performance data since composite materials are in most cases tailored to fit special design requirements.

Another important disadvantage lies in the complexity of analysis of composite materials due to the inherent nature of composites. There is a higher degree of complexity for its anisotropic nature when analyzing the new properties that result from the combination of the constituent materials. Moreover, the variety of materials that can be created from composites makes it difficult to create standards for analysis.

1.5. Failure and Fracture Mechanics of Composite Materials

Failure mechanics establishes the criteria for the prediction of failure and fracture of materials due to applied loads. In composite materials, fracture occurs in many more different ways compared to metallic materials due to their anisotropic nature and its fabrication processes. The accumulation of internal imperfections and damage caused by the nature of the constituent materials and manufacturing defects create failures that at the microscopical level consists of cracks in matrix material, breakage of fibers, and debonding at the interface between fiber and matrix. These failure mechanisms are related closely to the mechanical properties of the constituent materials of the composite laminate and vary with the type of loading applied to the composite part.

The nature of composite materials makes them susceptible to embedded imperfections that can develop in failures and can be controlled by the strength of the components of the lamina, the fiber-matrix bond or interfacial strength and the ability of

the composite to absorb energy under critical loading (i.e. energy absorption under impact loading).

The increment of loading conditions up to critical loads induces damage grow that manifests on a macroscopical scale in the form of cracks. As the cracks progresses, it reduces the stiffness and strength of the material leading to interlaminar, intralaminar, and translaminar catastrophic failure.

Interlaminar fracture or delamination describes separation of the individual plies; intralaminar fracture refers to fracture that occurs within the body of a ply parallel to the fiber direction; while translaminar fracture is defined as that oriented normal to the laminate plate. These failure types can be caused by three basic loading configurations, mode I (tension or opening mode), mode II (in-plane shear or sliding mode), mode III (out-of-plane shear or tearing mode), or any combination of the above loading mode. Figure 7 illustrates the three basic loading modes.

Figure 7: Loading Modes

Fracture types are controlled by the properties of the matrix and fiber-matrix interface. In the case of intelaminar and intralaminar fracture, the matrix properties

mainly control the behavior of the composite since the fracture occurs in the direction parallel to the fiber reinforcement. For translaminar fracture, the fiber-matrix properties are most important due to fiber fracture.

1.6. Thesis scope

The main scope of this thesis project is to study the effect fatigue cycle loading amplitude in tension-tension on composite laminated plates with initial delamination to determine the maximum number of loading cycles required to crack propagation and failure through the preformed delamination. The study will describe the manufacturing/fabrication of the test specimens, the experimental set up and procedure followed for testing, and discuss the experimental results. Moreover, it will encompass a comparison of experimental results with numerical analysis models.

CHAPTER 2: MANUFACTURE/FABRICATION OF THE TEST SPECIMENS

The carbon fiber plate test specimens were fabricated in the Aerospace Structures and Composite Laboratory at the California Polytechnic State University – San Luis Obispo building 41, room 136. With the need to perform both tensile and amplitude load testing, several test specimens were fabricated. Two types of carbon fiber plates were fabricated, one type without delamination for tensile testing and the other with initial delamination for amplitude load testing. Moreover, test specimens made of matrix (epoxy) were fabricated for tensile testing.

The first type of test specimens fabricated consisted of plates constructed of unilateral sheets of carbon fiber with cross-ply symmetric $([0/90]_s)$, $([90/0]_s)$ and angle-ply symmetric $([\pm 45]_s)$ stacking sequences. Test specimens were made for both tensile and amplitude load testing. The fabrication description and details are presented in section 2.0 through 2.2.

Due to a shortage of unilateral carbon fiber material, a second type of test specimens were fabricated and consisted of plates constructed with woven prepreg sheets of carbon fiber (T300/LTM45-1). Test specimens were also made for tensile and amplitude loading. The fabrication description and details are presented in section 2.3.

Hand lay-up was the manufacturing process selected to fabricate the test specimens using vacuum bagging and a composite press.

2.0. Composite Test Specimen Fabrication: Batch # 1

With the need to fabricate 2” x 6” cross-ply and angle-ply carbon fiber plates, it was decided to manufacture both stacking sequences from one 14” x 14” plate with a cross-ply of [0/90]_s. Two 14” x 14” plates of four cross plies each were fabricated using vacuum bagging to later form individual carbon fiber plates with a total of eight plies with initial delamination using the composite press.

2.0.1. Vacuum Bagging Preparation

Before preparing the plates, the vacuum bag was set up following a similar set up as in Figure 6. An aluminum composite manufacturing table was used as the composite plate mold. The table has been made especially for vacuum bagging with a suction system connected to an Edwards two stage rotary vane air pump and a programmable heating system to decrease curing time. A square perimeter of 16” x 16” was made with sealing tape and Airtech Dahlar 125 release film was put on the surface of the mold. The materials used in the vacuum bag process such as the release film, the perforated release film, the breather absorber fabric and the peel ply were cut to a size that will cover the composite laminate but no bigger than the size of the perimeter formed by the sealant tape. The only material cut to that size was the vacuum bag film that would create the seal to create a vacuum with the sealant tape.

The release film was taped to the mold surface within the perimeter formed by the sealant tape making sure that there were no ridges and wrinkles. The surface coating of the release film allowed it to stick to the surface of the mold by applying hand pressure and making sure that there were no air bubbles. It also allows easy of removal from the

laminate surface once it is cured. This will allow the bottom face of the plate to have a smooth and consistent surface without ridges and will prevent the accumulation of excess matrix to be trapped within air pockets that can be formed between the film and the laminate.

Once the laminate is in placed on top of the release film, a layer of Airtech Wrightlon 5200 perforated release film is placed on the top surface of the composite laminate. The perforated release film is treated so it won't bond to the laminate as well as to provide a smooth finished surface. The small perforations in the film allow excess resin to pass through it and become absorbed in the bleeder/breather absorber fabric material.

The next layer to be added is the Airtech Airweave N4 Breather Absorption Fabric that absorbs the epoxy excess that passes through the perforated release film. Besides absorbing the resin, the breather fabric ensures that the vacuum is distributed evenly within the bag. Since the layer of breather fabric only covered the surface of the composite material, additional pieces of breather fabric material were cut and placed along the edges of the laminate to absorb the excess epoxy that would be pulled toward the edges due to the pressure force applied by the vacuum. Moreover, smaller pieces of breather fabric were cut, folded and placed on all edges to prevent bridging and to direct the air flow within the bag ensuring that vacuum is achieved on edges opposite to the pump inlet.

Following the breather fabric layer, an Airtech Release Ease 234TFNP Peel Ply sheet was placed on top of the breather absorption fabric to prevent the excess matrix absorbed by the breather to make contact with the vacuum bag and stick to it.

The last layer was the Airtech Stretchlon 200 Vacuum bag that was applied along one edge at the time. To start sealing the bag, one corner was attached to the sealant tape by pressing the film against it whilst removing the release paper from the tape while moving along the edge and making sure that there were no wrinkles in order to prevent air leaks. At the time of sealing the last edge, the vacuum port was inserted inside the vacuum bag and the edges of the vacuum port were surrounded with sealing tape and then merged with the sealing tape attached to the mold surface.

The components of the vacuum bag are summarized below in Table 1 and a graphical representation of the set up is shown in Figure 6.

Table 1: Vacuum Bagging Components

Layer #	Description
1	Airtech Stretchlon 200 Vacuum Bag Film
2	Airtech Release Ease 234TFNP Peel Ply
3	Airtech Airweave N4 Breather Absorption Fabric
4	Airtech Wrightlon 5200 Perforated Release Film
5	Carbon Fiber Composite Laminate
6	Airtech Dahlar 125 Release Film

2.0.2. Carbon Fiber Plates Stack Preparation: Batch # 1

To manufacture the plates, eight 14” x 14” sheets of unidirectional carbon fiber were cut and weighted to calculate the total mass of the fibers. The matrix was prepared

using a mixture of Aeropoxy PR2032 epoxy resin, and Aeropoxy epoxy hardener PH3660. For the first set of 4 plies, a total of 130 grams of resin to 39 grams of hardener were used for a mixture ratio of 3:1 and a total matrix mass of 169 grams. The second set of 4 plies used 110 grams of resin and 33 grams of hardener for a total epoxy resin mixture of 143 grams. A summary of the carbon fiber reinforcement and epoxy matrix are summarized in Table 2 below.

Table 2: Carbon Fiber reinforcement and Epoxy matrix measurements

Reinforcement and Matrix Measurements						
Plate #	# of Carbon Fiber Sheets	Sheet Dimensions (in)	Carbon Fiber Sheets Weight (grs)	Resin Weight (grs)	Hardener Weight (grs)	Total Epoxy Weight (grs)
1	4	14 x 14	159	130	39	169
2	4	14 x 14	159	110	33	143

Before applying the matrix to the carbon fiber sheets, a global coordinate system was set to properly orientate the stacking sequence for both plates. The origin of the coordinate system was set at the bottom left corner of the sheets with the X-axis or direction 1 parallel to the fibers, the Y-axis or direction 2 transverse to the fibers, and the Z-axis or direction 3 being Out-of-Plane. Once the coordinate system was set, the carbon fiber sheets and matrix mixture were placed under a fume hood to vent any toxic vapors and the first carbon fiber sheet was set in direction 1 assuming the 0° direction to create the $[0/90]_s$ stacking sequence desired. The lay-up stacking sequence and fiber direction schematic is shown below in Figure 8.

Figure 8: Carbon Fiber Plate $[0/90]_s$ Lay-up Sequence

The first sheet was then impregnated on both sides with epoxy making sure that the matrix was evenly distributed and any excess was removed. The second sheet was placed on top of the first sheet following the lay-up sequence and with the unidirectional fibers transverse to direction 1 at 90° again impregnating both sides with epoxy and removing any excess. The third and fourth carbon fiber sheets were placed in the stack and impregnated with epoxy following the lay-up sequence in Figure 8. Once the stack was completed, a roller was used to remove any excess epoxy matrix within the carbon fiber layers before the stack was placed in a vacuum bag. The same process was followed to create the second stack that will be joined together to create the 8 ply carbon fiber plates.

Once the two stacks were prepared, they were placed in the vacuum bag where they cured for 12 hours. After the curing period, both carbon fiber plates were removed from the vacuum bag and prepared to be cut into single 2" x 6" plates with cross ply and angle ply directions. In order to achieve the same dimensions for each 2" x 6" plate, the 14"x 14" plates were taped along the edges to be cut at the same time. Blue tape was also used to mark the cutting sequence in Figure 9 and to serve as a straight edge guide. The

cutting sequence illustrated in Figure 9 shows the order in which the individual plates are cut as well as its designated layup sequence.

Figure 9: Individual Plates Cutting Sequence

The plates were cut using a Target tile saw, see Figure 10, following a specific cutting sequence to ensure that a total of six 2'' x 6'' plates were extracted from the 14'' x 14'' plates. A total of 5 cross ply plates, three of those of with a $[90/0]_s$ layup sequence and two with $[0/90]_s$ layup sequence. One angle ply plate would be extracted with a $[45/-45]_s$ layup sequence. Two other sets of 14'' x 14'' were fabricated.

Figure 10: Target Tile Saw

After all the single plates were cut, the remaining scraps from each plate were kept and used to verify that all the new cut individual plates had the same material properties. This was done using mass fractions where the volume ratio of matrix to fiber is compared for all the individual plates. Each piece of scrap material used for the mass fraction was weighted and individually placed in a small oven where the epoxy matrix was melted in order to separate each single ply that formed the plate.

2.0.3. Initial Delamination Setup: Batch # 1

After ensuring that all of the composite plates had the same material properties, the individual set of plates cut from the 14" x 14" plates were prepared to make the final carbon fiber composite plates with initial delamination that would be use for testing. Once again the matrix was prepared using a mixture of Aeropoxy PR2032 epoxy resin, and Aeropoxy epoxy hardener PH3660. A total of 115 grams of resin to 40 grams of hardener were used for a mixture ratio of 3:1 and a total matrix mass of 155 grams.

Before applying the epoxy matrix to the 2" x 6" plates, each plate was marked 2.5" from the shortest edge marking the position where the initial delamination would start. In order to create the initial delamination, the area selected for the initial delamination was covered with Airtech Release Ease 234TFNP Peel Ply in order to prevent epoxy matrix to join the selected area for delamination during the curing process.

For this last step of the carbon fiber plates with initial delamination fabrication process, a Tetrahedron composite press shown in Figure 11 was selected for this manufacturing process step. As compared to the vacuum bagging process, the composite press provides a more consistent finish as the curing process is programmed by cycles where different pressures and temperatures are applied to the plates at different rates. The composite press is programmed into steps where temperature, temperature rate, force, force rate, tool temperature and time are set. The number of steps and the parameters for the six different settings mentioned above are set based on the type of composite material and desired properties being prepared.

Figure 11: Tetrahedron Composite Press Machine

The composite press curing program cycle used to create the initial delamination is summarized in Table 3 and plotted in Figure 12 below.

Table 3: Carbon Fiber Plates initial Delamination Composite Press Curing Program Cycle

Process	Step 1	Step 2	Step 3	Step 4
Temperature (°F)	130	160	80	END
Temperature Rate (°F/min)	4	4	4	
Force (lb _f)	320	400	320	
Force Rate	12000	12000	12000	
Tool Temperature (°F)	70	70	70	
Time (Hr)	2	3	5

Figure 12: Carbon Fiber Plates with Initial Delamination Curing Cycle Graph

2.1. Composite Test Specimen Fabrication: Batch # 2

After putting some of the carbon fiber plates with initial delamination fabricated in batch # 1 through amplitude load testing; it was apparent that the fabrication method used for batch # 1 carbon fiber plates was not appropriate since the test specimens failed under low amplitude loads. It was then necessary to fabricate a second batch of carbon fiber test specimens using a different procedure that would ensure proper amplitude load testing.

The procedure followed to fabricate the second batch of specimens used vacuum bagging to cure the specimens. However, the stack sequence preparation and the initial delamination setup were done differently to guarantee that the specimens would be ready for amplitude testing.

2.1.1. Carbon Fiber Stack Preparation: Batch # 2

To manufacture the second batch of carbon fiber plates, a roll of unidirectional carbon fiber was used from where sheets of 3" x 7" were cut in the 0° and 90° direction as shown in Figure 13. Two symmetric layups, a $[0^\circ/90^\circ]_s$ and a $[90^\circ/0^\circ]_s$, were fabricated from the cut sheets containing a total of eight plies. The sheets of unidirectional carbon fiber used to fabricate the carbon fiber plate with initial delamination were then weighted to calculate the total mass of the fibers.

Figure 13: Unidirectional Carbon Fiber Sheets Orientation

The same matrix mixture and procedure to prepare the layup sheets that was followed to fabricate the first batch of carbon fiber plates was used for the second batch of composite plates. To create the $[0^\circ/90^\circ]_s$ layup, the first ply was placed in the 0° direction followed by two plies placed on the 90° direction. The fourth ply was then

placed in the 0° direction following the selected ply stacking sequence. The remainder four plies followed the same procedure as the previous plies.

The $[90^\circ/0^\circ]_s$ layup is fabricated in the same way but starting the first ply in the 90° direction followed by the second and third plies in the 0° direction. The fourth ply was then placed in the 90° direction. The remainder of the plies in this stacking sequence is placed in the same way as the previous four plies.

Both symmetric layups were divided on the plane of symmetry which is between the fourth and fifth ply. Between these plies, a piece of Airtech Release Ease 234TFNP Peel Ply is placed 2.5" from one edge of the layup where the initial delamination will begin. After the peel ply is placed, the remainder four plies are added to complete the designated layup. The schematic of the $[0^\circ/90^\circ]_s$ layup with the peel ply to create the initial delamination is shown in Figure 14.

Figure 14: $[0^\circ/90^\circ]_s$ Layup with Initial Delamination

Once the layup stacks were prepared, they were placed in a vacuum bag set up following the same procedure as described in Section 2.0.1, where they cured for 12 hours. A total of 8 layup stacks were placed in each vacuum bag. Figure 15 shows the vacuum bag set up of the carbon fiber plates.

Figure 15: Carbon Fiber Plates during Vacuum bag Curing

After the curing period, the carbon fiber plates were removed from the vacuum bag and weighted. They were then trimmed down from a 3" x 7" size to 2" x 6" size using the Target tile saw shown in Figure 10 and weighted again. It is important to note that after the carbon fiber plates were trimmed, the initial delamination distance was kept to 2.5" from one edge of the plate. The weight data collected was used to later calculate the total mass fraction of the plates as previously done during the fabrication of the first batch of carbon fiber plates.

2.2. Composite Test Specimen Fabrication: Batch # 3

The third batch of composite test specimens was fabricated to perform tensile testing in order to obtain the material properties of both the carbon fiber plates and that of the matrix itself.

2.2.1. Carbon Fiber Tensile Test Specimen Fabrication

The carbon fiber plates were manufactured following the fabrication procedure described in Section 2.1 with the difference that no initial delamination was created in these plates. The size of the layup stack was also 3" x 7", however once the plates were cured, they were trimmed to a size of 2" x 6".

2.2.2. Epoxy Matrix Tensile Test Specimen Fabrication

Due to the liquid state of the matrix, a metallic frame enclosure of 11" x 11" x 0.25" was used to fabricate a sheet plate of the same size as the enclosure. To fabricate the test specimens, a vacuum bag was set up to cure the matrix mixture at room temperature.

The metallic frame was placed on the aluminum composite manufacturing table where the vacuum bag was to be built. Once set in place, the first layer of the vacuum bag was tapped to the surface of the composite manufacturing table covering the metallic frame. Using a small air pump, a vacuum was created in the tapped enclosed surface covered by the first layer of the vacuum bag thus outlining the contour of the metallic frame where the matrix mix was poured in.

Figure 16: Epoxy Plate Vacuum bag Preparation

A matrix mixture ratio of 3:1 of Aeroepoxy PR2032 epoxy resin and Aeroepoxy PH3660 epoxy hardener was prepared and poured in the metallic frame enclosure.

Once the matrix mix was poured, a layer of Airtech Airweave N4 Breather Absorption Fabric was placed to cover the outside perimeter of the metallic frame in order to absorb any excess matrix. On top of the breather fabric, a layer of Airtech Release Ease peel ply was placed covering the inside perimeter of the metallic frame to avoid the matrix to stick to the vacuum bag and to ease of release once the curing time was over. The last layer consisted of the green vacuum bag film used in the first layer and was taped to the composite manufacturing table covering the first layer and closing the vacuum bag. Before closing the vacuum bag, another air pump was used to create a vacuum between the first and last layer starting the curing process. The total curing time was 32 hours. The vacuum bag preparation process is depicted in Figure 17.

a) Breather Fabric Layer

b) Matrix poured in inside metallic frame

c) Peel ply layer covering matrix

d) Sealed curing vacuum bag

Figure 17: Vacuum Bagging Process for Epoxy Plates

After the matrix was cured, a solid 11" x 11" matrix plate was removed and then cut into 1" x 7" strips that would be then use for tensile testing as shown in Figure 18.

Figure 18: Epoxy Tensile Test Specimens

2.3. Composite Test Specimen Fabrication: Batch # 4

The test specimens fabricated during batches 1 through 3 did not yield enough amplitude load test data due to manufacturing deficiencies in the interface between the test specimens and the testing hardware. The aluminum tabs designed as interface did not consistently performed as expected mostly due to debonding from test article while under low tensile and amplitude loads. Moreover, the initial aluminum tabs designs did not transfer properly the load and could have created bending moments on the test specimens. A detail description of the aluminum tabs designed and used in the testing is presented in section 3.2.

Due to a shortage of unilateral carbon fiber material, the new batch of specimens was made of woven prepreg carbon fiber (T300/LTM45-1) sheets. Dimensions and ply count were kept the same as the previous specimens to keep some consistency. The use of prepreg sheets accounted for a faster and cleaner manufacturing process.

Sheets of approximately 15" x 15" were cut and aligned to produce plates with a stack of 8 plies. During the stack layup, the initial delamination was created by placing a strip of peel ply between the middle plies (ply 4 and 5) across the width of the entire plate. The complete plate stack up including the initial delamination peel ply strip is shown in Figure 21.

Figure 19: Woven Prepreg Carbon Fiber Plate

Once the ply stack was complete, the carbon fiber plate was set for curing using the Tetrahedron Composite Press Machine as shown in Figure 11. Breather absorber fabric sheets and peel ply sheets were placed on top and bottom of the carbon fiber plates to prevent spillage of excess resin matrix while curing on the press machine. The curing cycle used for the test specimens was the same applied to the carbon fiber plates made in

batch 1. The curing cycle summary and representation are shown in Table 3 and Figure 12.

After curing, the plates were marked referencing the centerline of the peel ply strip, which was removed before cutting them. A picture of the marked plate is shown in

Figure 20: Woven Prepreg Carbon Fiber Plate Cutting Diagram

From the 15" x 15" plate, a total of two lots of 7 test specimens were cut. A total of 8 plates were fabricated. The after the fourth plate, the dimensions of the plate were increased to 17" x 17" to obtain more test specimens. A summary of the plates fabricated, the lot description and amount of test specimens cut is shown below in Table 4.

Table 4: Woven Prepreg Test Specimens Summary

Plate #	Lot Denomination	Plate Dimensions	# Specimens/ Plate
1	A-B	15" x 15"	7
2	C-D		7
3	E-F		7
4	G-H		7
5	I-J	17" x 17"	8
6	K-L		8
7	M-N		8
8	O-P		8

All the test specimens from the carbon fiber plates were cut to a size of 2" x 6" using the Target tile saw shown in Figure 10. From every single lot of specimens fabricated, two test specimens were designated for tensile testing while the remainder was used for amplitude testing.

CHAPTER 3: EXPERIMENTAL SET UP

The experimental set up will consist of two different tests to be performed on the carbon fiber plates using an Instron FastTrack 8801 series machine. First, a tensile test will be performed on carbon fiber and epoxy plates fabricated without any delamination in order to obtain the material properties of plates. Second, the carbon fiber plates with initial delamination will be tested applying a Mode I constant amplitude loading.

Before testing can be started, the test specimens need to be prepared in order to successfully mount them onto the Instron machine. To achieve this, aluminum end tabs would be fabricated and bonded to the test specimens. The test specimens used for tensile testing will use four aluminum tabs bonded at the free end of each surface. The test specimens used for Mode I constant amplitude load testing will use two aluminum tabs bonded at the free end that interfaces with the Instron machine clamps. To create a strong bond between the aluminum tabs and the test specimens, and to accelerate the curing process of the epoxy matrix, the tetrahedron composite press machine shown in Figure 11 was used. In addition to the aluminum tabs, strain gages will be added to the amplitude load test specimens.

In order to perform the Mode I constant amplitude testing, an aluminum fixture will be machined. The fixture will attach to the base of the Instron machine through two bolts and would serve as a fix base so the test specimens can be constrained in six degrees-of freedom.

3.0. Why use aluminum end tabs?

The nature of unidirectional carbon fiber composite specimens makes it necessary to use end tabs in order to perform testing. In order to prevent introducing unacceptable stress concentrations that can degrade the measured tensile strength of the specimen while gripping the composite ends when applying a load, end tabs or grips are clamped or bonded onto the test specimen ends. For this experiment, aluminum end tabs will be used in order to transfer the applied Mode I variable load or variable amplitude tensile force at the specimen surfaces into tensile stress in the specimen.

There are a variety of methods and options that minimize the effects of the gripping forces transferred to the test specimen. An option is to fabricate the specimen with minimal thickness usually around 1mm so that the specimens applied force and gripping area vary proportionally to the specimens width. Also using bigger grips that would distribute the clamping forces over a bigger area would decrease these effects. However, these two options pose great limitations and constraints on the design of the test specimens as well as on the equipment that can be used for testing.

An alternative method that avoids the limitations and constraints of the methods mentioned above is the use of bonded end tabs that properly reduce the gripping forces by transferring the shear forces through the adhesive used to bond the tabs to the specimen. The most common set up of the aluminum end tabs is shown in Figure 21.

Figure 21: Aluminum End Tabs

Even though the use of aluminum tabs decreases efficiently the gripping forces, they add a small source of stress concentrations at the end of the tabs opposite to the edge of the specimen where the tab is located. The stress concentration is produced by the sudden discontinuity of the added thickness on the composite plate created by the tabs. However, by tapering the tabs end, the discontinuity is reducing thus reducing the added stress concentration. The ASTM D 3039 (American Society for Testing and Materials) recommends that the aluminum tabs have a taper angle equal or greater than 5° . It has not been demonstrated thoroughly that the tapering angle of the aluminum tabs is as efficient as using square end tabs due to the fact that during tensile loading the tabs tend to curl outwards away from the side edges of the composite test specimen thus introducing stresses through the thickness of the specimen. The stresses caused by the curling effect can induce peeling of the surface layers of the composite plates thus weakening it.

There is a potential trade off when deciding on the type of end tabs to use. Square tabs provide more rigidity and stiffness that prevents the curling effect but when high gripping loads are applied and curling happens, they tend to induce the through thickness

stresses. On the other hand, highly tapered tabs are less resistant to curling but they do not produce high stresses through the thickness of the test specimen when they curl.

3.1. Aluminum End Tabs Fabrication

In order to be able to mount the carbon fiber plates into the Instron machine, two different types of aluminum end tabs were fabricated for the testing of the carbon fiber plates. One type was fabricated to perform tensile testing in order to derive the material properties of the carbon fiber plates (no delamination added) and the other to perform the amplitude variable loading testing on the carbon fiber plates with initial delamination.

3.1.1. Aluminum Tabs for Tensile Testing

The aluminum tabs used for tensile testing, as shown in Figure 22, were cut from a thin sheet of aluminum of 0.065" thickness to a rectangular shape of 1.0" by 1.5" to fit the test specimen used for tensile testing.

Figure 22: Aluminum End Tab for Tensile Test

The surface of the tabs that interface with the test specimen were cleaned and scratched in order to create some friction that would prevent the sliding of the tabs. Moreover, the area on the test specimen that would be covered by the tabs was sanded and cleaned.

A mixture of Epoxy resin and hardener was used as adhesive to bond the tabs to the test specimen. The epoxy mixture ratio was based on a 2 to 1 volume ratio of resin to hardener. The epoxy was spread on both the aluminum tab and the test specimen letting the epoxy partially cure in order to prevent sliding and misalignment of the tabs once the test specimens were placed on the composite press machine for final curing. For the pre-curing, both the test specimens and the aluminum tabs were exposed to heat using 3 small heaters for an hour. The pre-curing set up is shown in Figure 23.

Figure 23: Pre-curing of Tensile Test Specimens and Aluminum Tabs

The final step in the preparation of the test specimens for tensile testing was done using the Tetrahedron press machine where a curing cycle was programmed to apply a constant pressure force of 400 lbs to ensure a strong bond connection. The entire curing cycle settings is summarized in Table 5 and plotted in Figure 28.

3.1.2. Aluminum Tabs for Constant Amplitude Load Testing

Two different types of aluminum tabs were used to perform the constant amplitude load testing. The first type used was a rectangular shaped aluminum tab and later a triangular type with rectangular base aluminum tab was used.

3.1.2.1. Rectangular Shaped Aluminum Tabs

The rectangular shaped aluminum tabs were first designed to fit a fixture attachment that mounted on a shaker machine where the constant amplitude load testing was to be performed. After deciding to use the Instron machine for testing, a new fixture attachment needed it to be machined in order to fit the tabs and create an interface for load transfer between the Instron and the carbon fiber plates. The details of the fixture attachment for this type of tabs will be discussed in the next sections.

The rectangular aluminum tab used for constant amplitude load testing and its dimensions is shown in Figure 24.

Figure 24: Rectangular Shaped Aluminum Tabs

The tabs were cut from a sheet of aluminum 0.125" thick with a dimension of 2.3" by 2.0". It was necessary to cut these tabs wider than the width of the test specimens to machine its ends with an approximate 40° angle so the inner flanges of the fixture attachment could hold the aluminum tabs as shown in Figure 25. In this manner, the bottom surface of the tabs would be bonded to the surface of the test specimen allowing the transfer of the Mode I loading from the Instron machine to the test specimens thru the fixture attachment and aluminum end tabs.

Figure 25: Fixture attachment, rectangular shaped aluminum end tabs configuration

To machine the 40° angle of the aluminum tabs it was necessary to use a belt sander machine due to the small amount of material that need it to be trimmed away. Once trimmed to the desired angle, the bottom surface of the tabs was dented randomly using a Delta drill press machine creating small craters of different depths through the surface of the tabs. This was done to maximize the amount of epoxy use for bonding as well as to prevent sliding of the tabs once they are positioned on the test specimen and

while they undergo curing in the composite press machine. The belt sander and drill press used to machine the aluminum tabs are shown in Figure 26 and the bottom surface of the aluminum tabs with dents is shown in Figure 27.

Figure 26: Belt Sander and Delta Drill Press

Figure 27: Dented Bottom Surface of Aluminum Tab for Amplitude Load Testing

Once the bonded surface of the aluminum tab was machined, the test specimen's surface was cleaned by sanding down the area where the aluminum tabs were to be placed. The same mixture of epoxy resin and hardener used for the tensile test aluminum

tabs was used for the Mode I variable amplitude loading aluminum tabs. The same process pre-curing and curing process was followed as the one used with the aluminum tabs used for tensile testing. It is extremely important to avoid any misalignment of the aluminum tabs or loading grips as it prevents bending stresses that can be transferred to the surface of the test specimen weakening it.

Table 5: Rectangular Shaped Aluminum Tabs Composite Press Curing Program Cycle

Process	Step 1	Step 2	Step 3
Temperature (°F)	100	80	END
Temperature Rate (°F/min)	4	4	
Force (lb _f)	400	400	
Force Rate	12000	12000	
Tool Temperature(°F)	70	70	
Time (Hr)	4	8

Figure 28: Rectangular Shaped Aluminum Tabs Curing Cycle Graph

3.1.2.2. Triangular type with rectangular base Aluminum Tab

The triangular type with rectangular base aluminum tab was also used for the variable amplitude load testing after the rectangular shaped tabs peeled off the surface of the carbon fiber plates during testing. With the use of a new shaped aluminum tab, a new fixture attachment was designed as well.

The design of this aluminum tab provided a better interface with the fixture attachment since it was designed to be a tight fit which improve the load transfer from the Instron machine to the carbon fiber plates. The triangular type with rectangular base aluminum tab used for constant amplitude load testing and its dimensions is shown in Figure 29.

Figure 29: Triangular type with Rectangular base Aluminum Tab

The tabs were machined from 10 inch long aluminum rectangular bars of 0.5 inch by 0.75” using a vertical mill machine, an edge finder, and end mill cutters. The machine was set up using a vise to secure the aluminum bar. Once set in place, the edge finder was used to set a coordinate system to guide the cutting tools in the X and Y direction.

The machining process of the tabs consisted of two steps. In the first step, a $\frac{3}{4}$ inch diameter end mill cutter was used to remove material from the bottom side of the aluminum bar to create a smooth and even surface which would be bonded to the carbon fiber plate. In the second step, a 60 degree face end mill cutter was used. The end mill cutter was centered at the middle of the aluminum bar and then it was offset in the positive and negative Y-direction a distance of 0.363 inches to create the 60 degree angular ridges on each side of the bar. Once this process was completed, the machined aluminum bar was removed from the vise and deburred to removed sharp edges. The finished aluminum bars were then cut to a length of 2 inches to fit the width of the carbon fiber plates.

The mill machine, the edge finder and the end mill cutting tools are shown below in Figure 30 and Figure 31.

Figure 30: Mill machine used to fabricate Aluminum Tabs

Figure 31: Edge Finder and End Mill Cutting Tools

The triangular shaped with rectangular base aluminum tabs bottom surface was roughed using sand paper to create friction and prevent the tabs to slide away from the

carbon fiber plate while curing. In order to prevent the peeling of the aluminum tabs during testing, a mixture of structural adhesive resin and hardener was used to bond the tabs to the carbon fiber plates. The aluminum tabs were left to cure at room temperature for 48 hours with an applied pressure of 200 pounds.

3.2. L-shaped Aluminum Tabs

The triangular shaped aluminum tabs worked well during the testing of the unilateral carbon fiber test since they provided a uniform load transferring capabilities and their small bonding area. However, the lack of reusability of this tabs made them not a good choice due to a tedious manufacturing process that required the use of a mill machine and tight tolerances to fit in the fixture attachment designed for this specific tab. For the previous reasons, a simpler L-shaped aluminum tab was selected to be used with the batch of woven prepreg test specimens.

The L-shaped tabs were obtained from 8 ft long L-shaped bars and then cut into segments of 2" wide which accounted for a faster process of creating the aluminum tabs since no manufacturing was required. The overall dimensions of each tab were 2" x 2" x 0.125" with a leg length of 0.5". The length and width of the leg provided enough bonding area to the test specimens.

Once the test specimens were cut to the appropriate size, the L-shape aluminum tabs were bonded to the edge of the specimen with initial delamination using Scotch Weld 460 NS structural adhesive. The adhesive was applied with a glue gun and through a mixing nozzle that mixed the two part adhesive to the appropriate ratios. The adhesive, glue gun and mixing nozzle are shown in Figure 32.

Figure 32: Structural Adhesive, Mixing Nozzle, Glue Gun

A layer of structural adhesive was applied to the tabs base and let hang from a flat surface, then the test specimens were placed upon the adhesive layer aligning the width of the test specimen to the width of the aluminum tab. A flat surface was placed on the opposite side of the specimen (top side) where weights and clamps were used to provide pressure during the curing time. The specimens were left to cure for 10 hrs and then the same process was followed to bond the tabs on the opposite side of the test specimen. The bonding setup for the L-shape aluminum tabs is shown in Figure 33.

Figure 33: Aluminum Tabs for Woven Prepreg Test Specimens Bonding Setup

3.3. Instron Machine Testing Fixture Design and Fabrication

The Instron machine, as shown in Figure 34, is set up to perform tensile and compression tests where the test specimens are clamped at each end vertically by two clamps attached to the machine. The lower arm of the machine, which includes the clamp, has limited vertical motion while the upper arm height can be adjusted as desired up to a maximum height of approximately 36". The Instron machine also has the capability of performing fatigue testing which is the main focus of this thesis.

In order to mount the test specimens to the Instron machine for Mode I constant amplitude load testing, it was necessary to fabricate a test fixture that would hold the test specimen in a horizontal position with one end fixed and the other end free acting as a double cantilever beam.

Figure 34: Instron 8801 Series Machine

3.3.1. Fixture Design Considerations

There are a few design constraints that were taken into consideration while designing the testing fixture. First, it was necessary to account for possible interfaces between the Instron machine and the fixture. At the base of the Instron machine, where the lower arm of the machine starts, there are two screw holes located about 4.5” away from the arm that will be used as the interface points between the machine and the testing fixture as shown in Figure 35: Test fixture Interface to Instron machine

Figure 35: Test fixture Interface to Instron machine

The second design constraint was the height variation of the lower and upper arms of the machine. The upper arm of the Instron machine is set up at a constant height while the lower arm extends vertically as desired up to a maximum distance of 6 inches. In order to perform the amplitude load testing, it is necessary to place the test specimen between the arms so a tensile force can be applied at the upper and bottom surface of the delaminated portion of the test specimen. The distance to each arm of the Instron machine

to the surface of the specimen needs to be the same in order to provide an equal tensile force at each surface.

The last constraint consisted in the interface between the test specimens and the machine. The Instron machine clamps can only hold a specimen in the vertical position. For this reason, a fixture attachment interface between the clamps and the aluminum tabs bonded to the specimen was designed. The main intent of the fixture attachment interface is to effectively transfer the load from the Instron machine to the surface of the aluminum tabs in a horizontal position.

3.3.2. Fixture Attachments

The fixture attachment was design to create an interface between the Instron machine clamps that hold the test specimen in a vertical position and the carbon fiber plates which will be positioned horizontally. The tensile force applied from the Instron machine must be transferred to the each surface of the test specimen (top and bottom surface) in order to expand the initial fatigue created by the initial delamination in the plates. The fixture attachment takes the tensile load and creates a load path that transfers the load from its flange to its base where it interfaces with the aluminum tab that finally transfers the load to the surface of the carbon fiber plate.

Two different base shape fixture attachments were designed for the two types of aluminum tabs used. The minimum width of the flange was designed based on the maximum width of the Instron machine clamps. The length of the flange was designed based on the distance from each clamp to the base of the carbon fiber plate once attached to the main testing fixture. The base was designed based on the shape and dimensions of

The fixture attachment for the rectangular base and the triangular type with rectangular base aluminum tabs are shown below in Figure 36 and Figure 37 respectively.

Figure 37: Fixture Attachment for Triangular Shape with Rectangular Base Aluminum Tab

3.3.3. Testing Fixture

The main testing fixture was designed to hold the test specimen in a horizontal position and to provide a fixed constraint at one end of the carbon fiber plates. The fixture design was driven mainly by the design constraints mentioned above in section 3.3.1. However, it was also design to be adjustable along its base and height. At the base, the interface points with the Instron machine allow the fixture to slide towards and away the lower arm of the machine. This will make the fixture useable for future testing with test specimens with longer and wider dimensions.

The height of the fixture can also be adjusted by using two overlapping plates that slide and lock in place with two bolts. Figure 38 shows the adjustability interfaces of the test fixture.

Figure 38: Test Fixture Adjustability Interfaces

The test fixture was machined in separate blocks to due to the size of the fixture and to allow the design adjustability. Moreover, it was easier and faster to machine separate blocks than machine a whole block of aluminum with many different features using a vertical mill machine. It is composed of six parts as shown in the exploded view in Figure 39 and whose 2D drawings with dimensions are shown in Appendix A.

Figure 39: Test Fixture Exploded View

The assembled test fixture by itself and attached to the Instron machine is shown below in Figure 40.

Figure 40: Assembled Test Fixture

CHAPTER 4: EXPERIMENTAL PROCEDURE

4.0. Tensile Testing

The objectives of the tensile test were to obtain the main material properties of the specimens, the ultimate loads and the failure behavior. Moreover, the material properties obtained would be use in the Finite Element model for numerical analysis.

The tensile test was performed in the Aerospace Engineering Department Structures and Composites laboratory using an Instron 8801 machine. Before starting the tensile tests, the Instron machine needed to be prepared and set up.

Two different software packages were used to control the Instron machine. The FastTrack console was the user interface and controlled all of the functions of the machine. The Merlin Instron software was used to control the test.

4.0.1. Instron Machine Preparation and Set Up

The FastTrack console also served as a bridge port between the control and data acquisition software used for the test. It displays different signals such as position, load, strain, strain percentage and time during the course of a test. The FastTrack console test toolbar is shown in Figure 41.

Figure 41: FastTrack Console Test Toolbar

The FastTrack Console allows the user to prepare the machine to perform the testing by setting up the functions required to perform a specific type of test. The operator has the option of preparing the machine through the FastTrack Console or through the operator control board shown in Figure 42. Both set up options are interchangeable as some settings could be set up in the operator control panel and others using the FastTrack Console software.

Figure 42: Instron Machine Operator Control Panel

The FastTrack Console toolbar monitors the status and any malfunction of the compressed air lines that power the hydraulic system of the Instron machine. To start the machine a two step process is followed. First the hydraulic power is turned on by pumping the compressed air to the machine, and then the electric power system that controls the actuators is turned on. This process is monitored in the FastTrack Console toolbar by the controller button shown in Figure 41.

Once the machine is on, the machine upper crosshead was moved to a specific height where the upper and lower grips would clamp the aluminum end tabs bonded to each end of the test specimen. The upper grip is static and the lower grip rotates a maximum of $\pm 90^\circ$, due to this, the lower grip needed to be aligned to the upper grip in order to hold the test specimen in a straight position. This alignment is extremely important as it would prevent bending and buckling of the test specimen while under tensile loading.

As part of the initial set up is the calibration of the machine before starting the test. The calibration can be done using the FastTrack Console or the Operator Control Panel. The set up was done using the operator control panel in which the strain, load and position were calibrated and set to relative zero after the machine grips are set in place to hold the test specimen.

4.0.2. Merlin Software Set Up

The Merlin software was used to perform the tensile test. It displays and plots data as it is being recorded and calculates the mechanical properties of the specimen being tested once the test is over. To set up the test, the Tahry test method was selected as

shown in Figure 43, which is prearranged with all the parameters to direct the Instron machine to apply a tensile load at a specific rate.

Figure 43: Merlin Software, Test Method Selection Screen

Once the method was selected, the Merlin software workspace was shown. The workspace contains shortcuts to all the functions necessary to set-up and run the tensile test organized in toolbars. It includes the LabTool toolbar and the motion control toolbar. The LabTool toolbar contains various functional units to set-up the test; it includes the test control, sample, results, graph, and report labtools. The motion control toolbar allows the user to start and stop the test, return to gauge length and reset the gauge length. The Merlin software workspace screen and toolbars are shown in Figure 44 and Figure 45 respectively.

Figure 44: Merlin Software Workspace

Figure 45: Merlin Software Workspace Toolbars

The first task for setting up the test was to configure the test parameters in the test control LabTool. The test control section allows the user to indicate the type of data parameters and time intervals in which the data is to be recorded. For the test performed, the data capture was selected as automatic and the capture interval was preselected by the program as shown in Figure 46.

Figure 46: Test Control Set Up for Tensile Test

Next, the Sample LabTool was set-up. The test specimen dimensions such as length, width and thickness were input in this section. This section was subdivided in four categories: *Define*, *Specimen*, *Notes*, and *user Inputs*. For the tensile test, only the *Define* and *Specimen* categories were used. The *Notes* and *User Inputs* categories were omitted since they are only used to added additional descriptions and notes regarding the test. In the *Define* section, the name given to the sample, its geometry type and the number of specimens to be tested was inputted. In the *Specimen* section, the geometric characteristics of the test sample such as width, thickness and length were inputted. The sample set up screens is shown in Figure 47.

Sample - Tension

Define | Specimen | Notes | User Inputs

Name: Epoxy # 1 Edit...

Geometry: Rectangular Resume...

Number of specimens: 1 Replay...

Specimens tested: 0 End

End&Save...

Sample - Tension

Define | Specimen | Notes | User Inputs

Number: 1 (Untested) ☐ Excluded Measure... Next

☐ Reject Enable Reject

Specimen name: Epoxy # 1

	Initial		Final	
Width:	0.93000	in	0.93000	in
Thickness:	0.10000	in	0.10000	in
Length:	7.00000	in	7.00000	in

Figure 47: Sample Set Up Screens

The following LabTool to be set up was the results. However, there was no need to set it up since the settings of this LabTool had been previously set up and saved when the test method Tahry was created. The results requested were the maximum load, extension at break, Modulus of Elasticity, Stress at 0.2% yield, tensile strength, and extension at break.

Finally, the graph LabTool was set up. This LabTool allows the user to create plots of the data collected by the Merlin software. The axis and graph setup tool was used to select the data to be plotted and to arrange the details of the graph as shown in Figure 48.

Figure 48: Graph LabTool Setup Screens

4.0.3. Test Specimen Mounting and Set Up

After preparing the Instron software for the test, the test specimen was mounted onto the Instron machine. The hydraulic grips were opened and one end of the specimen was clamped to the lower grip of the machine as shown in Figure 49. While clamping the lower end of the specimen, it was necessary to use a straight edge to keep the specimen straight in the vertical direction while its upper end is clamped by the upper grip.

Once having the lower grip secured and clamped, the upper grip height was adjusted to fit the length of the specimen and match the upper end of the specimen. The upper grip was then lined up with the lower grip to keep the specimen straight and avoid any bending or twisting caused by misalignments between the grips and then clamped.

Figure 49: Test Specimen Mounting on Instron Machine

An Instron dynamic axial clip-on extensometer as shown in Figure 50 is attached to the middle of the specimen to measure the strain in the longitudinal direction as the tensile load is applied. The extensometer is attached to the specimen with rubber bands.

Figure 50: Instron Dynamic Axial Clip-on Extensometer

After the software and hardware had been set up, the test was started using the Merlin software. The tensile load was applied during the test and once the specimen got to its yielding point, the Merlin software alerts the user to remove the extensometer so it would not be damage after the specimen fails. Once the extensometer is removed, the test continues until the specimen breaks and the tensile load is the brought to zero.

4.1. Amplitude Load Testing

The main objective of the amplitude load test is to determine the number of loading cycles required for the initial delamination to start propagating through the specimen and characterize its fatigue behavior. The amplitude load test was performed at the same location and using the same machine as the tensile test but using a different load cell. A 1kN load cell was used in order to prevent over-testing the specimens due to the low forces required to break the test specimens.

To perform this test three software packages were used. The Instron FastTrack console and Single Axis Max (SAX) software were used to setup and control the test. Matlab was used to collect test data.

4.1.1. Single Axis Max Software Set Up

The Single Axis Max software was used to set up and run the test. It is designed for fatigue testing and allows the user to perform high and low cycle fatigue, service simulation, block loading and random loading. To begin the set up of the test, the Fatigue T-T test method was selected as shown in Figure 51. This method will apply a tension-tension load to the specimen.

Figure 51: SAX Software, Test Method Selection Screen

After the test method selection, the SAX software workspace was shown. The workspace is organized in allows the user to set up the test and to start and stop it. The setup is done in the wave generation and data logging sections. The workspace also shows a live progress summary of the test indicating the number of data points collected and the number of cycles. The SAX workspace screen is shown in Figure 52.

Figure 52: SAX Workspace Screen

The test parameters including the loading conditions were setup in the wave generator section. This section is divided in five categories: Control parameters, Shape, Test Start Action, Test Ends When, and Test End Action. The control parameters category allows the user to select the load input form. The waveform generator input screen is shown in Figure 53.

Figure 53: SAX Waveform Generator Input Screen

4.1.1.1. Waveform Generator Control Parameters

For this test, a load input was selected since the failure characteristics of the test specimens were defined in terms of forces. The amplitude load chosen was in the form of a sinusoidal wave. In order to define the characteristics of the input sinusoidal wave, it was necessary to determine the amplitude and mean force that will form the sinusoidal input. These two inputs were derived from the specimens tested under tensile load. Two specimens from each lot as designed in

Table 4 were selected from which an ultimate failure load average was calculated. An average value was chosen to be more representative of all the test specimens from the lot. Figure 54 shows a sample of the tensile load results for test lot A. Two specimens were selected and the ultimate failure load is obtained from the highest peak for each specimen. Then an average ultimate failure load is calculated as the reference amplitude of the sinusoidal load input.

Figure 54: Ultimate Failure Load for Test Lot A

The actual amplitude used for testing was a percentage of the average ultimate failure load derived from the tensile load testing. The specimens were tested to 72.5%, 69.5%, 66.5%, 63.5%, and 60.5% of the average ultimate failure force. A mean force of 50% of the average ultimate failure force was selected. Table 6 shows the inputs used for

amplitude load testing for test lot C. A pictorial definition of the amplitude and mean force inputs are shown in Figure 55.

Table 6: Amplitude and Mean Force Testing Inputs for Test Lot C

Plate Lot #	Ultimate Failure Load Average (lb)	% Failure Load	Testing Load (lb)	50% P_Fail = Mean Force (lb)	Amplitude Input (lb)	Upper Bound Amplitude (lb)	Lower Bound Amplitude (lb)
C2	94.34	72.50%	68.40	47.17	42.45	68.40	25.94
C3	94.34	69.50%	65.57	47.17	36.79	65.57	28.77
C4	94.34	66.50%	62.74	47.17	31.13	62.74	31.60
C5	94.34	63.50%	59.91	47.17	25.47	59.91	34.43
C6	94.34	60.50%	57.08	47.17	19.81	57.08	37.27

Figure 55: Amplitude and Mean Force Input Definitions

Frequency and sample rate were also part of the required inputs in the waveform generator. During the process of calibration both inputs were varied to see the effects on output and testing time. The frequency was varied from 0.5 Hz to 5 Hz during calibration

and it was chosen a testing frequency of 1 Hz. This frequency allowed the control system to closely match the input and output load. The sample rate was also varied during calibration to limit the amount of data outputted by the system. The sample rate was set for 0.05 kHz. A summary of the inputs required to start the amplitude load testing for test lot E is shown in Table 7.

Table 7: Waveform Generator Inputs for Test Lot E

Sample ID	Mean Load (lbf)	Amplitude (lbf)	Frequency (Hz)	# Input Cycles	Sample Rate (kHz)	% Ult Force	% Force Drop
E2	43.17	38.85	1.0	50000	0.05	72.50%	10.00%
E3	43.17	33.67	1.0	50000	0.05	69.50%	10.00%
E4	43.17	28.49	1.0	50000	0.05	66.50%	10.00%
E5	43.17	23.31	1.0	50000	0.05	63.50%	10.00%
E6	43.17	18.13	1.0	50000	0.05	60.50%	10.00%

Two test specimens from each test lot were used for tensile testing while the remainder specimens were used for amplitude testing. A total of 32 specimens were used for tensile testing and 88 for amplitude load testing.

CHAPTER 5: EXPERIMENTAL RESULTS

During the experimental phase of this thesis, a variety of samples were tested to tensile and amplitude loads. All unilateral and woven prepreg carbon fiber test specimens fabricated were tested under either load condition as well as during calibration of the testing hardware. Moreover, matrix test specimens were also tested under tensile load.

The experimental results presented as follows are only for the woven prepreg specimens.

5.0. Tensile Test Results

The tensile test was performed using the Instron machine and the Merlin software which recorded the data. A total of 32 woven prepreg specimens were tested under tensile loads and were designated in lots according to the plate they were cut from. Each plate fabricated yielded two lots of test specimens as summarized in Table 4. All specimens were tested to failure to obtain the input parameters used during amplitude testing.

The data is organized and summarized by plates in order to characterize the specimens fabricated from the same source to better explain the behavior during testing. The results presented in the following section will be detailed to every plate fabricated and categorized by lots.

A plot of the summary for all the tensile data for all the specimens tested organized by plates is shown in Figure 56.

Figure 56: Tensile Test Data for All Plates

Figure 56 shows the load per unit width vs. displacement summary for all woven prepreg specimens tested. All plates showed a similar behavior as indicated by the trend on the plot. Plates 1 through 4 and plate 7 had comparable property characteristics as the average of the ultimate failure strength is 54.9 lbs/in while the average ultimate strength of plates 6 and 8 is 32.1 lbs/in. A 52.5 % difference between the ultimate strength values of plates 6 and 8 compared to the rest can be explained to variances in the manufacturing process of these two particular plates such as layup, curing time among others and/or defects in the plates such as matrix voids. Figure 57 summarizes the average ultimate strength for all the plates.

Figure 57: Ultimate Strength Data

Since all the plates had similar trends, the data was averaged to yield the overall ultimate strength and stiffness of all the test specimens. Moreover, the general behavior of the specimens was best characterized by the averaged data. Figure 58 shows the average of all the specimens tested and presented in Figure 56. The woven prepreg carbon fiber specimens were controlled by a non-linear plastic behavior as shown in Figure 58 by the blue section of the curve. The linear elastic behavior of the specimens was represented by the red portion of the curve which in comparison was smaller than the non-linear plastic behavior.

Figure 58: Tensile Test Averaged Data

The ultimate strength failure load for the test specimens was 49.16 lbf/in which corresponded to a deflection of 0.049 in. The average stiffness of the specimens was 1832 lbs/in². Table 8 shows the tabulated data summary and average for all the plates tested.

Table 8: Tensile Test Tabulated Data Summary

Plate #	Yield Force/width (lbf/in)	Ultimate Force/width (lbf/in)
1	32.79	54.10
2	38.01	56.40
3	31.13	53.54
4	31.93	58.03
5	41.69	52.50
6	27.77	32.09
7	29.87	54.62
8	31.19	32.04
Average	33.05	49.16

5.0.1. Plate # 1: Lot A-B

Plate 1 was divided into lot A and B providing two specimens from each lot. The load per unit width (lb_f/in) vs. the vertical displacement (in) is shown in Figure 59.

Figure 59: Tensile Test Data – Plate 1, Lot A-B

All specimens tested from plate 1 had similar characteristics and mechanical behavior. The average yield force per with was 32.79 (lb_f/in) and occurred when the vertical displacement of the areas adjacent to the delamination reached 0.019 in. The standard deviation of the yield was 1.71 which indicated that the specimens from plate 1 yielded close to the average. Moreover, the average ultimate failure force per unit width was 54.1 (lb_f/in) and occurred at a vertical displacement of 0.06 in. A summary of the yield and ultimate force per unit width for all the specimens form plate 1 is summarized in Table 9.

Table 9: Tensile Test Data Summary – Plate 1, Lot A-B

Plate #	Lot ID	Specimen ID	Yield Force/width (lbf/in)	Ultimate Force/width (lbf/in)
1	A	A1	35.08	56.78
		A7	33.10	53.93
	B	B1	31.45	54.49
		B7	31.53	51.19
Average			32.79	54.10

The averaged data for the specimens from plate 1 is shown in Figure 60 and describes the overall mechanical behavior of plate 1. The carbon fiber plate's response was dominated by a plastic behavior as noted by the blue section of the graph. The linear elastic behavior was denoted by the red section of the graph. The average elastic stiffness was 1695.5 lbs/in².

Figure 60: Tensile Test Averaged Data - Plate 1, Lot A-B

5.0.2. Plate # 2: Lot C-D

Plate 2 was divided into lot C and D providing two specimens from each lot. The load per unit width (lb_f/in) vs. the vertical displacement (in) is shown in Figure 61.

The data for the specimens showed a small scatter range but followed a similar trend. Specimen “prepreg C1” as noted in the blue curve, showed a slight difference trend during the start of test as the initial loads to create a displacement were relatively higher than the rest of the specimens. This was attributed to misalignment of the aluminum tabs that creates an initial moment to be applied to the specimen therefore a higher initial load to obtain a vertical displacement. Once the tensile load overcomes the moment load, the specimen behaved similarly as the other specimens.

Figure 61: Tensile Test Data – Plate 2, Lot C-D

The average yield force per with was 38.01 (lbf/in) and occurred when the vertical displacement of the areas adjacent to the delamination reached 0.023 in. The standard deviation of the yield was 8.32 and was considered relatively low; however, it was driven by the low yield force from the specimen prepreg D1. Moreover, the average ultimate failure force per unit width was 56.4 (lbf/in) and occurred at a vertical displacement of 0.077 in. A summary of the yield and ultimate force per unit width for all the specimens form plate 2 is summarized in Table 10.

Table 10: Tensile Test Data Summary – Plate 2, Lot C-D

Plate #	Lot ID	Specimen ID	Yield Force/width (lbf/in)	Ultimate Force/width (lbf/in)
2	C	C1	45.60	61.56
		C7	44.69	52.78
	D	D1	29.48	55.35
		D7	32.26	55.89
Average			38.01	56.40

The averaged data for the specimens from plate 2 is shown in Figure 60 and describes the overall mechanical behavior of plate 2. The carbon fiber plate's response was dominated by a plastic behavior as noted by the blue section of the graph and similar to plate 1. The discontinuity shown at the end of the plastic region of the curve was caused by a high standard deviation in the data near to the fracture point in specimen prepreg C1. The linear elastic behavior is denoted by the red section of the graph as was greater than of plate 1. The average elastic stiffness was 1728.5 lbs/in².

Figure 62: Test Averaged Data - Plate 2, Lot C-D

5.0.3. Plate # 3: Lot E-F

Plate 3 was divided into lot E and F providing two specimens from each lot. The load per unit width (lb_f/in) vs. the vertical displacement (in) is shown in Figure 63. Specimen “prepreg F7” as noted in the green curve, showed the same type of behavior as specimen “prepreg C1” shown in Figure 61 where an initial moment was applied to the specimen instead of a direct tensile load. In this case, the transition between the moment load and the tensile load was different than the one seen in “prepreg C1”. This moment load was induced by the misalignment of the upper grip of the load cell creating a preload condition that allowed the load cell grip to adjust from the misalignment as the tensile load is increased. Even though no moment loads should be applied to the specimen, the

alignment of the load cell was not perfect in every case and the moment load applied was benign since it did not caused the specimen to yield.

Figure 63: Tensile Test Data – Plate 3, Lot E-F

The average yield force per with was 31.1 (lbf/in) and occurred when the vertical displacement of the areas adjacent to the delamination reached 0.018 in. The standard deviation of the yield was 2.92 which indicate that the specimens from plate 3 yielded close to the average. Specimen “prepreg F7” had low incidence in the standard deviation as it yielded around the same load per unit width as the other specimens. Moreover, the average ultimate failure force per unit width was 53.5 (lbf/in) and occurred at a vertical displacement of 0.1 in. A summary of the yield and ultimate force per unit width for all the specimens form plate 3 is summarized in Table 11.

Table 11: Tensile Test Data Summary – Plate 3, Lot E-F

Plate #	Lot ID	Specimen ID	Yield Force/width (lbf/in)	Ultimate Force/width (lbf/in)
3	E	E1	30.84	53.35
		E7	33.82	51.29
	F	F1	27.16	55.55
		F7	32.69	53.96
Average			31.13	53.54

The averaged data for the specimens from plate 3 is shown in Figure 64 and describes the overall mechanical behavior of plate 3. The carbon fiber plate's response was dominated by a plastic behavior as noted by the blue section of the graph and similar to the previous plates. The average elastic stiffness was 1659.7 lbs/in².

Figure 64: Test Averaged Data - Plate 3, Lot E-F

5.0.4. Plate # 4: Lot G-H

Plate 4 was divided into lot G and H providing two specimens from each lot. The load per unit width (lb_f/in) vs. the vertical displacement (in) is shown in Figure 65. Specimen “prepreg G7” as noted in the blue curve, showed the same type of behavior as specimen “prepreg F7” shown in Figure 63 however with a lower initial moment load. This induced moment load was benign as it did not cause the specimen to yield. The yield was caused by tensile load only.

Figure 65: Tensile Test Data – Plate 4, Lot G-H

The average yield force per with was 31.9 (lb_f/in) and occurred when the vertical displacement of the areas adjacent to the delamination reached 0.02 in. The standard deviation of the yield was 3.75. Moreover, the average ultimate failure force per unit width was 58.0 (lb_f/in) and occurred at a vertical displacement of 0.08 in. A summary of

the yield and ultimate force per unit width for all the specimens from plate 4 is summarized in Table 12.

Table 12: Tensile Test Data Summary – Plate 4, Lot G-H

Plate #	Lot ID	Specimen ID	Yield Force/width (lbf/in)	Ultimate Force/width (lbf/in)
4	G	G1	35.78	56.94
		G7	33.35	54.84
	H	H1	26.91	61.47
		H7	31.70	58.86
Average			31.93	58.03

The averaged data for the specimens from plate 4 is shown in Figure 66 and describes the overall mechanical behavior of plate 4. The carbon fiber plate's response was dominated by a plastic behavior as noted by the blue section of the graph and similar to the previous plates. The linear elastic region of the plates is denoted in red. The average elastic stiffness was 1763.6 lbs/in².

Figure 66: Test Averaged Data - Plate 4, Lot G-H

5.0.5. Plate # 5: Lot I-J

Plate 5 was divided into lot I and J providing two specimens from each lot. The load per unit width (lb_f/in) vs. the vertical displacement (in) is shown in Figure 67. Specimen “prepreg J8” as noted in the green curve, showed the same type of behavior as specimen “prepreg C1” shown in Figure 61 with an initial moment load present. Moreover, “prepreg J8” and “prepreg I1” showed that the yield and ultimate load occurred very close which indicated that there was no plastic region present in the specimens. This behavior was uncharacteristic and could have been caused by defects in the specimen specially the presence of voids in the matrix or poor curing conditions.

It is important to note that both “prepreg I1” and “prepreg J8” were adjacent to each other and shared the same peel ply strip which created the delamination.

Figure 67: Tensile Test Data – Plate 5, Lot I-J

The average yield force per width was 33.2 (lbf/in) and occurred when the vertical displacement of the areas adjacent to the delamination reached 0.02 in. The standard deviation of the yield was 4.06. Moreover, the average ultimate failure force per unit width was 54.4 (lbf/in) and occurred at a vertical displacement of 0.06 in. The average data calculated did not include specimens “prepreg I1” and “prepreg J8” since they did not have the same mechanical behavior as the rest of the specimens tested. A summary of the yield and ultimate force per unit width for all the specimens from plate 5 is summarized in Table 13.

Table 13: Tensile Test Data Summary – Plate 5, Lot I-J

Plate #	Lot ID	Specimen ID	Yield Force/width (lbf/in)	Ultimate Force/width (lbf/in)
5	I	I1	29.89	30.51
		I8	30.35	51.69
	J	J1	36.10	57.04
		J8	70.42	70.74
Average			33.23	54.37

The averaged data for the specimens from plate 5 is shown in Figure 68. The carbon fiber plate's response was dominated by a plastic behavior as noted by the blue section of the graph and similar to the previous plates. The linear elastic region of the plates is denoted in red. The average elastic stiffness was 1969.6 lbs/in².

Figure 68: Test Averaged Data - Plate 5, Lot I-J

5.0.6. Plate # 6: Lot K-L

Plate 6 was divided into lot K and L providing two specimens from each lot. The load per unit width (lb_f/in) vs. the vertical displacement (in) is shown in Figure 69. Specimen “prepreg L1” as noted in the red curve, showed the same type of behavior as specimen “prepreg I1” shown in Figure 67. In addition, “prepreg L1” did not show signs of yielding and showed immediate fracture after reaching its ultimate failure load. There was no evidence of a non-linear plastic region for this specimen.

Figure 69: Tensile Test Data – Plate 6, Lot K-L

The average yield force per with was 23.8 (lb_f/in) and occurred when the vertical displacement of the areas adjacent to the delamination reached 0.01 in. The standard deviation of the yield was 3.08. Moreover, the average ultimate failure force per unit width was 29.6 (lb_f/in) and occurred at a vertical displacement of 0.06 in. The average

data calculated did not include specimens “prepreg L1” since they did not have the same mechanical behavior as the rest of the specimens tested. A summary of the yield and ultimate force per unit width for all the specimens from plate 6 is summarized in Table 13.

Table 14: Tensile Test Data Summary – Plate 6, Lot K-L

Plate #	Lot ID	Specimen ID	Yield Force/width (lbf/in)	Ultimate Force/width (lbf/in)
6	K	K1	25.66	28.78
		K8	20.26	28.97
	L	L1	39.61	39.61
		L8	25.54	31.01
Average			23.82	29.58

The averaged data for the specimens from plate 6 is shown in Figure 70. The carbon fiber plate’s response was dominated by a plastic behavior as noted by the blue section of the graph and similar to the previous plates. The linear elastic region of the plates is denoted in red. The average elastic stiffness was 2004.7 lbs/in².

Figure 70: Test Averaged Data - Plate 6, Lot K-L

5.0.7. Plate # 7: Lot M-N

Plate 7 was divided into lot M and N providing two specimens from each lot. The load per unit width (lb_f/in) vs. the vertical displacement (in) is shown in Figure 71. All the test specimens behaved with similar mechanical properties.

Figure 71: Tensile Test Data – Plate 7, Lot M-N

The average yield force per with was 29.9 (lbf/in) and occurred when the vertical displacement of the areas adjacent to the delamination reached 0.02 in. The standard deviation of the yield was 3.37. Moreover, the average ultimate failure force per unit width was 54.6 (lbf/in) and occurred at a vertical displacement of 0.06 in. A summary of the yield and ultimate force per unit width for all the specimens form plate 7 is summarized in Table 15.

Table 15: Tensile Test Data Summary – Plate 7, Lot M-N

Plate #	Lot ID	Specimen ID	Yield Force/width (lbf/in)	Ultimate Force/width (lbf/in)
7	M	M1	29.32	56.19
		M8	26.24	56.99
	N	N1	29.52	50.29
		N8	34.39	55.01
Average			29.87	54.62

The averaged data for the specimens from plate 7 is shown in Figure 72. The carbon fiber plate's response was dominated by a plastic behavior as noted by the blue section of the graph and similar to the previous plates. The linear elastic region of the plates is denoted in red. The average elastic stiffness was 1992.9 lbs/in².

Figure 72: Test Averaged Data - Plate 7, Lot M-N

5.0.8. Plate # 8: Lot O-P

Plate 8 was divided into lot O and P providing two specimens from each lot. The load per unit width (lb_f/in) vs. the vertical displacement (in) is shown in Figure 73. Specimen “prepreg P1” as noted in the red curve, showed the same type of behavior as specimen “prepreg L1” shown in Figure 69. Moreover, specimen “prepreg O8” noted in the yellow curve showed similar behavior as specimen “prepreg C1” shown in Figure 61. The trend on this specimen showed an initial moment applied due to misalignment of the aluminum tabs. After the tensile load overcomes the moment load, the general behavior of the specimen is similar to the specimens in blue and green.

Figure 73: Tensile Test Data – Plate 8, Lot O-P

The average yield force per with was 31.5 (lb_f/in) and occurred when the vertical displacement of the areas adjacent to the delamination reached 0.01 in. The standard

deviation of the yield was 3.65. Moreover, the average ultimate failure force per unit width was 32.7 (lbf/in) and occurred at a vertical displacement of 0.04 in. The average data calculated did not include specimen “prepreg P1” since it did not have the same mechanical behavior as the rest of the specimens tested. A summary of the yield and ultimate force per unit width for all the specimens from plate 8 is summarized in Table 16.

Table 16: Tensile Test Data Summary – Plate 8, Lot O-P

Plate #	Lot ID	Specimen ID	Yield Force/width (lbf/in)	Ultimate Force/width (lbf/in)
8	O	O1	30.96	30.96
		O8	35.44	35.44
	P	P1	30.15	30.15
		P8	28.21	31.62
Average			31.53	32.67

The averaged data for the specimens from plate 8 is shown in Figure 74. The carbon fiber plate’s response was dominated by a plastic behavior as noted by the blue section of the graph and similar to the previous plates. The linear elastic region of the plates is denoted in red. The average elastic stiffness was 2099.3 lbs/in².

Figure 74: Test Averaged Data - Plate 8, Lot O-P

5.1. Amplitude Load Test Results

The amplitude load test was performed using the Instron machine and the Single Axis Max (SAX) software. The SAX software controlled the test and recorded all the data. A total of 88 woven prepreg specimens were tested under amplitude loads and were designated in lots according to the plate they were cut from. Each plate fabricated produce two lots of test specimens as summarized in

Table 4.

All specimens were tested to failure based on the ultimate failure loads obtained during the amplitude testing. The specimens were tested to amplitude loads equivalent to 72.5%, 69.5%, 66.5%, 63.5%, and 60.5% of the average ultimate failure load and at a

constant mean force equivalent to 50%. Section 4.1 of the experimental procedure includes more detail on the selection of the input parameters for the amplitude load testing. A sample input used for lot C testing is summarized in Table 6 and a description of the input loads definition is shown in Figure 55.

A constant amplitude load with a tension/tension load profile was used throughout the test. In order to avoid pre-stressing the specimens and low load failures, the tension/tension profile was selected. Figure 75 shows the input load for test specimen “prepreg D3”. The input load in tension/tension as the input load is always positive as seen in the graph. A compression load would be characterized as a negative load in the graph if compression load was present.

Figure 75: Input Load Sample

The failure criteria was selected to be a drop of 10% of the input force, once the failure criteria was met the test ended. The fatigue behavior of the test specimens showed that over time, as the delamination propagates, there is a decrease in stiffness which relates to a decrease in the input force until the failure criteria is met. This behavior is shown in Figure 76 as the input load over time decreases until the failure criteria is met. The load vs. input graph shown below was for specimen “prepreg D3”.

Figure 76: Input Load for Specimen “prepreg D3”

The different amplitude load percentages were tested on test specimens from each lot. Specimens from lot A were mainly used for load calibration under each amplitude load percentage. It was necessary to perform this calibration for each load type since corrections to the SAX software were needed in order to achieve the desired input load.

The fatigue test data for all the carbon fiber prepreg specimens tested is shown in Figure 77. The number of cycle to failure vs. the percentage ultimate failure load is presented.

Figure 77: Fatigue Test Data Summary

High rate loading was used all through the test in order to reach convergence. During preliminary runs, it was shown that using low loading rates would not yield convergence on the cycle life of the specimens and that a different failure criteria would have to be used in order to determine the number of cycles to failure. For such cases where low rate loading is used, strain failure criteria would be used to easily reach convergence since measurement would be based on delta displacements.

To easily show convergence on the data points collected during the test, an average on the number of cycles at each loading rate was used. The data that was

believed to be outliers due to early failure or run outs of the test were not included in the average. The average fatigue data is shown in Figure 78.

Figure 78: Fatigue Average Data

The trend shown in Figure 78 indicates that convergence is close to be reached and at ultimate failure load rates lower than 60% but not greater than 55% and above than 20000 cycles to failure. At this point where convergence would be reached, load rates less than the convergence rate would cause low effects on the life cycle of the specimens.

CHAPTER 6: NUMERICAL ANALYSIS

6.0. Finite Element Model

The finite element model (FEM) was created using MSC Patran. A 2-D representation of the test specimens including the aluminum tabs was modeled. The orientation of the specimen in relationship to the test hardware and the effect of the created delamination prompted to capture the effects of the loading through the thickness of the specimen.

Before creating the model mesh, the geometry was divided in surfaces representing the different interfaces within the model such as aluminum tabs to carbon fiber plate, delamination region, and delamination plane as shown in Figure 79.

Figure 79: Finite Element Model Interfaces

All the different interfaces are represented in different colors. The elements in red represent the aluminum tabs while the gold and green elements represent the interface between the carbon fiber plates to the aluminum tabs. Purple, gold, green and dark blue

represent the area of the model with initial delamination. Light blue and black colored elements represent the area without delamination. Since the model is representing the thickness of the carbon fiber plate, the plane of delamination corresponds to the interface between green, dark blue and light blue elements with gold, purple, and black elements.

The 2D model was constructed with CQUAD4 quadrilateral shell elements and CBUSH spring elements as shown in Figure 80. The shell elements were used to represent both the carbon fiber plate and the aluminum tabs and its properties were defined in the PSHELL cards. The spring elements were used to represent the stiffness of the matrix interface at the plane of delamination and its properties were defined in the PBUSH card.

All the nodes and elements in the FEM were referenced with respect to a local coordinate system located at the end of the delamination region; it was created to have a visual reference from where the matrix interface started.

Figure 80: Finite Element Model Element Descriptions

The PSHELL property card requires the input of the shell thickness. If the thickness it is not defined in the PSHELL property card, then it must be defined in the CQUAD4 entry. The finite element was modeled as a 2D representation of the thickness of the carbon fiber plate therefore the shell elements represent the thickness and the length of the specimen. A 1.5 in thickness used in the PSHELL property card represents in this instance the width of the carbon fiber plate. The finite element model width representation through the use of 2D properties is shown in Figure 81.

Figure 81: Finite Element Model Width Representation

6.1. FEM Material Properties

The finite element model used two different material properties to represent the components of the test specimen assembly. The aluminum tabs were represented using an isotropic material property definition MAT1 property card while the carbon fiber plate was represented using a shell element orthotropic material MAT8 property definition card. The material properties for the aluminum 2024-T81 were obtained from material property database website MatWeb. Since the material properties for woven prepreg

carbon fiber T300/LTM45-1 sheets were not available, the properties for T300/RS-3 were used instead and obtained from Tencate Advance Composites website.

Besides the material properties for both aluminum and T300/RS-3 carbon fiber, it was necessary to obtain the spring stiffness for the PBUSH card to represent the matrix interface at the plane of delamination. The material properties information for the matrix used on the carbon fiber prepreg sheets were not available and after a thorough research with no findings it was decided to fabricate matrix test specimens to obtain its material properties. The procedure to fabricate the matrix test specimens is described in section 2.2.2. while the tensile test procedure is described in section 4.0. The test articles were fabricated from a matrix mixture ratio of 3:1 of Aeroepoxy PR2032 epoxy resin and Aeroepoxy PH3660 epoxy hardener.

A total of 10 matrix test specimens were tested out of which 4 specimens yielded comparable data. The data was averaged to calculate the stiffness of the matrix specimens. The averaged stress vs. strain curve extracted from the test data is shown in Figure 82. The calculated average elastic stiffness was 297700 lbs/in².

Figure 82: Averaged Matrix Test Specimens Stress vs. Strain

6.2. FEM Loads and Boundary Conditions

The boundary conditions used in the finite element analysis simulated the test setup. A fixed constrain in all six degrees of freedom was applied to one of the aluminum tabs as well as to the opposite edge of the carbon fiber plate. These boundary conditions simulated the upper grip of the Instron machine which was set at a specific height above the centerline of the test specimen and the free edge of the carbon fiber plate which was clamped using the test fixture and a bolted plate as seen in Figure 83.

Figure 83: Test Specimen Boundary Conditions Description

The load location applied to the finite element model was simulated as in the test setup where the load was applied through the lower clamp on the Instron machine. The FEM loads and boundary conditions are shown in Figure 84.

Figure 84: Finite Element Model Loads and Boundary Conditions

6.3. Finite Element Analysis

A linear static analysis was performed to simulate the tensile testing of the carbon fiber plates using NASTRAN. The applied loading used in the analysis was created in various load cases incrementing the load applied at each load case. A total of 10 load cases were used to simulate tensile testing loading.

6.4. Finite Element Analysis Results

The objective of the finite element analysis was to correlate the testing results. Based on this premise, the parameters used to perform the numerical analysis correlation were mainly based on the amount of vertical displacement after the delamination region created by the linear static loads.

The maximum vertical deflection of the carbon fiber plate with initial delamination was 0.17 in and occurred at the top of the aluminum tab where the tensile load is applied as shown in **Error! Reference source not found..** The fringe plot shows the entire test specimen maximum deflection and the deflection through the length of the carbon fiber plate. The finite element model behaved as expected from what is was seen during the experimental part of this investigation. The same shape deflection was observed where the side of the carbon fiber plate attached to the loaded aluminum tab would experience higher deflections due to the tensile load. Moreover, the specimen deflected in the opposite direction of the applied load which may have been caused by small compression forces created by the deformation of the layers of the specimen experiencing a tensile load.

Figure 85: Finite Element Model Maximum Vertical Displacement

In order to correlate the finite element model with test data, the yielding criteria was used where yield of the test specimen would start at the end of the delamination region. Yielding then was seen in the deformed finite element once the spring elements representing the matrix interface start to deflect. The springs were connected to coincident nodes from adjacent elements from the top and bottom surface of the inner layers at the plane of delamination. In an un-deformed state or before yielding, both coincident nodes would show no deflection. Once yielding occurs, the coincident nodes would show deflection. The yield would then be related to the spring stiffness representing the stiffness of the matrix interface.

The beginning of yielding in the FEM is shown in Figure 86 and started at the end of the delamination region represented by the yellow spring element. The maximum vertical deflection once yielding started was 0.01 in.

Figure 86: Finite Element Model Yielding Interface

A stress contour plot of the highest stress area on the test specimen is shown in Figure 87. The maximum stress occurred at the end of delamination area where yielding starts as it was expected showing good correlation of the finite element model as the location of high stresses shall occur at the area where the test specimen would yield. There is presence of both tensile and compression stress around that area caused by the deflection of the carbon fiber plate as it starts to yield.

Figure 87: Finite Element Model Stress Contour Plot

CHAPTER 7: RESULTS AND DISCUSSION

7.0. Failure Analysis

The test specimens were tested under mode I loading (tension) and constant amplitude loading based on the failure load from the tensile testing. The main failure mode of all specimens tested was caused by interlaminar fracture due to propagation of an embedded defect added to the carbon fiber plates in the form of delamination. Under both loading conditions, the specimens presented damage growth that reduced the stiffness and strength of the carbon fiber plate leading it to yield and ultimate failures.

During the course of the experimental testing, a localized failure mode that was neither representative; nor induced by the embedded delamination was present in some test specimens. This failure mode was induced by the combined effect of misalignments of the aluminum tabs or the load cell grips with respect to the plane parallel to where the load was applied thus creating a local bending moment. In some cases, the amount of misalignment was small and the bending moment force created was overcome by the tensile load allowing the test specimens to experience a gradual increase of the tensile load up to their yielding point and then to its ultimate failure. On the other hand, when the misalignment was greater, the tensile load necessary to overcome the moment force caused the test specimens to reach their ultimate failure at a greater rate. In this case, the yield and ultimate load failures were almost the same showing purely plastic behavior in the carbon fiber plates.

Another less important failure mode that is just worth nothing was that the bending force from the misalignments of the aluminum tabs and/or the load cell grips

combined with the tensile loads, created enough force to overcome the bond strength between the aluminum tabs and the test specimen. This caused the aluminum tabs to fall off and in other instances created intralaminar fracture where part of the ply in contact with the aluminum tab broke off and stayed attached to the aluminum tab as it fell off.

The majority of specimens tested failed by interlaminar fracture as this was the failure mode to be expected. The localized failure modes were identified at the beginning of the testing phase of the investigation with the first batches of test specimens fabricated which allowed for corrections in the manufacturing process and the testing procedure. The corrections minimize the effects of localized failure modes yielding better data and maximizing the amount of test specimens tested.

7.1. Tensile Testing Analysis

The test specimens fabricated for tensile testing were organized by lots since they were manufactured from different plates as the composite press used to cure the specimens only allowed to cure layups of a maximum size of 18 in by 18 in.

The metric used to characterize all of the specimens' data was the stiffness obtained from the slope of the force per width applied against the vertical displacement produced by that force. The ultimate average strength failure load for the test specimens was 49.2 lbf/in which corresponded to a deflection of 0.049 in. The average stiffness of the specimens was 1832 lbs/in².

The carbon fiber specimens were controlled primarily by a non-linear plastic behavior in comparison to a smaller linear elastic behavior. The embedded delamination defect on the specimens and the orientation in the application of the tensile load (tensile

load applied through the thickness) allowed for a greater region of plastic behavior until ultimate failure was reached.

7.2. Fatigue Testing Analysis

The main objective of the constant amplitude load testing was to create a load per unit width vs. number of cycles curve to characterize the fatigue life of the carbon fiber plates with the initial delamination. The specimens were tested to a constant tensile-tensile amplitude load profile in order to prevent compression loads that could have produced contact between the delaminated sides of the specimens. The test setup was not designed to allow compression loads directly from the load cells of the Instron machine. If compression loads would have been present, it could have damaged the hardware used for the testing.

A total of five different tensile-tensile load profiles were used during the fatigue testing to characterize the optimal load profile to extend the fatigue life of the specimens with an initial delamination defect. The load profiles corresponded to 72.5%, 69.5%, 66.5%, 63.5%, and 60.5% of the average ultimate failure load. A mean force 50% of the average ultimate failure load was used which for some test specimens fell below the yield load but it allowed to decrease the amount of early failures due to high peak loads reaching above the ultimate failure loads.

The fatigue life of the carbon fiber plates with initial delamination would extend over 20000 cycles when the load rate applied is between 55% and 60% of the ultimate failure load. The summary of the number of cycles to failure at each loading rate is summarized in Table 17.

Table 17: Number of Cycles to Failure Summary

	Fatigue Loadin Rate (% Ultimate Failure Load)				
	72.50%	69.50%	66.50%	63.50%	60.50%
# Cycles to Failure	1668	2853	5160	9635	16071

7.3. Experimental vs. Numerical Analysis

The correlation between the experimental and numerical analysis was performed by the comparison of the stiffness if the carbon fiber plates obtained through the slope of the load per unit width applied to the specimen against the vertical displacement produced. Moreover, as means to verify the validity of the numerical model through the use of finite elements, the deformation shape, the maximum vertical displacement at yielding and the location of expected high stress areas (see Figure 87) were considered. The finite element model overall deformation shape due to the tensile loads simulates the experimental deformation shape as shown in Figure 88.

Figure 88: Experimental vs. Numerical Deformation Shape Comparison

The maximum average vertical displacement at yielding was compared for the experimental data and the numerical analysis performed with the finite element model. Table 18 shows a comparison summary for all the plates fabricated for testing with the percentage difference between experimental and numerical results. The overall percentage difference is 43.1%.

Table 18: Maximum Vertical Displacement at Yield Comparison (Experimental vs. Numerical)

Plate #	Avg. Experimental Yield Displacement (in)	FEM Yield Displacement (in)	% Difference
1	0.019	0.012	47.2%
2	0.023	0.014	49.8%
3	0.018	0.011	46.7%
4	0.018	0.011	43.2%
5	0.027	0.015	57.0%
6	0.013	0.010	29.0%
7	0.015	0.011	34.6%
8	0.014	0.011	22.7%
Average	0.018	0.012	43.1%

The average experimental stiffness yielded from the test specimens' was compared with the numerical analysis stiffness prediction. The stiffness was calculated from the slope of the load per unit width against vertical displacement plot shown in Figure 89. The red curve represents the averaged experimental data for the carbon fiber plates with a stiffness of 1832 lbs/in² while the blue curve represents the numerical data with a stiffness of 2778 lbs/in². The percentage difference between numerical and experimental was 41%.

Figure 89: Experimental vs. Analysis Comparison

The numerical analysis predicted a purely linear elastic behavior of the carbon fiber plates as a static linear analysis was performed. The non-linear plastic behavior of the test specimens was not predicted since a non-linear solver and the plastic material properties of the carbon fiber were not available.

CHAPTER 8: CONCLUSIONS

This study presented the experimental and numerical analysis for woven prepreg carbon fiber plates with delamination under tensile and constant amplitude loading. The failure modes and fatigue life were determined experimentally during tensile and constant amplitude testing respectively. A numerical analysis was performed using MSC Patran/Nastran to correlate a finite element model and test data for the tensile load cases. The finite element model was validated by comparing the deformation shape and the predicted high stress concentration areas of the test specimen during the experimental analysis with the predicted numerical analysis.

The effect of material defects such as delamination studied in this research accounts for significant decrease of the stiffness and a reduction in the overall strength of the material. The flexural stiffness is predicted to be reduced by approximately 200% by the addition of an initial delamination. The major factor creating a reduction so significant is that the failure mode is interlaminar affecting only the plies on the plane of delamination. The interlaminar fracture then propagates quicker as the only prevention for crack expansion is the matrix which may have its own defects and imperfections caused in the manufacturing process of the laminate.

The fatigue behavior of the test specimens showed that over time, as the delamination propagated, there is a decrease in stiffness which relates to a decrease in the input force until the failure criteria is met. The fatigue life of the laminates tested would extend over 20000 cycles at a load rate between 55% and 60% of the ultimate failure load if the input load drops above 10%.

The numerical analysis performed showed a difference of 41% to the experimental analysis. This percentage difference is attributed to the inputs chosen for the finite element analysis in specific to the material properties of the laminate. The matrix material properties used in the model were based on a different matrix as the one used in the actual prepreg which would account for the majority of this percentage difference. However, the finite element model was appropriate for numerical analysis based on the assumptions used since it predicted correctly the deformation shape and stress concentration areas seen during the experiment.

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APPENDIX

Appendix A: Test Fixture 2D Drawings

Figure 90: Test Fixture Bottom Base

Figure 91: Test Fixture Top Base

Figure 94: Test Fixture Corner Block

Figure 95: Test Fixture Holding Band