THE EFFECTS OF A DAMAGE ARRESTMENT DEVICE ON THE MECHANICAL
BEHAVIOR OF SANDWICH COMPOSITE BEAMS UNDER FOUR-POINT BENDING

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TITLE: The Effects of a Damage Arrestment Device on the Mechanical Behavior of Sandwich Composite Beams under Four-Point Bending

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ABSTRACT

The Effects of a Damage Arrestment Device on the Mechanical Behavior of Sandwich Composite Beams under Four-Point Bending

The demand for an insert on composite sandwich structures to aid in the arrestment of face-core delamination is of great need. This research studies the use of a damage arrestment device (DAD) that connects the carbon fiber face sheets to the foam core to find whether an increase in the structural integrity of the sandwich beam results. Experimental analysis was employed to test the samples and was verified by a theoretical and finite element approach.

The mechanical properties of LTM45/CF1803 pre-impregnated carbon fiber and Last-A-foam FR 6710 polyvinylchloride foam were experimentally analyzed using ASTM D3039 and ASTM D1621 standards respectively to verify the manufacturer's data for the given material. With all the mechanical data, the effects of adding DAD keys to a delaminated composite sandwich beam were studied under a four-point bending test using ASTM standard D6272 and compared with non-delaminated beams to see if an increase in ultimate strength could be achieved. The initial delamination in the beams under consideration was one inch in length and located in between the loaded span of the beam. Two control beams were utilized for comparison: one with no defects, and another with a one inch delamination introduced at the face-core interface. The DAD keys were added in two different configurations to potentially stop the delamination propagation and increase the ultimate strength. In the first configuration DAD keys were added 0.25 inches on either side of the initial delamination in the transverse direction and provided a significant increase in strength over the delaminated control beam. The second configuration had a DAD key running along the longitudinal axis of the sandwich beam and resulted in a significant increase in ultimate strength over the delaminated control beam. After testing ten successful samples for each of the six different configurations, it was concluded that the addition of DAD keys in both configurations significantly increased the structural integrity of both the delaminated and non-delaminated control beams.

With all the experimental data acquired, finite element models were created in COSMOS. The purpose of the finite element analysis was to validate the experimental results by comparing the deflections of the beam subjected to four-point bending during the experiment to the deflections found numerically. The deflections for the various DAD key configurations found in the experimental work were in agreement with the finite element results.

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LIST OF SYMBOLS

Latin

A	Area (in ²)
b	Width (in)
D	Sandwich Beam Deflection (in)
d	Depth (in)
E	Elastic Modulus (psi)
h	Specimen Height (in)
I	Moment of Inertia (in ⁴)
L	Specimen Length (in)
m	Slope
P	Load (lbf)
R	Load Rate (lbf/min)
V	Volume Fraction
Z	Strain Rate (in/in)/min

Greek

Δ	Change in a given variable
δ	Homogeneous Beam deflection (in)
ϵ	Strain
ν	Poisson's Ratio
ρ	Density (lbm/ft ³)
σ	Normal Stress (psi)

Subscripts

AL	Aluminum
c	Compression
fc	Foam Core
$fibers$	Relating to the fibers
fs	Face Sheets
l	Longitudinal
$matrix$	Relating to the matrix
max	Maximum Value
ST	Steel
t	Transverse
y	y-direction
x	x-direction
xx	x-axis

1 INTRODUCTION

1.1 COMPOSITES OVERVIEW

Composites date back to ancient times when indigenous people would use mud and straw to create a form of shelter. The composites of today's age still use the same principles. The straw used to reinforce the walls of the structure is now called the fiber, and the mud is called the matrix, which holds the fiber in place. We have since moved away from mud and straw for shelter to carbon fiber and epoxy to create our advanced structures of today.

Composites are two or more materials that are combined on a macroscopic scale to create a useful material. The word macroscopic is highly significant here because many materials such as metals are changed on the microscopic level leaving the resulting material homogeneous. Composites are non-homogeneous materials that can exhibit many improved characteristics on the macroscopic scale such as: increased strength, stiffness, fatigue life, corrosion resistance, and thermal insulation.

1.2 TYPES OF COMPOSITES

The three main types of composite materials are fibrous composites, laminated composites, and particulate composites. Fibrous composites are fibers in a matrix, such as carbon fiber in epoxy; laminated composites are different layers of various materials, such as a certain types of knight's armor; particulate composites consist of one or more materials suspended in a matrix of another material, such as concrete.

Fibrous composites, as seen in figure 1, depend highly on the length of the fibers in the matrix. Long fibers are generally much stiffer and stronger than the same material as one homogeneous bulk material. For example, ordinary plate glass fractures at stresses of only a few thousand pounds per square inch, yet glass fibers have strengths up to 400,000 to 700,000 psi¹. From this example we can see the geometry of the fibers place a critical role in the evaluation of the material's strength. The reason that fibers exhibit increased structural performance, is because the crystal structure is aligned along the axis of the fiber itself. In the bulk plate of glass, there are many dislocations of fiber crystal structure that hinder the overall performance of the plate. Typical fibers used in many composite applications include: E-glass, carbon, graphite, steel, aluminum, and titanium. The fibers would be completely useless unless there was a material used to bind them together to form a structural element to take loads. This binding material, as stated in the previous paragraph, is called the matrix. The matrix is essential to

support the fibers and transfer stresses and loads. The matrix is generally much lower in density, stiffness, and strength than the fibers; however when the constituents are combined the result can have a high stiffness and still maintain the low density.

FIGURE 1 – UNIDIRECTIONAL FIBROUS COMPOSITE

In laminated composites, a structure is created such that different layers of various materials create a new macroscopic structure that combines the best aspects of the constituent layers. There are five categories of laminated composites: bimetal, clad metal, laminated glass, plastic-based laminates, and laminated fibrous composites. Bimetals, which are illustrated in figure 2, are laminates of two materials with different coefficients of thermal expansion. When the two materials are bound together and there is a significant temperature change, then there will be a deflection change.

FIGURE 2 - EXAMPLE OF HOW BIMETALS INTERACT WITH EACH OTHER

Clad metal composites are very useful in allowing two materials with different characteristics to create another material with the best properties of both. For example, nails are clad with galvanization so that they do not rust when they are exposed to varying weather conditions. In this case, the strong steel nails that would normally exhibit corrosion are able to withstand harsh weather conditions by being clad with another material.

The most common example of laminated glass is what we call safety glass. Normal glass can be very dangerous because under relatively small strains the glass can fracture and send razor sharp shards everywhere. Another material that is as transparent as glass is polyvinyl butryal plastic. This material can withstand large strains, but has the disadvantage of scratching easily. Safety glass is laminated glass, in which there is one sheet of plastic covered with two sheets of normal glass. This laminated glass can tolerate higher strains and still not scratch so it takes on an improved form compared to normal glass.

Plastic-based laminates are sheets of different materials that are saturated with various materials and subsequently treated for many purposes. One example is Formica, which consists of many layers of phenolic resin-impregnated kraft paper overlaid by a plastic-saturated sheet which is then overlaid with a plastic cellulose mat. Heat and pressure are used to bind the layers together resulting in Formica¹.

Laminated fibrous composites are a mix of fibrous composites and lamination composites. In this type of composite, material is built up with the fibers and matrix, then oriented in different directions with each sheet such that there can be more stiffness in one direction or another. A fibrous laminate can be seen in figure 3 with a direction-specific stacking pattern. This is a common technique used in the aerospace, marine, and automotive industry, where there are specific design requirements that must be met.

FIGURE 3 - LAMINATED FIBROUS COMPOSITE WITH SPECIFIC STACKING PATTERN

Particulate composites consist of particles of one or more materials suspended in a matrix of another material¹. There can be both metallic and nonmetallic particles. One example of a particulate composite is concrete, where sand and rock are bound together by cement and hardened. Like concrete, the particles that are added to the mixture can be anything from rubber to glass flakes to steel. Figure 4 shows a particulate composite on the microscopic level; the different colors represent the different materials that make up the element.

FIGURE 4 – PARTICULATE COMPOSITE ON THE MICROSCOPIC LEVEL

1.3 SANDWICH COMPOSITES

ASTM (American Society for Testing and Materials) defines a sandwich structure as a special form of a laminated composite comprised of different materials that are bonded to each other so as to utilize the properties of each separate component to the structural advantage of the whole assembly. A sandwich structure, as seen in figure 5, is one that is layered with two very strong and stiff face sheets that are bonded to a lightweight and compliant core.

FIGURE 5 - A SANDWICH COMPOSITE WITH TWO CARBON-FIBER FACE SHEETS AND A PVC FOAM CORE

The premise behind sandwich structures is similar to the idea behind I-beams. These two structures are efficient because as much of the material as possible is placed in the flanges situated farthest from the center of bending or neutral axis². Only enough material is left in the connecting web to allow the flanges to act in unison and resist shear and buckling loads. In the sandwich structure, the faces take the place of the flanges and the core takes the place of the web.

In most sandwich structures used in industry, the core material is generally a thick, low-density, low-performing material and the faces are normally thin, high-density, high-performing material. This configuration allows the entire specimen to have the strength and rigidity of the face material and have a low density given from the core material.

1.4 ADVANTAGES AND DISADVANTAGES OF SANDWICH COMPOSITES

The biggest advantage of sandwich structures is their ability to utilize each material comprising the sandwich to its ultimate limit. Utilizing thin face sheets with high stiffness along with low density cores gives an overall specimen with a high stiffness-to-weight ratio and a high bending strength-to-weight ratio. Sandwich composites have the continuous support of the face sheet, unlike a stiffened structure, which implies that surfaces can remain flat even under quite high compressive stress without buckling². The ability of sandwich structures to remain flat under high loads is a very important quality that aircraft control surfaces must have. The use of foam cores in sandwich structures allows for them to be of great use in spacecraft because of the additional thermal insulation from the core; ensuring a low structural weight. High thermal insulation is what is called an “integrated function” for sandwich structures because this characteristic comes gratis with the concept. Sandwich composites also are free from any nuts, bolts, or rivets ensuring a continuous design, which is a more structurally sound design method. Unlike metals, sandwich composites can be manufactured in one piece, thus reducing assembly costs and ensuring smooth and continuous load paths. As with most design methods, there are numerous disadvantages associated with the sandwich structure.

Because metal has been around for hundreds of years, there are many standards, manufacturing techniques, and accepted methods to making structures utilizing these materials. However, because sandwich composites are relatively new, there are not nearly as many standards for manufacturing methods. Any used manufacturing methods are in their youth and are not common practice. Because there are no standards, any type of quality control is a difficult task especially when the structure being made is an aircraft or spacecraft that must pass the most strict design requirements. The limited data available on composites forces engineers to be extra cautious and conservative in their designs thus designing the structures heavier than needed, which contradicts the main goal of composites: saving weight.

1.5 MANUFACTURING METHODS

There are four main methods that industry uses to manufacture their composite parts: the wet lay-up method, the spray-up method, the vacuum resin infusion method, and the pre-impregnated lay-up method. The goal of all these methods is to insert the fibers in a matrix with a certain curing cycle so as to create a strong structural element to take loads.

The wet lay-up method, seen in figure 6, is one of the oldest methods to creating composites and is still widely used. In this method a male or female mold that is predesigned to the specified component dimensions is used to house the fibers and matrix for the curing cycle.

This method is very flexible yet labor intensive and is thus best used for components in a short production series. Once the mold is made, a special type of gel is coated on the surface to allow the part to be easily taken out once cured. After the mold is coated, the fibers can be added to the mold and the resin can be applied. This is the most labor intensive aspect of the process because the resin must be moved around by hand until the specimen has the correct saturation level of resin to matrix. Although this process is labor intensive and messy, an experienced wet lay-up manufacturer can do much better work than any machine used in the other methods.

FIGURE 6 - THE WET LAY-UP METHOD PICTORIAL REPRESENTATION

In the spray-up method a special mixture of resin and discontinuous fibers are mixed together and shot out of a gun onto a mold; this reduces the manual work required from the wet lay-up method. As can be seen in figure 7, the roving is moved through a chopper and mixed with the resin to makeup a paste of discontinuous and randomly oriented fibers. The manual labor of this method is far less than the wet lay-up method but the final specimen is of far less quality because of the many dislocations of the fibers, resulting in inferior mechanical properties. When using this method to create sandwich structures, the core material is the actual mold and the face material is sprayed directly onto the core.

FIGURE 7 - SPRAY-UP METHOD PICTORIAL REPRESENTATION

The vacuum resin infusion method seen in figure 8 illustrates how a part is created by pulling resin over a component via a vacuum and allowed to cure in the vacuum bag. The sandwich composite with its two faces and a core, are put into the vacuum bag with other materials such as flow media, breathing fabric, and separator to allow the resin to be flowed over the part. After all the components are in the bag and it is sealed, a hole on one side of the bag is created and a vacuum is assembled there. Another hole is made on the opposite side of the bag which allows resin to enter the system. When the vacuum is turned on at one side of the bag, the resin flows into the bag from the opposite side allowing the part to be saturated with the matrix material. The flow media is used so that there is an even layer of resin covering the part; the breather is in place so that the vacuum is always able to suck air and does not get full of resin before the process is over. One large drawback to this procedure is the fact that the component being laid-up does not always get a full and even coat of resin because of the way the resin flows in the bag. Another drawback is the ease at which the vacuum bag can start to leak. Any hole in the sealing tape or in the bag itself is a recipe for disaster since a hole creates air bubbles in the bag and allows for inadequate flowing of the resin. When the proper time and methods are used with the VRI technique, this process can be very effective in making quick accurate parts; however, any small mistakes can lead to disaster.

FIGURE 8 - VACUUM RESIN INFUSION LAY-UP METHOD

Another method that is in large use in the aerospace industry is utilizing heat to cure pre-impregnated (prepreg) carbon fiber. Prepreg is a type of carbon fiber that has already been manufactured into rolls that contain the correct ratio of resin to fiber. To make a part, the prepreg needs to be heated and cured at a specified curing cycle. Prepreg is the least messy, most reproducible, most quality controlled method for creating composite structures. The largest

drawback is the high cost of obtaining prepreg, which limits its use to the aerospace sector and more technical industries. Prepreg is very expensive because it takes many more manufacturing processes, time, and labor to make the composite product with the matrix pre-embedded into the fibers.

1.6 EXPERIMENTAL TESTING OF COMPOSITE SANDWICHES

The theory and differential equations behind composite sandwiches can get messy very quickly. To find such properties as stresses, strains, Young's modulus, Poisson's ratio, and other mechanical characteristics, it is sometimes easier to test the material. Theoretical estimations are sometimes good tools in the early design stages to obtain approximate mechanical properties. However, at later stages more accurate data might be a necessity and then one must rely on testing². Testing is the most important part of the design and verification process of a structure. For example, at some point in a design process one may need to verify the physical behavior of a sub-structure. As hand calculations can give good estimates of mechanical phenomenon, testing or numerical simulation is often necessary to get more accurate real life data.

The testing of composite sandwiches is unlike the testing of any other type of structure. Composites have very few ASTM standards to guide the tester with a proven method. Much of the research currently being conducted on composites involves how to come up with an accurate test method for certain properties. There are some general guidelines that must be followed when attempting to test a composite specimen. Taking extra precaution to avoid notches, uneven surfaces, undercuts, or creating delaminations is key when machining the parts. Also, when machining an entire sandwich specimen, extra measures must be taken to ensure that the sample does not get ruined because of the different materials comprising the sandwich. Some drilling procedures used to cut through the rigid face sheets can start to melt some of the softer cores with lower heat resistances.

The key to testing sandwich composites is to give extreme attention to detail to all lay-up, machining, and physical testing procedures. The extra time that it takes to write down configurations, dimensions, angles, etc. can save a lot of time later in the process when those details are needed.

There are many different physical properties that can be found from testing composite sandwiches. The mechanical properties of the face sheets, core, and entire sandwich can be found from either tension or compression testing in an Instron machine. These types of tests for tensile and compressive properties have ASTM and ISO standards to help guide the process. Other tests

that have ASTM standards relating to them include in-plane shear tests, flexural tests, three-point bending tests, four-point bending tests, impact tests, fatigue tests, and many more.

1.7 APPLICATIONS

The use of composites is in high demand because of their great mechanical characteristics and material properties. The use of the sandwich configuration is a hot topic in the aerospace industry because of its increased stiffness and lightweight properties when compared to the aviation standard which is aluminum. In recent years, the sandwich structure is becoming a widely researched topic because of the continual exploration of the perfect material for the newest spacecraft, car, or racing yacht.

In the civilian world the use of sandwich composites is seen in many of our common modes of transportation. Some of the big rigs we see on the road have storage containers built of sandwich composites. This design configuration allows for great thermal insulation to allow for the shipping of goods such as chemicals, livestock, and even fruit. In addition to the great thermal effects the design has, it also allows for a lower overall structural weight to allow the carrier to increase its payload capacity. Racecars and boats are also seeing a large movement into fiberglass and carbon fiber for the weight reduction. The use of composites in these modes of transportation allows the designers to create complicated geometries that are low in weight, structurally sound, with fewer parts. Figure 9 illustrates the first large commercial boat hull created entirely from sandwich composites.

FIGURE 9 - THE FIRST TEN TON SANDWICH COMPOSITE BOAT HULL

The military and aerospace industry have the ability to take the use of sandwich composites to the next level. One of the largest problems associated with designing aircraft is making a feasible design that is light enough to fly the desired mission. Sandwich composites allow just that. The two face sheets create a material that is almost as stiff as steel and the core

allows for a lower density, which makes the aircraft's total weight much less. Some of the heaviest structures of an aircraft such as the wings, floor, fuselage, and even control surfaces are able to be created from sandwich structures. Figure 10 shows the newest addition to the commercial aircraft transportation world: the Boeing 787. This is the first commercial aircraft in existence to be created almost entirely from composites. The military is currently looking into using sandwich composites on their tanks to allow aircraft to be able to carry multiple vehicles in one trip. As we can see, sandwich composites are a very versatile material that will hold a strong position in both the commercial and military future.

FIGURE 10 - BOEING'S FIRST COMPOSITE COMMERCIAL AIRCRAFT — THE 787 DREAMLINER

1.8 PREVIOUS WORK

To aid in finding the best materials, manufacturing methods, and test procedures, reviewing previous work on similar research is of great value. Researching previous work can help an investigator know what has worked in the past and what has failed, which can save time and money. All the previous work that has been reviewed has been published papers on Science Direct related to composite sandwiches, delamination, and three and four-point bending test methods. The work that has been the most helpful is J. Jakobsen's *Peel-Stopper Design for Sandwich Composites*³, Grenestedt's *Development of a New Peel-Stopper for Sandwich Structures*⁴, Wisnom's *Failure Mechanisms in Three and Four-Point Bending Tests*⁵, Zenkert and Burman's *Fatigue of Foam Core Sandwich Beams*⁶, and Kim and Lee's *Evaluation of Durability and Strength of Stitched Foam-Cored Sandwich Structures*⁷.

In J. Jakobsen's paper that addresses the peel-stopper, the purpose of the peel stopper is to effectively stop the development of delamination by rerouting it to a predefined zone in the structure. The peel-stopper design, as can be seen in figure 11, was experimentally tested with various types of materials to make sandwich beams that were subjected to a three-point bending load. This design was successful in stopping delamination in the face-core interface. What the

researchers found was that the peel-stoppers that worked the best were made with materials with large straining capabilities, i.e. ductile materials. This paper also explained that the three-point bending test is the test of choice for delamination research because it provides a constant shear load across the entire specimen. The experiment discovered that the ability for the peel-stopper to effectively stop crack propagation was highly dependent upon the stiffness of the inserted wedge. This finding of Jakobsen's is of high interest to the work discussed in this paper; the material used as the wedge, or in this case the DAD key, makes a large impact on the end result. Jakobsen also found that the peel-stopper only worked when it was embedded throughout the entire specimen, connected to both face sheets. The design under consideration in this paper does not connect both face sheets so the difference between the results of each experiment will be interesting to compare.

FIGURE 11 - PEEL-STOPPER CONCEPT DESIGNED BY JAKOBSEN³

Joachim Grenestedt's research on peel-stoppers for sandwich structures found that the specimen could be fabricated with the peel-stopper inserted without affecting the overall structural strength of the part. Grenestedt's idea of coming up with a new peel-stopper design arose from the failing of boat hulls when a small crack would make the skin debond and grow like a fatigue crack. Two main tests were performed: quasi-static mechanical tests were performed to verify the function of the peel-stopper, and the strength of the structure incorporating the peel-stopper⁴. The results concluded that the peel-stopper design was as strong as a control specimen without an insert when faced with a bending load. However, the specimen with a peel-stopper was not as strong as the control specimen when subjected to a shear load. This paper concludes that peel-stopping devices should be placed in areas where shear loads are not too high because they have an adverse affect on the overall structural integrity of the sample. Again, this method uses an anti-delamination device that connects the two face sheets. Like Jakobsen's paper, our results will be interesting to compare to the results of this paper to see how

a DAD key compares to a peel-stopping insert. Although the same basic method used in Jakobsen's and Grenestedt's paper has proved the ability for the insert to stop crack propagation, the ability for the insert's use in industry seems limited because of the complex fabrication techniques that must be used to create and employ the inserts.

FIGURE 12 - GRENESTEDT FOUND THAT THIS DESIGN FUNCTIONED BEST IN BENDING AND WORST IN SHEAR⁴

Michael Wisnom's paper that addresses the interaction between the overall interlaminar shear and stresses at terminating plies, concentrates on the fact that composite structures are susceptible to delamination where fiber plies are terminated. It was found via three-point bending tests that the delamination started in the matrix material in the area of the terminated plies. Wisnom also performed four-point bending tests and found that they too delaminated; however, they fail in flexure before they reach full delamination failure. This research has been helpful in showing that when testing specimens for delamination, three-point bending tests are preferred to four-point bending tests because they allow for a prolonged delamination state without the high flexure associated with the four-point test.

From all the research conducted, it is widely agreed that the largest contributor to the failure of these structures is face-core delamination, which is the crack initiation and propagation between the face-core interface⁸. Previous methods to study the effects of delamination include the famous double-cantilever beam tests under a monotonic load, and three and four-point bending tests. Crack initiation and propagation under a three-point bending load was studied by Zenkert and Burman who found that the failure started near the center of the specimen and moved to the face-sheets to continue delaminating outward⁶. A great amount of research has also found that an insert into the core-face interface exerts a significant influence on the fatigue life of the sandwich assembly. Face-core delamination was found to be the dominating failure mode. The tendency for sandwich structures to fail rapidly once in the face-core delamination mode make the configuration very dangerous for systems that must have a low safety factor.

A large amount of research has been dedicated toward finding ways to stop or inhibit delamination failure. One of the theoretical solutions being researched is called the stitching method, which physically connects the upper and lower face sheets with fibers. This method increases the fracture toughness between the core and the face sheets by several magnitudes⁷. Although this method used to inhibit crack propagation seems highly applicable to industry, it is extremely difficult to manufacture these sandwich specimens for large scale projects which limits their use.

1.9 OBJECTIVE OF WORK

The goal of this research is to study whether adding a DAD key into a sandwich composite beam can add strength to the specimen before failure due to delamination. All published research on stopping delamination through the utilization of an insert has only considered inserts that physically connect both face sheets through the foam core. Although this is a proven method to increase sandwich beam strength with an initial delamination, it is hard to implement on designs because of the component complexity. The DAD key is an innovative method that has not been considered in the past to add structural integrity to a sandwich beam that is also much easier to manufacture and implement than previous methods. The DAD key design that is considered in this paper as a means to help prevent delamination propagation can be employed on many aerospace structures such as cargo floors of commercial and military jets, the marine industry, and many others. The DAD keys could be implemented at places of high stress concentration where delamination is most likely to occur, which would raise the ultimate stress level of the local area. Another potentially far reaching use for the DAD key design is in repairing structures that are already starting to experience crack growth or unforeseen high stress concentrations.

1.10 SCOPE OF WORK

The remainder of this research is organized in the chronological order of experimental events that took place leading up to the final conclusion. Chapter one will focus on the fabrication and mechanical characteristics testing of the material to find a common production method for the sandwich beam. This chapter also goes through the process in which the elastic modulus of the face sheets, foam, and the sandwich beams were discovered experimentally. Chapter two covers the four-point bending test method used to obtain results for the ultimate strength of the control specimens as well as the specimens with a delamination and DAD keys. Chapter three goes through a finite element approach to this experimentation using COSMOS FEA software. Chapter four offers a comparison between experimental and numerical results for

the four-point bending test considered in chapter two. The last major section of this paper is the conclusion where all the test results are put into their final form and interpreted on a global scale.

2 MECHANICAL CHARACTERISTICS: TESTING, FABRICATION OF MATERIALS, AND THEORY

This chapter will discuss the three different fabrication methods considered for all sample testing throughout the experimental phase. This section will also address the testing of each fabrication method and have a comparison of all results to show which method will be best for laying up the sandwich beams. Finding the elastic modulus, ultimate strength, Poisson's ratio, and density of the face sheets, foam, and the two combined using the selected fabrication method is the goal of this chapter. At the end of the chapter there will be a comparison of theoretical and experimental results for the sandwich beam.

2.1 CARBON FIBER FACE SHEET MECHANICAL CHARACTERISTICS

2.1.1 OBTAINING A FABRICATION METHOD

There are too many ways to lay-up carbon fiber sandwich composite beams; therefore, a common method for all testing must be established. There are three common ways to lay-up prepreg carbon fiber: with heat and force, heat and force and vacuum bagging, and heat and vacuum bagging only. To come up with an established method of fabricating all specimens in the future all the characteristics of each method must be considered to find the best fit.

Samples of each of the three methods were tested and the mechanical characteristics were compared. For each method considered, an auxiliary test accompanied each set of samples that included a layer of sheet resin in between two layers of carbon fiber. The sheet resin is used to super-saturate the carbon fiber with resin, simulating the process that is used when bonding the face-sheets to the foam core. More often than not, the resin in the prepreg is not enough to make a strong enough bond to the foam core; therefore the sheet resin is utilized to make the bond stronger. The metric that made one process better than another was the method that yielded the highest consistent Young's modulus. In addition to providing the answer to the best fabrication method, the Young's Modulus is also essential in the numerical stage where the mechanical characteristics of each constituent must be known to create a valid finite element model.

2.1.2 THE THREE FABRICATION METHODS CONSIDERED

Each method uses LTM45 prepreg matrix with CF1803 bidirectional woven carbon fiber, which can be seen in figure 13. The LTM45 has a manufacturer's specification as to the cooking cycle of the laminates. The cooking cycle seen in figure 14, displays how the carbon fiber starts

at room temperature under the force of a vacuum or press and is heated to 149 degrees Fahrenheit at a rate of four degrees per minute and sustained at that level for sixteen hours then cooled to room temperature at 5 degrees per minute.

FIGURE 13 - LTM45/CF1803 PREPREG CARBON FIBER WITH FABRICATION MATERIALS

FIGURE 14 - LTM45 MANUFACTURER SUGGESTED CURE CYCLE

The first method considered uses the heating cycle specified above with the 1000 pound force of the Tetrahedron press seen in figure 15. The prepreg is cut into 12" x 12" squares and inserted between two layers of porous and non-porous material respectively. The stacking of the materials is as follows: non-porous material, porous material, two layers of bi-directional CF1803 prepreg carbon fiber, porous material, and non-porous material. The porous material is essential because it allows for resin to flow through its layer and fully saturate the prepreg carbon fiber. The non-porous material is used for multiple reasons. First, it does not allow resin to travel through its layer so it keeps the heating press clean from resin, and second, it also allows for the

carbon fiber plate to be peeled easily from the press because it does not stick. The porous material is also cut to the same dimensions as the prepreg; however, because the resin becomes liquid during the heating cycle, the non-porous material is cut to 14" x 14" so that the resin does not leak everywhere. This stacking pattern, seen in figure 13, allows the carbon fiber to fully cure while also keeping a clean environment for the heating press machine. It is crucial to line up the two sheets of carbon fiber at right angles to each other so that comparing results between two different panels is accurate. If the prepreg orientation were not implemented carefully, then any small angles of disorientation would have dramatic changes on the end result. The materials are subsequently placed between two heavy galvanized steel plates to create a perfectly flat surface for the plates of carbon fiber and then cured in the Tetrahedron press. This same method is repeated with a sheet of resin added between the two prepreg layers to simulate the case where the face sheets are bonded to the foam. The sheet resin is from the Advanced Composites Group lab in the United Kingdom and must be kept in the freezer. When the sheet resin is taken out of the freezer there is only about a two minute time period where the resin is solid before it starts to melt and run off the plate. It is important that the resin is kept in the freezer until it is needed so that it can easily be added between the two layers of prepreg before it begins to melt.

FIGURE 15 - TETRAHEDRON HEATING PRESS

The second method uses the same curing cycle but with vacuum bagging instead of the 1000 pound force used in the first method. Although there is no force, the heating press must still make contact with the specimen so there is a force set on the machine to ten pounds. The stacking of the materials in the bagging is the following: vacuum bag, non-porous material, porous material, carbon fiber, porous material, non-porous material, vacuum bagging. There is also a breather and a hole in the bag that allows for the vacuum to take out all air without sucking

in resin; the vacuum bagging materials are seen in figure 16. Like the first method, sheet resin can be inserted in between the two layers of carbon fiber and fabricated the same way.

FIGURE 16 - VACUUM BAGGING LAY-UP STACKING PATTERN OF MATERIALS

The third method uses the same curing cycle with force and vacuum bagging as the second method. This technique is the same as the second process except the heat press is set to 1000 pounds instead of ten pounds.

2.1.3 FACE SHEET MECHANICAL CHARACTERISTICS TESTING METHOD (ASTM D3039)

Testing the face-sheets that were laid up using the three different fabrication methods were performed according to ASTM standard D3039⁹—a process used to find mechanical characteristics of carbon fiber samples. In this standard, samples are cut to the dimension 10” x 1” as can be seen in figure 17. Cutting the specimens to the desired dimensions required a tile saw with an accurate measuring device to ensure repeatability between samples. When the specimens were cut, the order and orientation of each sample was noted so that an accurate comparison of results could be attained. With carbon fiber, a slight change in order or orientation could be devastating to a series of tests; it is important that the necessary attention to detail be paid for keeping an organized testing order.

Aluminum tabs, also seen in figure 17, were then purchased from a machine shop that were fabricated to the exact dimensions called for in the standard with a tolerance of +/- .005 inches. Adherence of this standard yielded accurate results. In the past, aluminum tabs were cut by hand without an accurate measuring device using a saw that left burred edges that have the potential to fracture the composite material. The tabs were then scored, as seen in figure 18, with

a cutting device. Scoring the tabs allows for a better grip between the smooth carbon fiber and the otherwise smooth aluminum; with the tabs scored, the bonded surface area increases significantly. These tabs were then cleaned and attached to the carbon fiber samples with a resin-epoxy adhesive. Once the samples were cured, they were ready to start the tension testing in the Instron machine. Figure 19 shows the final samples with the proper dimensions.

FIGURE 17 - PREPARATION OF 10 SAMPLES FOR MECHANICAL PROPERTIES TESTING

FIGURE 18 - THE SCORED ALUMINUM TABS USED TO TEST FOR MECHANICAL PROPERTIES

The standard tension testing method was then programmed into the Instron machine such that each sample was tested the same exact way. Each specimen was put into the Instron jig so that the specimen was parallel with the grips and perpendicular to the floor as can be seen in figure 20. The carbon fiber sample was then loaded in tension until it breaks or until the load drops by 40 percent. The Instron machine records all testing data: stress, strain, load, elongation, and ultimate stress. The data for each sample was recorded on the computer then analyzed to obtain the Young's modulus. The Young's modulus was found by graphing the stress against the strain and finding the value of the slope. The resulting slope in the linear region is the Young's modulus value. This standard testing process was then repeated for each of the three lay-up methods considered above.

FIGURE 19 - FINAL CARBON FIBER TEST SPECIMEN DIMENSIONS

FIGURE 20 - INSTRON GRIPS WITH SPECIMEN LOADED

2.1.4 RESULTS OF FACE SHEET MECHANICAL CHARACTERISTICS TESTING

The three different methods considered to lay-up the LTM45/CF1803 prepreg system were all tested according to ASTM D3039 testing standard and the results were all compared. The stress versus strain curves for each sample were plotted on a graph that pertained to a certain lay-up method. On each plot, ten samples are of two layers of carbon fiber and ten samples are from two layers of carbon fiber with a layer of sheet resin in between. In every method considered, the case with only two layers of carbon fiber had the higher elastic modulus. Specimens with sheet resin were all much lower in the modulus value. This phenomenon is expected because the sheet resin adds more cross-sectional area to the test specimen, which lowers stress values.

The slopes of the stress-strain curves in the linear region were all taken and the elastic modulus was calculated. The moduli for each test method were then averaged resulting in an elastic modulus that could be assigned to each method. Figures 21 through 23 illustrate the average elastic modulus for each case in addition to depicting how accurately each testing procedure was followed. The slopes of each specimen for the separate cases are almost on top of

each other, which demonstrates how there are distinct characteristics of each testing process that affect the laminae differently.

FIGURE 21 - MECHANICAL CHARACTERISTICS RESULTS FROM 1000 LBF LAY-UP METHOD

FIGURE 22 - MECHANICAL CHARACTERISTICS FROM VACUUM BAG AND 1000 LBF LAY-UP METHOD

FIGURE 23 - MECHANICAL CHARACTERISTICS RESULTS FROM VACUUM BAG LAY-UP METHOD

In addition to recording all the elastic moduli for each test method considered, the ultimate stress values were also recorded for each sample. This value is important when theoretically determining the ultimate stress of the entire sandwich beam. A summary of all the mechanical characteristics testing can be seen in table 1. This table shows the average elastic modulus, the average ultimate stress, and some important statistical factors that were considered in choosing a method for the rest of the research to be carried out.

TABLE 1 - SUMMARY OF MECHANICAL CHARACTERISTICS TESTING FOR FACE SHEETS

	Force Only	Force + SR	Force + VB	Force + VB + SR	No Force +VB	No Force + VB + SR
Average Elastic Modulus (psi), ASTM D3039	7,454,900	5,642,200	7,138,700	5,311,200	7,008,100	5,023,200
Elastic Modulus Standard Deviation (psi)	187,062	142,642	160,182	135,572	171,672	73,578
Elastic Modulus Standard Deviation (%)	2.51	2.53	2.24	2.55	2.45	1.46
Average Ultimate Stress (psi), ASTM D3039	112,300	86,700	104,200	81,800	101,600	83,300
Ultimate Stress Standard Deviation (psi)	2737	1826	1701	4179	7754	1912
Ultimate Stress Standard Deviation (%)	2.44	2.11	1.63	5.12	7.63	2.29

VB = Vacuum Bag, SR = Sheet Resin

The factors considered in choosing a fabrication method were the elastic modulus, ultimate stress, lay-up complexity, cost, and some statistics of the mechanical properties testing.

The need for a method that produces consistent results is of great importance when investigating sandwich beam behavior; for this reason some statistics such as averages and standard deviations were considered for each method. Standard deviations were taken of the average elastic modulus and the average ultimate stress to make sure that the results were not misleading, and that the use of that method would be repeatable in the future. As seen in table 1, all of the standard deviations of the data are within statistical reason to be considered repeatable and accurate. The smallest standard deviation for the elastic modulus was 1.46 percent and the largest was 2.55 percent, which conveys statistical confidence in the values obtained. The ultimate stress had standard deviations that ranged from 1.63 to 7.63 percent. The first method, with only force from the heat press, was the easiest to perform, had the lowest operating costs, lowest material costs, and yielded the best mechanical properties.

The standard deviations for the method with only force were 2.51 and 2.44 for the elastic modulus and the ultimate stress respectively, which shows that this method is statistically repeatable and accurately tested. The average elastic modulus was 7,454,900 psi and the average ultimate stress was 112,300 psi, which were both the largest values of each category. For these reasons, this method was chosen for the production of sandwich samples used in further investigations.

In addition to finding the elastic modulus and ultimate strength of the face sheets, a strain gauge was added in the lateral direction to the loading in order to find the Poisson's ratio of the material. This is found by taking the negative of the strain in the lateral direction and dividing it by the strain in the longitudinal direction.

2.1.5 POISSON'S RATIO OF FACE SHEETS (ASTM E132)

The method used for finding the Poisson's ratio of the face sheets follows ASTM E132¹⁰ testing standard, which is a subsidiary standard of ASTM D3039. This method follows the exact fabrication and test method as the ASTM D3039 standard, which finds the elastic modulus of a carbon fiber sample. The only difference between this test and the previous test is that a strain gage is added in the transverse direction in order to capture the two-dimensional behavior of the laminae.

The Instron machine calculates the strain in the longitudinal direction during the tension test so the extensometer strain gage is added to each sample in the transverse direction and loaded as seen in figure 24.

FIGURE 24 - CARBON FIBER SAMPLE LOADED IN THE INSTRON MACHINE FOR POISSON'S RATIO TESTING

To obtain the values of Poisson's ratio the ASTM standard suggests plotting the average strain versus the load for both the longitudinal and transverse direction as seen in figure 25.

FIGURE 25 - POISSON'S RATIO OBTAINED BY DIVIDING SLOPES OF THE STRAIN-LOAD CURVES

To obtain the Poisson's ratio from this data, the derivative of the strain (slope) in the transverse direction is divided by the derivative of the strain in the longitudinal direction as seen in equation 1.

$$v = \frac{\left(\frac{d\epsilon_t}{dP}\right)}{\left(\frac{d\epsilon_l}{dP}\right)} \quad (1)$$

Where v is the Poisson's ratio, P is the applied load, and ϵ_t and ϵ_l are the transverse and longitudinal strains respectively. A plot of the strain versus load curve for the average strains in the longitudinal and transverse directions can be seen in figure 26. The final Poisson's ratio of the face sheets was found to be 0.091, which is a common value for materials like the bi-directional carbon fiber sheets that are being used.

FIGURE 26 - POISSON'S RATIO OF LTM45/CF1803 CARBON FIBER

2.1.6 DENSITY OF FACE SHEETS THEORETICAL AND EXPERIMENTAL VALUES

Face sheet density is relevant to this research because, during the finite element analysis, the mass of each element is essential in calculating various mass property values. Experimentally the values of density are easily found by taking a sample of the material and performing various volume and mass calculations to find the density.

To find the density of the LTM45/CF1803 carbon fiber face sheets, a sample that was already cured was cut to a 12" x 12" square where lengths and thicknesses were measured with a micrometer. The weight was then measured. This procedure was repeated for 10 samples to

ensure statistical accuracy. The density was then found by dividing the masses of the samples by the volumes of the samples, which came out to be an average of 93.31 pounds per cubic foot.

To validate the experimental density, the theoretical value was calculated using the densities of each constituent along with the volume fraction of the laminae. The density of the LTM45 resin and CF1803 carbon fiber was provided by the Advanced Composites Group¹¹ Company and was 1.24 and 1.76 grams per cubic centimeter respectively. With the volume fraction of 60 percent known, equation 2 can be used to find the density of the entire laminate:

$$\rho_{total} = V_{fibers} * \rho_{fibers} + V_{matrix} * \rho_{matrix} \quad (2)$$

with this equation, the theoretical value of 96.89 pounds per cubic foot was found, which differs by only 3.7 percent when compared with the experimental value obtained.

2.2 PVC FOAM MECHANICAL CHARACTERISTICS

2.2.1 FOAM MECHANICAL CHARACTERISTICS TESTING METHOD (ASTM D1621)

The test method for obtaining the PVC (polyvinylchloride) foam mechanical characteristics follows ASTM D1621¹² standard: the test method for finding compressive properties of rigid cellular plastics. This test method describes the procedure for determining the compressive properties of rigid cellular materials, particularly expanded plastics. In this procedure, data is acquired and a complete load-deformation curve is obtained, which yields the compressive stress at any load as well as the effective modulus of elasticity.

The test specimen is made from PVC rigid foam and is cut to a 2"x 2" square cross-section with a height of 2 inches. Extra care is taken to ensure the loaded ends of the specimen are parallel to each other and perpendicular to the sides. If samples contain any defects it is imperative that the sample is discarded and a new one made. Because the foam is only 0.5 inches thick, the layers had to be stacked in order to obtain the proper dimensions according to the testing standard. Figure 27 shows how the foam was cut from the larger sheet with a straight edge and razor blade, and figure 28 illustrates a finished sample.

FIGURE 27 - CUTTING THE 2" X 2" FOAM SAMPLES

FIGURE 28 - FINISHED FOAM SAMPLES READY FOR TESTING

Before starting the actual compressive testing, all samples are measured with a precision measuring device with a tolerance of $\pm 1\%$ of the total dimension. All dimensions are recorded three times and averaged to obtain an average dimension. The specimen is then positioned in the Instron machine that is equipped with two parallel plates used to compress the test specimen, ensuring that the sample is centered in the plates so that the load is uniformly distributed over the entire specimen. The specimen is then compressed at a rate of 0.1" per minute for each inch of specimen thickness. The samples loaded in the Instron machine between the parallel anvil plates can be seen in figure 29. The load-deformation curve is then generated and the mechanical properties are obtained. The sample is compressed until a yield point is reached or until the specimen has compressed 13% of its overall thickness

FIGURE 29 - THE FINAL SAMPLE LOADED IN THE INSTRON MACHINE TO FIND ELASTIC PROPERTIES

After the samples are tested, the load-deformation curve is generated by the Instron machine which allows for the elastic modulus to be determined. The elastic modulus can be calculated by using the following equation from the testing standard:

$$E_c = \frac{Ph}{AD} \quad (3)$$

Where E_c is the elastic modulus in compression, P is the load at a given deflection, h is the initial specimen height, A is the specimen cross-sectional area, and D is the deflection for a given load.

2.2.2 FOAM MECHANICAL CHARACTERISTICS RESULTS

After the experiment is performed as described in the previous section, the data is obtained and ready for analysis. The load-deflection curve allows for the stress-strain curve to be generated as can be seen in figure 30. As shown on the graph, the average ultimate strength of the samples tested was 270 psi and the average elastic modulus was 7700 psi. The manufacturer's provided data for ultimate strength and elastic modulus were 351 psi and 13,000 psi respectively, which corresponds to an error of 23% and 41% respectively. There are many sources of error with this test because the sheets of foam were cut so thin that they needed to be stacked in order to comply with the testing standard. The stacking of the sheets made the samples compress more than if there was just one homogeneous sample, which yielded significantly lower ultimate strengths and elastic moduli.

FIGURE 30 - STRESS-STRAIN CURVE OF PVC FOAM USED TO OBTAIN MECHANICAL PROPERTIES

2.3 SANDWICH BEAM MECHANICAL CHARACTERISTICS

2.3.1 SANDWICH BEAM FABRICATION METHOD

After performing the mechanical properties testing on the face sheets and foam core, the method that uses the force from the tetrahedron heat press has been determined as the method of choice. In this method two layers of LTM45/CF1803 prepreg carbon fiber were combined to make a face sheet in which there are two sets of face sheets per sandwich beam. A layer of sheet resin was added on each side of the foam core to allow the bond between the face sheets and core to be absolute. These constituents were then placed between some composite fabrication materials and put in the heat press to cure at the manufacturer's suggested curing cycle. Figure 31 illustrates how the sandwich beam was prepared before being put into the heat press.

FIGURE 31 - LAY-UP OF A SANDWICH PLATE

The first step of the fabrication method is to cut the foam to the correct dimensions of 12" x 12"; this is performed by using the tile saw to cut the sheet to the desired size. After the foam is cut, the carbon fiber is taken from the freezer and cut to 12" x 12" so that it fits flush with the foam core. Before placing the carbon fiber on the foam core to be cured, a layer of sheet resin is placed on the foam to ensure a strong bond between the foam and the face sheets. The face sheets are then placed on the sheet resin one at a time to make sure that the orientation of the carbon fiber sheet is square with the foam and with the other carbon fiber sheets. This part of the process must be handled with care because if a sheet is not squared with accuracy, results between specimens can vary drastically. This process is repeated for both sides of the foam so that there are two sheets of carbon fiber, and a layer of sheet resin on both sides of the foam core. These constituents are then placed between two layers of porous material to allow the resin to move

through its walls; this is then put between two layers of non-porous material, which prohibits the resin to move through its walls and ensures that the resin does not leak all over the heating press. A picture of the entire specimen before it is put into the heating press can be seen in figure 32.

FIGURE 32 - ENTIRE LAY-UP OF SANDWICH PLATE BEFORE CURING

The constituents are cured at the manufacturer's suggested curing cycle which can be found in figure 14. Figure 33 shows a picture of a fully cured sandwich composite plate before it was cut to the specified testing dimensions. When fully cured, the sandwich panel is then cut to the dimensions that are required in the testing procedure.

FIGURE 33 - SANDWICH COMPOSITE PLATE BEFORE CUT TO TEST DIMENSIONS

2.3.2 SANDWICH BEAM MECHANICAL PROPERTIES TEST METHOD (ASTM D6272)

The sandwich beam is tested according to ASTM standard D6272¹³. This test method allows the researcher to determine the mechanical properties of the beam to be found through the

use of a four-point bending test. The properties that are essential to this research and are found from this test are the elastic modulus and ultimate stress of the entire sandwich beam.

In this testing procedure, a beam of rectangular cross section rests on two supports and is loaded by two internal point forces as shown in figure 34. The distance between the loading point forces is one-third the length of the support distance. The supports are distanced 16 times the thickness (depth as the standard calls it) of the specimen apart from each other.

FIGURE 34 –FOUR-POINT LOADING OF THE SANDWICH BEAM ACCORDING TO ASTM D6272

The specimen is then loaded until rupture or until the maximum fiber strain of 5% is reached. The specimens are cut to the dimensions that are called out in the standard: the thickness of the beam is considered the “depth” dimension; the length of the beam is the support span “L” plus one inch on either side for the beam to overhang the supports, the width of the beam may not be greater than one-quarter the support span. The beam dimensions that are used in this experiment are summarized in table 2.

TABLE 2 - BEAM TEST SPECIMEN DIMENSIONS

Dimension	Size (in.)
Support Span (L)	9.232
Actual Beam Length	11.94
Depth (d)	0.577
Width (b)	1

Ten specimens are cut to the precise measurements above to ensure statistical accuracy in the method. Figure 35 shows the test specimens cut to the precise dimensions above.

FIGURE 35 - TEN SANDWICH BEAMS READY TO BE TESTED WITH ASTM D6272 STANDARD

The rate at which the sample is loaded (R) in flexure is given by equation 4, which is from the ASTM standard:

$$R = \frac{0.185 * Z * L^2}{d} \quad (4)$$

where Z is the strain rate of the outer fibers, which is .01 (in/in)/min for this test. The maximum stress (σ_{max}) of the beam located in the middle of the load span is also given by the ASTM standard and is:

$$\sigma_{max} = \frac{PL^2}{bd^2} \quad (5)$$

where P is the load in pounds. The maximum strain (ϵ_{max}) is given by equation 6, and pertains to the strain in between the load span:

$$\epsilon_{max} = \frac{4.70Dd}{L^2} \quad (6)$$

where D is the midspan deflection, which is found from the Instron machine. Because this equation is based on empirical data, an extensometer strain gage supplied by the Instron Company will be used to verify the strain in the outer fibers. After the test is complete and a load-deflection curve is generated, the slope of the curve (m) can be used to find the elastic modulus given by equation 7:

$$E = \frac{0.21L^3m}{bd^3} \quad (7)$$

2.3.3 EXPERIMENTAL RESULTS FOR THE MECHANICAL PROPERTIES OF THE SANDWICH BEAM

A total of 20 samples were tested according to ASTM D6272. The Instron machine recorded time, cross-head position, load, deflection, and strain. The only values that were actually used from the Instron data were the load and deflection figures. From the test method outlined in the ASTM standard, the values of stress in the outer fibers, strain in the outer fibers, and elastic modulus could be found as seen in the test method section that precedes this section.

The load versus deflection data was plotted for each non-delaminated control sample as seen in figure 36. The slope of the steepest region of the load-deflection curve (m) is used along with equation 7 and the dimensions of the sandwich beam to find the combined modulus of elasticity of the beam in bending. The average of all 20 elastic moduli was found to be 898,300 psi.

The ultimate strength of the sandwich beam is equal to the maximum stress in the outer fibers at the moment the beam breaks. It is calculated by using equation 5 with P equal to the force at the moment the structure fails. With the stress plotted versus strain data, illustrated in figure 37, we can see that the average ultimate strength of the sandwich beam is 6874 psi.

FIGURE 36 - SANDWICH BEAM LOAD VERSUS DEFLECTION TO HELP FIND MECHANICAL PROPERTIES

FIGURE 37 - SANDWICH BEAM STRESS VERSUS STRAIN CURVE TO FIND ULTIMATE STRENGTH

The ultimate strength could not be found theoretically because of the way the beams fail. The beams fail due to face-core delamination before they fail due to an ultimate stress level in the materials. The normal theories of failure such as Tresca and Von Mises do not work in this case because of this failure mode. These methods have the potential to work but would have to be re-derived with a fracture mechanics approach, which is beyond the scope of this thesis. Figure 38 illustrates how the beams typically failed during the test.

FIGURE 38 - TYPICAL FAILURE MODE OF THE BEAM WAS FACE-CORE DELAMINATION

2.3.4 SANDWICH BEAM MECHANICAL PROPERTIES THEORETICAL RESULTS

The method used to determine the theoretical mechanical properties was taken from Jones's *Mechanics of Composite Materials*¹. All the values used in this section for the elastic moduli of the face sheets and foam are the manufacturer's values, not the values found from testing. The method is used to find an equivalent elastic modulus for two separate materials. To find this value a large assumption must be made: the strains in the face sheet and foam are equal. A pictorial representation essential to the understanding of this theory is illustrated in figure 39.

FIGURE 39 - THEORY BEHIND MECHANICAL PROPERTIES OF A SANDWICH BEAM

Because of the assumption of equal strains in the foam core and face sheets, we can write the separate stresses in each material as seen in equations 8 and 9:

$$\sigma_{fs} = E_{fs}\epsilon \quad (8)$$

$$\sigma_{fc} = E_{fc}\epsilon \quad (9)$$

where the subscripts *fs* and *fc* stands for face sheet and foam core respectively. We can now say that the average stress acting on the entire cross-sectional area *A* is σ_L . The cross-sectional area of the face sheets and foam are A_{fs} and A_{fc} respectively. Therefore, the force on the entire cross-section can be displayed as is equation number 10:

$$P = \sigma_L A = \sigma_{fs} A_{fs} + \sigma_{fc} A_{fc} \quad (10)$$

if we then substitute equations 8 and 9 into equation 10 we get the following relation for the entire beam:

$$\sigma_L = E_L \epsilon \quad (11)$$

where E_L is the elastic modulus in the longitudinal direction. We can now rewrite this equation in the following form:

$$E_L = E_{fs} \frac{A_{fs}}{A} + E_{fc} \frac{A_{fc}}{A} \quad (12)$$

however, the volume fraction of the face sheets and core can be written as in equations 13 and 14:

$$V_{fs} = \frac{A_{fs}}{A} \quad (13)$$

$$V_{fc} = \frac{A_{fc}}{A} \quad (14)$$

The entire elastic modulus of the composite beam can now be written in terms of each component's elastic modulus and contribution to the volume of the specimen as seen in equation 15:

$$E_L = E_{fs}V_{fs} + E_{fc}V_{fc} \quad (15)$$

Equation 15 was then used with the manufacturer's given values of the elastic modulus to find the theoretical value for the entire beam's equivalent elastic modulus. The manufacturer's material data can be seen in table 3. The carbon fiber data is approximate because the Advanced Composites group that makes the product has not officially published any mechanical data; however, a consultant provided these approximate values.

TABLE 3 - MANUFACTURER'S DATA ON MECHANICAL PROPERTIES OF FACE SHEETS AND FOAM

	Carbon Fiber	Foam Core
Elastic Modulus (psi)	About 7,800,000	13,000
Ultimate Strength (psi)	About 130,000	351

Using these values for the carbon fiber and foam and a volume fraction of 0.873 and 0.127 for the foam and face sheets respectively, we get the equivalent elastic modulus to be 898,300 psi.

2.4 COMPARISON OF EXPERIMENTAL AND MANUFACTURER PROVIDED PROPERTIES

A summary of all the experimental, theoretical, and provided data taken from the carbon fiber, foam, and sandwich beam can be seen in tables 4 through 6.

TABLE 4 - SUMMARY OF CARBON FIBER MECHANICAL PROPERTIES

LTM45/CF1803 PREPREG CARBON FIBER MECHANICAL PROPERTIES		
	Manufacturer's Value	Experimental Value
Elastic Modulus (psi), ASTM D3039	7,800,000	7,454,900
Elastic Modulus Standard Deviation(psi)		187,062
Elastic Modulus Standard Deviation (%)		2.51
Ultimate Strength (psi), ASTM D3039	114,000	112,300
Ultimate Strength Standard Deviation(psi)		2737
Ultimate Strength Standard Deviation(%)		2.44
Poisson's Ratio, ASTM E132		0.091
Poisson's Ratio Standard Deviation		0.011
Poisson's Ratio Standard Deviation (%)		11.95
Density (lb/ft³)	96.89	93.31
Density Standard Deviation (lb/ft ³)		1.72
Density Standard Deviation (%)		1.85

The carbon fiber elastic modulus varied only 4% between the experimental and manufacturer's data, which shows that the ASTM tension testing procedure is an accurate method and also shows that the material is also in good condition. The ultimate strength of the face sheets had only 2% difference between the experimental and manufacturer's values. The manufacturer did not include the value of Poisson's ratio in the mechanical properties section of the material data sheet; however, the experimental value of 0.091 for Poisson's ratio is reasonable because many similar materials have the same approximate value. The manufacturer provided the density of the carbon fiber to be 96.89 lb/ft³, which was found to be consistent with the experimental value found of 93.31 lb/ft³, which is only 1.85 percent lower than the provided value.

The mechanical properties of the foam used as the core for the sandwich beam are found in table 5. The PVC foam core was found to have an elastic modulus 7700 psi, which is 41% different from the manufacturer's provided value of 13,000 psi. The ultimate strength provided was 351 psi in compression and was only 23% different than the value of 270 obtained experimentally. The Poisson's ratio of the foam was not provided by the manufacturer but the experimental value found by an experiment on the same foam was .31, which is in the range that the book *The Handbook of Sandwich Construction*² says that PVC foam of this density should be in. The manufacturer did provide the density of the foam and it was 10 lb/ft³. The experimental value found consistent results of 9.86 lb/ft³ after measuring and testing a number of samples.

TABLE 5 - PVC FOAM CORE MECHANICAL PROPERTIES SUMMARY

LAST-A-FOAM FR 6710 MECHANICAL PROPERTIES¹⁴		
	Manufacturer's Value	Experimental Value
Elastic Modulus (psi), ASTM D1621	13,000	7700
Elastic Modulus Standard Deviation(psi)		175.5
Elastic Modulus Standard Deviation (%)		2.28
Ultimate Strength (psi), ASTM D1621	351	270
Ultimate Strength Standard Deviation(psi)		17.7
Ultimate Strength Standard Deviation(%)		6.56
Poisson's Ratio, ASTM E132		0.31
Poisson's Ratio Standard Deviation		
Poisson's Ratio Standard Deviation (%)		
Density (lb/ft³)	10	9.86
Density Standard Deviation		0.16
Density Standard Deviation (%)		1.62

The entire sandwich beam was theoretically determined to have an elastic modulus of 1,052,166 as described earlier in this section. The theoretical elastic modulus was only 14% higher than the experimental value found using ASTM D6272. Even though the theoretical value was larger, this was expected because if each of the elastic moduli of the face sheets and foam had larger manufacturer values than what was experimentally found in the lab, then it is safe to say that theory would predict a larger value. The ultimate strength of the beam was found to be 6,874 psi; this value will be used as the control value for the ultimate strength of a beam with any initial delamination.

TABLE 6 - SUMMARY OF MECHANICAL PROPERTIES OF THE COMPOSITE SANDWICH BEAM

SANDWICH BEAM MECHANICAL PROPERTIES		
	Theoretical Value	Experimental Value
Elastic Modulus (psi), ASTM D6272	1,056,066	898,300
Elastic Modulus Standard Deviation(psi)		14,642
Elastic Modulus Standard Deviation (%)		1.63
Ultimate Strength (psi), ASTM D6272		6,874
Ultimate Strength Standard Deviation(psi)		167
Ultimate Strength Standard Deviation(%)		2.4

Using the ASTM testing standards allowed for the precise calculation of all the important values needed for the analysis of the sandwich beam. The values found theoretically, and experimentally were all very close to the manufacturer's provided data, which leads to the conclusion that the fabrication methods considered all yield consistent results from test to test.

3 EXPERIMENTAL TASK: FABRICATION AND TESTING OF SANDWICH BEAMS

The aim of this chapter is to discuss whether or not the DAD keys added to the sandwich beam can increase the structural integrity of the beam when an initial delamination exists. The beams will be loaded in a four-point bending jig and tested for their ultimate strength according to ASTM D6272. There will be six cases that are addressed in the analysis: a control specimen with no delamination, a specimen with a one inch initial delamination, two specimens with no delamination and DAD keys added in the transverse and longitudinal directions respectively, and two specimens with a one inch initial delamination with DAD keys added in the transverse and longitudinal directions respectively. An in-detail discussion will address the fabrication of all materials for testing as well as go over the testing method. The chapter will be concluded with a comparison of the results to see if the DAD keys provided an increase in ultimate strength.

3.1 THE CONTROL SPECIMEN (NO DELAMINATION)

3.1.1 FABRICATION OF CONTROL SPECIMEN

The fabrication of the control specimen is of the most importance because it is the basis for how all other beams will be manufactured. The control specimen was made the same way that the beam was created in chapter two on page 30. Please refer to this page in order to obtain the full fabrication method.

3.1.2 CONTROL SPECIMEN TEST METHOD (ASTM D6272)

The control specimen test method follows the same testing standard as that explained in chapter two on page 31. Please refer to this page in order to view the entire testing method.

3.1.3 CONTROL SPECIMEN TEST RESULTS

After the beams were laid-up and tested according to ASTM Standard D6272, the Instron machine was able to export its results in an excel file to be analyzed. Every sample's stress-strain curve was plotted, as seen in figure 40, and the ultimate strength was found by finding the largest stress value associated with each beam. The ultimate strength of 20 samples was calculated and the average and standard deviation was also noted to ensure statistical significance was achieved between tests.

The average ultimate strength of the control specimen was found to be 6870 psi with a standard deviation of 167 psi. The standard deviation was only 2.4 percent of the entire ultimate

strength value, which means that the testing, fabrication, and analysis methods all yielded statistically significant results.

FIGURE 40 - STRESS VERSUS STRAIN CURVES FOR SANDWICH BEAM CONTROL

3.2 BEAM WITH INITIAL DELAMINATION

3.2.1 FABRICATION OF DELAMINATED BEAM

The delaminated beam is created the same way as the control beam except that an initial delamination is introduced between the foam core and face sheet interface. The initial delamination is introduced to the specimen by adding a thin layer of non-porous material between the face sheets and foam core. The non-porous material does not allow any resin to flow through its boundary thus not allowing the two interfaces to bond together.

The layer of foam is covered with a layer of sheet-resin just as with the case of the control specimen. Next, the layer of non-porous material is added between the sheet-resin and face sheets as seen in figure 41. Because the sheet resin starts to cure even at room temperature, it gets very sticky quickly, which allows the layer of non-porous material to stay in position when placed on the sample. To ensure that the non-porous material is situated in the right position (in the direct center of the plate), the lines of the delamination location are marked on the foam and can be seen through the transparent sheet resin.

The layers of carbon fiber are added to the foam the same way as the control specimen with two layers of LTM45/CF1803 on each side. These layers are covered with porous and non-

porous material and cured in the tetrahedron heat press with the same curing cycle specified by the manufacturer.

FIGURE 41 - NON-POROUS MATERIAL ADDED TO A SANDWICH PLATE TO CREATE A DELAMINATED SECTION

3.2.2 *DELAMINATED BEAM TEST METHOD (ASTM D6272)*

After the specimen is cured, the 12" x 12" plate is cut to the standard beam size of 12" by 1" by 0.577" as seen in figure 42.

FIGURE 42 - DELAMINATED BEAM SAMPLES CUT TO THE STANDARD SIZE

The delamination is difficult to view once the specimen is cut but it is essential to know its location so that it could be loaded in the Instron machine correctly. The delamination location is important because when the beam is loaded into the four-point bending jig, the delaminated section of the beam must be located directly between the load span as seen in figure 43. The extensometer strain gage is then added directly on the opposite side of the delamination to measure the maximum strain in the outer fibers of the beam.

FIGURE 43 - BEAM WITH DELAMINATED SECTION LOCATED DIRECTLY BETWEEN THE LOAD-SPAN

The Instron machine collects the same data as the control beam (position, load, deflection, stress, strain).

3.2.3 *DELAMINATED BEAM TEST RESULTS*

All of the delaminated beams failed due to face-core delamination as can be seen in figure 43. Face-core delamination is the typical failure mode of sandwich composites that are loaded in bending. The problem with these specimens is not the fact that the materials are not strong enough for a given structure; it is the interface between the two constituents that creates the distinctive failure mode.

The plot of stress versus strain was created according to the ASTM standard to find the ultimate strength. A total of ten samples were tested and their plots were superimposed as seen in figure 44.

FIGURE 44 - STRESS VERSUS STRAIN PLOT OF SANDWICH BEAM WITH INITIAL DELAMINATION

The ultimate strength was found by seeing where each sample fractured and that stress value was noted. The ultimate strength of all samples was averaged to find the mean value of 4590 psi.

3.3 DELAMINATED BEAM WITH TRANSVERSE DAD KEYS

FIGURE 45 - SANDWICH BEAM WITH TRANSVERSE DAD KEYS EXPANDED VIEW

3.3.1 FABRICATION OF DAD KEYS

The DAD keys are used in order to potentially increase the ultimate strength of the delaminated sample. The DAD keys are fabricated from fiberglass strands that are oriented

unidirectionally as seen in figure 45. There are 15 strands of fiberglass for each bundle seen in figure 46, wrapped by rubber bands in order to keep them together. Each fiberglass bundle is cut so that it measures 14 inches, which is enough length such that overlaps the 12 inch mold that each bundle is laid-up in. The mold, seen in figure 47, is made of aluminum and can hold 22 bundles of fiberglass at a time. The mold creates 0.125 inch radius semicircular DAD keys.

FIGURE 46 - FIFTEEN-STRAND FIBERGLASS BUNDLES USED TO CREATE DAD KEYS

FIGURE 47 - FIBERGLASS MOLD USED TO FABRICATE DAD KEYS

Before the bundles of fiberglass are added to the mold, the mold must be waxed by a releasing agent that allows the DAD keys to be easily removed once they are cured. The wax is

added by hand onto the mold until the entire sheet of aluminum is completely covered as illustrated in figure 48.

FIGURE 48 - ADDING RELEASE WAX TO THE MOLD FOR EASY DAD KEY REMOVAL

The bundles of fiberglass are then laid-up by hand using Aeroepoxy 24-hour-cure resin as seen in figure 49. Great care is taken when laying up the fiberglass by hand to ensure that the entire DAD key is completely saturated with resin.

FIGURE 49 - HAND LAY-UP METHOD USED TO FABRICATE DAD KEYS

Each bundle of fiberglass is then inserted into the aluminum mold and a layer of porous and non-porous material are added on top the mold so that resin does not stick to the plate. The plate is used to completely compress the DAD keys into the mold. Weight is then added on top of the plate to ensure the complete compacting of the fiberglass into the mold as can be viewed in figure 50.

FIGURE 50 - 180 POUNDS ADDED ON TOP OF THE PLATE TO COMPACT THE FIBERGLASS INTO THE MOLD

Once the DAD keys are completely cured 24-hours later, the materials on top of the mold are taken off and the keys are sanded down until they are all separated by the aluminum as seen in figure 51.

FIGURE 51 - DAD KEYS ARE SANDED DOWN UNTIL EACH IS SEPARATED BY THE ALUMINUM MOLD

The final DAD key dimensions are 12 inches long with a semicircular radius of 0.125 inches.

3.3.2 FABRICATION OF FOAM CORE TO ACCEPT DAD KEYS

The foam must be cut precisely to accept the DAD keys such that when they are inserted a flat surface results. If the grooves are cut too deep into the foam the DAD keys will not be able to bond to the face sheets; if the grooves are too shallow the DAD keys will stick out of the foam and the face sheets will not have a complete bond with the foam core. Because the fabrication of the foam is such a delicate procedure, the Haas CNC machine was used to cut the grooves to the exact dimensions required. Figure 52, illustrates the CNC vertical mill being used with a 0.25 round bit to cut the grooves into the foam.

FIGURE 52 - CNC MACHINES USED TO CUT GROOVES INTO THE FOAM TO ACCEPT DAD KEYS

The finished foam pieces used to accept the longitudinal and transverse DAD key configurations can be seen in figure 53.

FIGURE 53 - FINISHED FOAM CORE PIECES READY TO ACCEPT DAD KEYS

3.3.3 FABRICATION OF DELAMINATED SANDWICH BEAMS WITH DAD KEYS

Once the DAD keys and foam were fabricated the delaminated beams could be fabricated. To create the beams, the DAD keys were first added to the foam using Aeroepoxy applied to the DAD keys as seen in figure 54. It is essential to add the epoxy to the DAD keys so that there is a full bond between the key and the foam.

FIGURE 54 - AEROEPOXY ADDED TO DAD KEYS

The DAD keys are then inserted into foam being careful to ensure that the top of the DAD key is flush with the top of the foam as seen in figure 55. A layer of sheet resin is then added on top the DAD keys to help the face sheets bond to the foam and DAD keys. A one inch wide strip of non-porous material is added directly in between the DAD keys and on top of the sheet resin to create the initial delamination. The layers of non-porous material, porous material, and carbon fiber are added to each side of the foam core as with the previous beam fabrication methods.

FIGURE 55 - FOAM WITH DAD KEYS AND INITIAL DELAMINATION INSERTED

The sandwich lay-up is then put into the tetrahedron press to cure at the manufacturer's suggested curing cycle. Once the sandwich panel is fully cured it is cut with the tile saw to the same specifications as the previous beams: 12" x 1" x 0.577" as can be seen in figure 56. From the figure one can see that the face sheets are completely attached to the DAD keys and foam.

FIGURE 56 - SANDWICH BEAMS WITH TRANSVERSE DAD KEYS CUT TO FINAL TESTING DIMENSIONS

3.3.4 DELAMINATED BEAM WITH TRANSVERSE DAD KEYS TEST RESULTS

Once the beams were tested according to ASTM D6272 as all the previous beams were tested, all the data could be exported from the Instron machine to excel and Matlab to be analyzed. The ultimate strength was found by taking the stress value at the point of sample

rupture. Figure 57 shows the stress versus strain curve of the ten samples tested along with the average ultimate stress value of 6630 psi.

FIGURE 57 - STRESS VERSUS STRAIN CURVE OF DELAMINATED BEAM WITH TRANSVERSE DAD KEYS

The ultimate strength value of 6630 psi shows that there is a 45% increase in strength over the beam that is delaminated without DAD keys. This increase in ultimate strength means that adding DAD keys to a delaminated sample does decrease the tendency for the face-core delamination failure mode. None of the test samples had failure due to face-core delamination except for one, which was a partial delamination as seen in figure 58. As the figure illustrates, one of the DAD keys did its job by inhibiting delamination propagation and the other DAD key failed allowing the delamination to propagate to the load support.

FIGURE 58 - ATYPICAL FAILURE OF BEAM WITH TRANSVERSE DAD KEY PLACEMENT

The rest of the samples failed just as the control specimen, which did not involve any face-core delamination. Figure 59 shows that this typical failure mode is more a result of the fracture of the carbon fiber face sheets and not a result of the failure of the interfacial bond between the two constituents.

FIGURE 59 - TYPICAL FAILURE MODE OF DELAMINATED SPECIMENS WITH TRANSVERSE DAD KEYS

3.4 NON-DELAMINATED BEAM WITH TRANSVERSE DAD KEYS

3.4.1 FABRICATION OF SANDWICH BEAMS WITH TRANSVERSE DAD KEYS

All the non-delaminated beams with the transverse configuration of DAD keys were fabricated using the same method as the delaminated beams except for the initial delamination. The DAD keys and foam were all fabricated using the same method as that described in the previous section. The step that uses non-porous material to insert an initial delamination between the core and the face sheets is left out for this fabrication method.

3.4.2 NON-DELAMINATED BEAMS WITH TRANSVERSE DAD KEY TEST RESULTS

All of the non-delaminated beams with the transverse DAD keys failed in the same mode as the control specimen: due to a face sheet fracture as seen in figure 60.

FIGURE 60 - ALL THE NON-DELAMINATED BEAMS FAILED SIMILARLY TO THE CONTROL SPECIMEN

All the non-delaminated specimens in this test failed due to face sheet fracture at the point where the load support meets the beam as seen above.

Once all the tests were completed according to ASTM standard D6272, the results were analyzed and the average ultimate strength seen in figure 61 of 6920 psi was found.

FIGURE 61 – STRESS-STRAIN CURVE FOR NON-DELAMINATED BEAM WITH TRANSVERSE DAD KEYS

Because the control specimens had an average ultimate strength of 6870 psi and the non delaminated beams with transverse DAD key placement had an ultimate strength of 6920 psi, it

can be assumed that there is no change in the ultimate strength of the beams when DAD keys are added with no delamination.

3.5 DELAMINATED BEAM WITH LONGITUDINAL DAD KEYS

FIGURE 62 - SANDWICH BEAM WITH LONGITUDINAL DAD KEY EXPANDED VIEW

3.5.1 FABRICATION OF SANDWICH BEAMS WITH LONGITUDINAL DAD KEYS

The foam and DAD keys are all fabricated using the same methods described in the previous sections with the other DAD key orientations. The difference between DAD keys being inserted in the longitudinal and transverse orientations is that the DAD key runs along the longitudinal axis of the beam instead of perpendicular to that axis. Figure 63 shows the orientation of the DAD keys in the foam before they are laid up.

FIGURE 63 - LONGITUDINAL CASE DAD KEYS ADDED TO THE FOAM READY TO BE LAID-UP

The sandwich core with DAD keys is sandwiched between layers of sheet resin, two layers of LTM45/CF1803 carbon fiber, porous material, and non porous material. The entire sample is placed between two steel plates just like the previous methods and cured with the same curing cycle in the Tetrahedron heat press.

The plate is then cut such that the DAD keys run along the longitudinal axis of the beam. Each specimen is the same dimensions as the previous tests but this time the DAD key is runs directly down the middle of the beam as seen in figure 64.

FIGURE 64 - LONGITUDINAL CASE DAD KEY ORIENTATION SIDE VIEW

3.5.2 *DELAMINATED BEAMS WITH LONGITUDINAL CASE DAD KEY TEST RESULTS*

The delaminated beams with the longitudinal case DAD key orientations had two typical failure modes: the first mode is the same as the control specimen where the face sheets fracture and the second is where the face sheet delaminates to the load then crosses through the foam to continue propagation on the opposite face sheet as seen in figure 65.

FIGURE 65 – THE TWO FAILURE MODES ASSOCIATED WITH THE LONGITUDINAL DELAMINATED BEAM

The ultimate strength was found using the same testing standard used in all the other beam configurations (ASTM D6272). The stress versus strain plot was generated for each sample and the ultimate stresses were averaged to attain the mean ultimate strength of the beams. The

average ultimate strength for this beam configuration was found to be 7020 psi as can be seen in figure 66. This ultimate strength value gave a 53% increase over the original delaminated beam, which had an ultimate strength of 4590 psi.

FIGURE 66 – STRESS-STRAIN CURVE FOR DELAMINATED LONGITUDINAL BEAM WITH DAD KEY

3.6 NON-DELAMINATED BEAM WITH LONGITUDINAL DAD KEYS

3.6.1 FABRICATION OF NON-DELAMINATED SANDWICH BEAMS WITH LONGITUDINAL DAD KEYS

The non-delaminated sandwich beams are fabricated the same way as the delaminated beams except the initial delamination is taken out so that the face sheet is completely attached to the foam core. The fabrication of DAD keys and foam are exactly the same as the previous beam configurations. The constituents are all organized in the same manner as the previous cases and cured with the same curing cycle in the Tetrahedron heating press. Once cured, the final beams are cut to the standard dimensions of 12" x 1" x 0.577" as seen in figure 67.

FIGURE 67 - NON-DELAMINATED BEAMS WITH LONGITUDINAL DAD KEYS

3.6.2 *NON-DELAMINATED BEAMS WITH LONGITUDINAL DAD KEY TEST RESULTS*

All sandwich beam samples were tested according to ASTM D6272 standard to find the average ultimate strength. The typical failure mode was face-core delamination mixed with a foam core fracture as can be seen in figure 68.

FIGURE 68 - TYPICAL FAILURE MODE OF NON-DELAMINATED BEAMS WITH LONGITUDINAL DAD KEYS

The results were exported from the Instron machine as an excel file and analyzed to generate stress-strain curves for every sample tested. The curves were superimposed and the average ultimate strength was obtained according to the standard's specifications. The ultimate strength attained was 7620 psi as illustrated in figure 69. This value is a 66% increase over the 4590 psi generated from the beam with only an initial delamination and an 11% increase over the control beam. This large increase is expected because the bond between the face-core interface is much larger and the stiffness of the entire beam is greatly increased.

FIGURE 69 – STRESS-STRAIN CURVE FOR THE NON-DELAMINATED BEAM WITH LONGITUDINAL DAD KEYS

3.7 COMPARISON OF SANDWICH BEAM RESULTS

The results of all the sandwich beam tests were essentially expected: the more the surface area and stiffness between the face-core interface, the larger the ultimate strength. The primary conclusion found from this testing is that the addition of DAD keys to delaminated beams greatly increases the structural integrity and ultimate strength of the beams. The addition of DAD keys to a non-delaminated beam does not have as great of an effect as the delaminated case but it was still signified by small gains in strength.

A summary of all results can be seen in table 7 comparing the average ultimate stresses, standard deviations, and percent differences from control beams.

TABLE 7 - SUMMARY OF ALL BEAM TEST RESULTS

DAD Key Orientation	Non-Delaminated			Delaminated		
	No DAD Keys (Control)	Transverse	Long.	No DAD Keys (Control)	Transverse	Long.
Average Ultimate Strength (psi)	6870	6920	7620	4590	6630	7020
Ultimate Strength Standard Deviation (psi)	166	225	237	312	291	344
Ultimate Strength Standard Deviation (%)	2.42	3.25	3.11	6.79	4.39	4.9
Increase over Non-Delaminated Control	0%	1%	11%	-33%	-3%	2%
Increase over Delaminated Control	50%	51%	66%	0%	44%	53%

The delaminated configurations with DAD keys showed the largest gains in ultimate strength, which demonstrates promise for the future of utilizing DAD keys in industry. The transverse and longitudinal configurations had a 44% and 53% increase over the delaminated control beam respectively. The standard deviations of the delaminated beams were larger than

the non-delaminated beams but still small comparatively. The non-delaminated beams all had very small standard deviations on the order of three percent. The percent difference from one testing method to another was so small that these results can be considered statically significant and repeatable.

4 NUMERICAL TASK: VERIFICATION OF EXPERIMENTAL DEFLECTION

The aim of this chapter is to verify the deflections found experimentally in each of the sandwich beams cases by using COSMOS finite element analysis software for mesh generation and analysis. The control, transverse, and longitudinal sandwich beams are all numerically verified. The section provides a detailed description as to how the beams are meshed, loaded, and analyzed. This chapter ends with a final comparison of all the experimental and numerical deflection results.

4.1 VERIFICATION OF SANDWICH BEAM DATA

The ASTM standards used to find the ultimate strengths and other mechanical data use equations which are functions of the beam deflection. Experimentally, the deflection is obtained directly from the Instron machine for a specified load. Because deflection values are of the utmost importance to all the data of this research, it is necessary to verify the values found.

All the beams are to be verified numerically by discretizing the sandwich beam geometry for the given case and applying the same load configuration and boundary conditions as seen in the experimental testing. Load levels are chosen to keep the response in the linear region of the stress-strain curve are to be used and the assumption of small deflections is applied to verify data.

4.2 CONTROL SANDWICH BEAM VERIFICATION

4.2.1 MESH GENERATION AND LOADING OF CONTROL BEAM

The control beam, seen in figure 70, was created in COSMOS by generating a separate volume for each of the different constituent materials. Each separate volume can be meshed and have mechanical characteristics defined solely for that volume. For the foam, the mechanical characteristics provided by the manufacturer were used for those particular elements, and for the carbon fiber face sheets, the mechanical properties found by experimental testing were used. The volumes of the sandwich beam can be seen in figure 71.

FIGURE 70 - CONTROL BEAM TO BE MODELED IN COSMOS

FIGURE 71 - VOLUMES USED TO MESH THE CONTROL BEAM

A total of seven separate volumes were created to model the control beam. The four volumes on the upper face sheet seen in the figure above are created such that the load can be applied on the curves instead of node-by-node, which is too tedious. The center volume on the upper face sheet is there to allow for an initial delamination to be added in future analysis.

Each volume is meshed such that the elements resemble the geometry of a cube, which has the highest accuracy in finite element analysis. When the elements get too elongated or distorted, the accuracy of the model decreases. The element type used for this case and all cases in the research is the eight-node solid element, which can be seen in figure 72. The solid element has a hybrid integration type, global stress-strain direction, and linear elastic small displacement properties. The mechanical properties of each constituent are then applied to each element group volume-by-volume.

FIGURE 72 - EIGHT-NODE SOLID ELEMENT USED FOR ALL MESHING¹⁵

The 100 pound load is applied along the two curves (50 pounds each) on the upper face sheet as seen in figure 73. The load value of 100 pounds is chosen because it results in a linear response and yields small deflections. The boundary conditions are added so that the numerical analysis reflects the same conditions as the four-point bending jig. As with the experimental analysis, the translation in the y and z directions are fixed at the boundary points just like the experimental conditions. The experimental jig is on rollers that allow the sandwich beam to translate along the x-axis but the finite element model needs this movement to be fixed or else it turns into a dynamic model. To solve this problem, the translation in the x-direction is fixed at the midspan point as seen in figure 73. The fixation of the translation in the x-axis in the center allows the beam to still translate at the point of the rollers but also keeps the beam centered between the rollers so that the model is static. Note: due to symmetry, the beam could have been modeled as one-half the beam.

FIGURE 73 - CONTROL BEAM WITH MESH, LOADS, AND BOUNDARY CONDITIONS APPLIED

4.2.2 RESULTS AND ANALYSIS OF CONTROL BEAM

The post-processing analysis of the sandwich beam is conducted statically under the specified loads and boundary conditions. The displacement contour plot is then able to be plotted and compared with experimental data. The average deflection found at 100 pounds of force experimentally was .09736 inches at the midspan. The deflection found numerically was .08739 inches as can be seen in figure 74.

FIGURE 74 - DISPLACEMENT CONTOUR PLOT OF CONTROL BEAM

The value of deflection found numerically was only 10.24 percent lower than the values found experimentally, which gives great verification that the control beam's data is significant. Just this one mesh is not enough for the researcher to say that the solution found is a converged solution.

To ensure that the deflection found numerically is a converged solution, the same geometry and load conditions were plotted for four different meshes of different element sizes to show that as the mesh gets more fine, the solution converges. The mesh for the solution above had 33,792 elements; three other meshes that get as coarse as 132 elements were analyzed and their deflection values were plotted in figure 75.

FIGURE 75 - DEFLECTION CONVERGENCE OF THE CONTROL SANDWICH BEAM

The values of deflection found for each of the meshes analyzed are as expected: as the mesh gets more coarse, the accuracy of the model is depleted. Adjacent elements of different size or material properties greatly increase the condition number for the system of equations, which in turn reduces the accuracy of the solution. This trend is observed because as the mesh gets more crude, the size of the elements in the face sheets are about ten times smaller than the elements in the foam core, which forces the elements to be less like their ideal cubic shape. The elements in the refined mesh are perfect cubes and fit the geometry perfectly, which is why the solution is a converged solution.

4.3 CONTROL SANDWICH BEAM WITH DELAMINATION VERIFICATION

4.3.1 MESH GENERATION AND LOADING OF CONTROL BEAM WITH

DELAMINATION

The loading, boundary conditions, geometry, and volumes of the delaminated control beam are the same as the control beam in the previous section. However, there is one large difference between the control beam and the control beam with a delamination: the nodes between the foam core and middle volume of the face sheet are disconnected to simulate a delamination at the face core interface. Figure 76 shows the disconnected nodes at the face-core interface.

FIGURE 76 - DELAMINATION MODELED BY DETACHED NODES AT THE FACE-CORE INTERFACE

4.3.2 RESULTS AND ANALYSIS OF CONTROL BEAM WITH DELAMINATION

The static analysis and postprocessing of the delaminated control beam was performed in the same manner as the previous section.

FIGURE 77 - STRESS CONTOUR PLOT OF THE DELAMINATED REGION

To verify that the delaminated region is indeed working, a plot of the stress contours was generated. Figure 77, which illustrates the stress diagram, shows that there is a region of delamination (indicated by the white arrow) where the stress in the face sheet is not transferred in the foam core. This area of no stress transfer verifies that the simulation of the delamination works.

Figure 78 demonstrates that the finite element simulation of the delaminated control beam has a midspan deflection of .08741 inches, which is only 8.95 percent lower than the experimental value measured of .09600 inches.

FIGURE 78 - DEFLECTION OF CONTROL BEAM WITH DELAMINATION

4.4 TRANSVERSE DAD KEY SANDWICH BEAM VERIFICATION

4.4.1 MESH GENERATION AND LOADING OF TRANSVERSE DAD KEY SANDWICH BEAM

The process in which the transverse sandwich beam is verified is the same as the control beam. The geometry of the model, seen in figure 79, is created in COSMOS by generating separate volumes for each constituent as seen in figure 80. Each volume is then meshed one by one applying the eight-node solid element as with the control beam along with all the material properties of that volume.

FIGURE 79 - TRANSVERSE SANDWICH BEAM TO BE VERIFIED IN COSMOS

FIGURE 80 - VOLUMES OF NON-DELAMINATED TRANSVERSE SANDWICH BEAM

The mesh of the sandwich beam is idealized by creating each element such that its sides are nearly the same dimensions to ensure accuracy. In addition to ideal sized elements, there are no large jumps from an element of one size to an element of an extreme different size, which also adds to the accuracy of the model.

The loads and boundary conditions are then added to the mesh as can be seen in figure 81. The load of 100 pounds is separated into two separate loads of 50 pounds each and loaded along the curves seen on each side of the DAD keys. The boundary conditions are implemented in the same manner and orientation as the control beam. The mechanical properties used to model the DAD keys were found from another student's research on the fiberglass material¹⁶. The elastic modulus found was 5,700,000 psi.

FIGURE 81 - LOADS AND BOUNDARY CONDITIONS APPLIED TO THE TRANSVERSE SANDWICH BEAM

4.4.2 RESULTS AND ANALYSIS OF THE TRANSVERSE DAD KEY BEAM

Once the mesh generation is complete with all the desired loads and boundary conditions applied, the solution phase and postprocessing of the discretization can be performed. The mesh is run statically for the 100 pound load that lies in the linear region of the load-deflection curve. The displacement contour plot is then generated to find the midspan deflection due to the specified load. The displacement plot, seen in figure 82, illustrates that the midspan deflection

for this specific case is .08679 inches, which is only 7.96 percent less than the experimental value measured of .09430 inches.

FIGURE 82 - DISPLACEMENT CONTOUR PLOT OF TRANSVERSE CASE BEAM

In order to verify that the deflection solution is a converged solution, four different meshes with varying element sizes were created to illustrate the convergence of the transverse case beam. As can be seen in figure 83, as the number of elements increases from a coarse mesh to a fine mesh, the midspan solution converges to the result obtained. Because the version of COSMOS used has a limit of 50000 elements, the most elements that could be used for this geometry was about 28,000.

FIGURE 83 - DEFLECTION CONVERGENCE OF THE TRANSVERSE CASE SANDWICH BEAM

4.5 TRANSVERSE CASE SANDWICH BEAM WITH DELAMINATION VERIFICATION

4.5.1 MESH GENERATION AND LOADING OF TRANSVERSE CASE SANDWICH BEAM WITH DELAMINATION

The volumes, loading, and boundary conditions of the delaminated transverse case beam are all the same as the non-delaminated transverse case beam addressed in the previous section. The delamination was created by detaching the nodes at the interface of the face sheet and foam core as seen in figure 84.

FIGURE 84 - SIMULATION OF THE DELAMINATED REGION IN THE TRANSVERSE CASE SANDWICH BEAM

4.5.2 RESULTS AND ANALYSIS OF TRANSVERSE CASE SANDWICH BEAM WITH DELAMINATION

To verify that the delamination was successfully simulated in the finite element model, a contour plot of the stress distribution of the sandwich beam was created. In the upper portion of figure 85, it can be seen that there is a transfer of stress between the connected face sheet and foam core, which is expressive of the non-delaminated beam. However, in the lower portion of the figure, the stress in the delaminated region is not transferred to the foam core, which conveys that the delamination was successfully simulated.

FIGURE 85 - VERIFICATION OF THE DELAMINATION'S EXISTENCE IN THE TRANSVERSE SANDWICH BEAM

The deflection of the transverse case delaminated sandwich beam can be seen in figure 86. The midspan deflection was found to be .08679 inches, which is only 10.53 percent lower than the experimental value measured of .09700 inches. Because this value is statistically significant, the delaminated transverse case beam can be considered verified.

FIGURE 86 - DEFLECTION OF THE DELAMINATED TRANSVERSE CASE SANDWICH BEAM

4.6 LONGITUDINAL CASE SANDWICH BEAM VERIFICATION

4.6.1 MESH GENERATION AND LOADING OF LONGITUDINAL CASE SANDWICH BEAM

The longitudinal case sandwich beam has the same loading and boundary conditions as all the previous cases. The longitudinal case sandwich beam, seen in figure 87, was created in COSMOS by extruding 13 different volumes representing the different sections of the beam. The volumes of the longitudinal case sandwich beam can be viewed in figure 88.

FIGURE 87 - THE LONGITUDINAL CASE SANDWICH BEAM TO BE VERIFIED IN COSMOS

FIGURE 88 - VOLUMES GENERATED IN COSMOS TO MODEL THE LONGITUDINAL SANDWICH BEAM

The eight-node solid element mesh was applied to each volume with its corresponding mechanical properties. The mesh, illustrated in figure 89, has the same boundary conditions as the experimental setup where the y and z-direction translation is fixed in addition to constraining the middle of the beam to have no translation in the x-axis. This set of boundary conditions

allows the beam to rotate at the rollers, but keeps the beam from sliding longitudinally with the x-direction fixed.

FIGURE 89 - LONGITUDINAL CASE SANDWICH BEAM'S LOADING AND BOUNDARY CONDITIONS

An end view of the beam is a convenient way to view the way in which the DAD key was simulated in the mesh and can be viewed in figure 90.

FIGURE 90 - END VIEW OF THE LONGITUDINAL CASE SANDWICH BEAM'S MESH

4.6.2 RESULTS AND ANALYSIS OF LONGITUDINAL CASE SANDWICH BEAM

After the mesh generation and loading, the longitudinal case sandwich beam could be verified. The loads totaling 100 pounds were placed at the same points along the span of the beam as the previous beams studied. The load of 100 pounds was chosen because it lies in the linear region of the load-deflection curve. Because the simulation assumes small angles of deflection and linearity, the load value of 100 pounds works great for the model. Contours of the deflection of the longitudinal case sandwich beam can be seen in figure 91. As illustrated, the midspan deflection was found to be .080645 inches, which was only 9.39 percent lower than the value measured of .08900 inches. The increase in stiffness and face sheet to foam core bonding

given from the DAD key adds a significant amount of strength to the specimen, giving it a decrease in deflection of 7.72 percent found numerically from the control beam.

FIGURE 91 - MIDSPAN DEFLECTION OF LONGITUDINAL CASE SANDWICH BEAM

As with the previous cases the mesh was checked to ensure that the result was a converged solution. Four different cases were plotted to see the effect that the number of elements has on the final solution. In each of the points plotted in figure 92, the number of elements in each volume is multiplied by 2^3 because the number of nodes in each direction is doubled from the case before. For instance, a model with 4000 nodes would then have 32,000 at the next point etc. It is clear from the figure that the solution converges around the 4000 element point because the difference in deflection between that value and the next is less and one-tenth percent.

FIGURE 92 - CONVERGENCE HISTORY OF THE LONGITUDINAL CASE SANDWICH BEAM SOLUTION

4.6.3 MESH GENERATION AND LOADING OF LONGITUDINAL CASE SANDWICH BEAM WITH DELAMINATION

The mesh generation, loading, and boundary conditions were all implemented in the same manner as the previous cases studied. The delamination, like the other models, was added in between the loaded span of the beam. This was accomplished by detaching the nodes in the region of the delamination so that the face- core interface is free.

4.6.4 RESULTS AND ANALYSIS OF LONGITUDINAL CASE SANDWICH BEAM WITH DELAMINATION

To ensure that the delamination was properly modeled in the mesh, a plot of the stress contours was generated. Figure 93, illustrates that the delamination was successfully modeled because there is no transfer of stress between the face-core interface like there is with the non-delaminated sample.

To verify that the experimental deflections measured were accurate, figure 94 was generated to illustrate the deflection contours of the beam. As seen in the figure, the midspan deflection of the delaminated longitudinal case sandwich beam was found to be .08065 inches, which is 6.20 percent lower than the experimental value measured of .08601 inches. This value of error is consistent with the other values found for the different beam cases.

FIGURE 93 - STRESS CONTOURS VERIFYING THE DELAMINATION IN THE LONGITUDINAL CASE BEAM

FIGURE 94 - DEFLECTION CONTOURS OF THE DELAMINATED LONGITUDINAL CASE SANDWICH BEAM

4.7 COMPARISON OF EXPERIMENTAL AND NUMERICAL DEFLECTION

The validation of the deflections found experimentally was successful. The final comparison of numerical and experimental values can be found in table 8. The table demonstrates that all the deflections used in the equations to find the mechanical data of the sandwich beams are significant.

The fact that all the values found numerically are 6-10 percent lower than the values of deflection found experimentally add to the confidence that the simulation was successful. In addition, for standard displacement based elements, the response is stiffer than the actual values. The error is likely due to the fact that the mechanical characteristics of the foam supplied by the manufacturer have an exaggerated elastic modulus. Because the foam was stacked (which is not part of the ASTM standard) when testing for the mechanical characteristics of the foam, the results of the test were not used because they yielded a much lower elastic modulus than the manufacturer provided. However, when the elastic modulus from the manufacturer is used, it is too stiff and the deflections found resulted in smaller values. For research purposes, the elastic modulus value found from testing the foam was used in the model and the same amount of error resulted but this time the beams were not stiff enough and all the deflections were about 10 percent larger. The best thing to do would be to obtain a single sample of the foam to avoid stacking and get the correct mechanical properties of the samples (which would probably be in between the values tested and the values supplied by the manufacturer) and use that for the simulation.

TABLE 8 - COMPARISON OF ALL NUMERICAL AND EXPERIMENTAL DEFLECTIONS

	Control		Transverse Case		Longitudinal Case	
	Non-Delaminated	Delaminated	Non-Delaminated	Delaminated	Non-Delaminated	Delaminated
Experimental (in)	0.09736	0.09600	0.09430	0.09700	0.08900	0.08600
Numerical (in)	0.08739	0.08741	0.08679	0.08679	0.08060	0.08070
Percent Difference	10.24	8.95	7.96	10.53	9.39	6.20

4.8 VALIDATION OF MODEL

To ensure that the values of deflection found are accurate, a model of a composite beam was created with the same loads and boundary conditions as the sandwich beams tested and compared with theory. The model is made out of a layer of steel ($E_{ST} = 30 \times 10^6$ psi) sandwiched between two layers of aluminum ($E_{AL} = 10 \times 10^6$ psi) as seen in figure 95.

FIGURE 95 - SIMPLY SUPPORTED COMPOSITE BEAM USED FOR VALIDATION

The method of equivalent stiffnesses¹⁷ and superposition¹⁸ was used to find the model's deflection theoretically. This type of linear elastic Euler-Bernoulli beam theory works by taking the cross-section of different homogeneous materials and making one equivalent cross-section that has the same bending stiffness as the original. Because the elastic modulus of the steel is three times that of the aluminum, we can make one equivalent cross-section of aluminum by replacing the steel with aluminum that is three times as large which can be seen in figure 96.

FIGURE 96 - EQUIVALENT SECTION BASED ON THEORY

The total moment of inertia was then found for this new section using equation 16:

$$I_{xx} = \frac{1}{12}bh^3 + Ad^2 \quad (16)$$

The moment of inertia was found for each section using this equation and then summed to obtain the total moment of inertia for the entire cross-section, which was .03776 in⁴. With both the moment of inertia and the elastic modulus of the new section, the deflection could be found through super-position. The equation used for the super-position was for one load (see equation 17), and must be multiplied by two to obtain the result for the beam with two loads.

$$\delta = \frac{Pb(L^2 - b^2)^{2/3}}{9\sqrt{3}EIL} \quad (16)$$

Where δ is the maximum deflection of the beam, b is the distance from the right support to the load location, and L is the length of the beam. Using this method, we find the deflection of the beam to be .006919 inches for the case with two loads of 100 pounds each.

For the numerical simulation in COSMOS the loads and boundary conditions are applied in the same mannar as all the previous sandwich composite beams. The material properties of each material were added to the elements corresponding to that constituent. The same eight-node solid element used for the previous analysis was also used for this comparison. The deflection was numerically found to be .006945, as can be seen in figure 97, which is only 0.375 percent larger than the theoretical value obtained.

The small difference in deflection found in this model validation indicates that the deflection values found in the previous examples were highly accurate.

FIGURE 97 - NUMERICAL DEFLECTION CONTOURS OF THE VALIDATION EXAMPLE

5 CONCLUSION

5.1.1 OVERVIEW OF RESEARCH AND RESULTS

The use of a damage arrestment device (DAD) key that connects the carbon fiber face sheets to the foam core to find whether an increase in the structural integrity of the sandwich beam results was the scope of this research. An experimental method aided by theory was employed to test the samples and was verified by a finite element approach.

ASTM standards D3039 and D1621 were used to verify the manufacturer's data for the mechanical properties of LTM45/CF1803 pre-impregnated carbon fiber and Last-A-foam FR 6710 polyvinylchloride foam respectively. With all the mechanical data, the effects of adding DAD keys to a delaminated composite sandwich beam were studied under a four-point bending test using ASTM standard D6272 and compared with non-delaminated beams to see if an increase in ultimate strength resulted. The initial delamination in the beams under consideration was one inch in length and located in between the loaded span of the beam. Two control beams were utilized to compare experimental results with: one with no defects, and another with a one-inch delamination introduced at the face-core interface. The DAD keys were added in two different configurations signifying the worst and best possible cases to potentially stop the delamination propagation and increase the ultimate strength. In the first configuration DAD keys were added 0.25 inches on either side of the initial delamination in the transverse direction and is considered the worst case. The second configuration had a DAD key running along the longitudinal axis of the sandwich beam and is considered the best case.

The key conclusions drawn from this research were:

- Adding DAD keys to delaminated beams increases the ultimate strength of the beam by 44 percent in the transverse scenario and by 53 percent in the longitudinal scenario over the delaminated control beam.
- Adding DAD keys to a non-delaminated beam increases the ultimate strength by one and 11 percent in the transverse and longitudinal cases respectively over the non-delaminated control.
- Without DAD keys, the control beam's primary failure mode is face-core delamination.
- With DAD keys, the failure mode is material fracture at the load.

With all the experimental data, finite element models were created in COSMOS to compare the test results to numerical data. The purpose of the finite element analysis was to validate the experimental results by comparing the deflections of the beam subjected to four-point

bending during the experiment to the deflections found numerically. All of the beams were successfully validated with only a 6-10 percent difference in the deflections found between the experimental and numerical data. All of the cases studied numerically were a small percentage lower than the experimental values found, which means that the potential source of error was in the mechanical properties of the material tested.

5.1.2 FUTURE USE FOR THE DAD KEY CONCEPT

A way to decrease the size of the delamination or cease the delamination from propagating at the face-core interface can provide many benefits and advantages. The DAD keys reduce the delamination growth, diminishing safety hazards. The reduction of delamination growth will decrease the need for repair or replacement of the composite structure, reducing cost. Maintaining the lightweight design reduces the time and the costs for transportation. In addition, the increased structural integrity of the composite structure will enhance its dependability and endurance.

This research has shown that there is great potential for the use of DAD keys in industry. As the DAD key concept is still in the research phase, there would need to be a lot of time and money dedicated toward their implementation into structures before they can ever be utilized in industry. Any place where a load is located that creates a bending moment in a structure is a potential place that the DAD key inserts can be used. A pilot standing on a fuselage floor, a mechanic stepping on a wing, a wrench being dropped on a cargo truck floor are all common occurrences that can be addressed by the use of DAD keys in design.

5.1.3 FUTURE WORK

DAD key inserts have proven that they will likely have a future whether it is only in research or in industry. Nevertheless, the concept still needs a large amount of future work to get the idea into use. More investigation into size of the delamination, geometry of the DAD keys, and the orientation of the DAD keys is of great need. Furthermore, research into the effects of DAD keys after having the sandwich beam impacted is also pertinent to the future of the DAD key.

There is a whole area of structural research on the subject of the geometry and material of peel-stopping devices. Characteristics such as material selection, thickness, and orientation are all attributes that are under investigation to see their effects on the impedance of face-core delamination.

In this research only the best and worst (longitudinal and transverse) case DAD key orientations were studied. Research to see how the angle of the DAD key along the beam has an effect on the structural integrity of the sample is also an essential area of study that needs further investigation.

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