**Effects of Seawater on the Mechanical Behavior of Composite Sandwich Panels
Under Monotonic Shear Loading**

A Thesis

Presented to

the Faculty of the Graduate School

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Aerospace Engineering

By

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January 2012

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Committee Membership

TITLE: Effects of Seawater on the Mechanical Behavior of Composite Sandwich Panels
Under Monotonic Shear Loading

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DATE SUBMITTED: December 12, 2012

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Abstract

Salt water environments are very harsh on materials that are used within them. Many issues are caused by either corrosion and/or internal degradation to the materials themselves. Composites are better suited for this environment due to their high strength to weight ratios and their corrosion resistance, but very little is known about the fracture mechanics of composites. The goal of this study is to gain a better understanding for the behavior of a composite boat hull under a shear loading, similar to the force water applies on the hull as the boat moves through the water; then attempt to strengthen the composite sandwich panel against the shear loading.

A parametric study was conducted to investigate monotonic in-plane shear loading for composite sandwich panels used in commercial naval vessels. In order to model a conventional composite boat hull, test specimens were composite sandwich panels made of a Divinycell H100 foam core with four layers of fiberglass on both sides of the core. Specimens were tested under a monotonic loading with a rate of 0.2 in/min, and tested until complete failure using the standard test.

Seawater specimens were manufactured in the same manner as the original test specimens, but then were submersed in either filtered seawater or the ocean. The differences between the filtered pieces and the ocean allowed us to determine if any changes found in the composite sandwich panels were related to environment conditions or if the changes were related to the saltwater interaction itself. To create these different environments the seawater specimens were taken to the Avila pier where 36 specimens were placed in a tub that was fed filtered saltwater, while 30 specimens were placed in a plastic mesh with weights and lowered to a depth of approximately 30 ft. in the ocean.

Three specimens were then removed at monthly intervals from both filtered and ocean environments.

Shear Keys were created as a method to strengthen the composite sandwich panels against the shear force that the previous specimens had been tested to. Eight Shear Keys were then placed into groves cut into the foam core (four on each side) and the four fiberglass layers were laid on top.

Testing showed that the seawater did have an initial effect on the composite sandwich panels. The filtered pieces showed a decrease in yield strength and stiffness the longer they were subjected to the seawater. The raw unfiltered pieces placed in the ocean saw an even higher decrease in their yield strength and decrease in stiffness. However, for both the unfiltered and raw specimens there was an increase in the ultimate strength and fracture point of the specimens. The effects of the sea water seemed to taper off after the 3rd month however.

The Shear Key specimens were tested with a 4mm and an 8mm Shear Key. The 8mm Shear Keys showed a decrease in shear strength, which was primarily due to removing too much material from the core and weakening the specimen. It was concluded that the decrease in area created a force concentration at the deepest part of the Shear Key causing the premature failure. The 4mm Shear Key showed an increase in the yield strength, ultimate strength, and fracture point. A finite model was built to simulate the original test specimen along with the 4mm and 8mm Shear Key cases, and the results were compared to the experimental results.

The numerical results showed that it was possible to relate the experimental results to the linear or elastic portion of the plots. There was a difference between the maximum displacement of the model and the actual specimens, but this was attributed to potential inaccurate comparison of the loading on the model compared to the actual specimens. The correlation between the model itself and the experimental data was close enough to conclude that it could be used for predicting baseline trends.

Further investigation of the specimens should include looking into the effects of a cyclic shear loading on the specimens. This combined with the seawater element used in this thesis would provide further insight to the initial degradation seen in the seawater specimens, and could potentially provide a closer relation to current hull failures. In addition to including a cyclic loading another numerical model should be created. A model that could be constrained both locally and globally would provide more accurate results. The FEM should also include the ability to run a crushable foam core model within the solver which would also increase the accuracy of the numerical solution.

ACKNOWLEDGEMENT

I would like to start by thanking my thesis advisors Dr. Faysal Kolkailah and Dr. Eltahry Elghandour for without their guidance and support none of this would have been possible. Among other faculty I would like to thank Dr. Mello for allowing us to use the Mechanical Engineering Composite Lab and Instron Machine; Dr. Eric Kasper for his support and guidance with numerical methods, and Dr. Nilanjan Mitra for allowing me to work on this grant which allowed to me to finish the work on my thesis under his supervision. I would like to thank Dr. Kristina Jameson for providing her advice and guidance whenever it was needed.

I would like to give special thanks and recognition to Michael Jacobson who helped me with almost every aspect of the grant, and stood by as a friend throughout the process, and without whom this grant's success and many learning opportunities would not have been possible. Thanks to all my family and friends who supported and believed in me from the start, and who have helped shape me into the person that I am today. Thanks to my parents for helping to motivate me and provide me with the opportunity to follow my dreams. Thank you to my sister for providing her love and support, making this journey easier.

I would like to thank to my friends Eugene Eswonia, Richard Balatbat, and Dominic Surano for their support and advice. In addition I would like to thank Kodi Rider for his help and guidance with the use of the COSMOS Geostar software.

Big thanks to Charlotte Belsick and Lockheed Martin for their support and for providing me with an opportunity to use the skills acquired at school over these past few years.

I would like to thank the Cal Poly Aerospace Engineering Department, for without the use of their labs and equipment none of this research would have been possible. Thank you to C3RP for providing the funding and support, for such interesting work to be carried out.

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1.0 Introduction

Throughout my life I have always had a fascination with aircraft and spacecraft, so when I decided to choose a major I chose Aerospace Engineering. I have always enjoyed hands on challenges too; so I decided my thesis would have to allow me to design, build, and test. The aerospace industry has always looked for lighter and stronger materials to help improve efficiency, reliability, and performance of current and/or future craft. It was my hope that by choosing a thesis surrounding composites I would be able to help broaden my knowledge base. This knowledge base included things such as structural applications, testing, and manufacturing for the aerospace industry; while still meeting my personal requirements for my thesis. This chapter will give a basic introduction and overview into the work of my thesis and the research that was completed.

1.1 Background on Composites

Composite materials have become a major part of almost every aspect of engineering in today's world. As the technology has evolved so has the demand for new materials that can meet very specific requirements. However, composites usage dates back to ancient times where mud and straw were combined to create bricks used for building structures. Since then, people have vastly improved the capabilities to manufacture and design composites to meet the demands of technology in today's world. Composites are now used for airplane and automobile structures shown in Figure 1, spacecraft, sports equipment, housing, and more.

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Figure 1: The Lamborghini Reventon (left) and the F-22 Raptor (right) are two examples of modern technology using composites

A composite is defined as “a material that contains two or more constituent materials that are combined on a macroscopic level” to create a new material. The purpose of a composite is to create a material that exhibits all of the strengths’ of its constituents, and sometimes create strengths which neither material possess. Creating a composite does not strengthen all aspects of the material; however an engineer or designer can choose which properties they want enhanced by choosing the proper materials to incorporate into the composite. Some of the properties that are improved within composite materials are strength, stiffness, ductility, corrosion resistance, fatigue resistance, attractiveness, weight, fatigue life, temperature-dependent behavior, thermal insulation, thermal conductivity, acoustic insulation, and vibration dampening. When the requirements for the material have been identified an engineer faces the decision of choosing what type of composite to use, what fibers and matrix combination are needed, number of laminates and direction, and what layup technique will ultimately lead to a product that will meet all design requirements.

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1.2 Types of Composites

When choosing a composite type it is important to understand that there are three types of composite materials including: fibrous composites, particulate composites, and laminated composites. Fibrous composites contain fibers and a matrix that holds the fibers together, shown below in Figure 2. Particulate composites are composed of non-fibrous particles combined with a matrix such as concrete and particle board. Laminated composites consist of layers of two or more materials that are bonded together. Since this thesis is focused on fibrous composites, particulate and laminated composites will not be mentioned any further.

Fibrous composites are simple in their design. The purpose of the matrix is to support and protect the fibers, while helping to distribute the load evenly across the fibers. This bond of materials produces a new material that can be stiffer and stronger than the same materials in their bulk form. In addition to being stronger than the same materials in bulk form, fibrous composites have fewer defects in the fibers due to the crystals within being aligned along the axis of the fiber. The key to the strength of these composites comes from the geometry and orientation of the fibers used in the composite. By specifically aligning fibers with the load(s) an engineer can create a lighter part, while still maintaining its required strength. Having a high fiber aspect ratio allows for an effective load transfer via the matrix to the fibers, which takes advantage of the material properties used within the composite. There are several types of fibers used in most composites presently that including glass, Carbon, Kevlar, Aramid, Boron, graphite, and ceramic fibers. Fiber choices differ between applications since each type of fiber has its own unique properties.

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Figure 2: An example of a fibrous composite structure.

The matrix of a composite is responsible for binding fibers together, protecting the fibers from damage and/or corrosion, and transferring the loads between the fibers. These responsibilities lead to the matrix being very influential on the overall behavior of the composite such as shear, compression, transverse modulus, tensile, and elastic properties. It also can place limitations on a material's uses such as a melting point at which the matrix melts and the composite ultimately fails. Polymers and plastics are the most widely used matrix material for fiber composites due to their low costs, ease of production, high availability, chemical resistance, and low specific gravity. The main disadvantages of polymer matrices originate from their low strength, low Modulus, and temperature limitations. Metals can also be used as matrix material for a composite to counter the disadvantages seen in polyester and epoxy resins. They provide higher strength and Modulus, less limitations by temperature, and more impact strength. This comes at a cost though since metals are more subjective to corrosion, are much denser, require high processing temperatures, and can potentially react with the fibers.

1.3 Methods of Composite Fabrication

There are four different mainstream types of layup processes that are currently used in industry for creating polymeric composites. The simplest of the four processes is called a "wet layup" technique. A wet layup involves working resin through the dry

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fibers by hand before being cured. Major advantages to this method include no special requirements, low cost, an easy learning curve, and no additional equipment. Some of the disadvantages associated with this type of layup involve inconsistencies in resin-to-fiber ratio, and potentially damaging or destroying fiber integrity while working the resin into the fibers.

The second method is known as “Pre-preg” which refers to a composite that has been pre-impregnated with resin at the factory. The main advantage to this layup method is the Pre-preg contains a consistent fiber-to-resin ratio, which allows the strongest part possible for a set weight. There are several disadvantages to this layup however such as: extreme costs for the material itself, precise heating/curing cycles required to cure the Pre-preg, and the equipment needed to store (it requires a freezer that can achieve very cold temperatures to prevent the epoxy in the fibers from curing) and cure the Pre-preg (ex. Autoclave).

The third method is known in industry as a resin infusion process or a vacuum assisted transfer molding (VARTM) system. This method involves the use of suction force to pull resin across a part as well as using the pressure created by the vacuum to infuse the fibers with resin. At Cal Poly this process is known as VRI which stands for Vacuum Resin Infusion. The advantage to using the VRI system is that it fits between the two other methods providing a good balance of quality and cost. It utilizes a vacuum pump to draw resin across the part being manufactured preventing fiber damage by reducing the amount of handling the fibers see. VRI also provides more consistent resin content throughout the part when compared to a wet layup, which leads to more consistent testing results (This is assuming that neither part is placed in an autoclave for

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curing, where the additional pressure alleviates most of the inconsistencies). At the same time, VRI does not have the same perfect fiber-to-resin ratio that Pre-preg has, but it also does not have the cost associated with it. However, VRI is limited by the work-time of the resin being used, since the epoxy must be mixed with the hardener before being pulled across the part. This means the resin starts to cure and harden as the vacuum process begins, which limits the size of the part that can be made up. This method is a good choice where cost, speed, and consistency are major factors in which results have to be produced.

The fourth method for composite fabrication that is seen in today aerospace industry is known as Filament Winding. In this process fibers and resin are tension-wound together over mandrel or a mold. The mandrel or mold is then removed once the composite has cured. Filament winding is typically found in industry where composite tubing is needed, however the technology for the filament winding has been receiving improvements over the years. The greatest example is the Boeing 787's fuselage that is a single composite piece fabricated using a filament wound technique.

1.4 Composite Sandwich Panels

Composite sandwich panels are the combination of a core with a skin (also known as a facesheet) on both sides of the core. Although composite sandwich panels are not always one piece this thesis will focus on the properties of the composite sandwiches that are a single entity. The concept behind using composite sandwiches revolves around the material's increased bending moment while providing an even greater strength to weight ratio, thus increasing the strength of the part. This is because when a force is applied to the composite, it introduces a tension force to the facesheet in contact, which through a

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shear force to the core, effectively compresses the other facesheet. By increasing the thickness of the core the composite panel's strength is effectively increased similar to the way an I-Beam's strength is increased. Furthermore, composite sandwiches are designed such that they fail within the core of the material, thus taking full advantage of the material properties and making shear strength one of the driving factors in the composite design. This will be further discussed in the failure analysis section.

In addition, composite sandwiches are tailored to their usage requirements and maintain all the normal strengths that composites are known to possess. This is because the facesheets are made from stiff materials with a high Modulus of Elasticity (when compared to the core) such as metal alloys, plastics, and fiber resin combinations. Core materials have a low Elastic Modulus and are expected to yield without failure in the higher deflection areas. The typical cores used consist of a range from opened to closed cell structured foams to metallic and fibrous honeycomb structures depending on the structure's needs.

1.5 Previous Works

There have been numerous studies on model development for fluid ingress in composites (e.g. Ionita and Weistman (Mechanics of Materials 39 (2007))); however, the effects of sea-water on mechanical performance of composite sandwiches have been investigated by very few researchers.

Kolat, et al. (Composite Structures 78 (2007)) determined the effect of fracture toughness of composite sandwiches subjected to sea water conditions. However, in this study the sea water effect was simulated by conditioning with steam a 5% solution of

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sodium chloride. Li and Weistmann (Composites: Part B; 35 (2004)) investigated the effect of sea water on fracture behavior of composite materials, as well as face/core interfacial de-bonding. A study by Veazie, Robinson and Shivakumar (Composites: Part B; 35 (2004)) also determined effects of a marine environment (elevated temperature, elevated temperature and moisture; and only sea water) on interfacial fracture toughness of composite sandwiches. However, the effect of sea-water on standard tensile, compression, shear and fatigue loadings was not determined in any of these investigations. Moreover, the studies by Li and Veazie utilized sea-water at room temperature without the real environmental conditions of actual sea water. A more recent study was done by Aktas and Ozun (Composite Structures 85 (2008)), which simulated the effect of real environmental sea-water conditions on bearing strength of woven glass fiber composites. There have also been some studies on mechanical performance degradation with sea-water aging on glass fiber composites (Davies et al. 2001) but these did not consider composite sandwich panels. Therefore, a true evaluation of the long-term combined effects of the marine environment on the mechanical performance of composite sandwiches is still an open topic.

1.6 Thesis Overview

This project originally started as a C3RP grant with the main focus of the grant being the investigation of the effects of sea water degradation on a fiberglass composite sandwich under a shear loading. Once this was determined, methods of strengthening the composite panel to reduce the degradation effects were investigated. This was done to give more insight about composite sandwich panels in sea water along with the fracture mechanics and the failure modes. An investigation was conducted to gain a better

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understanding for the behavior of a composite boat hull under a shear loading, similar to the force water applies on the hull as the boat moves through the water; then attempt to strengthen the composite panel against the shear loading.

A parametric study was conducted to investigate monotonic in-plane shear loading for composite sandwich panels used in commercial naval vessels. Testing was modeled after the ASTM C273 Standard Test Method for Shear Properties of Sandwich Core Materials. In order to model a conventional composite boat hull, test specimens were composite sandwich panels made of a Divinycell H100 foam core with four layers of fiberglass cloth on both sides of the core. Manufacturing of the composite sandwich panels required a VRI process to meet the requirements for specimen consistency and cost effectiveness. The sandwich specimens were cut to 16" x 2" x 1.3" (length x width x height) and adhered to the test jigs and then placed in the INSTRON 1331/8801 Servo Hydraulic Test System. Specimens were tested under a monotonic loading at a rate of 0.2 in/min, and tested until complete failure. These results were used as a comparison to the seawater immersed specimens to determine the effects that the environment had on the composite sandwich panels over time.

Seawater specimens were manufactured in the same manner as the original test specimens, but then were submersed in either filtered seawater or the ocean. The differences between the filtered pieces and the ocean would allow determination of any changes found in the composite panels to be related to environment conditions or if the changes were related to the saltwater interaction itself. The main differences between the raw and filtered conditions involved oceanic current and pressure differences as well as the formation of biological on the specimens. To create these different environments, 36

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salt water specimens were placed in a tub with filtered saltwater from the ocean. A separate batch of 30 salt water specimens were placed in a plastic mesh with weights and lowered to a depth of approximately 30 feet in the ocean. Three specimens were then removed at monthly intervals from both filtered and ocean environments. The specimens were then tested to the same specifications as the original test specimens such that the initial specimens could act as a control group. All specimens were tested at ambient conditions only.

Shear Keys were created to increase the shear strength of the composite sandwiches. The Shear Keys were made by placing strands of fiberglass in a semi-circular mold and then using VRI to infuse them with resin. Using VRI, eight Shear Keys were placed into grooves cut into the foam core (four on each side) and four fiberglass layers sandwiched the foam core and Shear Keys. The panels were made using VRI and the test specimens were then made from these test panels.

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2.0 Manufacturing Procedure and Experimental Setup

This section will cover the design of the testing jigs and explain the testing setup. It will follow that up by an explanation for how the specimens were manufactured and the fabrication process that was utilized to create all of the composite sandwich panels. Then it will explain the fabrication of the Shear Keys and how they were implemented into the specimens. The section will end with the explanation of the sea water setups that were used along with the specimen and testing preparation required.

2.1 Test and Specimen Design

In order to conduct a proper investigation of the in-plane shear of composite sandwich panels, testing was conducted using the ASTM C273 standard “Standard test method for shear properties of sandwich core materials” for reference in providing standard specimen geometry, preparation, and testing procedures. Tests were conducted using the Cal Poly Mechanical Engineering INSTRON 1331 Universal testing machine or the Cal Poly Aerospace Engineering INSTRON 8801 Fatigue Testing System, shown in Figure 3. Both of these systems allowed full control of the rate of displacement, which was kept at a constant 0.2 in/min. Guidelines were also given for adhesive materials, fabrication methods, specimen geometry and preparation, and testing procedures among others.

However, ASTM C273 states that the only acceptable mode of failure is a core failure. Because of this the standard was used as a guide instead of having all the experiments conducted per the standard. By having both delamination and core failures

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allowed the results to be comparable to that of naval vessels, which was the main interest of the grant. This involved investigating core failures as well as delamination failures where the ASTM C273 only allowed for core failures as previously stated.

Figure 3: INSTRON 8801 (left) and INSTRON 1331 (right) Servohydraulic Testing Systems

The testing jigs were designed for a specimen geometry of 16" x 2" x 1.3" (length x width x height) using a 30 mm Divinycell H100 foam core. The specimen length chosen was very important since it was designed such that any anomalies that occurred at the ends would not influence the results or stop the test. This provided results mainly focused on the shear properties of the composite sandwich panel, and not the material response to the normal force. The length of the specimen had to also take into account the testing machines displacement capabilities, and make sure to allow for a complete failure of the specimen. In addition to being able to negate the initial boundary failures, choosing the length of the specimen was done such that the angle in which the specimen rested with regards to the clamp was minimized. The normal force came from the design of the test jigs themselves. Based on the design of the testing jigs per ASTM C273 the

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steel ends did not reach the point where the center of the core would line up. Because the ends did not line up perfectly with the specimens core their test jig and specimen sat at a small angle. This angle was decreased with the lengthening of the specimen allowing the majority of the ultimate strength recorded to be attributed to the shear component and not the normal.

An example of this is shown below in Figure 4. These cracks and tears initiated but then stopped at about 20% of the overall load, and had no further effect on the piece or failure.

Figure 4: Boundary conditions that were minimized by increasing specimen length. Dimensions were drafted up (shown below in Figure 5) in a CAD program and then transferred to a 3-D model in Solidworks, shown in Figure 6.

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Figure 5: Testing Jig drawing with dimensions.

Figure 6: 3-D model of Testing Jig created in Solidworks.

Specimens were attached to the testing jig using DP460NS structural epoxy which is considered to be a high performance adhesive. The testing jig (shown on the right in Figure 7) was fabricated from steel according to the ASTM C273 standard.

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Figure 7: CAD drawing of the testing apparatus per ASTM C273 (left) with an actual specimen loaded on the INSTRON 1331 (right).

2.2 Specimen Manufacturing

Since the goal of this experiment was to research the behavior of composite sandwich panels that were used in commercial naval vessels, materials had to be chosen such that they could be related. This led to the use of a 30mm thick Divinycell H100 closed foam core, which was surrounded on both sides by 4 layers of two types of fiber glass. The two types of fiber glass (E-glass) consisted of a chopped strand mat and woven roving (explained later) that were alternated with each other such that the woven roving was on the outside and the final layer of the chopped strand mat rested against the core. The woven roving which consisted of bi-woven layers of E-glass in a $0/90^\circ$ orientation was used to provide most of the laminate strength. The chopped strand mat

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consisted of many chopped fibers randomly oriented providing a better force distribution through the laminate.

2.3 Fabrication procedure

To fabricate the specimens a Vacuum Resin Infusion process was developed and used, since this would provide the most consistent specimens to test while maintaining affordable cost. Vacuum Resin Infusion (in this case) is a process that uses a vacuum pump to pull resin, or the matrix, across dry fibers. Figure 8 shows an example of a part fabricated using VRI.

Figure 8: Finished example of a part manufactured using VRI.

The following materials were used for this process:

- Vacuum pump
- Spiral Tubing
- Vacuum tubing
- T-Fittings
- Vacuum bag
- Sealant tape
- Chopped Strand Fiber Glass mat
- Woven Roving Fiber Glass (0°/90°)
- Epoxy system (West System 105/206)
- 30mm Divinycell H100 Foam
- Aero weave (cotton breather cloth)
- Release cloth (peel ply)
- Vice grips
- Mixing cups
- Cutting tools
- Stirring sticks
- Flow media (green)

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The first step for the manufacturing process was to cut the foam core material to the correct size for the layup. As a precaution, the foam piece was cut bigger than the necessary size to provide a safety margin for trimming and post layup cutting purposes. This margin was typically 1 inch of extra material on each side of the specimen, and was extended to all cloth and core materials in preparation for the layup. Layups were typically sized 18"x10" (l x w) such that four specimens could be made from each. The width was decided from the cure time of the epoxy and the length of time it took for the epoxy to flow across the part. Figure 9 shows a sample of the foam core that was cut with the chopped strand mat and the foam core.

The next step was to cut the chopped strand mat to the same size as the foam core. Two pieces of strand mat were needed for each side of the specimen, which resulted in four pieces for each layup.

Figure 9: PVC Foam Panel (left), Chopped Strand Mat with Foam Core (right)

Next, the woven roving was cut to the same size as the foam core. Just like the chopped strand mat, a total of four pieces were needed. Woven roving was cut between the strands to reduce the chances of separation and produced cleaner edges on the final part. The weights of the fiber glass was then measured and recorded. This was used to determine the amount of resin needed for the part according to the fiber to resin ratio.

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The release cloth was then cut large enough to fold around the foam core and the fiber layers with a few inches of extra space on each side. The green flow media was cut to match the release cloth except a little longer, but not wider. The vacuum bag was sized to be folded around the layup while retaining at least 2 inches larger on all sides of the part to allow sufficient space for the sealant tape and resin tubes.

With the prep work completed, the materials needed to be set in the following layup order (bottom layer to top layer):

1. Vacuum bag	7. Chopped strand mat
2. Green flow media	8. Foam core
3. Release cloth	9. Chopped strand mat
4. Woven roving	10. Woven roving
5. Chopped strand mat	11. Chopped strand mat
6. Woven roving	12. Woven roving

The release cloth and flow media were then folded over the foam core and the fiber layers. It was important to make sure that the release cloth and flow media had no folds and were as tight as possible to the foam and the fibers to make sure a consistent part every time. Section of spiral tubing was cut to the length of the folded side of the flow media, and a T-fitting was inserted at the approximate center of the spiral tubing. A piece of folded cotton breather cloth was placed on the side of the core, opposite the fold. The vacuum hose was placed inside the cotton folds to absorb the resin. This also prevented the tube from sucking in the vacuum bag, which would seal off the pump.

Before sealing the vacuum bag, the edges of the bag had to be cleared of all fibers and cloth in order to ensure a sufficient seal. One end of a length of vacuum tube was connected to the open end of the T-fitting, and the other end was placed in the epoxy

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reservoir. A small length of sealant tape was placed over the tube to ensure a tight seal. To seal the bag, sealant tape was placed on three sides of the part. The wax coating of the sealant tape was peeled away one side at a time, thereby completely sealing the bag. After the bag was sealed, the seals on the edges were checked and firmly pressed so that the part was completely sealed and airtight. Figure 10 shows the completely sealed part within the vacuum bag.

Figure 10: Example of a completely sealed bag before resin has been infused.

To determine the required weight of the resin, the weight of the fibers was then multiplied by $\frac{5}{6}$. The calculated fraction was used because the resin-to-hardener ratio of the West System epoxy system being used is 5:1. The hardener, which weighed $\frac{1}{6}$ of the total fiber weight, was added to the resin to create the epoxy mixture. This calculation lead to the manufacturer's recommended resin-to-fiber ratio for the part, however additional resin was flowed through the part at a 1:1 resin-to-fiber ratio.

A schematic of all the constituent parts required to perform the VRI process can be seen below in Figure 11.

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Figure 11: VRI Schematic

The reason for the additional resin was to ensure that the part was fully saturated and that none of the fibers within the part remained dry. Dry fibers had the potential to lead to premature failure through delamination of the layers. The picture on the left in Figure 12 shows the epoxy system used for this project. Prior to use, the hardener and resin had to be thoroughly mixed because unmixed resin and hardener do not cure as epoxy.

When the vacuum pump was activated, the resin flowed across the part. The hose that was not connected to the vacuum was placed into the bottom of the cup full of mixed epoxy, such that it would not let in any air while the resin was pulled across the part. This prevented any air bubbles from forming that would create voids and eventually cure within the part, weakening its strength.

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Figure 12: West Systems 105/206 Resin System (left) being pulled across a part using vacuum (right).

Once the resin was about $\frac{4}{5}$ across the width of the part, the resin flow was stopped by clamping the resin hose with vice grips. The fiberglass was fully saturated when the fibers became almost clear and the yellow foam color could be clearly seen. It was important to make certain that no air entered the part and that no epoxy was left on the vice grips or any other materials. After the hose was clamped, the part remained undisturbed for at least 12 hours to cure under vacuum at ambient temperature.

Once the sandwich panel had cured it was removed from the bagging and peel ply. Next the panel was taken over to the tile saw in the aerospace lab, shown in Figure 13. The tile saw was used to first cut off all of the excess material on the edges aligning the cut with the fibers. Once the edges were trimmed off of the panel, it was cut into however many 16" x 2" x 1.3" specimens could be made from the panel (typically about 4).

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Figure 13: Specimens being cut on the tile saw (Eugene Eswonia).

2.4 Initial Shear Key Manufacturing

For the Shear Key manufacturing, a female mold was created from Divinycell H 100 foam to allow for different shapes of Shear Keys (shown in Figure 14). Using a foam mold instead of aluminum or steel saved costs in both time and materials.

Figure 14: Example of different Shear Key configurations that were manufactured and tested.

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A mill was used to make multiple 8mm-diameter grooves with the foam core in which fibers could be laid up side by side. The mold was created such that enough Shear Keys could be taken from the mold to populate two full test panels, shown in Figure 15.

Figure 15: Shear key mold with loose fibers being laid in.

The woven-roving cloth was separated to obtain glass fibers. These glass fibers were then placed in the grooves of the foam core. The VRI process was then used to cure the glass fibers creating the Shear Keys, shown in the Figure 16. Several issues did arise with this method of manufacturing, including permanent damage to the mold when removing the Shear Keys themselves.

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Figure 16: Picture of VRI on the foam mold with Shear Keys.

Because of this, a different manufacturing method was created to produce all of the future Shear Keys.

2.5 Final Shear Key Manufacturing Process

The new process for manufacturing the Shear Keys used an aluminum female mold that would allow multiple uses. A mill was used to cut 4mm and 8mm-diameter semi-circular grooves into two separate pieces of metal. These grooves were made to a length of 8 inches. Figure 17 shows the milled metal mold for the Shear Keys. The mold was designed in SolidWorks. Aluminum was used for the mold because it reduced machining time. Prior to any Shear Key layups, the mold was coated with a release agent so that the Shear Keys could be removed once they had cured; High-Temp Wax was used

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to ensure that the Shear Keys would not stick to the mold like the previous Shear Keys had done.

Figure 17: Straight Shear Key mold being milled (left) with the finished product on the right.

After the mold was coated with at least three layers of wax, the woven roving was pulled apart such that there was a large stack of large fibers remaining. For this process, 35 fibers with lengths greater than 5” were used for each Shear Key. This number was determined from trial and error and ensured that there were enough fibers to fill the mold but not too many as to prevent center fibers from absorbing the resin.

Initially, the VRI process was used to manufacture the Shear Keys again. However, after several attempts, it was discovered that the resin could not absorb into all the fibers in the grooves. It was also discovered that placing the semi-stiff fibers into the Shear Key mold and ensuring that they were all soaked with resin was a difficult task.

After failing to produce acceptable Shear Keys using VRI, a wet layup procedure was utilized to manufacture the Shear Keys. Twenty-eight fibers were cut to even lengths

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to make each Shear Key. The fibers were weighed and then placed flat onto a piece of plastic. The proper amount of epoxy was mixed with a 1:1 weight ratio of the fibers to resin and was then spread on top of the fibers. A plastic scraper was used to spread the epoxy and equally distribute it throughout the fibers. It is important to note that speed was an important factor in this process due to the epoxy already beginning to cure (which was started once the resin and hardener were mixed). Figure 18 shows epoxy being worked into the fibers to help better saturate them.

Figure 18: Soaking glass fibers with resin before placing them in the mold.

While the fibers were being saturated, a small amount of epoxy was poured into the bottom of the Shear Key mold. This was done to ensure that the bottom of the Shear Keys would come out with a smooth finish. The fibers were then slightly rolled together and placed into the Shear Key mold, as seen in Figure 19. Although the fibers appeared much larger than the actual mold due to the epoxy in the fibers, the vacuum bag and

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weight both applied sufficient pressure to ensure that the keys turned out to be the proper size.

Figure 19: Soaked fibers are placed into Shear Key mold.

After Shear Key fibers were in the mold, a piece of peel-ply was placed over the mold, and a piece of breather cloth (cotton) was placed on top of that. A vacuum bag, similar to the one mentioned in VRI Layup section, was cut slightly larger than the mold and sealed with tape. A vacuum tube was also placed in the bag. Only one vacuum tube was needed because its purpose was to apply even pressure and absorb excess epoxy rather than drawing more epoxy across the part as in the VRI process.

Once the bag was properly sealed, a large flat metal plate was placed on top of the part, and about one-hundred pounds of weight was set on top of the plate, as shown in Figure 20. This weight ensured that the fibers were completely pressed into the mold and that no air would remain within the part. The vacuum pump remained active for at least eight hours, and the Shear Keys were left to cure for an entire day.

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Figure 20: Weights on Shear Key mold to help ensure the fibers stayed pressed into the mold.

Once the epoxy had fully cured, the Shear Keys were removed from the mold. All of the Shear Keys came out as one piece due to the excess epoxy. The Shear Keys were then cut, separated, and hand sanded to remove any excess epoxy.

For specimens with Shear Keys, the foam was machined to the correct Shear Key size (prior to inserting the Shear Keys) using manual mill, shown in Figure 21.

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Figure 21: Foam being milled to insert Shear Keys for VRI layup of composite sandwich panel.

The Shear Keys were then placed into the machined foam. The Shear Keys also needed to be carefully sanded to ensure the Shear Key was undamaged and had a tight flush fit into the foam. Once the Shear Key fit snugly in the foam, a small amount of epoxy was poured into the groove, and the Shear Key was inserted. After these steps were taken, the layup proceeded without change from the previous procedure in the VRI Layup section. Figure 22 is a picture of a VRI layup, with the sheer keys included.

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Figure 22: Final layup of Shear Key specimen. Note that the Shear Keys are visible through the fiberglass while the glass is wet.

2.6 Saltwater Setup

Creating a saltwater (seawater) environment for the specimens involved the use of the Cal Poly Pier and its facilities. The pier in Avila, California shown in Figure 23 provided the ability to create both filtered and raw seawater environments. It was decided that the filtered specimens would be kept inside the facility at the end of the pier to shelter them from any environmental effects, while the raw sea water specimens would be placed in the actual ocean.

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Figure 23: Cal Poly Pier in Avila where the seawater specimens were stored.

The facility on the pier allowed for the storage of 36 filtered specimens in tubs. These tubs were fitted with a hose in and a hose out to allow the water to be circulated and changed so the filtered seawater wouldn't be stagnant around the pieces. Because of their buoyancy, the specimens had to be anchored down by a weight which came in the form of bricks and rocks depending on what was available for use. Several specimens are shown (Figure 24) in one of the tubs at the end of the Cal Poly Pier.

Figure 24: Filtered seawater specimens.

Placing the specimens in the raw environment of the ocean was a little trickier. Before placing the specimens in the raw seawater, they had to be placed into a container

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that would keep them from drifting away. This was developed using a mesh like plastic that was doubled over and tied together with Zip-Ties to form a bag, shown below in Figure 25. Pieces were then placed inside the bag and the other side was zip tied shut so the pieces wouldn't move out.

Figure 25: Mesh bags shown with specimens and weight (left), and a top down view of the bag (right) showing how the pieces are held in place and the bag is tied together.

Once the pieces were secured inside each piece was tied down to prevent any additional movement that might cause damage to the pieces from one another, shown above. These pieces were then tied to a predetermined amount of weight that would allow the bags to stay submersed 30 feet in the water. This buoyancy calculation at a 30 foot depth yielded a required weight for each bag of 12 pounds. Bags were then grouped together with the appropriate amount of weight, making sure that the bags could be hoisted back up by hand after they had been placed into the water. The weights and the specimens were held together with the use of a metal link and tied together securely with rope and tape. Once the bags and the weight were secured together they were lowered into the water using 60 feet of rope (shown in Figure 26), such that the specimens could

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be lowered 30 feet from the pier into the water and then an additional 30 feet into the ocean.

Figure 26: Multiple specimens being lowered into the water together.

2.7 Specimen and Testing Preparation

Specimen preparation was a very important part of this experiment. Before the specimens could be adhered to the jig, the surfaces had to be cleaned of contaminants. This was done by sanding the surface of the specimens by hand using fine grain sandpaper, and then wiped with acetone. Removing contaminants allowed for a stronger bond between the test jig and the specimen. It was important to assure proper adhesion between the specimen and test fixture. If the bond between the specimen and test fixture failed before the specimen core, the test would be invalid and the specimen wasted.

The specimens were glued to the testing jig using the DP460NS structural adhesive (shown in Figure 27), the adhesive was left to cure for a minimum of 24 hours

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at room temperature suggested by the manufacturer, which was extrapolated from the manufacturer graph shown in Figure 29. Proper application of the adhesive was very important because enough adhesive was needed such that it wouldn't fail before the test concluded. In addition any excess adhesive had to be wiped off of the sides because once hardened it wouldn't deform with the foam and would create a force concentration at the part that would cause a premature failure of the specimen and invalidate the experiment in a similar manner as previously explained.

Figure 27: Structural glue (left) along with the glue gun (center) and mixing nozzle (right).

After a test was conducted a band saw was used to cut the foam and separate the two halves of the jig. Initially a die grinder with a coarse bit was used to remove the fiberglass and structural adhesive from the jigs, but this process took several hours to clean the four surfaces (since both jigs were cleaned at the same time). To reduce working hours the jigs were placed on the disc grinder (similar to the one shown in Figure 28) in the Cal Poly hangar. However, this process still required about an hour of work time to clean the testing jigs.

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Figure 28: Example of a die grinder (left) and a disc sander (right).

After most of the fiberglass and the adhesive had been removed on the disc sander the jigs were polished clean using a die grinder. From here the process of cleaning the fixture surface repeated itself as previously explained. The surfaces of the jigs were cleaned using acetone and prepped for the next set of specimens.

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Figure 29: Manufacturers graph of Cure Time vs. Cure Temperature.

2.8 Testing Procedure and Methods

Testing of the specimens was carried out with the use of the INSTRON 1331 and the INSTRON 8801, both of which were paired with the Merlin software package. The tests were carried out using the ASTM C273 standard for guidance as mentioned previously, using a 100 kN load cell. The 100 kN INSTRON grips that were paired with the load cell are shown in Figure 30.

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Figure 30: 100 kN grips shown for the INSTRON 1331 and the INSTRON 8801.

The Merlin software was used to record the data and choose the set of data output. For this experiment data and graphs were focused on displacement versus load along with stress versus strain. Several different graphical user interface (GUI) options were available as shown in Figure 31. These graphs allowed the monitoring of the test as it took place helping the tester to observe anything out of the normal.

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Figure 31: Various interface screenshots taken from the Cal Poly Aerospace structures INSTRON computer.

On top of providing the data and the graphs, the Merlin software allowed for full control of the test. In order to meet the ASTM C273 standards the displacement rate was set to 0.2 in/min with a maximum deflection set to 3 inches (well past the full displacement capability of the specimen). Setting the deflection at such a high point insured that the test would only stop once the specimen had completely failed, however this meant the user had to make sure there was more than 3 inches of room for the bottom grip to move. This was very important since the test would stop if the grip bottomed out and the INSTRON could not displace any further. Additionally the failure criterion was set to a 20% load drop. This was raised from the default value of 10% (ASTM C273) in order to ignore the initial failures at the ends of the jigs, and allow proper analysis of the shear failure of the specimen.

Before testing could begin the machine was turned on and allowed to self-calibrate. Once calibration of the load had finished the specimen and testing jig were placed in the INSTRON machine and held in place via the testing grips. At this point the machine positioning was zeroed out and the displacement rate was confirmed at 0.2

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in/min. Once everything had been calibrated and checked over the test was run until complete failure of the specimen. The Merlin software then saved the data in an excel format to be stored. At the same time the testing jig and specimen were removed from the machine and the next specimen was added for testing, otherwise the machine was shut off and the data was moved over to an email and stored for later analysis and usage.

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3.0 Failure Types

This chapter will explain the failure modes that were seen in the conventional specimens during testing. It will then go on to discuss the failures seen in the Shear Key specimens that were tested.

3.1 Shear Failures in Control Specimens

By manufacturing our jigs and specimens based on the ASTM C273 standard jig, testing produced two valid types of failure modes. The first failure involved delamination where the specimen's core debonded and tore away from the skin, shown in Figure 32. This failure was an issue since it represented a poorly designed or poorly manufactured specimen as a properly engineered panel should fail within the core. This will be discussed later with the Shear Key section.

Figure 32: Test specimen where failure occurred by the fiberglass debonding due to the shear load.

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This failure started in the middle of the length of the specimen and spread down the bond line. This was due to a force concentration build up at the line where a tear formed and continued to propagate down the specimen's length until it had completely failed.

The second type of failure began with a crack near the centerline of the core. This crack then spread through the core and then delaminated along the bond line until the specimen had completely failed. An example of this is shown in Figure 33.

Figure 33: Complete failure of test specimen where the failure occurred through the core.

Another example of the second failure is shown in Figure 34. However this specimen failed on the lower half of the specimen, since the crack started propagating below the centerline and thus failed before the upper half had a chance to propagate the crack.

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Figure 34: Failure of a specimen where the crack started to propagate on one side of the centerline.

3.2 Shear Failures in Specimens with Shear Keys

The failures in the Shear Key specimens were similar but different from the control group and seawater specimens. In the previous section it was discussed how two different failures were seen during testing. The Shear Keys were implemented in hopes of increasing the strength of the specimens under a shear force and eliminating the delamination issue (first failure mode). The Shear Keys were successful with removing

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the delamination failure from the results, however during the initial design and test of the Shear Key, several other failures arose.

The triangular Shear Keys, shown previously, were initially designed because they would provide the lightest addition to the composite while maintaining the desired surface bond with the facesheets. This design had to be scrapped however, because the point of the Shear Key introduced a force concentration at the tip ultimately causing premature failure in the specimen. When using the Shear Keys that were not staggered and instead placed on top of one another a different problem surfaced. Placing the Shear Keys on top of one another removed too much of the area of the foam. This combined with a force concentration at the surface of the Shear Key again caused a premature failure. Finally by staggering the semi-circular Shear Key, the initial design requirements were met. The implementation of the Shear Keys now prevented the debonding from occurring and cause the failure to start in the center of the foam as shown in Figure 35 and Figure 36. In addition to preventing the failure along the bond line, the Shear Keys were also responsible for a higher load distribution towards the centerline of the specimen, such that the ultimate failure happened much quicker with the Shear Keys than without.

In Figure 35 you can see that the initial failure starts in the center of the core and not along the facesheet. From there it propagates down to the facesheet and then across the facesheet until it reaches the Shear Key (Figure 36).

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Figure 35: Initial failure of the specimen starting at towards the centerline of the specimen's core.

Figure 36: Complete failure of the Shear Key specimen.

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4.0 Experimental Results and Analysis

This chapter will cover all of the experiment testing and results. It will start with discussing the volume fraction and burn test results. The next section will discuss the testing of the material properties, which includes the tensile tests for the fiberglass along with the compression testing done on the foam. Next, all of the control and seawater results are shown and analyzed and compared against each other followed by a section discussing weight differences of the specimens with relation to time in the water. This is followed by the test results and analysis for the Shear Key specimens, and lastly followed with a discussion about carbon nanotube specimen research that was conducted.

4.1 Volume Fraction of Laminated Skin

A series of volumetric fraction tests were done separate from the rest of the testing. This testing was done in order to ensure that the fiber content was consistent across several different layups, and that the specimens would be relatively equal in strength. This was an important factor when looking to see how time in the salt water affected the specimens.

In order to conduct a proper volumetric fraction test on the facesheet a series of separate layups followed by burn tests were required. The burn test was based on a simple 3 step process. First a 1" x 1" specimen was cut from a 4 layer fiberglass facesheet. Then the specimen was placed in a small ceramic oven (shown in Figure 37) and the resin was burned off. Once all of the resin was gone, the fibers that remained were removed from the oven and weighed. These weight results combined with the

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equations in the theoretical analysis section allowed for the calculation of the volumetric fraction for the specimens.

Figure 37: Ceramic oven shown next to the metal plate with specimen fibers.

The 1" square specimens were baked in the oven for approximately 45 minutes at 700 °F. This was different when compared to baking carbon specimens because those specimens could withstand higher temperatures (~1200 °F) allowing the resin to burn off faster. However at this temperature glass fibers would burn away and the weight of the fibers would become immeasurable. Thus a lower temperature and longer time period was used to ensure that the fibers remained intact for the final weighing.

Three separate burn tests with four specimens each were conducted. The results are shown in Table 1. It is important to note that these results were used to ensure that the layup procedure and techniques used produced consistent results, not the strongest specimens possible.

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Table 1: Results from the 3 burn tests that were used to verify the manufacturing process.

	Burn Test 1			Burn Test 2			Burn Test 3		
	Weight Before	Weight After	Weight Fraction	Weight Before	Weight After	Weight Fraction	Weight Before	Weight After	Weight Fraction
Specimen 1	1.01g	0.58g	57.4%	1.02g	0.61g	59.8%	0.97g	0.57g	58.8%
Specimen 2	1.01g	.059g	58.4%	1.03g	0.62g	59.2%	0.99g	0.58g	58.6%
Specimen 3	1.03g	.061g	59.2%	0.99g	.057g	57.6%	1.01g	0.59g	58.4%
Specimen 4	0.98g	.057g	58.2%	0.99g	.057g	57.6%	1.00g	0.58g	58.0%
Average	1.01g	0.59g	58.3%	1.01g	0.59g	58.6%	0.99g	0.58g	58.4%

The table shows the weight of the specimen before, the weight of the fibers without resin, and the weight fraction of the fibers. Since the weight and the volume fraction are directly proportional to one another, it was possible to gauge the results by just looking at the weight percentage. The difference between the weight fractions for each run was within tenths of a percent and deemed acceptable. The difference in weight fractions of fibers may have originated from the inaccuracy of the scale since it was also limited to hundredths of a gram. From these results of the burn test the conclusion that the procedure and the techniques used in manufacturing the specimens were consistent and would provide the proper results. After a complete error analysis of the weights it was shown that all the initial and final weights were within $\pm 1.4\%$ of their respective mean values and the error was deemed acceptable as well.

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4.2 Testing Material Properties

In order to conduct a comparison between a numerical analysis solution and experimental data, a Finite Element Model had to be properly developed. The first step in creating this model was to gather the material properties.

Uniaxial tensile tests were performed for both woven roving and chopped strand mat in an INSTRON machine as per ASTM D3039 “Standard test method for tensile properties of polymer matrix composites” to determine the ultimate tensile strength, Modulus of elasticity and poisons ratio of the materials. The chopped strand mat and the woven roving specimen are made up of two layers of chopped strand mat and woven roving sheets respectively bonded together with epoxy resin. Figure 38 shows the materials being tested.

Figure 38: ASTM D3039 tests shown for chopped strand mat and woven roving per "Composite sandwich Report" - Mitra, Jacobson, Woo.

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In the experimental investigations as demonstrated above, the mode of failure as observed for the specimens was brittle. As observed from the experimental investigation, a linear elastic material model is utilized to represent the behavior of both woven roving and chopped strand mat. The Poisson's ratio for the woven roving was measured as 0.01; which meant that there was no coupling between the longitudinal and the transverse strain when loaded uniaxially. For the chopped strand mat, the Poisson's ratio was observed as 0.4. The Modulus of elasticity of woven roving was recorded as 2.0×10^6 psi (13.8 GPa) whereas for the chopped strand mat was recorded as 1.7×10^6 psi (11.8 GPa). The failure stress for chopped strand mat samples were recorded as 12000 psi at 7100 micro-strain whereas for the woven roving samples were at 43700 psi at 14700 micro-strains.

4.3 Longitudinal versus Transverse Layup Results

Longitudinal and transverse were in reference to how resin was flowed across the part during the layup. Longitudinal referred to a layup where the resin was run in parallel to the direction of which the shear force would be applied to the specimen. Transverse referred to a flow that was perpendicular to the direction which the shear force would be applied to the specimen. This test was conducted to understand whether or not there was an effect created by the layup process in order to keep the future test conditions consistent. The stress versus strain graph for the longitudinal and transverse layups is shown in Figure 39. In this graph there are six composite sandwich specimens that were tested, with all specimens of a group staying within family.

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Figure 39: Stress vs. Strain graph for the longitudinal and transverse flow showing that there is a difference in strength between the two layups.

All of the specimens were tested in the same manner described previously in accordance with the ASTM C273 standard. The tests revealed that the longitudinal layup produced parts that were significantly stronger and had a higher Modulus of Elasticity. Because of these results all future layups were carefully done so that the resin flow across the part was in parallel with the direction of the shear force.

To confirm that the control specimens were properly laid up a comparison was done between the longitudinal specimen, transverse specimen, and four of the conventional specimens that would be used as a control group. From the graph in Figure 40 one can see that the control group data is consistent with the data for the longitudinal layup.

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Figure 40: Stress vs. Strain graph of control group specimens compared to longitudinal and conventional layup specimens.

Seeing the longitudinal curve in the graph above is difficult due to the fact that the Control number 3 and the longitudinal are almost the exact same. Again these specimens exhibited a higher ultimate strength as well as a higher Modulus of Elasticity when compared to the transverse specimens as expected.

4.4 Seawater Specimens Experimental Data

The next few sections cover the experimental data taken from the seawater specimens as they were tested. It is important to note that in the seawater sections several pieces were averaged together to create the “month”, “longitudinal”, “transverse”, and “control (conventional)” curves. In order to create a single trend line for the set of specimens all the values for certain displacements were taken and averaged. Then the trend line was created based on the data points taken from the averages. Trend lines for the data will be shown for comparison purposes with the numerical table being shown at the end of all of the seawater data.

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In the discussion of the seawater graphs the Elastic Modulus is used when talking about the shear strength. With composites the shear Modulus does not correspond to the Elastic Modulus the same as an isotropic material does. However the assumption was made that since the facesheets were glued to the steel and represented an infinitely rigid beam compared to the foam the linear portion of the experimental data could be largely attributed to the foam. Since the foam was an isotropic material it could be analyzed using the isotropic shear Modulus formula which is directly proportional to the Elastic Modulus by Poisson's Ratio. For trending purposes the 2 terms were used almost interchangeably in the next few sections, however this is only based on the assumption previously stated. Additionally the specimens were almost completely in shear with a small component of the load going in to the specimen as a normal component. Because of the assumption that the analysis was focused on the core material the shear strength was directly related to the ultimate strength shown in the graphs.

4.5 Filtered Seawater Specimens after 1 Month in the Water

The first set of sea water specimens tested were the 1 Month filtered specimens. Four separate specimens were randomly selected from the tanks within the facility at the Avila Pier. These specimens were taken and weighed for later comparison, and then allowed to dry for several days. This was to help improve the accuracy of the comparison between the filtered sea water and the raw sea water specimens, since the raw sea water specimens required a drying period which will be discussed later.

The filtered one month specimens showed a slight decrease in stiffness and in strength when compared to the control specimens. In the graph shown in Figure 41, the 4 control specimens shown in the previous graphs have been averaged and are shown in

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blue. This was done to help give a graphical idea of where the control group lay in comparison without cluttering the chart too much.

Figure 41: Stress-Strain curve used for comparison of the control group and the filtered 1 month specimens.

With the exception of the first 1 month filtered specimen tested, the data showed very consistent trends. The first 1 month specimen was improperly situated on the Instron testing machine, where the grip bottomed out and could not move any further thus ending the test. The rest of the data showed a very similar trend to the transverse group of specimens that were previously tested.

4.6 2 Month Filtered Seawater Specimen Comparison

A comparison of data for the 1 month and 2 month filtered seawater specimens along with the 3 control specimen types is shown in Figure 42. In this graph the 4 separate specimens that were tested after 2 months of being in the filtered sea water are compared with the previous 1 month data trend along with the control specimens. The

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graph shows that there is degradation in the stress capability of the 2 month specimens when compared to the 1 month specimens along with the control specimens.

Figure 42: Stress-Strain curve used for comparison of the filtered seawater specimens after 2 months.

The 2 month specimens also show a trend of an increased shear strain at the point of complete failure. This trend still exists with the removal of specimen 2mo_2 which failed at a higher ultimate stress level along with a higher strain. The reason for 2mo_2 being an outlier is the loading rate was changed from 0.2 in/min up to 0.5 in/min. This test error was the result from shutting down the Instron machine and recalibrating it without remembering to change the test setting back to the right displacement rate. This rate change made a huge difference in the way the specimen responded and failed, which had been previously tested in the aerospace lab during the initial test design phase.

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At this point in testing the sea water seemed to have an effect on the shear capacity of the composite sandwich panels. The specimens showed a steady decline in both their ultimate strength as well as their Modulus of Elasticity (stiffness).

4.7 3 and 4 Month Filtered Seawater Specimen Comparison

For the third and fourth month graphs all of the specimens had their values averaged together as described at the beginning of the section. At this point showing all of the individual curves began to get too cluttered. In Figure 43 the batch of 3 month specimens has been added to chart. In this chart the 3 month specimens clearly show a decrease in their ultimate stress when compared to the control group and the 1 month specimen group, but not as much of a difference from month 2. When comparing the decrease in ultimate stress capacity between month 1 and 2 versus month 2 and 3 there is a significant difference. There is only a slight decrease between month 2 and 3.

Figure 43: Stress-Strain curve used for comparison of the filtered seawater specimens after 3 months.

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Figure 44 is the same as Figure 43 except the 4th month of filtered seawater specimens has been added. Similar to what was seen in the 3 month comparison, there is very small decrease in the ultimate stress level of the specimens. However the 4th month of specimens had a few key differences. These specimens showed a noticeable difference in their stiffness as well as the failure point. The nonlinear region of the month 4 specimens showed a similar failure to the 2nd month of specimens. This is because after being averaged, both month 2 and month 4 specimens had both single core failures and multiple core failures. In other words, the reason for the different trend involves specimens that had multiple failures (cracks) form before completely failing, which was different from the other specimens that just had a single crack and then failed. Interestingly enough all of the 3 month specimens failed with a single crack in the core that moved to a complete delamination along the bond.

Figure 44: Stress-Strain curve used for comparison of the filtered seawater specimens after 4 months.

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4.8 Filtered Seawater Specimens after 6 Months in the Water

The final 2 months were added to the same graphs used for the 3 and 4 month specimen comparisons, shown in Figure 45. Looking at the graph the 5 month and 6 month specimens lay almost directly on top of the 2 month, 3 month, and 4 month trend lines. One of the things to notice is the 6 month trend line cuts off before the failure of the specimens. This is because the Instron stopped recording data for these specimens for some unknown reason. The error was not realized until the data was reopened to be placed into the graph for comparison purposes. Because there were only 2 specimens that were left to test for the 6 month group there was no way to fix this issue and test more specimens without another 6 month period. The graph showed little difference in month 5 and 6 when compared to months 3 and 4.

Figure 45: Stress-Strain curve used for comparison of the filtered seawater specimens after 6 months.

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4.9 Raw Seawater Specimens after 1 Month in the Water

The first month of raw seawater specimens showed a similar trend to the filtered seawater specimens. Comparing the data from the first month of raw seawater specimens against the control groups showed a drop in the specimen's stiffness and ultimate strength capabilities, shown in Figure 46.

Figure 46: Stress-Strain curve used for comparison of the raw seawater specimens after 1 month.

The second specimen had a glue failure and stopped the recording of the data for which the reason of the data stop is unknown. The specimen is shown here just to show that it actually had different results than the other specimens, but the data showed a similar trend for the linear region.

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4.10 Raw Seawater Specimens after 2 Months in the Water

The comparison of the second month was done using trend lines. These were created from averaging the several pieces from the specific month to create the line as done before. The comparison of the first and second month, Figure 47, showed almost no change in ultimate strength but did show a slight reduction in the stiffness.

Figure 47: Stress-Strain curve used for comparison of the raw seawater specimens after 2 months.

This was interesting since based on the results seen with the filtered seawater specimens a greater decay in strength and stiffness was expected. The reason for the second month of raw seawater specimens showing no change could have originated from a change in testing preparation. Because of fixture adhesive failures, the specimens were left out of the water for 3 weeks compared to 1 week before being tested.

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4.11 Raw Seawater Specimens after 3 and 4 Months in the Water

Comparing the third month of raw seawater specimens showed the expected results, shown in Figure 48. There was a more significant decay in ultimate strength with a similar decay in the specimen's stiffness.

Figure 48: Stress-Strain curve used for comparison of the raw seawater specimens after 3 months.

The specimens that were removed after 4 months in the ocean showed a matching trend to the 3 month specimens, which was expected. Comparing the gap between the third and the fourth month in Figure 49 was very minor, which was similar to what was seen in the filtered seawater specimens.

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Figure 49: Stress-Strain curve used for comparison of the raw seawater specimens after 4 months.

With the data difference between the filtered and raw seawater specimens only occurring at the 2 month period it is speculated that the change in testing procedure was the cause for this difference. The rest of the specimen groups behaved as expected with little difference in strength capabilities showing after the 3month period.

The fifth month only contained 2 specimens since that was all that was left in the water. These specimens were not shown in a graph, but the trend line if shown would lie almost identically on top of the Month 3 specimens. In addition the 6 month lay directly on top of the 4 month trend and was not shown as to not add clutter to the graph. Showing the fourth month decay may not have been consistent and a larger testing group would be needed to determine any major differences in performance.

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4.12 Filtered versus Raw Seawater Specimens – 1 Month

A comparison of the conventional specimen with the first month specimens for both filtered and raw seawater environments is shown in Figure 50. Here it shows there is decay in both stiffness and ultimate strength for both environments, but the raw seawater specimen group did showed a significant degradation. These results were expected since the raw specimens were also exposed to environmental conditions like current along with a higher pressure since they were placed deeper in the ocean. Filtered specimens were covered in approximately 1 foot of water compared to the 30 foot depth for the raw specimens. Also the biological that formed on the raw seawater specimens may have had an effect in additionally weakening the specimen, where the filtered seawater specimens had no biological growths on them.

Figure 50: Stress-Strain curve used for comparison of the raw and filtered seawater specimens after 1 month.

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4.13 Filtered versus Raw Seawater Specimens – 1 and 2 Month

The comparison with the conventional specimen and both raw and filtered specimens for the first and second month is shown in Figure 51. The decay is expected with the filtered seawater, but as previously discussed with the raw seawater specimen there is little decay. Again this is assumed that the change in testing conditions is what created this difference, but is shown since it is a possible outlier and other reasons for this difference need to be considered.

Figure 51: Stress-Strain curve used for comparison of the raw and filtered seawater specimens after 2 month.

After looking at the trends for filtered and raw seawater data the conclusion still remains the same. The decay is consistent within the specimens for a period of 3 months after which the decay seems to go away suggesting the water saturation theory may be correct. The thought behind this theory is that the specimens expanded slowly due to water saturation over a period in time. This weakened the specimens due to an increase

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in volume and area in the core. However, once the specimens were done saturating the degradation ceased and the specimen strength no longer changed.

4.14 Weight and Dimension Differences

After each specimen was manufactured and cut it was weighed before being placed into the plastic mesh bags. The purpose for doing this was to observe if any changes occurred to the specimens while they were submerged in the ocean. Weighing was done on the scale in the Aerospace Engineering Structures lab which has an accuracy of up to a five ten-thousandths of a pound.

The results from weighing the specimens showed some interesting trends that were somewhat consistent between both the raw and filtered sea water specimens. From the data shown in Table 2 it is obvious to see that there was a change in specimen weight that did occur. The raw seawater specimens' weight increased by approximately 1.25% of their initial weight over the first month, 3.10% increase over the second month, and approximately 5.99% over the third month. There was a similar trend with the filtered seawater, but the values were lower with an increase in weight of 0.81% over the first month, 2.26% increase over the second month, and approximately a 3.67% increase over the third month. For both the filtered and raw seawater specimens there seemed to be a saturation point at around 3 months, where the weight of the specimens no longer increased. This saturation point interestingly enough was the same point at which the shear capacity degradation found in the specimens seemed to taper off. This led to property changes due to water absorption leading to a theory, that the increase in ductility and displacement capabilities came from the saturation of the water and not any physical changes to the composite materials themselves.

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It is important to note that the raw seawater specimens seemed to retain more weight than the filtered seawater specimens. This is due to the biological growth found on the specimens after they were removed from the ocean. The longer the specimens stayed in the water the more time barnacles and other biological had time to form along the surface. Interestingly enough, after roughly 2 months in the ocean the specimens were fully covered with biological growth from the ocean. The pieces were weighed as is when taken from the water and were not initially cleared of the biological growth suggesting that the water retained within the raw seawater specimens may actually be closer to the weights seen in the filtered seawater specimens. After performing an error analysis on the weights the results showed an error of 1.41% of their respective mean values and were deemed acceptable.

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Table 2: This table shows the weight of the raw sea water specimens in grams before they were placed into the ocean and after they were removed, along with the differences in weight.

Raw Sea Water Specimen Weights																		
	Month 1			Month 2			Month 3			Month 4			Month 5			Month 6		
	Initial	Final	% Difference	Initial	Final	% Difference	Initial	Final	% Difference	Initial	Final	% Difference	Initial	Final	% Difference	Initial	Final	% Difference
Spec. 1	0.401	0.405	1.00%	0.404	0.416	2.97%	0.403	0.426	5.71%	0.407	0.430	5.65%	0.401	0.425	5.99%	0.404	0.429	6.19%
Spec. 2	0.397	0.403	1.51%	0.407	0.420	3.19%	0.400	0.424	6.00%	0.402	0.429	6.72%	0.397	0.425	7.05%	0.410	0.436	6.34%
Spec. 3	0.403	0.407	0.99%	0.401	0.415	3.49%	0.402	0.428	6.47%	0.403	0.427	5.96%	0.399	0.424	6.27%	0.406	0.431	6.16%
Spec. 4	0.404	0.410	1.49%	0.403	0.414	2.73%	0.398	0.421	5.78%	0.405	0.431	6.42%	0.403	0.427	5.96%	0.406	0.430	5.91%
Average Difference	1.25%			3.10%			5.99%			6.19%			6.31%			6.15%		

*Biological growth not removed prior to weighing

Table 3: This table shows the weight of the filtered sea water specimens in grams before they were placed into the ocean along with their weight after they were removed, and the percent difference between the two weights.

Filtered Sea Water Specimen Weights												
	Month 1			Month 2			Month 3			Month 4		
	Initial	Final	% Difference	Initial	Final	% Difference	Initial	Final	% Difference	Initial	Final	% Difference
Spec. 1	0.400	0.404	1.00%	0.401	0.410	2.24%	0.401	0.417	3.99%	0.400	0.415	3.75%
Spec. 2	0.402	0.405	0.75%	0.397	0.406	2.27%	0.403	0.418	3.72%	0.401	0.413	2.99%
Spec. 3	0.398	0.400	0.50%	0.396	0.406	2.53%	0.401	0.415	3.49%	0.401	0.414	3.24%
Spec. 4	0.398	0.402	1.01%	0.403	0.411	1.99%	0.405	0.419	3.46%	0.399	0.410	2.76%
Average Difference	0.81%			2.26%			3.67%			3.19%		

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5.0 Shear Key Research

The Shear Key specimens were tested under the C3RP grant which was to be published as my thesis, however the Shear Key data was published ahead of time by “A Methodology for Improving Shear Performance of Marine Grade Composite sandwiches: Composite sandwich Panel with Shear Key” in one of Dr. Mitra’s research papers. It is important to note that “A Methodology for Improving Shear Performance of Marine Grade Composite sandwiches: Composite sandwich Panel with Shear Key” listed the Shear Keys by their diameter where the rest of this report sizes the Shear Keys by their radius. For consistency, this thesis uses (and references) the same figures used in the research paper.

Shear keys were implemented as a method to increase the specimens shear strength capabilities along with helping to prevent debonding effects which were discussed previously. The thought was the Shear Keys would help naval vessels make full use of the core strength of the composite. As previously discussed improperly designed composite sandwiches would fail along the bond line, which meant that the core material in the composite was not properly being used. Excessive core material adds weight to the composite reducing the strength-to-weight ratio that is so appealing to composite usage.

The following section will discuss the results of the experiments with Shear Keys implemented into the specimens. These results include the usage of different size, shape, and materials used in manufacturing the Shear Keys. All shear key testing was done in ambient conditions with no environmental changes.

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5.1 Shear Key Experimental Results

Data gathered from one of the experiments is shown in Figure 52. In this chart there is a comparison of trends between the conventional specimen and the test specimen containing the staggered 4mm semi-circular fiberglass Shear Keys.

Figure 52: Data on the conventional specimens compared against the 4mm Shear Key specimens. This graph was taken from Dr. Mitra's paper on "A methodology for improving shear performance of marine grade composite sandwiches: Composite sandwich panel with Shear Key".

In order to create the trends for the Shear Keys several runs had their points averaged together and then re-plotted to create the chart shown previously. This was done similar to the seawater charts shown before to make viewing and comparing easier. Looking at the data provided from the chart, the 4mm Shear Keys increased the shear capability of the foam by approximately 15%, but decreased the shear strain angle the

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specimen could withstand. The reduction of the shear strain angle capability came from a force concentration forming at the peak of the Shear Key as displacement increased to a point where failure occurred. In addition the Shear Keys added some rigidity to the specimen also reduction the shear strain in the specimen.

Several other cases of Shear Key data were compared during the research and testing, in search of a method that would help strengthen the composite panel against the shear capacity degradation. Just like the previous chart several sets of data for one type of Shear Key were averaged to create the trend line for the specific case. The cases were then matched against one another for comparison purposes.

The next case involved using similar sized, but different shaped Shear Keys to see if there was potentially any other benefit in changing shape. A comparison of the data for the staggered 4mm semi-circular Shear Key specimens with that of the V-shaped Shear Key is shown in Figure 53.

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Figure 53: Data on the 4mm Shear Key specimens compared to a similar sized V-shaped specimen with the conventional specimen being used as a reference point. This graph was taken from Dr. Mitra's paper on “A methodology for improving shear performance of marine grade composite sandwiches: Composite sandwich panel with Shear Key”.

The data for the staggered 4mm semi-circular Shear Key specimens compared with the data for the V-shaped Shear Key proved useful. When testing the V-shaped Shear Key there was a similar increase in initial strength since the bond area was the same between the two different Shear Key types. However, the point at the tip of the V-shaped Shear Key created a force concentration causing a much quicker failure in the specimen.

Moving forward it was decided that the next approach would be to try different Shear Key sizes and see how that affected the test specimens. By doubling the diameter of the Shear Key it was thought that the strength of the specimen might greatly increase.

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This was not that case as the data shown in Figure 54 shows that the 8mm Shear Key specimens proved to be weaker than the 4mm Shear Key specimens.

Figure 54: Data on the 4mm Shear Key specimens compared to the larger 8mm Shear Key specimens, again using the conventional specimen as a reference point. This graph was taken from Dr. Mitra's paper on "A methodology for improving shear performance of marine grade composite sandwiches: Composite sandwich panel with Shear Key".

Because there was more surface area between the Shear Key and the facesheet there was some added rigidity and strength. However, by using larger Shear Keys a large amount of the core was removed to fit the Shear Key. This reduction in core area ended

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up causing a force concentration at the tip of the Shear Key, weakening the specimen and ultimately causing the premature failure.

Since the tips of the Shear Keys seemed to create force concentrations within the core material it was thought that by using a softer material as the Shear Key might improve the strength of the specimen. The results of this comparison are shown in Figure 55 below.

Figure 55: Data on two separate 4mm Shear Key specimens, where one set of Shear Keys was made from fiberglass and the other balsa wood. This graph was taken from Dr. Mitra's paper on "A methodology for improving shear performance of marine grade composite sandwiches: Composite sandwich panel with Shear Key".

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The balsa wood Shear Keys performed similarly to the fiberglass Shear Keys initially, but still proved to be weaker in the end. It is possible that the actual difference between the two different Shear Keys had more to do with the manufacturing process than the material's performance during the test. With the balsa wood Shear Keys, inserting them into the layup caused a couple issues. During the VRI process the pressure from the vacuum would compress the wood causing the fiberglass of the facesheet to dip into the Shear Key groove. This created an uneven surface along with force concentrations at the Shear Key. To avoid this problem the Shear Keys were made slightly bigger than the groove such that they would properly fit once compressed, but this may have added to the failure of the specimens as well. Regardless of the exact reason that caused the balsa wood specimens to be weaker, they were disregarded since they added no structural benefit over the fiberglass Shear Key specimens.

The final Shear Key comparison was done between the 4 mm staggered Shear Key specimens and the 4 mm un-staggered Shear Key specimens, shown in Figure 56. This comparison was done to see if the same issue with reduction of area that occurred with the 8mm Shear Keys would happen with the 4mm Shear Keys if they weren't staggered. Testing of the separate specimens showed that the staggered specimens did indeed perform better. However there was much less of a difference between the 2 different Shear Keys than was seen when the 8 mm Shear Keys were used. Since the un-staggered 4mm Shear Keys do still retain more of the core surface area between them it is possible that the reduction in strength still originated from the same cause.

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Figure 56: Data on the unstaggered 4mm Shear Key specimen compared with the staggered 4mm Shear Key specimen. This graph was taken from Dr. Mitra's paper on “A methodology for improving shear performance of marine grade composite sandwiches: Composite sandwich panel with Shear Key”.

5.2 Carbon Nanotube Research

Another additional way thought up to strengthen the composite panels against shear was to infuse the resin with carbon nanotubes (CNT). CNT are allotropes of carbon with a cylindrical nanostructure, and are significantly stronger than steel while still maintaining a low weight profile. It was hoped that by adding the CNTs to the resin a stronger bond would form between the core and the facesheets to prevent delamination

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from occurring and increasing the strength of the composite panel under shear. Several of these pieces were manufactured to be tested, but it was found that the flow media prevented the CNTs from properly mixing within the resin during the VRI process as shown in Figure 57. It was determined that a hand layup would be needed to properly inlay the CNT's.

Figure 57: Top down view of a CNT specimen where the CNTs are actually visible as lots of tiny black dots in the facesheet.

In addition to a change in the manufacturing process, a different technique for removing the CNT specimens from the test jigs needed to be developed. This is due to the fact that sanding the CNTs and releasing them into the air could be very hazardous to an individual's health.

6.0 Theoretical Analysis

This section will cover the equations that were used for any calculations during this thesis. The volume and weight calculations were important to ensure that the

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manufacturing results were consistent along with providing a check for the experimental Elastic Modulus. Equations involving composites were utilized within COSMOS and are shown to give more understanding on how the solver worked. The shear equations were important since these were used to justify the graphs and their shear capabilities.

6.1 Volume and Weight Calculations

Finding the right fiber to resin ratio is very important when fabricating composite materials. Having too much resin leads to a part that is heavier and reduces its strength. A composite that doesn't have enough matrix or resin however will not properly protect the fibers or their alignment, which could prevent proper transfer of loads, lowering the overall strength and life of the material. In order to calculate the volume fraction and weight fraction for the composite sandwich panels, the following equations were utilized. The results of these were compared to burn tests performed on samples from the composite panels to ensure the resin to fiber ratio met requirements.

Determining the properties of the composite panels requires understanding the composition and proportions of matrix and reinforcing material. These properties can be obtained through either use of the weight fraction (W) or the volume fraction (V). Because the weight fraction can be obtained while fabricating and or experimental testing it is the easiest to use to determine the proportions used. The volumetric fraction for the fibers and the resin is more useful in the theoretical analysis but tougher to initially obtain. However, the volumetric fractions and the weight fractions can be calculated from one another if the density (ρ) properties are available. Equation 1, is the equation for the complete volume (v) of the composite, where the "c", "f", and "m" subscripts stand for the composite material, fiber, and the matrix or epoxy respectively.

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Equation 1: Volume of Composite Equation Derived from the Fibers and Matrix of the Composite as Denoted by the Subscripts

$$v_c = v_f + v_m$$

The volume fractions for the fibers and the matrix can be related to the volume of the composite using Equation 2.

Equation 2: Volume Fraction Equation for the Fibers and Matrix in the Composite

$$V_f = \frac{v_f}{v_c}, V_m = \frac{v_m}{v_c}$$

Similarly to the equations for the volume of the composite and volume fraction, the equations for the weight (w) of the composite material is shown below in Equation 3.

Equation 3: Weight of Composite Derived from the Fibers and the Matrix

$$w_c = w_f + w_m$$

The weight fraction relationships were then derived from the equation for the weight of the composite, shown in Equation 4.

Equation 4: Weight Fractions for the Fibers and Matrix

$$W_f = \frac{w_f}{w_c}, W_m = \frac{w_m}{w_c}$$

As stated before the volumes and the weights can be directly related through the densities of the fibers and matrix. Equation 5 shows the volume and weight fraction relation which are dependent on their densities. This equation is a general equation that applies to the fibers and the matrix. To change between the two one would simply replace the subscripts “t” with an “m” for matrix or an “f” for fibers.

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Equation 5: Generalized Equation of the Volume and Weight Fraction Relationship

$$V_i = \frac{\rho_c}{\rho_i} W_i$$

Finding the Elastic Modulus of the composite for both longitudinal and transverse directions involved using the relationships between the volume fractions combined with the Elastic Modulus for the fibers and matrix in Equation 6 and 7. The subscripts 1 and 2 for the Elastic Modulus of the composite correspond to the longitudinal and transverse direction of the fibers, respectively. In addition to the information used in equation 6, the equation for the Transverse Elastic Modulus used Poisson's ratio (ν) for the matrix. It is important to note that all of the Elastic Moduli and Poisson's ratios are measured experimentally.

Equation 6: Longitudinal Elastic Modulus of Composite

$$E_1 = V_f E_f + V_m E_m$$

Equation 7: Transverse Elastic Modulus of Composite

$$E_2 = \frac{E_f E'_m}{V_f E'_m + V_m E_f (1 - \nu_m^2)}, \text{ where } E'_m = \frac{E_m}{1 - \nu_m^2}$$

An essential part of a composite's design is the critical fiber volume fraction, V_{crit} , which is a fraction that cannot be exceeded. The goal of a composite design is to create a composite that is as close to this number without going over, since this will ensure the strongest and lightest part while still containing enough of the matrix to properly protect the fibers and their orientation. For composite design the critical fiber volume has to be larger than the actual fiber volume that was calculated from the results of the volume fraction test.

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The critical fiber volume fraction is calculated from the longitudinal strength of the composites, σ_{cu} , the ultimate strength of the fibers, σ_{fu} , the matrix stress at the fiber fracture strain, $(\sigma_m)_{ef*}$, and the volume fraction of the fiber. The longitudinal strength of the composites can be calculated from experimental results of the fiber laminate only. The equation for the critical fiber volume fraction is show in equation 10 with equation 8 and 9 being used to derive the equation.

Equation 8: Ultimate Stress of Composite Equation 1

$$\sigma_{cu} = \sigma_{fu} V_f + (\sigma_m)_{ef*} (1 - V_f)$$

Equation 9: Ultimate Stress of Composite Equation 2

$$\sigma_{cu} = \sigma_m (1 - V_f)$$

It is important to note that this analysis assumes the laminate to be a plate or a thin shell. Because the thickness is considered infinitesimally small when compared to the width and length of the laminate it is ignored.

Equation 10: Critical Fiber Volume Fraction Equation

$$V_{crit} = \frac{\sigma_{cu} - (\sigma_m)_{ef*}}{\sigma_{fu} - (\sigma_m)_{ef*}}$$

The fiber and matrix stress can then be calculated from the ratios of the Elastic Modulus of the constituent material along with its stress, shown in Equation 11. In addition, the ultimate composite failure stress can also be used to calculate its constituent stress for the fiber and matrix.

Equation 11: Stress/Elastic Modulus Ratio

$$\frac{\sigma_o}{E_o} = \frac{\sigma_f}{E_f} = \frac{\sigma_m}{E_m}$$

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6.2 Composite Sandwich Panel Analysis - Agarwal

The Elastic Modulus for the composite sandwich panel can be calculated by combining the constituent Elastic Moduli of the facesheet and the core. This is done by using the extensional matrix, A ; shown in Equation 12. This equation can be derived from the reduced stiffness matrix, (which is composed of the A , B , and D matrices), along with the layer of the center, h_k . Here the center laminate is defined as the foam core and two facesheets (one on each side of the core). However, the equation for the actual specimens would have two reduced stiffness matrix, one that represented the facesheet and a separate one for the foam.

Equation 12: A Generalized Form of the Extensional Stiffness Matrix

$$A_{ij} = \sum_{k=1}^n (\overline{Q}_{ij})_k (h_k - h_{k-1})$$

The height at which each layer starting from the center of the sandwich is defined, is shown in Figure 58. This figure helps give a visual representation for how layers are mathematically organized and represented within the equation itself.

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Figure 58: Laminate heights with respect to the center. (Agarwal)

Once the Elastic Modulus for the composite sandwich panel as a whole has been obtained, there is an alternate stiffness matrix that can be utilized; shown in Equation 13. The Elastic Modulus “E” in this equation represents the whole composite sandwich instead of just the facesheet or core. The equation is also in terms of the thickness “t” and the overall Poisson’s Ratio, ν .

Equation 13: Extensional Stiffness Matrix with Respect to the Overall Elastic Modulus

$$[A] = \begin{bmatrix} \frac{Et}{1-\nu^2} & \frac{\nu Et}{1-\nu^2} & 0 \\ \frac{\nu Et}{1-\nu^2} & \frac{Et}{1-\nu^2} & 0 \\ 0 & 0 & \frac{Et}{2(1-\nu)} \end{bmatrix}$$

Since this is a singular equation with two independent variables we need another equation. The second equation that is needed to make this solvable is the General

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Constitutive Equation for forces with a symmetric plate. N denotes the force and ϵ denotes the strains in the equation shown below. By using experimental data to plug in for the values of the forces and the strains, the Elastic Modulus and the Poisson's Ratio for the composite sandwich panel can be calculated.

Equation 14: General Constitutive Equation for Forces with Acting on a Symmetric Plate

$$\{N\} = [A]\{\epsilon^0\}$$

In order to calculate the instantaneous core shear stress “ τ ” the following equation is used. The core shear stress is found by taking the instantaneous force P on a specimen and dividing that by the surface area of the specimen. In Equation 15 “ L ” is length and “ w ” is width.

Equation 15: Equation for Core Shear Stress

$$\tau = P/(Lw)$$

To calculate the engineering shear strain “ γ ” (also known as the effective core shear strain), the instantaneous displacement “ u ” was divided by the thickness of the core “ t ”. This is shown in Equation 16.

Equation 16: Equation for the Engineering Shear Strain.

$$\gamma = u/t$$

The Core Shear Modulus “ G ” was calculated by dividing the Core Shear Stress by the Engineering Shear Strain shown in Equation 17.

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Equation 17: Equation for the Core Shear Modulus

$$G = \frac{\tau}{\gamma} = \frac{\left(\frac{\Delta P}{\Delta u}\right) t}{Lw}$$

The relationship for the Elastic Modulus and the Shear Modulus is Equation 18. This equation is very important since it demonstrates how similar the 2 Moduli are for isotropic materials. It is important to note that the shear Modulus and Elastic Modulus for composites does not relate the same way. This was used for analysis done with the core material only.

Equation 18: Equation for the relationship between the Core Shear Modulus and the Modulus of Elasticity

$$G = \frac{E}{2(1 + \nu)} \text{ or } E = 2G(1 + \nu)$$

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7.0 Numerical Analysis

This chapter will start by discussing the creation of the numerical model and the mesh. It will then go into depth about the choice of loading and boundary conditions used in the model. The final section will cover the analysis and results of the Finite Element Models (FEM) solutions.

7.1 Creating the Finite Model

For comparison purposes three separate FEM were created in COSMOS GEOSTAR 2.0 256K, which is a software package developed by SolidWorks. These FEMs were used to help verify the experimental results produced from the conventional specimens along with the results for the staggered 4mm and 8mm Shear Key specimens. A FEM was not created for the other Shear Key specimens since they were discarded as options. Creating a model that could accurately reflect the experimental results would also allow for further representation of results without requiring more testing. To help create a more realistic model, it was decided that a 3-Dimensional (3D) model would provide better results than a 2-Dimensional (2D) model would.

The first step to reaching a numerical solution required the modeling of the test specimens. These specimens were first modeled in 2D along the side of the specimen and then extruded to create the volumes. A model of the conventional specimen is shown in Figure 59. This model was based only on the geometry of the specimen and did not include any part of the testing jigs or the Instron Machine. The reason behind this decision was that adding the testing jigs would add excessive elements to the model while having little added value to the accuracy of the solution. It was assumed that since the

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Modulus of Elasticity was so much higher for steel than it was for the core of the specimens that the test jig could be considered infinitely rigid in comparison. Further explanation for not including the testing jigs will be discussed later within the “Loading and Boundary Condition” section.

Figure 59: Model generated in COSMOS

The conventional model consisted of just a test specimen, which was made to the same dimensions as the tested specimens (16” x 2” x 1.3”). The test specimens were broken down into two separate facesheets with a core in between them. It was decided that modeling the facesheet as a single laminate instead of each of the individual layers of fiberglass would help provide a more efficient mesh and subsequently a quicker solution. An example with 2 layers of fiberglass was compared to the conventional model with a single layer of fiberglass and the results showed no difference. The fact that there was no difference at all stemmed from the difference in strengths of the fiberglass and the core.

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The stiffness of the fibers compared to that of the core showed that the fibers would have a very small displacement when compared to that of the foam core.

The Shear Key specimen models were based on the same dimensions and concepts as the conventional model, but with a few key differences. The main difference came from installing the Shear Keys into the foam. Because of the way meshes are required to be made, each of the Shear Keys were placed into a separate section of surfaces that would be merged later. This was done such that the surfaces defining the area with the Shear Key started at one side of the key and ended at the other. An example of the model after it has been meshed is shown in Figure 60. In this example the facesheet is highlighted with a light blue and a red circle is placed around the Shear Key. It is important to notice how the quadrilaterals are formed where the Shear Key is located since quadrilaterals were chosen as the element shape to be used in the FEM solver. The model was created to support this by using as many quad-friendly surfaces as possible, thus curves were only found near the Shear Keys themselves.

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Figure 60: Close up picture of the mesh around the Shear Key.

7.2 Creating the Mesh

All of the models created in COSMOS used solid elements which allowed for the calculation of stresses and strains within the test geometry. An example of an element mesh of the base model is shown in Figure 61. Each of the models was meshed using a parametric mesh of 8 node quadrilateral elements, which means that a user defined the number of elements in the X, Y, and Z direction. This was useful since it allowed for full control of the element size and placement. The concept for meshing a model is pretty simple; the smaller the elements are the more that are needed to cover a certain volume. This provides a more accurate solution but comes at the cost of time to solve, processing power required to complete the calculations, and memory. The key to meshing is to find a balance that will provide the fastest solution and require the least computer work

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without sacrificing the accuracy of the results. To help accomplish this, larger elements were placed in areas of less interest and were condensed in areas that required more attention or tougher geometries.

Figure 61: Mesh of the base model without Shear Keys.

The mesh for the base model was kept consistent throughout since there was no complicated geometry or interfacing between surfaces. The full mesh consisted of 15,360 elements and 18,837 nodes with 128 elements being used in the X-direction, 12 elements in the Y-direction, and 10 elements in the Z direction. The mesh for the Shear Key specimens was quite a bit different from the mesh of the control specimen. Meshing the 8mm Shear Key specimen required 22,320 elements and 26,847 nodes to properly capture the geometry. The 4mm specimen required 23,120 elements and 27,747 nodes since the smaller geometry required smaller elements to properly capture the geometry along with more nodes to merge. Table 4 shows the number of elements and nodes used.

Table 4: Number of nodes and elements used for the 3 separate cases.

	Nodes	Elements
Control	18837	15360
4mm Specimen	27747	23120
8mm Specimen	26847	22320

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A picture of the 8mm Shear Key specimen is shown in Figure 62 which depicts the 3D mesh used.

Figure 62: Mesh of the 8mm Shear Key specimen.

It is important to notice how the density of the elements increases around the Shear Key and in the core, while the elements around the outside are larger and less dense.

Meshing the Shear Keys properly was the most difficult part of this process. As shown before in Figure 60, the Shear Key meshing required a different approach. If care was not taken to properly mesh all the elements, triangles would sometimes form instead of quadrilaterals which would provide an error within the solver. This is shown below in Figure 63 where triangular elements formed inside the Shear Key geometry, which caused an error in the solver since it was expecting only quadrilateral elements. This case

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is software dependent where some software has the capability of using both triangular elements and quadrilateral elements. The choice for using quadrilateral elements came from the reduction in calculation requirements since more triangular elements are needed to form a volume with the same accuracy. The triangular elements do provide an added accuracy but it was determined that it was not worth the increased time and processing requirements to mesh the whole model with them.

Figure 63: A mesh in which triangular elements were formed.

To properly mesh the Shear Key specimens, each Shear Key was placed within its own surface such that quadrilaterals could be used to mesh the geometry of the semi-circle. A picture of the surface break-down with the Shear Keys is shown in Figure 64.

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Figure 64: Close up of the mesh around the Shear Keys and the element division that was used.

In Figure 64, the elements directly above the Shear Key are different sizes compared to the elements within the volumes to the left and right of the Shear Key. This is an example of how the parametric mesh was used to reduce calculation time in certain areas while increasing element count to properly capture the geometry elsewhere and maintain the proper accuracy of the results.

7.3 Finite Element Model Loading and Displacement

Once the model had been properly meshed, loading forces and displacement constraints had to be added to the model. First the displacement constraints were added to the model. To imitate the displacement constraints of the actual tests that were conducted, the top of the specimen was constrained in the X, Y, and Z directions. The constraints are displayed as yellow arrows on the model in COSMOS shown in Figure 65. Because the test jig had a pin connection between the Instron grip and the test specimen itself, the test specimen was able to swivel and thus no moment was transferred.

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Figure 65: Shear key model shown with the forces and constraints applied. Top shows the Shear Keys and volumes where the bottom shows the Shear Keys by themselves.

The loading of the specimen was placed only in the X-direction along the bottom surface of the specimen's facesheet, which would help determine the shear strength of the specimen core. A separate case was done to model the exact loading in which case there was a normal force added. This normal force came from the fact that when the test jig was loaded the specimen was at a 4 degree angle offset from being completely vertical. However comparing the results of the 2 numeric cases showed there was no difference in the shear strength of the specimen. There was a difference in the ultimate load of the specimen, but since the research was only focused on the shear capacity it was decided that this component could be left out. This would simplify the model and analysis which in turn would decrease the time required to solve each case. A load of 4500 lbs. was applied as a pressure load over the surface of the top facesheet to imitate the force applied by the Instron machine. This allowed for an even distribution of the force across the specimen which was assumed from the infinitely rigid test jig assumption. The choice for using 4500 lbs. was based on using a load that would remain within the specimen's

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linear range for comparison, and was chosen by averaging the maximum tensile loads experienced by the control specimens, and then taking $2/3$ of the value. This rounded down from 4666 lbs. to a nice even number came out to be 4500 lbs. which showed to be within the linear range of all the stress strain curves taken from the Instron machine while testing the control specimens (composite sandwich). Assuming that the Shear Key specimens carried more strength than the control specimens meant that the 4500 lb. load would be within the linear region for the Shear Key specimens as well. By staying within the linear region of the specimen, a better comparison of the shear properties could be conducted between the control specimen and the Shear Key specimens.

7.4 Finite Element Analysis and Results

Upon completion of the mesh along with the loading and displacement constraints, the model was finally ready to be run through the solver. The first model that was run through the solver was the control specimen with no Shear Keys. The shear stress response of the model is shown in Figure 66, with a close up of the stress concentration at one of the ends. This initial numerical solution showed failures at the ends which matched the experimental case, however the specimens during the tests experienced these early on in the test and continued past since the 20% failure criteria of the Instron was not met. As the test would continue on the core of the specimen showed a displacement similar to the one found in the displacement plot produced from COSMOS. In Figure 67 the displacement plot for the control specimen is shown. Here the ends have failed and delaminated from the structure thus showing the most deflection from the original analysis. It is important to note that if the ends of the displacement plot are ignored similar to what was done for the experiment then the plot represents an

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accurate solution. The displacement increases the further away the constraint gets with the facesheet having the largest of the final displacements at the end of the specimen.

Figure 66: Stress response of the whole control specimen (left) with a close up of the top end of the specimen (right).

Figure 67: Displacement response of the whole control specimen (left) with a close up of the top end of the specimen (right)

Another contributor to the specimen deforming improperly at the ends involved the way the upper facesheet was constrained. In the numerical analysis it was free to move about, however during the experimental tests it was adhered to the test jig. Since the shear properties of the specimen and the central part of the specimens were reflected

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accurately in the numerical results, the constraints were not changed. This was expected since the test had been designed to ignore the initial boundary failure and there was no way to avoid this in the numerical solver.

Next the 8mm Shear Key specimen was run through the solver. This was done knowing the same boundary failure that occurred in the control group could potentially exist within this solution as well. The results for the stress plot are shown in Figure 68, and the core behavior was similar to what was seen during that actual experimental tests.

Figure 68: Stress response from the 8mm Shear Key case (left) with a close up of the force concentration around the Shear Key (right).

Again the same issue with the boundary failure appeared and with the model not having the proper constraint along the facesheet. However, the response along the Shear Key was exactly what was expected. There is a force distribution that can be seen throughout the core, though there is not a high enough force concentration that would weaken the part. The displacement plot shown in Figure 69 is as expected as well. The displacement increases the further away from the constraint the point of interest is located. This is because there is very little give in the fiberglass when compared to the

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foam core, which can be explained with their huge differences in their respective Modulus of Elasticity values.

Figure 69: Displacement response from the 8mm Shear Key case (left) with a close up of the Shear Key area (right).

The final numerical case run involved an analysis on the 4mm Shear Key specimen model. This model provided results that again were in line with expectations. The behavior seen in the stress response shows similar trends to that of the 8mm stress plot, but there is less of a force concentration build up around the Shear Key with the same load applied. This is shown in Figure 70. Some of the decreased stress concentration can be attributed to the fact that the smaller Shear Keys do have a small amount of flex within themselves as well, where the 8mm Shear Keys are much more rigid.

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Figure 70: Stress plot for the 4mm Shear Key specimen case.

In the displacement plot for the 4mm Shear Key specimen case shown in there is a smoother transition through the core. With the 8mm Shear Key specimen there was very little displacement near the constrained facesheet up to the tip of the Shear Keys. At that point that amount of displacement increased more rapidly through the core moving towards the facesheet where the load was applied. This increase in displacement, shown in Figure 71 as well as previously in Figure 70, show potential for improving the shear capability of the composite sandwiches when compared to the initial control specimen. Both of the Shear Key models were able to transfer loads from the facesheet into the core preventing a failure due to delamination. Further research will be needed to create a more accurate numerical model from which better results can be taken.

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Figure 71: Displacement plot for the 4mm Shear Key specimen case.

8.0 Comparison of Experimental and Numerical Results

Initially it was hoped that the model and numerical results would be verified by the experimental data and trends for the control specimen. Then once the model properly represented the experimental results and trends it could be used to investigate the Shear Keys more thoroughly. This plan ran into some issues when it was realized that there were some limitations within COSMOS.

As shown in the previous section with the displacement plots, there were two major issues. Since a crushable foam model was not used, the initial analytical failure continued from the edges moving inward, which never occurred during the experimental tests. This also made any comparison with actual numerical values difficult since the results would only be accurate up to the point of the initial failure. The point of initial failure of the specimens occurred at a load of roughly 1000 lbs. which left almost no deformation and a very small stress distribution throughout the part except for at the edges. This coupled with the potential errors of ignoring random sampling created issues for an actual comparison of numerical values to be done.

The second issue involved the facesheet displacement along the loaded side that occurred within the solver. An attempt to constrain the specimen was implemented, but the added constraint method proved to be a failure. This was because COSMOS constraints are based on a global coordinate system instead of a local coordinate system. By making the top facesheet infinitely rigid in COSMOS also prevented all displacement within the specimen providing zero results.

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Since one of the goals for the numerical solution was to hopefully gain more understanding of what the Shear Keys actually did, a comparison was conducted with the original analysis in hopes of finding some information and not letting the numerical solution go to waste. What was discovered from inspecting the stress plots was more helpful than expected. The comparisons between numerical strain results and the numerical stress response for the 4mm and 8mm cases are shown in Figure 72 and Figure 73. The hope with the comparison of these plots was to gain ideas of why the numerical analysis failed and any potential paths forward that would allow for the creation of a better model within COSMOS.

Figure 72: Numerical strain results for the 4mm and 8mm Shear Key specimen.

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Figure 73: Numerical stress response for the 4mm and 8mm Shear Key specimen.

The comparison of the strain results and the stress response did give some insight to how the Shear Keys behaved under load. In both figures the Shear Keys can be seen taking some of the force and distributing it into the foam from the side view. Looking at the facesheet the Shear Keys start to build a force concentration at the edges of the key as the Shear Key itself starts to buckle. Having the load distribution transferred into the Shear Key decreased the amount of displacement similar to what is shown in the Stress-Strain plots. This added rigidity allowed for the Shear Key specimens to withstand a higher shear stress than the conventional specimens.

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Comparing the numerical stress plot with the Stress-Strain curve confirmed that the Shear Keys were performing the task that they had initially been designed to do (stop delamination). In addition it confirmed the reasoning behind why the 4mm Shear Keys had performed better compared to the 8mm Shear Keys. The result of the comparison was that further correlation had to be conducted between the model and the data to show that the model was in fact correct. This was done by analyzing several cases using a loading that would be found well within the linear range. Using the experimental stress-strain curves provided a load of 100 lbs that would fall well within the linear range of the foam. The numerical results were then compared to the experimental values by taking several points on the model and using the numerical scale to help estimate the Shear Modulus. After averaging the different values for the Shear Modulus, which was taken from the various points of the model shown in Figure 74, the compared results showed values close to the expected data, as shown in Table 5. Thus it was concluded that the numerical model, given a more accurate non-linear representation, would have been able to properly represent the experiment.

Table 5: Results found in the comparison of the numerical and experimental values for the Shear Modulus.

Numerical Shear Modulus	Experimental Shear Modulus
16.8 ksi	18.9 ksi

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Figure 74: Linear load specimen shown with the displacement results shown on top and the stress response shown below it.

With this information in hand, it was decided to observe the errors seen between the two plots to come up with a path forward for future work. Since the concept of the Shear Key had held up to what it was designed to do, it was necessary that a proper numerical model be created. An attempt to replicate the results with Tresca was done in hopes of comparing against the Von Misses results, which would hopefully provide a slightly more accurate solution. This was to no avail though since COSMOS did not contain a proper Tresca failure criterion.

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The purpose of any future model should be to help optimize the shape and size of the Shear Keys, without having to actually test hundreds of specimens. In order to do this, it is very likely that a new software pack will be needed such as ABAQUS that will allow for proper constraints to be built into the model. Additionally the software pack will need to be able to accommodate a crushable foam model thus allowing the model to ignore the initial boundary failures in the same fashion that the experimental tests were designed to do so.

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9.0 Conclusion

The results of this thesis showed that the seawater continues to degrade shear capacity in both raw and filtered specimens in the initial 3 months of submersion; after that, the degradation rate slows. The first 3 months, trends showed that there was a gradual decrease in the shear capacity of about 10% and an increase in the ultimate strength and fracture point of the specimens. After the first three months there was little to no change in weight thus leading to the conclusion that the specimens were fully saturated.

An interesting point is that the specimens that were placed in the ocean itself (raw) were weaker than the filtered sea water pieces. It is possible that the specimens were weakened due to the environment from biological growth on all surfaces of the specimens. However further tests are needed to gain a better understanding of why the raw seawater pieces are actually weaker.

The addition of the Shear Keys show promise in the experimental specimens. They seem to have an increased ultimate load and shear capacity. However with the control specimens the delamination and failure times were much slower suggesting that they could potentially be noticed and repaired. With the Shear Keys the specimens waited until right before they had reached their ultimate load before showing signs of failure. Within a naval vessel this would be considered an instantaneous failure which would be harder to detect prior to an event, and could be a more critical failure with a higher risk.

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The Shear Key specimens were tested with a 4mm and an 8mm diameter Shear Key in varying configurations. The 8mm Shear Keys showed a decrease in strength, which was primarily due to having less area in the core creating a higher stress. Out of all the configurations of Shear Keys tested, the staggered 4mm proved to be the strongest addition to the specimens with the trends showing an increase in shear strength of roughly 15% to the 8mm staggered Shear Key specimen's 10% increase.

The numerical results showed that it was possible to replicate the linear or elastic portion of the experimental results. There was a difference between the maximum displacement of the model and the actual specimens, but this was attributed to potential inaccurate comparison of the loading on the model compared to the actual specimens. The correlation between the model itself and the experimental data was close enough to conclude that it could be used for predicting baseline trends but not quantitative results without further refinement of the tool and model.

The biggest difference between the numerical solutions and the experimental data involved the crushable foam response, since COSMOS did not have a function for a programmable model. However there was little difference when comparing the shear capabilities, which were taken from the linear region of the experimental stress-strain curves, to the numerical values. This was further confirmed through the comparison of the theoretical value and the numerical values found from the models used.

9.1 Lessons Learned

Throughout the entirety of the work done for this thesis there were many lessons learned. Some of the lessons learned are discussed in this section of the thesis.

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The first lesson was to properly plan out what you hope to accomplish and to understand the requirements behind the plan. In the initial phase of the manufacturing and testing the budget was not properly reviewed, since there was no concept of what was to actually be tested. This led to an overrun in time and money, which could have been avoided and potentially increased the information taken from the final results.

Secondly, it is important to conduct proper statistical analysis when trying to record results. Because of the lack of random sampling among other things, only trends could really be acknowledged from this report and not a standard deviation from the error percentage. Having this would definitely add more value to the results presented.

While manufacturing the specimens many lessons were learned and passed on to other students that allowed for more consistent and stronger parts to be created. Lessons such as how large a VRI part could be without running into mid-flow curing issues, and reduction of airflow techniques were all utilized in these tests. Also the importance of proper surface preparation came into play. When this was not done properly some of the specimens improperly failed along the bond line before the test had completed. This failure resulted in the loss of specimens that had been in the ocean for some time and reduced the sample size from which the data was pooled. This was reduced after the first incident by returning to using MEK instead of acetone to clean the jigs along with sanding down the specimens to remove any debris along the surface that could contaminate the bond. Ensuring a proper bond was also critical to the result comparison since the assumption was that everything from the Instron Machine leading up to the specimen itself was to be considered infinitely rigid.

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9.2 Future Work

There was a lot of knowledge gained from the work done on this thesis, but there is still more work to be done. Starting with looking into how the Shear Keys perform after being placed into both filtered and raw sea water environments. Looking at the results from this thesis it may also be of interest to see how the sea water specimens fare under a fatigue loading. This seems more likely to be the cause of the delamination and core failures found in the naval vessel, since the time soaking seems to have done very little to the material after the first initial months. Additionally it would be interesting to see how the Shear Key specimens that were soaked in the sea water responded to the fatigue loading as well.

Also, more experimental testing is needed for different Shear Key geometries such as size and shape variation along with position variation. It was suggested that Shear Keys be placed vertically along the sides of the specimen instead of horizontally across the width. A comparison of these two options is one of the many possibilities that have still to be tested as a method for better improving the shear capacity of the composite sandwich panel.

However before any further research with the seawater specimens can be done a new process has to be created in which to clean the test jigs. With the current safety issues, time requirements, and lack of a dedicated facility, the research cannot continue. It could be beneficial for a student to come up with a re-design of either the process or the testing jigs that would eliminate these current issues.

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On the numerical side there is a lot of work that is still needed to be completed as well. An FEM that does a better job of taking into account the non-linear characteristics of the foam is needed. This will provide more accurate results and allow for better future modeling as well as doubling as an optimization tool for future Shear Key geometries. In addition many of the changes discussed in the comparison section between the numerical and experimental results will need to be implemented as well.

It is my hope that this research is placed to good use in benefitting future students' research with composite sandwich panels.

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