THE EFFECT OF BIOCOMPOSITE MATERIAL IN A COMPOSITE STRUCTURE UNDER
COMPRESSION LOADING

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Benjamin A. Sweeney
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COMMITTEE MEMBERSHIP

TITLE: The Effect of Biocomposite Material in a Composite
Structure under Compression Loading

AUTHOR: Benjamin A. Sweeney

DATE SUBMITTED: February 2017

COMMITTEE CHAIR: Faysal Kolkailah, Ph.D., P.E.
Professor of Aerospace Engineering

COMMITTEE MEMBER: Eltahry Elghandour, Ph.D.
Professor of Mechanical Engineering

COMMITTEE MEMBER: Dianne DeTurris, Ph.D.
Professor of Aerospace Engineering

COMMITTEE MEMBER: Andrew Davol, Ph.D.
Professor of Mechanical Engineering

ABSTRACT

The Effect of Biocomposite Material in a Composite Structure under Compression Loading

Benjamin A. Sweeney

While composite structures exhibit exceptional strength and weight saving possibilities for engineering applications, sometimes their overall cost and/or material performance can limit their usage when compared to conventional structural materials. Meanwhile ‘biocomposites’, composite structures consisting of natural fibers (i.e. bamboo fibers), display higher cost efficiency and unique structural benefits such as ‘sustainability’. This analysis will determine if the integration of these two different types of composites are beneficial to the overall structure. Specifically, the structure will consist of a one internal bamboo veneer biocomposite ply; and two external carbon fiber weave composite plies surrounding the bamboo biocomposite. To acquire results of this study, the hypothesized composite structure will consist of varied trapezoidal corrugated specimens and tested in uniaxial compression loading. Thereafter, this test data will be used to ultimately design, manufacture, and test a structural biocomposite/composite box, intended to carry extremely high compressive loads; relative to its own weight. A finite element analysis of this test will be used to validate experimental data. After running the experiment, the carbon fiber with bamboo test sample results were compared to that of only carbon fiber test sample. The carbon fiber samples resulted in a maximum compressive load difference of only 23% higher loads when compared to the carbon fiber with bamboo, on average. These findings are discussed throughout.

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1 INTRODUCTION

In this chapter an overview of composites will be introduced. Also, the history of composites will be discussed along with an explanation of biocomposites and natural fibers. Later in the section, the uses of bamboo, bamboo's anatomy, and the manufacturing process of veneer will be described.

1.1 Composite Materials Overview

When composites are discussed today they are met with a familiarity that was not present just a couple decades ago. Composite materials have made their way into all facets of engineering and have become a staple in some industries. With their unique material properties, it's no wonder that companies have invested time and money into exploring the limitations of composites. Metals, which used to be the 'go-to' material for almost all engineering applications, are now challenged as a preferred material selection.

The definition of a composite is the combination of two materials that are different either chemically, physically, or both; that produce a new material with different individual properties [1]; as seen in Figure 1. Some examples of composite materials include concrete, ceramics, wood, human bones, papier-mâché, and of course fiber

Figure 1: Fiber reinforced composites [2]

reinforced polymers. It may not be very apparent but composite materials surround us everywhere. More specifically, most bike frames, kayaks, tennis racquets, hockey sticks, bullet-proof vests, drive shafts, commercial

airline wings, and rotary propellers are made from composite materials. The most common types of composites today are fiber reinforced polymers. Conventional fiber reinforced polymers are a combination of a resin or epoxy, which are classification of a 'matrix', and synthetic fibers (carbon fibers, fiberglass, aramid fibers, etc.).

Meanwhile, there is another type of composite that referenced not nearly as often as the composite materials described above: biocomposites. Biocomposites are a different class of composite materials because they consist of a standard or plant-derived resin system, and natural fibers (bamboo, hemp, cotton, etc.). Natural fibers, such as bamboo, are cheap, renewable, strong, and friendly to the environment. Biocomposites have the potential to be comparable, if not greater than conventional composites in terms of their mechanical properties.

A very important mechanical property seen in natural fiber composites is 'sustainability'. The words "sustainable materials" are usually used describe how natural, biological environments and ecosystems can remain intact and preserved indefinitely. But in engineering and structural scenarios, "sustainable materials" refers to the material durability and structural durability of a material.

Therefore, bamboo fiber composites and their sustainability will be thoroughly examined in this report; as well as a focus on the edgewise compressive behavior of combining bamboo and carbon fiber composites. Bamboo will act as the core of the structure since it will be located in between plies of carbon fiber. More information on composites, biocomposites, and the experiment using bamboo will be discussed throughout.

1.2 A History of Composite Materials

The origin of composite materials dates back to the ancient times in world history. It is documented that the ancient Mesopotamians first created composite materials by gluing wooden strips together, essentially inventing plywood around 3400 B.C.E. [3]. Fast forward a couple thousand years, we see early civilizations such as the Mongols reinventing composites by creating weapons made from bone, bamboo, or wood in combination with resin or sap extracted from pine trees, circa 1200. Whilst revolutions and phenomenal advancements in chemistry occurred throughout the next 7000 years, the first fiber reinforced polymers (FRP) began to emerge in the 1930's and 1940's.

Fiberglass would be the first FRP to exist and utilized on a mass scale. From the surge in production caused by World War II to the budding car industry, fiberglass composites became fairly common. Meanwhile, the next couple decades led to advancements in resin systems and the creation of newer epoxies and thermosets. It wasn't until the 1960's that carbon fiber would be introduced to the engineering industry; and not until the 1970's that carbon fiber reinforced polymers (CFRP) were actually applied to the aerospace, sporting, automotive, medical device, and various other industries. For example, the B-2 Bomber, see Figure 2, which was began its initial design phase designing in the 1970's, was built mainly out of carbon fiber

composites; but was not fully operational until the 1990's [4]. By the time the 1990's and 2000's rolled around, composite materials could be considered as an option in almost any engineering application. The same

Figure 2: Northrop Grumman's B-2 Bomber [4]

is true for today; although natural fiber composites have been under investigation and are slowly making their way towards the spotlight, which will be discussed in detail later.

1.3 Conventional Composites Materials

As far as conventional composite materials go, they usually are made from synthetic fibers and industrial processed resin, thermosetting systems. Carbon fibers, which are usually synthesized from polyacrylonitrile (known as PAN), require a slow and energy intensive process [5]. The fibers undergo multiple heating processes to align the carbon atoms into its respective shape. The final heating stages, which can exceed temperatures of 4000 degrees Fahrenheit, will ultimately decide the Young's modulus for the material. Another conventional composite fiber is fiberglass; which is made up of glass fibers, or silica [6]. Silica also requires energy intensive heating processes to get the material to its final textile, fibrous state. Carbon fiber composites, in comparison, may carry higher loads in tension and compression, but due to their stiff material properties do not handle elongation or deformation as well as fiberglass composites. Aramid fibers, such as Kevlar, could also be considered a conventional composite material. Kevlar specifically, requires a chemically heavy process in order to be synthesized. The chemical name of Kevlar is poly paraphenylene terephthalamide [7]; which can only be obtained via multiple chemically heavy molecular reactions. Kevlar composites, while generally not as strong as carbon fiber or fiberglass, are mostly known for their ability to withstanding and absorb high impacting forces. All of these fibers are one way or another used in many engineering industries for their exceptional weight savings, strength, or application-specific material properties. To select the most efficient composite, structural engineers generally take a look at a composite material's strength to weight ratio (force at

failure divided by its weight) when comparing composites to one another. These composite fibers require a resin system, such as an epoxy, to complete the transformation into a composite material. Epoxies are usually a two part system (a resin and a hardener), that when mixed in a specific ratio will react and harden.

1.4 Biocomposite Materials

Unfortunately, the conventional composites described above require intensive manufacturing processes that make them not very environmentally friendly. This does not even take into account the rancid, industrial chemicals required to produce resin systems such as epoxy. Many epoxy systems are derived from petroleum, which increases our carbon footprint, and are toxic to humans and the environment. And once a composite, cured or uncured, has attained purpose it will be discarded or recycled. Unfortunately, if it gets recycled it will be incinerated at high temperatures in an energy intensive process while expelling chemical by-products into the atmosphere. Or if it gets discarded, it will be thrown into a landfill where it will remain for thousands of years and contaminate the surrounding soil. Whilst there is research ongoing about more energy efficient ways to recycle composites, there is nothing currently available.

Enter the world of biocomposites. Biocomposites are the result of environmental awareness that has been growing over the past couple decades. The idea of biocomposites is not very different from its conventional counterparts. It consists of natural fibers and, usually but not always, a polymer thermoset synthesized from plants or natural products; as shown in Figure 3 [8]. But the significance of biocomposites is their renewable and environmentally friendly properties. The lifecycle of a biocomposite would be infinitely continuous, as they can be efficiently recycled and reproduced in

harmony with the environment. Natural fiber composites can biodegrade to improve soil conditions; or if they are recycled via incineration, no excess contaminant emissions will release other than the carbon already stored in the structure [9]. If structures contained just 1% biocomposite materials, then there would be 1% less of a carbon footprint in the atmosphere. This is an important idea because while biocomposites are strong and rival that of conventional composite materials, they might not exceed their material performances in certain applications. But if biocomposites are utilized more frequent and its material properties are exposed in the right scenarios, then it will ultimately benefit the environment. And not only do biocomposites benefit the environment, but they are cheaper and more readily available.

Figure 3: Biocomposite materials [8]

1.5 Natural Fibers

There are multiple different types of natural fibers that exist and are utilized today. Natural fibers are extruded from natural vegetation or are animal-based. The natural fibers that exist today can greatly reduce the carbon emissions that occur with normal composite fibers while minimalizing waste. Some examples include bamboo, cotton, jute, flax, and hemp fibers. Natural fibers are usually composed of three primary components: cellulose, hemi-cellulose, and lignin [10]. The ratio of the three vary per fiber type, but are all usually present in the composition. Natural fibers, as described

previously, are not only cheaper than conventional, synthetic fibers but they are environmentally friendly. They can be recycled into compost, soil enhancer, or simply be allowed to biodegrade. Meanwhile synthetic fibers require stringent regulations and standards in order to dispose.

Some examples of natural fibers include a study that reported 1 ton of jute fibers would take just 10% of the production energy that it takes to produce synthetic fibers [9]. Another report publicized that hemp is a recommended fiber for Chinese homes because those fiber have the ability to absorb toxic gases and pollution; which is common in metropolitan areas of China [9]. As of late, flax fibers have been used in automotive industries to replace fiberglass in some applications, for its weight savings [9]. Natural fibers such as flax, jute, hemp, cotton grow maximum 120 days, 150 days, 180 days, and 200 days out of the year, respectively. Meanwhile bamboo will actually grow year around and yields the most fibers per production [11]. Natural fibers all have their own benefits and should be used accordingly per engineering application.

1.6 Dry Fibers and Prepreg

There are two main types of composites materials: dry fibers and prepreg. Dry fibers are simply composite fibers that have not been introduced to an matrix, such as a resin or epoxy. Most commonly, a ‘wet layup’ technique is used to combine dry fibers and a resin system or epoxy. This is done by hand and requires a technician to saturate fibers in an epoxy solution. But there are still many different ways to layup and cure composites. Once an epoxy has been incorporated into a dry fiber layer, they can be cured. ‘Curing’ refers to the process in which the matrix hardens and the fiber and epoxy become a ‘composite’. Curing composites ultimately depend on the conditions that will

harden the epoxy. Each epoxy, usually a thermosetting polymer, requires a specific heat and/or pressure to harden. The most common curing processes include using an autoclave, a table press, a heat table, or simply atmospheric conditions. Depending on the layup technique used, vacuuming bagging or compression molding might be used. For almost all wet layups, as well as prepreg material, vacuum bagging is required to get an even distribution of epoxy across the part. Meanwhile, prepreg material is the unification of fibers and epoxy at the manufacturing level so that epoxy mixing and saturating by hand is not necessary. Prepreg material must be placed in freezing conditions so that the impregnated epoxy does not start flowing or curing; which could happen even at room temperature if enough time is allowed. Prepreg material is usually more reliable than wet layups as the ratio of resin to fibers is closely monitored. This allows for less error in the layup process and more consistency in the final product. Also, prepreg fibers come in weave patterns as well as unidirectional (fibers all aligned in one direction); while most dry fibers come in weaves. The ply orientation can tailor a composite to a specific loading condition or scenario. These processes will be discussed in detail throughout this report.

1.7 A Detailed Look at Bamboo

Before jumping into the utilization of bamboo in this experiment, it seemed important to first understand the basic facts of bamboo.

1.7.1 Origins and Properties of Raw Bamboo

One of the most eye-opening facts is that over 1 billion people live in bamboo homes [12]. This goes to show that not only is bamboo wildly abundant in the world, but the sheer amount allows bamboo to be relatively inexpensive on the market so that even

people in impoverished countries can afford a shelter. A square foot of bamboo veneer is a relatively expensive piece of bamboo, but it's still less than half the price of a square foot of carbon fibers, according to current market price values [13] [14]. Meanwhile a raw stock of bamboo is close to free if you live in the right area, according to the map Figure 4 shows [15]. There are literal forests of bamboo in Asia; especially China.

Bamboo can grow in other locations, such as Canada, but it is domesticated and usually a farmed crop.

Figure 4: Geographical locations where bamboo grows naturally [15]

Meanwhile, there are over 1,000 species of bamboo that grow in the world. Some are better for structural applications while others are better for aesthetics. Bamboo can grow up to 8.25 inches a day, they are considered the fastest

growing plant, they can grow into their full length anywhere from 6 months to a year, and they fully mature after about 6 years, and grow year round [11]. "Full length" is documented as anywhere from 15 feet to 39 feet [16]. They are neither a tree nor a plant; they actually belong to the grass family, Poaceae, and the subfamily, Bambusoideae [16]. Also, bamboo is constantly absorbing and expelling water from the air to keep itself in a balanced equilibrium; which is known as a hygroscopic material [17]. Therefore bamboo is always retaining water to some degree; purifying the water as well as the surrounding air. All while removing carbon dioxide from the environment and producing 35% more

oxygen, than standard trees [15]. And with bamboo making a steady comeback as a structural material, the bamboo industry was valued at 60 billion USD in 2015 [15].

Unfortunately, bamboo's full potential has yet to be recognized due to outdated policies and guidelines used to certify bamboo. The Forest Stewardship Council (FSC) is a governing entity that certifies natural commodities seeking to be sold on the market by inspecting their sustainability characteristics and comparing them to a set of standards. But the FSC has not taken the time or steps to create a new set of requirements for bamboo because it's considered a 'grass' even though it resembles a 'tree' [18]. But the usage of bamboo continues to increase, so this certification may not be very important.

1.7.2 Anatomy of Bamboo

Amidst all the benefits of bamboo properties, it is also important to take a look at its anatomy. Bamboo contains an interesting anatomical composition. Belonging to the family of grass, it seems to follow the same patterns by sprouting vertically upward from the ground where their rhizome roots are grown. Their rhizome roots and budding shoots grow underneath in all directions, as can be seen in Figure 5 [19]. Later, the bamboo's

Figure 5: Stages of bamboo growth [19]

cylindrical-shape forms underground and then sprouts and grows upward. Bamboo follows a very simple build, dividing its culm, or main stalk, into sections. Each section of culm is divided by a solid layer of bamboo, called ‘nodes’, that fills the cross-sectional area of the bamboo; see Figure 6 and Figure 7. The spaces between each node, called internodes, are the hollow cavity that allows area for bamboo fibers to straighten into its respective direction. Internodes range in size depending on the species type but can be generalized as 9 inches [11]. The internodes grow exponentially with time until they’ve fully matured. Meanwhile, branches with leaves can grow outward, anywhere along the culm. An adult structure of bamboo can be characterized as anisotropic material, like wood. But due to its internal fiber orientations it would also be orthotropic, like synthetic composites. Wood has fibers that typically go along the grain making it have different mechanical properties with the respect to the direction. But since bamboo has fibers oriented in the axial and radial directions at the node locations along the culm, it would be considered an orthotropic material.

Figure 6: Matured bamboo stalk [19]

Figure 7: Section view of a bamboo stalk [22]

The internode and nodes are like scaffolding that supports growth for long bamboo stalks to grow. Internodal regions of bamboo usually consist of semi-structural, unidirectional fibers called ‘vascular bundles’ [20]. Vascular bundles are more importantly pathways for nutrients and water to

move inside the plant. The strength of the bamboo is directly related to its vascular bundles [20]; see Figure 8. These bundles, which run in the vertical axis, are accompanied by the purely structural, ‘cellulose fibers’ that keep the plant stable and resistant to flexural forces. They are usually most evident towards the outer diameter of the bamboo and fade moving inwards [21].

Towards the center of the bamboo culm, and the hollow cavity that exists, radial fibers begin to exist [22]; see Figure 9. The axial fibers discontinue their path upon the following node while radial and transverse fibers appear to form the node [23].

Figure 8: Bamboo nodal fibers [21]

Nodes, on the other hand, are distributed in no particular fashion, and usually whenever the plant decides it needs one. Each node location on a bamboo culm has an upper and lower ridge that separates the internode cavities from each other. A solid cross section of a bamboo node does not have a uniform thickness because these locations contain disoriented fibers joining one another in an intertwined network [21]. These dense networks of fibers create a planar cross section inside the nodal space. The nodes of bamboo have been recorded as the strongest location for compression loading and are nearly isotropic [21].

Figure 9: Cross section of bamboo internode [23]

Bamboo is made up of about 50% to 70% cellulose, 20% to 30% hemicellulose, and 20% to 30% lignin; not including stored water. The organic compound ‘cellulose’ is a

polysaccharide (simple sugar carbohydrate), that can be classified as a long chained, linear polymeric carbohydrate. This long chain of beta-glucose sugar molecules has been recorded to chain anywhere from 1,000 to 14,000 atomic mass units together. This long chain of polymerized molecules act as a fiber that has great covalent bonding between one another. Upon taking a closer look at cellulose, its organizes its chains into a microstructure known as microfibrils. These microfibrils fibers compile together radially until a cellulose fiber is formed. It is the main structural component in the cell wall of bamboo; see Figure 10. [17]

Meanwhile hemicellulose is a matrix of polysacchaides, instead of a long chain, that form around cellulose fibers. Hemicellulose's molecular structure is less organized when compared to cellulose, but is dispersed around cellulose fibers and compacting the internal plant structure. The increase in density that hemicellulose offers actually help the cellulose fibers hold shape and orientation. They are almost always found in plant cell walls, accompanying cellulose. [17]

Lastly is lignin, which is considered to be “nature’s adhesive”. It is a large macromolecule chemical compound that fills the gaps between cellulose and

Figure 10: Cellulose, Hemicellulose, Lignin Structure [24]

hemicellulose. This could be described in layman composite terms as the ‘matrix’ to the fibers, giving bamboo it’s natural stiffness and rigidity. It’s mechanical properties keep the structure held together throughout the entire culm. Figure 10 shows the cellulose, hemicellulose, and lignin structure together [24]. Meanwhile Figure 11 shows

the structure of a plant cell diagram [25]. [17]

For this study, bamboo was chosen as the material to be analyzed in combination with other composite materials. Almost all synthetic, conventional composite materials are professionally manufactured to specific tolerances and regulations. This ultimately allows superb material properties to be

exploited repeatedly. On the other hand, natural fibers and biocomposites do not share the same level of consistency. Raw materials exist in nature as is. There are not guidelines or standards that nature follows.

That is why, when bamboo was selected as the natural material to be examined in this

Figure 11: Plant cell structure [25]

report, a search to obtain the most uniform type of material was conducted. Eventually, bamboo veneer sheets were discovered as the answer to the problem. Bamboo veneer sheets are dry fiber rolls of bamboo that consist of unidirectional fibers and a uniform thickness. Therefore, due to consistency throughout the bamboo fibers, this veneer material would generate reliable, consistent results used as a composite.

As discussed earlier, there are over 1,000 different species of bamboo in the world. Some are used for their aesthetics while other are used for their structural properties. But when it came to decide on which bamboo veneer would be utilized for this experiment, there was not very many options. In fact, there was only one option that was harvested and manufactured into bamboo veneer; and available at the moment: *Phyllostachys edulis* (or *Phyllostachys pubescens*). Also known as ‘moso bamboo’,

Phyllostachys edulis is the most common type of bamboo that is used in textile industry [26]. Its origins are native to China. This bamboo can grow up to 92 feet, reproduces asexually, produces edible shoots, is quickly biodegradable, has antimicrobial properties, and can be made into bamboo sheets, bedding, & blankets [26] [27]. Another beneficial property that moso bamboo exhibits is its high durability as a textile when compared to other natural fibers such as cotton and wool. Moso has an average breaking tenacity of 11.4 while cotton and wool show 3.5 and 1.2, respectively [27]. Breaking tenacity is the strength given to a fiber or yarn; usually used in the textile industry. This durability is desirable when the bamboo will act as a lightweight core in a composite structure, which will be discussed later. Also, moso bamboo culm that is four years old is recommended to be manufactured into pulp and paper. For culms to be used as timber and structural members, six to eight year old culms of moso is recommended [28]. Since veneer is too rigid to be paper but not stiff enough to be used as timber, it could be safe to speculate that moso bamboo veneer is taken into production when culms are about four to six years old.

1.7.3 Bamboo Fiber Extraction

In order to extract the fibers from the raw material, there are a couple different methods that are used in textile industries. Table 1 displays various different ways the industries extracts bamboo fibers [29]. Usually a combination of chemical and mechanical extraction processes are used to efficiently get the fibers out of the culm. The nodes of bamboo are initially removed since bamboo fibers residing in the internodes are the resource that textiles seek to extract. With chemical extraction, alkali or acidic solutions are used to soften the fibers from the bamboo internodes. This usually will destroy some of the internal anatomy discussed above; such as destroying lignin content or cellulose

fibers [23]. Once the strips of bamboo have been treated in a chemical bath, they will undergo a drying process and then a cleaning process until the right consistency is

Table 1: Bamboo extraction methods [29]

Method	Cost of equipment	Energy consumption	Installing area	Environmental impact	Aspect ratio of fiber	Control of fiber property	Bamboo age and species
Mechanical extraction	Reasonably expensive	Relatively low	Small	No	Low	Acceptable	Young (2~8months)
Alkali treatment	Cheap as long as excluding waste water treatment	Medium	Huge	Yes	High	Good	Thin F.: ~12months Medium F.: 1~2 years. Coarse F.: 3years.~
Steam explosion	Expensive	High	Large	No	High	Good	Preferable: younger than 2 years. Thick F.: ~5 years.

achieved. Conversely, mechanical extraction is also an option. This method usually starts by using steaming, crushing, or grinding techniques to soften and expose the bamboo fibers. Each mechanical process has pros and cons. For instance, the steam explosion process can reduce the natural strength of the bamboo but can remove a significant amount of lignin. The less amount of lignin, the freer the fibers are to be collected. Lastly, a technique using both chemical and mechanical extraction can be utilized. It starts again with an alkaline, chemical bath to soften the fibers and lignin is expelled. After bathing the fibers for an adequate amount of time, compression molding technique (CMT) or roller mill technique (RMT) can be utilized to force the free fibers back together and in a usable state. CMT will press the fibers between two plates at extremely high loads. RMT will roll the treated fibers through two rollers that are set to a specific thickness. Either way, strips of varying length are manufactured. [23] [20]

1.7.4 Manufacturing Bamboo Veneer

While bamboo extraction methods are very important, the process to manufacture bamboo veneer does not end there. There are actually quite a few more steps before bamboo can be considered ‘veneer’. After bamboo stalks are cut and taken to a storage warehouse, they’re taken to a mechanical splitting machine; using the mechanical extraction method in this example. The splitting machine cuts the bamboo into strips that are still too sharp and rigid on the edges. Therefore after the initial splitting, the bamboo strips will then be cut into even smaller sized, smoother strips; see Figure 12. [30]

Figure 12: Initial bamboo gathering and slicing [30]

Next the strips are placed into a boiling water bath to remove any sugars, proteins, or living organisms such as insects. This is the step at which sometimes stronger chemicals are added to the bath to guarantee removal. After, the strips are dried to decrease all the moisture absorbed during the bath. There is an intermediate step here that is completely dependent on the customer (step 5). Sometimes bamboo is taken to a carbonizing tank that heats up the bamboo to produce a darker color for purely cosmetics. This type of bamboo is called ‘carbonized bamboo’. It exhibits the same structural properties as the non-carbonized bamboo. Refer to Figure 13. [30]

Figure 13: Chemical baths and carbonization [30]

After drying the bamboo strips, the strips are taken to a large slicing machine. They are cut again into specific sizes for processing purposes. The strips are then sorted by color and size. Once the strips are sorted, they are taken to a heated press. The press uses extremely high pressure and heat to promote exothermic, surface adhesion from strip to strip. The bamboo forms into a block after the press. See Figure 14. [30]

Figure 14: Sorting and pressing [30]

The bamboo block is too thick and hard at this step to be cut into sheets. Therefore the manufacturer will put the blocks in a water bath for a day to relax the fibers and prepare for slicing. Right after the blocks are soaked for a day, they are sliced into a

veneer sheet while wet. A heated environment is then used to dry the sheets off while simultaneously flattening the out the sheet; see Figure 15. [30]

Figure 15: Thinly slicing and heating processes [30]

Lastly the dried veneer sheets are checked for quality, cut into size for distribution, and then packaged for shipping; as can be seen in Figure 16. [30]

Figure 16: Final packaging and preparation [30]

1.7.5 Concerns Harvesting Bamboo

Environmentalists tend to get concerned with all the attention that bamboo is now receiving. The bamboo industry has seen a large boom for demand in the United States. A major export from China has environmentalists concerned about the effects of mass harvesting on the native ecosystems. In particular, environmentalists have shown

great concern for one of the most lovable of species: the giant panda. The impact on the endangerment of the giant panda is second hand. China has put forth many strict laws to allow the species to live in harmony. Nevertheless, with the explosion of bamboo demands in the U.S., many Chinese farmers are clearing their lands to make way for growing bamboo [31]. Some of these farmers live deep in bamboo forests which are a natural habitat for the panda. But these bamboo forests are seemingly massive, so it is not the deforestation that concerns environmentalist; after all bamboo can be regrown quicker than any other plant. People are more worried about the use of fertilizers and chemicals to help grow and harvest bamboo quickly that might lead to poisoning the environments of pandas. Pandas consume 20 to 40 pounds of bamboo daily [32]. That is a lot of bamboo that can be potentially tainted. But aside from a slight encroachment on panda habitats, China has built a network of 67 panda reserves, which seems almost an excessive amount [33]. Some sources state that pandas are at a very small risk, if any, in terms of industrial bamboo production harvesting [34].

1.7.6 Bamboo Veneer and Carbon Fiber Cost Analysis

Bamboo veneer, while a costly material imported from China, is still significantly cheaper than carbon fiber. The 4-harness satin carbon fiber weave fabric used in this experiment is \$6.66 per square foot [14]. Bamboo veneer is currently \$1.86 per square foot [35]. That's roughly a 3.5 times difference in price between the two materials. This cost advantage in relation to the potential material properties will be explained later.

1.8 Research Objectives

In this research, the sustainability of bamboo veneer material, when used as a core composite, will be analyzed. According to the dictionary, the word ‘sustainability’ has two definitions. It’s defined as, “the ability to be sustained, supported, upheld, or confirmed.” And also, “[Environmental Science] The quality of not being harmful to the environment or depleting natural resources, and thereby supporting long-term ecological balance.” [36] This is very important because these definitions get used interchangeably. The first definition is one of the main objectives of this thesis; because ultimately, bamboo veneer is being evaluated for its ability to ‘support’ or ‘uphold’ the composite structure. But the “quality of not being harmful to the environment” is also a secondary objective that bamboo happens to exert. The bamboo veneer will be treated as a composite material, like carbon fiber fabric; but will also perform as a ‘core material’ since it will be embedded between the carbon fiber plies. Meanwhile, compression-structures are always an area of personal interest because their applications are endless; especially in regards to new structural materials, such as bamboo composites. As listed above, everything from commercial buildings to airplane flooring are subject to compressive loads. Therefore the proposed composite structure with a biocomposite material will be introduced to compression testing.

While there are plenty of different types of compression testing standards, the setup described in this experiment mostly aligned with that of an edgewise compression test. This testing involves loading the edge of the structure in compression. Upon researching scientific publications regarding biocomposite/composite structures with a core, an ASTM (American Society for Testing and Materials) standard kept surfacing: “ASTM C0364 Standard Test Method for Edgewise Compressive Strength of Sandwich

Structures”. ‘Sandwich structures’, which usually refer to honeycomb core structures, can also be used to describe any structure with a ‘core’. Since the proposed test samples will contain a lightweight, filler ‘bamboo core’, as well being as loaded uniaxially, this ASTM standard seemed applicable.

Related works involving biocomposites and compression testing include a thesis by Justin Tafoya: Effect of Sustainable and Composite Materials on the Mechanical Behavior of Sandwich Panels under Edgewise Compressive Loading [37]. In Justin’s thesis he uses the same ASTM standard to justify and normalize his experimental work. Justin was trying to avoid buckling and bending during his testing and manufactured smaller sized specimens to promote pure compression. But at the same time Justin’s thesis focuses on the sustainability aspects that his structure demonstrated. Another reason Justin’s thesis influenced this thesis is because of his biocomposite layup procedures. He used hemp cloth, and other materials, and infused it with epoxy to create laminate faceplates. Initially it was very eye opening to see that even natural fibers can behave exactly like conventional composite fibers. Therefore edgewise compression testing was further explored.

1.9 Scope of Thesis

The introduction of this report tries to convey the importance of natural materials for structures and the research goals. Moving along to chapter 2, a more definitive analysis of the materials used is discussed. The process to achieve material properties is detailed. This includes the manufacturing of the material testing samples, strain gage installation, and testing. After obtaining material property values, chapter 3 will discuss the entire manufacturing process from start to finish. Chapter 4 will explain the testing

set up as well as results from testing. In order to validate values from the testing, a quick theoretical analysis will be conducted in chapter 5. Following the theoretical analysis, the finite element analysis (FEA) results will be displayed in detail in chapter 6. After chapter 6, the report will come to a close. Chapter 7 will discuss the main results and future applications.

2 MATERIAL PROPERTY TESTING AND RESULTS

Before running any experimental, theoretical, or numerical tests, the materials used in this experiment needed to be examined and documented. In this chapter the behavior of the proposed materials will be calculated.

2.1 Bamboo Veneer Donations and Specifications

The material selection of this research stemmed from generous donations and readily available materials. With the focus of the research on exploring the capabilities of bamboo fiber composite as core material, the first objective was to seek out how to obtain bamboo fibers. More specifically, and upon initial research, bamboo veneer sheets were chosen as the ideal product. As explained previously, veneer sheets exhibit a constant thickness and uniformity that will equate to repeatable results. These characteristics make veneer an excellent candidate for material testing, where multiple specimens are manufactured and tested.

Therefore the next step was contacting manufacturers of bamboo veneer and exploring the possibilities in the industry. Thankfully there were a couple manufacturers that were in the United States, as many bamboo manufacturers exist in China or other parts of Asia. Initially, a company called PlyBoo was contacted about any potential donations of bamboo veneer to this research effort. PlyBoo, based out of San Francisco, California, generously sent 6 inch by 6 inch bamboo veneer samples. Their veneer could be ordered in two thicknesses: 2mm (~.08 inches) and .6mm (~.024 inches). The next company contacted was Higuera Hardwoods, stationed in Poulsbo, Washington, and had many of the same products that PlyBoo carries. A main difference is that Higuera

Hardwoods has a manufacturing plant in China, the location where most bamboo is grown. Higuera Hardwoods was also extremely kind by donating a roll of bamboo veneer to this effort. Their roll was about 30 inches wide by about 8 feet long. Generic bamboo veneer rolls looks similar to Figure 17 [30]. Their veneer also had a fleece backing bonded with a NAUF (No-Added Urea Formaldehyde) substance, making it more environmentally friendly and OSHA approved. But before committing to a single company to supply bamboo veneer sheets for this research, one last company was contacted: M Bohlke Veneer Corp. MB Veneer, headquartered in Fairfield, Ohio, was the most generous by far and gladly donated 5 sheets of 4 foot by 8 foot sheets of quality bamboo veneer (.025 inches thick). Additionally, this company had an extensive amount of bamboo veneer options with information on species type, various color choices, and manufacturing process descriptions. It was also impressive to see that the Forest Stewardship Council (FSC), which was discussed earlier, certified their bamboo; and the backing of the veneer was a fleece backing bond with a NAUF adhesive. Upon

Figure 17: A roll of bamboo veneer [30]

further communication with MB Veneer, I learned the fleece backing is essential to keeping the fibers together as they would fall apart without it. Meanwhile, in order to keep material properties consistent, the same type of bamboo veneer would need to be used across the entire experiment. Since MB Veneer donated a sufficient amount of material, this was the bamboo veneer chosen for the entire length of research. The

additional benefits listed about their bamboo veneer made the choice easy. Thanks to all of these companies, especially M Bohlke Veneer Corp., the lab in which the experiment was conducted was fully stocked with ample bamboo veneer.

2.2 Carbon Fiber Fabric Selection

Although bamboo veneer had been selected for this experiment, there still needed to be a decision on which carbon fiber to use. Since the bamboo veneer are dry fibers, it would require a wet layup technique (wetting fibers in resin by hand) to transform them into a composite material; Figure 18 shows dry carbon fibers as an example. This eliminated the option of using prepreg materials because they already contain an internal

Figure 18: Carbon Fiber 4HS Weave

epoxy system and do not need additional epoxy of a different chemistry. By introducing two different epoxy systems into one composite, the results may be very inconsistent because now the structure has a higher chance of interlaminar failure. One matrix might fail sooner than the other or there could be compatibility issues between the two chemically-reacting thermosetting polymers. If one epoxy system is used

throughout the composite, the structure is more reliable and orthotropic. Also, if prepreg material was laid on top of a wet layup, the results would probably produce warped laminates or bubbles in the finish. So with prepreg material not an option, dry carbon fibers would also be utilized. Thankfully the Cal Poly Aerospace Composite and Structures Lab carry a selection of different dry carbon fibers. The two most applicable carbon fiber weaves available are a 2x2 Twill weave (style 94140) from BFG Industry

[38]. The other weave option in question was a 4 Harness Satin weave (style 3K-70-CS)

[38]. The difference between the two can be seen in the Figure 19 and Figure 20 [39]. But the thicknesses of the two are basically identical: .01 inches thick.

Figure 20: 2x2 Twill Weave [39]

Figure 19: 4HS Weave [39]

Ultimately in order to decide on which weave type is the best, both fabrics were manufactured into ASTM D3039 specimens and tested in tension. The 4 Harness Satin Carbon Fiber weave was the superior fabric by failing at higher loads and therefore was selected for his experiment. Meanwhile, with the material selection more or less decided, the materials and instruments required to manufacture composites were introduced for familiarity.

2.3 Manufacturing Composite Laminates and Testing Specimen

In this section, the different materials required, equipment used, curing techniques, and final composite productions will be discussed.

2.3.1 Materials Required

First and foremost, depending on the type or geometry of the composite piece, a level surface must be found. Figure 21 shows a similar diagram of the required materials [40]. For laminate plates, a smooth, reflective, flat surface will give the most consistent and best surface on the final product. Therefore a large flat piece of aluminum was found

and set aside. In this layup, a large aluminum plate was accompanied by multiple, smaller stainless steel plates that will be discussed later. The next material required was a piece of non-porous, cotton, vacuum bag, and thin blue film all cut to the right specifications dependent on the size of the composite. The non-porous is laid down first to protect the aluminum surface against epoxy curing to its surface. The non-porous material is also non-stick so the next layer, the composite material, can release easily. An intermediary step before placing the composite down is to layout a closed curve of double sided gum tape. This acts as a barrier to keep the epoxy of the composite in a general area and to straighten the thin blue film. After this step, the composite material can be laid down on the non-porous and inside the gum tape curves. Once the composite has been laid down onto the non-porous material, a thin blue film, similar to vacuum bag, is tightly stretched across composite and forced onto the sticky gum tape. After, the smaller stainless steel plate(s) were placed on top of the thin blue film. Essentially the steel plates give a very evenly distribution of force on the composite, and the composite will clone the reflective, shiny finish from the blue film. Next, a piece of cotton fabric (fleece), also known as breather or bleeder in industry, is used to distribute the vacuum pressures across the entire composite and absorb any excess resin. The cotton is usually the last layer before the vacuum bag, so the bottoms of the vacuum ports are placed strategically on top of the

cotton layer. Next is the vacuum bag layer than covers the entire composite and usually more. The tops of the vacuum ports will get screwed into their respective bottom counterparts once the top vacuum bag layer has been sealed. Lastly the vacuum bag is stuck to an outer boundary of gum tape that is usually close to the edge of the large

Figure 21: Similar vacuum bagging schematic [40]

aluminum plate. Turn on the vacuum pump, and the part will be ready for the next phase.

2.3.2 Curing Equipment and Instron Machine

The next phase is curing the composite piece in a pressurized oven, also known as an autoclave. Figure 22, shows an alternative machine. The autoclave is just one of the many machines that can be used to cure composites, albeit the most common.

Figure 22: Heated table press

Another machine used often is a thermal table press.

Specifically the ‘MTP-8, 10 Versatile Bench Top-Precision Press’ is used in this experiment [41]. It’s really only applicable to laminates since it is a press.

Also, it has less pressurized strength capacity and lower maximum heat limits when compared to an autoclave. A picture of the autoclave is in Figure 23.

Meanwhile, the autoclave in the Cal Poly Aerospace Composite and Structures Lab is made by the American Autoclave Co. It can reach 70 psi and 275° Fahrenheit internally. The cure cycle of the epoxy system used will decide the pressure, temperature, and time settings of the composite part. This autoclave was used to cure the laminates of the material testing

Figure 24: Composite autoclave

specimens. Once the materials are fabricated, they will be tested on an Instron machine. Specifically the Instron model 8801 can apply loads of up to 22,000 pounds. Its grip pressure is also modifiable up to 200 psi. The Instron can be set up for tensile, compression, and bending tests. See Figure 24.

Figure 23: Instron machine (left); Blue Hill 2 software (middle); Instron controller (right)

2.3.3 Wet Layup Procedure

Before the composite gets cured or even vacuumed, the fibers in this research undergo a wet layup procedure. The wet layup requires supplies and time to

perfect. It is a technique that gets better with practice and requires attention to detail. The detail starts at the measuring of the dry fibers. The bamboo veneer is quite easy to cut because the fibers remain together due to the fleece backing. Meanwhile the carbon fiber weave, which has no backing, will fall apart if no constraining force is keeping the fibers together. That's why blue painters tape is used to outline all carbon fiber weave cuts. It is only really needed on one side of the weave, but can be applied to both sides for more stability and fiber constraint. Once all the fibers are cut and set aside, a trash-bagged work area is required. The trash bag will protect any surface from epoxy and can be simply thrown away after.

2.3.3.1 Epoxy Selection

Next, plastic cups, a scale, and epoxy resin are required. The correct amount of epoxy must be poured into the plastic cups and measured on the scale. Initially, an organic, plant derived epoxy was considered for the manufacturing process. A company named EcoPoxy creates natural based epoxies that are competitive to synthetic epoxies [42]; see Figure 25. Their products were initially identified for their environmentally friendly properties. And, upon contacting them, they generously sent a small donation of

Figure 25: EcoPoxy natural epoxy

their epoxy, synthesized from soybean proteins, to the Cal Poly Aerospace Composites and Structures Lab. Unfortunately, after laying up a couple laminates with this epoxy, the finished product was not nearly as stiff as most laminates, and the excess cured epoxy was extremely gummy. This will be discussed later in detail. However, this eliminated EcoPoxy as a potential epoxy and discouraged the push for a green epoxy. Therefore a more reliable, synthetic epoxy was explored for this experiment.

After researching reliable synthetic epoxies for composites, the epoxy used in this study was a locally stocked epoxy system produced by West Systems [43]; see Figure 26. This epoxy uses 5 parts resin to 1 part fast hardener by weight. The cure time is dictated by the hardener, which is roughly 5-6 hours with the fast hardener. While this specific epoxy is not a produced from natural materials, it emits a very small amount of volatile organic compounds (VOC) and is extremely dependable and will allow for repeatability [43].

Figure 26: West System synthetic epoxy [43]

Once the epoxy is poured and measured into its respective ratios, both parts must be mixed until a homogeneous solution is formed. The pot time of the West Systems

epoxy is roughly 9 to 12 minutes, so the mixed solution must be spread out and applied to composite fibers in that time. The fibers are massaged with epoxy until both sides are saturated using a plastic spreader and quarter size or more of epoxy. The actual applied amount of epoxy per ply is not measured since goal is to saturate each ply with epoxy and it can vary. Consequently, any excess or unnecessary epoxy will eventually bleed out when the composite part is put under pressure during the curing process. Next, using a steady hand, the saturated-fiber plies are transferred to the specified non-porous area one ply at a time. While the plies are being transferred, the saturated fibers are simultaneously examined for bubbles, foreign objects, and uniformity throughout the laminate. An attention to detail is extremely important at this step because it can ultimately decide the grade of finish on the cured part. Following the hand layup, the orders in which the next layers are applied are detailed previously in the ‘required materials’ section. Once the composite has been sealed and vacuumed, it can be placed into the autoclave to be fully cured.

Now that a good understanding of the layup technique, lab layout, and equipment required has been established, the multiple layups can be detailed with their results. Also, from this point forward, anytime a layup procedure is mentioned, please refer to the previous paragraphs that detail the layup technique for any clarification. The layup procedure is exactly the same each time.

2.3.4 Cured Composite Laminates and Testing Preparation

Achieving a perfect composite laminate with a uniform surface can take quite a bit of practice. In this experiment, it took six different layups total before quality laminate plates were produced. Each time there was a small issue the process that resulted in a

Figure 27: Defective laminates made with EcoPoxy

failed part. But eventually with practice, the laminate plates became more uniform with fewer defects; see Figure 27. In order to run the ASTM tests, enough composite material was needed. Five smaller laminates plates were manufactured to be able to run all the tests: 0, 90, 45 degree bamboo laminates, and 1 large carbon fiber laminate. Once the respective materials were all cut and epoxy-infused, they were delivered to the autoclave for a cycle of 275 degrees Fahrenheit for 90 minutes at 70 psi. During the first composite laminate layup process, the previously discussed ‘EcoPoxy’ was used. See Figure 28 reference the layup processes.

Unfortunately once the cycle was complete, it was apparent the EcoPoxy just was not stiff enough to be considered; the laminates were all flexible and gummy. Therefore the next layup was a repeat of the same process using a more conventional epoxy: West Systems Epoxy. Unfortunately, the 45 degree laminate was warped due to a

Figure 28: Material testing specimen layup and bagging

nonsymmetrical layup; this led to repeating the layup process again and testing the flawed pieces on the Instron for practice. After testing the practice samples in the Instron, the same layup process had to be carried out for the third time and fourth time, until finally the bamboo laminates and carbon fiber laminates came out perfect. Following the approval of the laminates, the respective ASTM standards were read so the laminates could be marked accordingly. After being marked, they were taken to the wet tile saw machine, cut, sanded down for uniformity, measured, and lastly recorded on a spreadsheet for testing; see Figure 29. During testing, emery cloth tabs were used because the grip pressure on the Instron was up so high that aluminum tabs were not necessary. The testing of the tabs are as follows in the following ASTM sections below. ASTM's are mostly used for material property testing. And since all the material used in this experiment is wet lay technique, there are no data sheets that can be referred to for material properties. Therefore the material properties must be explored all on their own.

Figure 29: Cured composite plates and specimen cut to size

2.4 Material Property Procedures and Results

This section discusses the different testing standards used to generate the material properties of the composite and biocomposites used in this experiment.

2.4.1 Tensile Testing Procedure and Results (ASTM D3039)

One of the first tests run in order to get material data was the ASTM D3039 (*Standard Test Method for Tensile Properties of Polymer Matrix Composite Material*). This test uses the previously mentioned Instron machine to pull on specimens in tension. When the specimens get clamped in the Instron, tensile force is applied by lowering the bottom head; or conversely raising the head for compression. The Instron is connected to a data collecting program called Bluehill 2. The software will output several very important constants such as Young's Modulus (E), also known as the elastic modulus,

Table 2: ASTM D3039 Recommended Sizes [44]

D 3039/D 3039M – 08						
TABLE 2 Tensile Specimen Geometry Recommendations ^a						
Fiber Orientation	Width, mm [in.]	Overall Length, mm [in.]	Thickness, mm [in.]	Tab Length, mm [in.]	Tab Thickness, mm [in.]	Tab Bevel Angle, °
0° unidirectional	15 [0.5]	250 [10.0]	1.0 [0.040]	56 [2.25]	1.5 [0.062]	7 or 90
90° unidirectional	25 [1.0]	175 [7.0]	2.0 [0.080]	25 [1.0]	1.5 [0.062]	90
balanced and symmetric	25 [1.0]	250 [10.0]	2.5 [0.100]	emery cloth	—	—
random-discontinuous	25 [1.0]	250 [10.0]	2.5 [0.100]	emery cloth	—	—

^a Dimensions in this table and the tolerances of Fig. 2 or Fig. 3 are recommendations only and may be varied so long as the requirements of Table 1 are met.

tensile strength, and even Poisson's ratio. Specifically this test will help find the Young's Modulus values for the material which will be required during the finite element analysis phase. For this test, the ASTM recommended that the size of specimen be dictated by the fiber orientation, as can be seen in their geometry recommendations chart [44], Table 2.

Another important factor is whether the composite materials are unidirectional or weave fabric. For unidirectional fibers, like the bamboo veneer, the test will need to be conducted twice; once for 0 degree specimens and another for 90 degree specimens. This is because unidirectional composites are considered transversely orthotropic, so Young's Modulus in the fiber direction (E11), will not be the same when compared to fibers in the perpendicular direction (E22). Meanwhile, the carbon fiber weave will only need to be

tested once in tension because the fibers running in the longitudinal and transverse directions are assumed to be identical. Therefore the Young's Modulus in the direction of the load (E11) and perpendicular to the load (E22) will actually be equal to each other; but only for woven fabrics. Any out of plane values like E33 are not necessary since the FEA model is using shell elements and the compression tests are assumed to be completely in-plane. Equation 1 shows how to calculate Young's modulus, ' E '. ' P ' represents the force applied, ' A ' is the area (cross-sectional) of the specimen, ' ΔL ' is the change in length, and ' L_o ' is the original length.

$$E = \frac{\text{stress}}{\text{strain}} = \frac{P/A}{\Delta L/L_o} \quad (1)$$

Therefore the bamboo veneer needed to abide by the recommendations for 0 degrees and 90 degrees. For the 0 degree case, the recommended specimen size was 0.5 inches wide, 10 inches long, and 0.04 inches thick [44]. The thickness is directly related to the number of plies used. For the 90 degree case the specimens are recommended to be 1 inch wide, 7 inches long, and 0.08 inches thick [44]. Tabs are also recommended for this test so emery cloth tabs were taped to the ends of the specimens. If the specimens had been thicker, an aluminum tab would have been used. Figure 30 shows specimen ready to be tested. As specified in the ASTM the tensile tests were run at 0.05 inches per minute. And the test was stopped after 40% of the maximum loading had dropped; signifying to the machine that the specimen is failed and discontinuous. After the specimens had been prepped and ready for testing, they were placed into the grips of the Instron. At this point an extensometer was rubber banded to the specimen; which will be described in more detail in the Poisson's testing section. Once the test begins running, it

is paused to take off the extensometer, and then resumed. Once the test is complete, whether or not the specimen has broken, data is sent to the Bluehill 2 software. It is then transferred into an excel spreadsheet for further analysis of the elastic constants. Figure 31 shows specimen being tested.

Figure 30: Bamboo and carbon fiber specimens ready for testing

Starting with the 0 degree bamboo tensile test, Figure 32 can be seen having a sharp cut downwards towards the right. This is when the test stopped automatically after failing. During testing, an extensometer was attached to the specimen with rubber bands, but taken off around roughly 5% of the total maximum load. If the extensometer was left on during failure, it would likely break. During testing, sometimes samples do not produce good results, and therefore are tossed out from the data set. This is true and explains why the number of test specimens varies from material to material.

Figure 31: Tensile testing composite materials

As expected the graphs show the 0 degree specimens handled higher loads and stress than the 90 degree bamboo specimens (see Figure 33) because the 0 degree fibers were in the direction of the load. The Young's Modulus and tensile strength was calculated for both cases below. The Young's Modulus, or elastic modulus, of the 0 degree bamboo can be considered E_{11} , while the 90 degree bamboo's modulus is considered E_{22} . Meanwhile, Figure 34 shows the carbon fiber samples results.

Figure 32: Tensile Stress versus Tensile Strain (0 Degree Bamboo)

Figure 33: Tensile Stress versus Tensile Strain (Carbon Fiber Weave)

Figure 34: Tensile Stress versus Tensile Strain (90 Degree Bamboo)

After testing the bamboo, the carbon fiber was tested for its elastic properties as well. The carbon fiber samples failed at a much higher ultimate load when compared to the other bamboo tensile test specimens; but this was expected. Below are the elastic constants for all materials. As described above, the Young's Modulus of the carbon fiber is considered to be the same in the 0 and 90 degree directions. The values for the tensile strength and modulus are averaged values across each individual data set are in Table 3.

Table 3: Tensile Properties of Materials

	0 Degree Bamboo	90 Degree Bamboo	Carbon Fiber Weave
Young's Modulus [psi]	110000	243000	5170000
Tensile Strength [psi]	10900	1940	79200

2.4.2 Poisson's Ratio Testing Procedure and Results (ASTM E0132)

After testing specimens in tension, enough data was captured to be able to calculate the Poisson's ratio of the materials while using ASTM E0132 (*Standard Test Method for Poisson's Ratio at Room Temperature*) as a reference. Enough data was captured due to the fact that an extensometer and strain gauges were used throughout the tensile tests. Specifically, the extensometer was used on every sample, while a strain gauge was attached to the last two samples. By using two strain measuring devices, the strain can be read in multiple directions to help calculate Poisson's ratio.

But first this started with soldering of strain gauges to the composite specimens. While the extensometer reads strain in the longitudinal direction, the strain gauge can read strain in the transverse, or perpendicular, direction. Strain gauges are very sensitive and required specific steps and techniques to mount to a surface. Using the video that Vishay Precision Group has published online; soldering the gauges was much easier than

expected [45]. An in-depth look at this process can be found online as it is a lengthy process to explain. But very quickly, the strain gauges are mounted onto the samples

Figure 35: Soldering and strain gauge installation equipment (left); strain gauges (left middle); soldering gun (right middle); soldered strain gauge on specimen (right)

using a special adhesive. Next, using a soldering gun and soldering wire, copper wires are attached to the strain gauge so that it may be plugged into the data acquisition box during Instron testing. Once the gauges were attached, a voltmeter was used to check for functionality. If the voltmeter returns the correct resistance of the strain gauge, then it is verified as working. Figure 35 shows most of these materials.

Poisson's ratio is a ratio of the slopes of the average transverse strain over the longitudinal strain with respect to the applied load, as seen in equation 2 [46]. Figure 36 shows a specimen being tested with a strain gauge attached. It should be noted that the slopes are the average slopes of the strains in the longitudinal and transverse direction from each data set. Poisson's ratio ' ν ' is equivalent to the change in transverse strain ' $\partial\epsilon_t$ ' over the change in applied load ' ∂P ', all divided by the change in longitudinal strain ' $\partial\epsilon_l$ ' over the change in applied load.

$$\nu = \frac{\partial\epsilon_t / \partial P}{\partial\epsilon_l / \partial P} \quad (2)$$

After plotting the two directional strains versus the applied loads, bamboo's Poisson's ratio was about 0.18. It is hard to validate this value because there is no data sheet to compare to; but fortunately there was a published paper that details the Poisson's ratio of laminated bamboo. The paper specifies that after testing, it found a Poisson's ratio for laminated bamboo to be in between 0.013 and 0.278; in which the Poisson's ratio found here falls between. See Figure 37 and Figure 38 for results. [47]

Figure 36: Average Tensile Strain versus Applied Load (Bamboo Poisson's Ratio)

The Poisson's ratio of the carbon fiber weave was about .068. And just like the bamboo, there is no material datasheet that validates this number. Fortunately, there is plenty of literature available that details the mechanical properties of composite materials; especially carbon fiber. One of the most relied upon sources for mechanical properties is the Composite Material Handbook Volume 2 that is used

Figure 37: Testing specimen with strain gauge

by the U.S. Government's Department of Defense. Nevertheless after looking the handbook for Poisson's ratio values of a similar carbon fiber weave style, an 8 harness satin weave's properties were found. With the same general thickness properties as the 4 harness satin weave used in this experiment, it appeared similar enough to compare values. The Composite Material Handbook showed that the Poisson's ratio of this carbon fiber was 0.059 [48]. The values were similar and therefore the Poisson's ratio found through experimentation was validated. Table 4 has the results compiled.

Figure 38: Average Tensile Strain versus Applied Load (Carbon Fiber Weave Poisson's Ratio)

Table 4: Poisson's Ratio Results

	Bamboo Veneer	Carbon Fiber Weave
Poisson's Ratio	0.18	0.069

2.4.3 Shear Testing Procedure and Results (ASTM D3518)

Another very important variable to establish when characterizing a material is the Modulus of Rigidity (G_{12}). The next test ran to get this data was ASTM D3518

(Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a 45 Degree Laminate). The plies of bamboo were laid up in a $[+45/-45]_{ns}$ fashion; where ‘n’ is the number of plies and ‘s’ is for symmetrical about the neutral axis [49]. The number of plies of bamboo was 8 and it followed the ASTM D3039’s recommended dimensions as a “Symmetric and Balanced” type of specimen [44]. Figure 39 shows tested specimen. Since the material is not isotropic, a different formula, derived from stress-strain relationships of plates, is required in order to solve for the shear modulus [50]; seen in below in equation 3. The Young’s modulus, ‘E’, respective to a certain direction and ‘ ν ’ is the Poisson’s ratio found earlier. While ‘ G_{12} ’ is the shear modulus or Modulus of Rigidity, ‘ E_{45} ’ is the elastic modulus in the 45 degree direction, ‘ E_{11} ’ is the elastic modulus in the 0 degree direction, ‘ E_{22} ’ is the elastic modulus in the 90 degree direction, and ‘ ν_{12} ’ is Poisson’s ratio found earlier.

$$G_{12} = \frac{1}{\frac{4}{E_{45}} - \frac{1}{E_{22}} - \frac{1}{E_{11}}(1 - 2\nu_{12})} \quad (3)$$

The shear modulus formula requires the modulus of elasticity of the composite when the fibers are at 45 degrees. It is important to take the modulus of elasticity in the elastic range of the graph; otherwise the calculation may be unreliable. This is why there

Figure 39: Tested 45 degree bamboo specimens

is a small black rise over run triangle in the shear modulus testing graph (Figure 40), because this is the region from which the elastic modulus was calculated. Then, while using the elastics from the previous tests, the modulus of rigidity, or shear modulus, was calculated to be 155754 psi.

Figure 40: Shear Stress versus Shear Strain (45 Degree Bamboo Shear Modulus)

Meanwhile, the shear modulus for the carbon fiber weave composite took a different path. Since the values found from experimentation were not outputting any comparable or realistic data, the set had to be scrapped. Fortunately, the Composite Material Handbook Volume 2 has a wide variety of carbon fiber composite properties. And upon further inspection, a comparable carbon fiber style, in terms of thickness, density, and elastic constants were found. Therefore this carbon fiber was going to be used to assume the modulus of rigidity at 634000 psi [48]. With further research into the modulus of rigidity constants amongst carbon fiber composites, there appeared to be an average of 0.7 Msi across most woven fabrics [48] [51]. This includes data from

HEXCEL one of the largest manufacturers of carbon fiber composites. This only validated the assumed constant further, as the assumed constant and average values were fairly similar in magnitude. Table 5 shows this data.

Table 5: Shear Modulus Results

	Bamboo Veneer	Carbon Fiber Weave
Shear Modulus [psi]	156000	634000

2.4.4 Fiber Volume Fraction Procedure and Results (ASTM D2584)

Lastly the fiber volume fraction test is important to defining a material because it will help establish the density of the material. Following ASTM D2584 (*Standard Test Method for Ignition Loss of Cured Reinforced Resins*), the fiber volume fraction as well as the density was calculated. Figure 41 shows the oven used for this test. During this test the ASTM was used as a reference and not followed as rigorously as some of the other tests. For example, the ASTM suggest 1 inch by 1 inch sized specimens for this test, but the scale in the composites lab is not very accurate and cannot read small weights [52]. Therefore a larger size, 3 inches by 1 inch, was used.

Another deviation from this test is the exclusion of the bamboo veneer. Bamboo fibers, like timber, when exposed to the right conditions will catch fire inside the oven chamber. They are not as chemically enhanced as synthetic composite fibers like carbon fiber. Therefore in order to avoid a fire in the lab, the bamboo veneer samples were not

Figure 41: Epoxy burn oven

used in this test. Table 6 shows the results from testing. Once again since there are no

data sheets from the manufacturer of fibers in a composite there are no other values available for comparison. But the fiber volume percentage is a good guess as to the accuracy since composites are usually 60% fiber and 40% resin [53]; and calculated using equation 4. And this experiment shows a slightly lower 55% fibers and 45% resin. The values can be seen in Table 6 below. ‘ V_f ’ represents the volume fiber fraction, ‘ W_f ’ is the weight of the fibers, ‘ ρ_f ’ is the density of the fibers, and ‘ ρ_m ’ is the density of the matrix.

$$V_f = \frac{\frac{W_f}{\rho_f}}{\frac{W_f}{\rho_f} + \frac{1 - W_f}{\rho_m}} \quad (4)$$

Table 6: Volume Fiber Fraction Results

	Bamboo Veneer	Carbon Fiber Weave
Coupon Thickness [in]	N/A (BAMBOO FIBERS CATCH FIRE)	0.09
Coupon Length [in]		3
Coupon Width [in]		1
Weight Before Burn [lbs]		0.01279
Weight After Burn [lbs]		0.00573
Matrix Weight (Difference) [lbs]		0.00705
Fiber Density [lbs/in ³]		0.02123
Matrix % By Weight		44.83%
Fiber % By Weight, V_f		55.17%

3 MOLD AND SPECIMEN RESEARCH, DESIGN, & MANUFACTURE

In this section the overall research, design, and manufacturing of the mold and trapezoidal specimen is discussed. This includes everything from 3D models of the original design all the way to the final manufactured product.

3.1 Test Specimen Research and Design

This section will give a detailed overview of the background research, selection, and optimization of the test specimens in this experiment.

3.1.1 Corrugated Structures Introduction

After the appropriate measures were taken to determine the material properties, the next step was to research, design, and manufacture how to utilize these materials. The main scope of this effort includes testing bamboo and carbon fiber composite structures in compression loading. Therefore, with manufacturing any composite structure, an optimized geometrical shape needed to be researched and selected. The geometrical shape chosen will exist as a template in which the composite structures will be modeled.

Since the testing mode is in compression, failure modes such as bending, buckling, and bearing are all possible. But since this research is focused on pure compression failure, bearing failure is the only acceptable mode. Therefore a flat plate or specimen is not very ideal because it will almost guarantee bending or buckling failures and be quite unstable. This meant that a cross-sectional area other than a flat line (plate laminate) would be necessary.

Corrugated structures were initially considered for their various cross sectional designs and frequent use in structural applications. Most commonly seen as stiffeners,

corrugated structures exist in cross sectional designs like square, triangular, sinusoidal, and trapezoidal. They are extremely common in shipping container design, bridge infrastructure, and even impoverished housing; these examples can be seen in Figure 42 [54] [55] [56].

Figure 42: Corrugated structures in various applications [54][55][56]

3.1.2 Geometry Selection and Shape Optimization

The most optimized cross sectional area of corrugated structures is very dependent on the application. Nevertheless, square, triangular, sinusoidal, and trapezoidal were all examined thoroughly; see Figure 43. The first two cross sectional designs that were ultimately phased out included the square and triangular shapes. The square cross section has a good area and stability associated with its design. But the sharp corners of the square would be an area of concern, because under compressive loads stress concentrations would form along those edges and corners instead of equally distributing the load. The same can be said for the triangular shape's sharp corners that would give way to destructive stress concentrations. Also it does not have very cooperative surfaces for bonding. Therefore both of these shapes were ultimately dismissed as possible designs.

Figure 43: Cross sectional shape selections

The next two shapes in consideration were the sinusoidal (semicircular) and trapezoidal cross sectional designs. Both designs are very applicable in terms of their geometrical characteristics that it was not very easy to select one over the other. They were so closely matched in fact that the first two molds in this project consisted of a sinusoidal shape while the third and final mold was trapezoidal shaped. Nevertheless, the final selection between the sinusoidal and trapezoidal cross section was initially decided by using the bending stress equation:

$$\sigma_{bending} = \frac{My}{I} \quad (5)$$

The bending stress equation relies on the inertia term, 'I', which defines a structural member's geometrical characteristics. It also relies on the moment term, 'M', and the perpendicular distance from the neutral axis, 'y'. It should be noted that the bending stress equation was initially used because although bending is not typically desired in this scenario under compression loading, it is fairly realistic. Unfortunately this formula does not entirely and realistically represent the compression system. But it helps

as a reminder that a higher moment of inertia term ‘I’ is desirable to minimize the stresses caused from bending and will increase the buckling resistance.

The inertia of both cross sections was calculated with the assumption that they both have the same area. It was important to not only keep the cross sectional area values constant when calculating ‘I’ between the two shapes, but also to take the Area Moment of Inertia with respect to the same axis on both shapes for uniformity. This was done by using the Parallel Axis Theorem to shift the Area Moment of Inertia from the centroidal axis of each shape to the x-axis.

$$I_{Parallel\ Axis} = I_{Centroidal\ Axis} + Ad^2 \quad (6)$$

These calculations were performed on a 3D modeling software called Unigraphics NX. Each cross sectional shape was modeled in the software initially. After, the software calculated the Area Moment of Inertia about each shape’s centroidal axis. The centroidal axes were not the same distance from the x-axis, so therefore the Parallel axis theorem was used here to get both Area Moment of Inertia calculations in sync.

After calculating the Area Moment of Inertias about the x-axis for both shapes, the trapezoidal cross sectional design had a slightly higher value. Therefore it would ideally accept more stress and thus was chosen over the sinusoidal shape; see Figure 44.

Figure 44: Second Moment of Inertia calculations

3.1.3 External Design Influences

The Area Moment of Inertia was not the only reason the trapezoidal shape was chosen, though. The sinusoidal shape is seen in many applications such as roofing and exterior surface finishing on buildings. In this specific scenario, the sinusoidal shape was considered because of its resemblance to bamboo stalk. Bamboo stalk is in itself cylindrical, and when cut in half, longitudinally, you get a semicircular shape; which is not exactly the same as a sinusoidal wave, but it is realistically the closest comparison. Meanwhile this idea of replicating a bamboo stalk's semicircular shape in composites stemmed from another project performed in the California Polytechnic State University's Aerospace Engineering Composite/Structures Laboratory; see Figure 45.

Figure 45: Carbon fiber and raw bamboo stalk box project

A box, roughly 20" by 14" by 12", was built using carbon fiber composite as the skin, and longitudinally halved bamboo stalk as the 'core' or internal structure. See Figure 45. But although replicating a semicircular, or sinusoidal, shape based off of nature's original design would sound promising in theory, it was not backed up by the mathematical analysis. It had a lower Area Moment of Inertia and a complex bonding surfaces. It would make a lot more sense to bond to a flat plate to a flat surface; instead of a flat plate to a rounded surface, where there is minimal contact. Also in the case of the

box, bamboo veneer had not been discovered, which meant the team had to rely on raw bamboo stalk. Meanwhile, this project allows for the bamboo veneer sheets to mold to almost any shape. Nevertheless, the trapezoidal cross sectional area shape was chosen. Now that the shape of the composite coupons, also known as ‘specimens’, had been decided, the next step was to specify the dimensions of the product.

3.1.4 Size Recommendations, Optimization, and Assignment

Many compression tests involving composite structures usually consist of sandwich composite structures. A sandwich composite structure usually consists of two thin, stiff composite laminate skins and a “lightweight but thick core” [57]. In this specific scenario, the bamboo veneer used acts as the ‘core’ material. Therefore the final composite structure product can theoretically be labeled as a ‘sandwich composite structure’. Fortunately this gives room to an ASTM that governs compression testing of sandwich structures. That ASTM is C0364, “Standard Test Method for Edgewise Compressive Strength of Sandwich Constructions”. It’s similar to killing two birds with one stone because it also explicitly describes the type of compression testing conducted: edgewise. Edgewise is important because it describes how the composite coupons are tested; because there is surprisingly a wide array of standard testing options for compression testing. Nevertheless, since ASTM C0364 was selected it gives way to specific dimensions that are used when designing the composite models. For example, it gives a recommendation for the length, width, and thickness of the specimen; see table 7 [58].

Table 7: ASTM C0364 size recommendations [58]

Dimension	Recommended Range
Length, L (in.)	$L \leq 8 \times t$
Width, W (in.)	$2.00 \leq W \leq L$; $W \geq 2 \times t$; $W \geq 4 \times$ cell widths (honeycomb only)
t , total panel thickness (in.)	As required, in order to be representative of intended use
Facesheet thickness, t_f (in.)	As required, in order to be representative of intended use
Core thickness, t_c (in.)	As required, in order to be representative of intended use

3.1.4.1 Specimen Thickness

ASTM C0364 gives dimension recommendations for the coupon specimen sizes. The recommendation given by C0364 specifies that the thickness should be “As required, in order to be representative of intended use”. This essentially means that the thickness parameter is more flexible than the other two, length and width. Also, it should be clearly noted here that the ‘thickness’ dimension in C0364 is referring to the distance from the top to bottom face of the composite coupon, and not the thickness of the composite plies themselves. The reason it is defining the overall distance from the top face to the bottom face is because ASTM C0364 is mainly used for sandwich structures. Sandwich structures usually consist of honeycomb core. Honeycomb core is a thick material, when compared to a thin composite ply. But in this project the ‘core’ material is considered to be the bamboo veneer sheet. The bamboo veneer is just slightly thicker than the carbon fiber plies, which means that is fairly thin; especially when compared to honeycomb core. Therefore the ‘thickness’ parameter here, which normally defines the thickness of the entire material structure, is replaced by measuring the thickness of the cross sectional area from top to bottom. This is why the word ‘depth’ may be used to describe the thickness as well. Figure 46 has a graphic of this explanation.

Figure 46: Thickness, or depth, of the structure (left); material thickness (right)

While the selections of the coupon dimensions were nearly simultaneous, ‘thickness’ was chosen as the first dimension to establish before moving forward. Fortunately this task was quite easy as there was a physical limitation on the thickness, or depth, that the coupons could be. Since the final aluminum molds were only 1 inch in thickness, the coupons had to take this into account. Therefore the composite coupons needed to be less than 1 inch thick but also deep enough for ease of manufacturability. If the depths were too small, it would be hard to get the composite material to stay in small grooves; versus the ease of laying into deep valleys. Based off of personal experience with composite layups an initial depth of 0.5 inches was selected. It was a nice round number and half the thickness of the aluminum block that it would eventually be machined. Upon further analysis and revision with Dr. Elghandour, this value was changed to 0.6 inches to allow for more stability and realistic dimensions for the top flanges and base.

3.1.4.2 Specimen Length

The next dimension selected was the length of the coupons. ASTM C0364 recommends that the specimen length is less than or equal to 8 times the thickness of the coupon. The thickness multiplied by 8, results in a value of 4.8 inches. Subsequently, the coupon lengths needed to be less than 4.8 inches. But the ASTM does not specify how

small the length of the specimen can be. After critically thinking, there appeared to be a sweet spot that existed in between upper and lower limits of the length parameter. Figure 47 displays this relationship, but it should be explicitly noted that the bell curve shape of the graph is not calculated; rather it is just for the aesthetics of representing a ‘sweet spot’. Essentially, if the specimens are manufactured too long, they will likely result in buckling and bending failures which are not desired. Oppositely, if the specimens are too small, the data will not be very helpful because ASTM C0364 is for ‘sandwich’ core structures. They need to be long enough to represent the material and not the boundary effects. And these specific coupons do not have a thick core filling the cross sectional void. Meanwhile, if manufacturability is factored in, the goal is to yield the most qualified specimens per cure. Therefore a length of roughly 2.25” was selected; and would yield 2 coupons per trapezoidal valley since the maximum length of the stock aluminum is roughly 5.6”. Refer to Figure 47.

Figure 47: Specimen Length Evaluation

3.1.4.3 Specimen Width

Lastly, with the thickness and length determined, the width of the specimen was needed. ASTM C0364 says that the width of the specimen needs to be larger than 2" and smaller than the length (4.8"). It will be discussed more in detail later, but the aluminum mold stock dimensions before machining were roughly 12" wide by 5.6" long by 1" thick. Since the aluminum block was 12 inches wide and the goal is to yield the maximum about four coupons per cure, a width of 2" was selected. This was the smallest specimen width size recommended, but it would allow for good stability and 4 trapezoidal valleys. Figure 48 shows the dimensions discussed.

Figure 48: Cross sectional dimensions of test specimen geometry

3.1.4.4 Material and Ply Thickness

A dimension not be overlooked is the 'ply thickness'; see Figure 46. The ply thickness consists of two outer carbon fiber plies and one internal bamboo veneer ply; three plies total. While the thickness of the bamboo and carbon fiber are quite thin, their thicknesses add up quickly, which is a concern when using a wet lay of composite materials. Wet laying composite is a delicate process and does not allow for much

alteration once wet cloth is laid down. So when many multiple plies of composite are required being wet laid, the manufacturing time increases exponentially, as well as the required technical skill. Unfortunately, as described in a previous chapter, while carbon fiber does come in a prepreg material, bamboo veneer does not. And to keep the epoxy resins uniform throughout the experiment, the wet lay technique must be used. It should also be noted that this project is only capable with the generous donations of bamboo veneer to this effort. Once the supply of bamboo is out, it will be hard to get ahold of any more. Therefore knowing these key design parameters, a minimal amount of composite material is the most optimized arrangement for this experiment in terms of manufacturability. If the number of plies was increased to four, five, or more, there would be a blatantly-obvious insufficient supply, an enormous time imbalance, and the aluminum mold would need to be altered to allow for a new ply thickness offset. Accordingly, two carbon fiber plies surrounding the one bamboo ply would result in three plies for this experiment. Table 8 shows the thickness data.

Table 8: Material Thicknesses

	Material Thickness [in]
Bamboo	0.025
Carbon Fiber Weave	0.01

3.1.5 Test Specimen Geometrical Variations and Cases

Once the dimensions of the final product had been selected and optimized, the application, or ‘cases’, needed to be described in detail. More specifically, the geometrical application of the way the coupons would interact with the loads needed more work. In light of trying to capture the most credible and usable data for this

experiment, four geometrically different cases were chosen. While it would be interesting to see how the coupons would respond to compressive loads with the originally designed case described above, an increased educational opportunity would arise by varying the shapes of the cross section for an optimized design. Questions such as, “What would happen if a flat plate is bonded to the front face of the specimen?” were part of the reason for exploring multiple geometric cases. The four cases, which can be see below in Figure 49, are variations of the original case and bonded face sheets. Specifically, the fourth case, which is also the largest, was investigated more thoroughly than the others. CASE 4 is the situation that was manufactured with the bamboo and carbon fiber combination, and a separate set from solely carbon fiber samples. With the blueprints for the final products completed, the mass manufacturing process began production.

Figure 49: Cross sectional shapes and 3D models of the four different test specimen cases

3.2 Mold Research, Design Iterations, and Manufacture

This section will detail the complex process of researching, designing, and manufacturing the test specimen’s mold.

3.2.1 Mold Introduction

Before any composite lay-up techniques could be utilized, a mold was required. Molds are very important when working with composites because they allow the composite to conform to its shape. Molds can be made from a variety of different materials including foam, medium density fiberboard (MDF), metals such as aluminum, and many other materials. The main characteristic of a good mold is ease of manufacturability and reusability. In terms of ease of manufacturability would refer to a mold that does not require excessive preparation before use. Some molds require primer coatings which take days to cure in between lay ups. Other molds make use of the smooth back-side on tape as a release surface. But tape can frequently shear off when releasing a cured composite part from a mold, as well as creating small indentations in the final product. Molds that require primers or tape prep include any porous material, such as foam or MDF. If there is no surface separating the epoxy from the porous mold, the resin will seep into the mold and cure; causing irreversible damage. Another factor to consider with mold materials is reusability. Some mold such as foam, or of the like, can be very flimsy and lead to breakage during lay-ups or release processes. This is why metal molds are known as the most trusted material to fabricate molds. Metal molds typically exhibit a different coefficient of thermal expansion (CTE) when compared to polymer reinforced composites, it is does not create a large enough impact on the scale of this experiment to make a notable difference. Meanwhile in industry, large-scale project molds are created from composite materials to match the CTE and avoid any variability in the final product.

3.2.2 First Mold

Nevertheless when it came time to officially design and fabricate the first mold for mass production, some steps were skipped which resulted in a lot of wasted time and a useless mold. More specifically, before an aluminum mold was ever created, the very first mold was machined out of medium density fiberboard (MDF). The first design was not useful, nor optimized. It was a rather hasty attempt before fully understanding ASTM standards or cross sectional area considerations.

3.2.2.1 First Mold Design

The first steps of machining the first mold started with obtaining stock material for the mold. While metal molds are the most recommended choice for molds, they are expensive. Meanwhile MDF and foam materials are considerably less expensive and therefore a first option. Fortunately the first design, while impromptu, was machined from the less-expensive MDF. The process started with an initial design on SolidWorks. Unfortunately the cross sectional design optimization and selection discussed earlier was not available at this point in the experiment. Therefore by trying to force progress without sufficient research, the first mold was based off a semicircular cross section; which would be similar to a halved bamboo stalk. Figure 50 shows a model of this design. In order to get a clean surface finish on the composite part, a two-piece, male-female mold technique was utilized. This technique uses two molds that are essentially geometrically inverse parts of each other so that they fit inside one another. Fitting the two molds together, with the composite material inside, allows for surface contact across all sides of the composite part. A thorough surface contact between the composite material and mold forces the epoxy to take the shape of the mold and form into a homogeneous, uniform surface.

Uniform surfaces with composites are important because it means any random surface discontinuities are eliminated. Random surface discontinuities, while quite common in composite manufacturing, lead to stress concentrations and areas of likely failure. It should be noted that uniform surfaces are also aesthetically pleasing to the eye.

Figure 50: 3D SolidWorks Model of the first mold attempt

3.2.2.2 First Mold Machining Process

A meeting or revision with Dr. Elghandour would have been quite helpful at this point and saved a lot of time. Nevertheless, once models of each mold were complete, they were taken to California Polytechnic State University's d[Fab] Laboratory (Digital Fabrication Lab); see Figure 51. The d[Fab] lab has the capabilities to using a CNC router to machine out the shape designed on SolidWorks. The first step is to convert the SolidWorks files into RhinoCAM (a Computer Aided Manufacturing software) files. After the files were approved for machining, the stock MDF material was gathered and prepared.

Figure 51: d[Fab] lab's publically available computers with CAM software

Once the machining was complete, the impromptu molds were analyzed and immediately shelved due to their poor design. Another mold was needed to be fabricated. Figure 52 shows machining of the mold.

Figure 52: MDF stock material (left); HAAS CNC router machine (middle); first machined mold (right)

3.2.3 Second Mold

This section will detail the background and execution of the second mold's manufacturing process.

3.2.3.1 Second Mold Design

The knowledge gained from the first mold allowed for a more updated and prepared second mold. The design of the second mold was slightly altered from the first. Still there was a lack of evidence or research to confidently choose one mold design over the other. But in attempts to force and time efficiency, the general cross sectional area remained a semicircular shape to mimic that of a halved bamboo stalk. But the number of valleys, or semicircular corrugations, on the mold was increased in a new SolidWorks file. The increase in number of corrugations resulted in smaller diameters and distances

between each corrugation. With the design becoming more compact, the same technique was used from the first mold: male-female. A male-female mold would allow for higher surface contact in the compact semicircular sections of the new mold design. Refer to Figure 53.

Figure 53: 3D SolidWorks model of the second mold attempt

3.2.3.2 Second Mold Machining Process

Once the design had been completed and discussed with Dr. Elghandour, the fabrication of the molds began. The same stock material, medium density fiberboard was used due to its cheap and availability. All the steps from the first mold fabrication were repeated. The models were taken to the d[Fab] Laboratory and eventually machined on a HAAS CNC router machine; see Figure 54.

Figure 54: Stock MDF material machined on a HAAS NCN router machine (left; middle); finished mold (right)

3.2.3.3 Surface Finishing and Preparation

After the second mold was machined, it began to undergo surface preparation for its first layup. Instead of using layer of tape for surface preparation, a paint primer known as DURATEC Grey Surface Primer (Figure 55) was mixed and painted onto the mold.

The Grey Surface Primer is designed specifically for composite molds. They can hold up at high heats and sand down to a smooth and nonstick surface. It is best when applied using spray gun, but still applicable with paint brushes. The primer is catalyzed with MEKP (Methyl Ethyl Ketone Peroxide) and has a pot time of only about

Figure 55: Dura Tech Grey Surfacing Primer

15 minutes before it thickens and solidifies. Figure 56 shows this process. It takes about 12 to 24 hours before the primer is completely cured and ready for sanding.

Figure 56: Mixing and application via paintbrush of grey surfacing primer

Before coating the molds, 300 grams of primer was mixed with 6 grams of MEKP. This yielded about 3 coats of the primer to be applied to each mold, waiting about 5 minutes between each coat. The molds were then left out for 24 hours to be fully cured. After the cure time, the surface of each mold was rough and required a process of sanding to get the surface smooth. At this point only one mold was focused on because although there was not that much primer material on the molds, sanding is a labor and detail intensive process. Therefore the male mold was taken aside wet-sanded with 220 grit sandpaper. Once the 220 grit had served its purpose, a supply of 800 grit sandpaper was used to finish the job; refer to Figure 57.

Figure 57: Sanded primer surface (left); surface release chemicals (middle); prepped mold surface (right)

After hours of constant sanding, the final surface was surprisingly smooth to the touch. Instead of returning to the other mold and repeating the same sanding process, the newly sanded mold was decidedly selected for a layup. Now by using only one mold, it essentially defeats the purpose of making a male-female mold system. But with respect to time efficiency, it seemed that returning to the other mold for sanding would be an inefficient way to spend time. Therefore without much deliberation the newly surfaced mold was coated twice in a chemical sealer (ChemTrend Chemlease 15 Sealer EZ) and followed with three coats of a release agent (McLube MAC 1038). These chemicals are essential for the composite material to not stick to the surface of the mold.

3.2.3.4 First Layup on Second Mold

Once the mold was completely prepared, the first layup using a standard vacuum bagging process was initiated; refer to Figure 58. The mold was placed on a large metal sheet as a base for the vacuum bag to envelope the layup. Meanwhile, the respective sizes of carbon fiber cloth, bamboo veneer, cotton breather, vacuum bag, and non-porous materials were cut. The epoxy and hardener were mixed in a designated area. Almost all

wet layups are accompanied by a large, plastic trash bag underneath as a sacrifice surface that can be thrown away after use. Otherwise the epoxy would cure to any surface and

Figure 58: Layup process and vacuum bagging second mold

eventually destroy it. Once the trash bag is taped down to resist movement then the bamboo veneer and carbon fiber layers were infused with epoxy by hand. As soon as the cloth looks sufficiently saturated in epoxy is when it can be laid upon the mold. The wet composite plies were then laid in their respective orders directly onto the mold: carbon fiber, bamboo, carbon fiber. For this specific layup, a sheet of nonporous went directly on top of the composite material, followed by the cotton for uniform pressure distribution, and lastly the vacuum bag. At this time the sectioned off area was sealed with gum tape, vacuumed, and left to cure at room temperature for 24 hours. While vacuuming the part, small metal rods that fit in the canals of the mold were placed on top of the bag with a ten pound weight on top of those. This was to push the composite material down into all the crevices of the mold. Usually heat is applied to speed up the curing process, but since this was the first attempt using the new mold no heat was initiated to help the composite conform to the mold more efficiently. The autoclave process was also skipped this time as more of a trial and error method. The autoclave is a very costly, energy intensive, and time-consuming process so alternative avenues are seen as beneficial.

After 24 hours, the part was removed from the vacuum bag. Using a rubber mallet and screw driver, the cured part had to be pried away from the mold because it was inadvertently stuck. This is usually a result of not using enough release chemicals. And unfortunately when using tools to pry off composites from molds, irreversible damage is highly likely. For example, when prying off the cured composite part from the mold deep scratches removing the top primer coat were made. This makes it more likely for epoxy to bond into these scratches and potentially make it even harder to release the part from the mold. Nevertheless after about an hour the part was successfully removed from the mold. The top side of the composite was smooth and had a wavy, sinusoidal shape; which is not correct since the cross sectional design of the mold is semicircular with flat flanges in between each hump. Meanwhile, the bottom of the part was a complete disaster as seen in Figure 59. On the flat sections the epoxy had pooled up and solidified in a discontinuous and bubble filled mess. This almost always means that there was no surface contact between the part and the mold. Therefore it can be implied that not enough weight was used to push down on the composite.

Figure 59: Cured composite panel (left); underside of composite with unsatisfactory surface (middle); mold damages and excess epoxy remnants (right)

3.2.3.5 Second Layup on Second Mold

Since the first layup did not produce great results, another shot was given at laying up on the gray surface primed mold. Since there were quite a few noticeable scratches, dents, and epoxy residue from the previous cure, high grit sandpaper was used to resurface the top primer coat. After sanding the top layer again, the same sealer agent as before (ChemTrend Chemlease 15 Sealer EZ) was properly applied to the top layer; about 2 coats with 30 minute intervals to allow each layer to cure. Then instead of using the same McLube release agent as before, a new release agent (ChemTrend Chemlease 41-90 EZ Release) was applied 5 times within 30 minute intervals as well. The replacement of the release agent is because the ChemTrend brand products work better together and are a very reliable. The same steps from the first layup were then followed with the only difference between the two being that a different epoxy was used. The EcoPoxy, described earlier in previous sections, was substituted for the West Systems conventional epoxy system. This was done simultaneously during the material characteristic process so therefore the EcoPoxy itself had not yet been ruled out as an epoxy selection. Nevertheless the carbon fiber cloth and bamboo veneer were saturated with this EcoPoxy resin epoxy system and then laid onto the mold in the same order as before. As with the first layup, the bamboo veneer is slightly rigid and does not like to conform to the shape of the mold until vacuumed; this can attribute to any non-contact areas with the surface. The mold was then bagged, vacuumed, and then weighted with small metal rods and 100+ pounds of weight on top; as shown in Figure 60. The mold was left on a heat table at 275 degrees Fahrenheit for 12 hours, with the pumps running continuously.

Figure 60: Double bag technique (left; left middle); cured composite part (right middle; right)

After the cure time was completed, the weights and the bag were removed. Next the part surprisingly came off the mold with ease. This was met with excitement until there appeared to be something wrong with the composite part. It was soft and had a gummy feel to it. It was completely cured but barely stiff enough to be considered cured by most epoxy standards. After seeing this same problem with the laminates for the material properties, the problem was the EcoPoxxy epoxy. This was unfortunate because the part came out smooth on both sides, due to good surface contact, and took the shape of the mold fairly well. Unfortunately the mechanical properties of the newly cured part were not up to standard and therefore trash.

3.2.4 Third Mold

This section will detail the background and execution of the third, and final, mold's manufacturing process.

3.2.4.1 Third Mold Design

Fabricating molds and manufacturing composites requires a huge amount of time; so each failure is severely progress-halting. With multiple failed mold and layups attempts, the project needed some serious intervention. The first MDF mold was scrapped

due to an incorrect design, and the second MDF mold was deteriorating after each cure due to poor technique. A new mold machined from metal was now becoming the most obvious option; but the materials and machining capabilities were still not available. That's when Dr. Elghandour sought out the help from another professor named Trian Georgeou, an industrial manufacturing instructor. Trian donated a block of aluminum metal to this project and would go on to machine the blocks of aluminum into two male-female molds. He required that the donated block of metal be cut into two, and to prepare a SolidWorks model of the final product. Fortunately from the previous two failures, revising and creating a SolidWorks model was relatively easy; shown in Figure 61.

Figure 61: 3D SolidWorks model of the third and final mold attempt

With the last two molds ending in failure, there was no more room for error on the third attempt; especially when using metal for the mold material. Therefore the cross sectional design optimization trade study, discussed early, became the basis for the third mold design. The trapezoidal cross section was selected over all other designs due to a number of factors, specifically manufacturability. A new SolidWorks model was drafted

and analyzed alongside Dr. Elghandour before being approved for machining. The research earlier in this chapter discusses the rationale behind the dimensional choices.

3.2.4.2 Third Mold Machining Process

Therefore the first step was to get in touch with one of the Aerospace Engineering Department's lab technicians. With their help, the block of aluminum which was only about an inch thick, was cut using their band saw. It was cut into two blocks each 12 inches in length. After using the band saw, the lab technicians placed the block of metal into their HAAS CNC router machine to face the edges of the material. Facing the block helps flatten the sides or edges so that there are straight and ready for the next CNC machining process. This process can be seen in Figure 62.

Figure 62: Stock aluminum block (left); cutting block with band saw (left middle); facing the cut block to exact dimensions (right middle); aluminum blocks measured and ready for machining (right)

Once the lab technicians had faced the metal block, it was measured with large calipers for exact dimensions and taken to Professor Trian. Along with the SolidWorks file, Professor Trian set up the CAM steps and began to run the machining process on a HAAS CNC router machine. The mold was set for a very fine step over rate to keep a continuous flat surface. This is very helpful when designing composite molds because

composites will take the shape of even the smallest ridges. The machining process took about 4 hours per mold to machine. Once the machining was complete, the two blocks were taken back to the Aerospace Composites and Structures Lab; see Figure 63.

Although the two new molds came out impressively shiny due to the fine finish from the machining process, there were still extremely small ridges that could be felt with the touch of a hand.

Figure 63: Aluminum molds machined and checked for accuracy.

3.2.4.3 Third Mold Surface Finishing

To eliminate any ridges, the molds were wet sanded with high grit sandpaper. Once the surface felt smooth to a touch, a buffing wheel and polish were used to promote a very uniform finish. A polished surface, or mirror finish, on a metal part is the most helpful and significant characteristic of a composite mold as seen in Figure 64. It will result in a shiny finish on the composite part and double as a non-stick surface for the mold itself.

Figure 64: Using polishing agent and a buffing machine to give the aluminum a smooth finish

3.2.4.4 Hole Tapping the Third Mold

Finally, the last step before the first layup on the new molds was to tap the six through holes with a $\frac{1}{4}$ - 20 screw hand tap. The holes on the mold allow for alignment between the male and the female when they are joined together. When laying up composite, screwing in bolts increases the pressure on the part as well. This was the last step before the molds were officially ready to be used. Refer to Figure 65 for the tapping process.

Figure 65: Hand tapping holes with tapping tool and coolant

3.3 Manufacturing Test Specimens

This section will discuss the labor intensive process of manufacturing each test specimen in this experiment.

3.3.1 Aluminum Mold Layup Technique and Specifications

Once the mold had been successfully manufactured, the next step was to begin making the composite test specimens. Fortunately, as seen in Figure 66, this time no vacuum bag, cotton breather, non-porous, gum tape, or vacuum pumps were needed! This

Figure 66: Aluminum molds being prepped with release agents

drastically increased the time efficiency when compared to the two previous molds. The only materials needed were carbon fiber fabric, bamboo veneer, and epoxy. Of course before laying any wet composites down, the same sealer (ChemTrend Chemlease 15 Sealer EZ) and release (ChemTrend Chemlease 41-90 EZ Release) were used, respectively. The sealer was applied twice with 15 minute intervals and the release was applied 5 times with 30 minute intervals. The only time another coating of sealer and release would be needed from there on out is if a coat of acetone is applied to the molds to remove any excess cured resin. But for the most part, only one sealer-release application was necessary; which also saves lots of time.

Moving forward, the carbon fiber and bamboo veneer were cut into sheets of 13 inches by 6 inches and soaked in West Systems epoxy resin (100 grams resin to 20 grams epoxy). In order to cut carbon fiber dry weave, there must be a binding material holding the fibers in place. On large rolls of dry fiber weave, the sides are stitched so that the fibers do not simply fall apart. But when cutting out smaller pieces of weave fabric, the stitched ends must be replaced with something else. In this experiment, blue painters tape was used to keep all the fibers in the cut sheet together. Next, the resin and hardener needed to be thoroughly mixed before the chemical reaction can start to occur. The

directions suggested, at minimum, a 1 minute mixing time. Once the epoxy was mixed, it was then applied and spread to the carbon fiber and bamboo; shown in Figure 67.

Figure 67: Mixing, pouring, and lathering fibers with epoxy

A wetted carbon fiber ply was then placed on each mold first; with the bamboo applied last since it is in the middle. Unlike the weave carbon fiber fabric, the bamboo veneer is a unidirectional material. Therefore it was carefully laid up in the 0 degree direction with respect to the load. The technique to yield high quality composite parts using these molds took more than a few attempts. But ultimately the most efficient way was to slowly press the carbon fiber plies onto each mold; paying attention to the surface contact between the carbon fiber and mold. By avoiding any air pockets in the beginning no bubbles or pooling of epoxy would occur during the final product. Next, the wetted bamboo needed to be pressed into the crevices of the mold and held in place as best as possible with all 5 fingers; all while simultaneously grabbing the other mold with the other hand. Then in one quick motion, taking the other mold and placing it on top of the other mold with the carbon fiber and bamboo, all while quickly removing your fingers. The bamboo will slowly slide into place as the molds are tightened with the screws. It should be noted that it does not matter which mold, male or female, is used to place the bamboo on at first. Once the screws are tightened down, the mold is ready to be cured. Fortunately the compact size of the mold allows for it to be placed directly into the heated

table press. It cured at 275 degrees Fahrenheit with 1000 pounds of force (not psi) for about 1 hour and 30 minutes; see Figure 68. Sometimes a piece of cotton was placed below the mold before being put into the press to soak up any excess epoxy that might leak out the sides. This was the process for almost all 20+ cures using these aluminum molds for trapezoidal, corrugated, carbon fiber-bamboo specimen.

3.3.2 Problems Encountered during Layups

There was a slight learning curve when laying up on the new mold for the first couple of times. For example one problem that seemed to happen at the most random times was shearing of the 1/4-20 screws. This seemed to happen at the most random times, but obviously it was due to over tightening. The hex head would shear off, leaving the threaded hole with a sheared screw; shown in Figure 69. It was not easy and required a lot of time to remove the screw when this happened. Another problem that occurred and was slightly discussed earlier was the bubbling or cured pools of resin that was happening initially before the process was understood. This was because for whatever reason the carbon fiber was lifting off of the mold, even while under pressure, and allowing no

Figure 68: Tightening wet composite materials into mold (left); mold placed into heated table press to cure (middle); cured composite part (right)

surface contact. This results in a discontinuous surface. Fortunately this was fixed by slowly laying down the carbon fiber first, and holding the bamboo in place before closing the molds.

Figure 69: Sheared screw bolt (left); inconsistent cured epoxy surface due to air pockets and lack of mold contact (right)

3.3.3 Laminate and Faceplate Production

In order to bond a laminate faceplate to each specimen, the faceplates needed to be fabricated first. Using the same technique as the material characterization laminates, the specimen faceplates started on a flat metal plate. Large plies of carbon fiber and bamboo veneer were cut, requiring a larger amount of epoxy as well. At the same time, the nonporous, the vacuum bag, the cotton breather, and blue nonstick film were cut out. Next the epoxy was measured, mixed, and poured onto the composite fabrics. The saturated plies were then transferred onto the nonporous film and surrounded by gum tape. The blue nonstick film was carefully laid down on the wet composite while simultaneously sticking to the gum tape and debulking any air pockets. Now just as the material properties laminates were laid fabricated, another flat metal plate was utilized. The metal plate sits directly on top of the composite and then is covered with the cotton

breather and vacuum bag. The layup is then vacuumed and transported to the autoclave where it undergoes a 90 minute cure at 275 degrees Fahrenheit with a pressure of 70 psi. After the autoclave runs, the composite is removed and the bag is opened. From here the laminate plates can be cut into respective sizes for specimen faceplates; as shown in Figure 70.

Figure 70: Laminates layup process

3.3.4 CASE 1 Specimens

Once the process of laying up composites on the molds was thoroughly understood, a mass production was started. Using the same layup process described above for the 20+ layups, the focus eventually turned to the final product production. There were 4 different geometrical cases that were being explored in this experiment; and each case required 8 specimens for data accuracy. The very first case was the basis for which the rest of them build upon. A model of CASE 1 is shown in Figure 71.

Figure 71: CASE 1 specimen 3D model

Fortunately the CASE 1 was the easiest to manufacture because it did not require any additional manufacturing of composite laminates or bonding. Manufacturing one cured trapezoidal composite panel would supply enough specimens to run the test. It took a little more than 100 hours to cut the specimen into size, sand to level, and measure every dimension. A close eye to detail was especially required because not only did the specimens in each case need to be almost identical to one another, but they also needed to be completely flat when stood up vertically. Nevertheless the process started out with using a Rigid Brand wet tile saw machine to cut off the any excess on the sides of the newly cured trapezoidal panels; such as visible blue tape or epoxy. Then the panels were taken inside, measured, and marked with lines for cutting. In order to get the most accurate lines to cut along, the molds were used as a template to measure out the specific distances. By placing the composite panel back into the mold, it would quickly show where lines needed to be drawn for cutting. Then a return trip to the tile saw to cut along the marked lines. At this point, the widths and lengths were measured to get an idea of what the most common distances were. Since the entire specimen in a group must be identical to one another, a common width and length are designated. It is usually the smallest width or length that is chosen because you cannot add material at this stage, but only remove. Due to human errors during manufacturing, the dimensional sizes shown in the 3D CAD models above are seen as guidelines and not limiting factors. Nevertheless, once the common length and width distances had been selected, they are taken to a belt

sander. While sanding the specimen to identical dimensions, the sander is also used to flatten the sides of the specimen so that they are perfectly straight during the compression testing. After sanding, the specimens are checked for flatness and uniformity across all the samples. If more material needs to be removed or the specimens are not vertically straight, a second round of sanding is conducted until they are standardized. Lastly, the specimen's length, width, and depths are measured and recorded. As well as marked for the specimen type and number. At this point the specimens are ready for testing! The process can be seen in Figure 72.

Figure 72: Composite materials curing in heated table press (top left); collecting cured panels (top middle); cutting samples to size (top right); measuring specimens for uniformity (bottom left); sanding as needed (bottom middle); samples prepared for testing (bottom right)

3.3.5 CASE 2 Specimens

While all the cases follow the same exact manufacturing steps as that CASE 1's specimen experienced, in terms of cutting, sanding, measuring; each case has a small variation from one other. In CASE 2, a flat laminate is bonded to the front of the specimen, creating a new geometrical cross section. A model is shown in Figure 73.

Once the respective laminates for faceplates were manufactured, they were taken to the tile saw machine to trim off excess epoxy and material around the edges. Following this, each laminate was then measured with respect to one of the trapezoidal panels. Most of the laminates yielded enough face plates for four full trapezoidal panels which equates to plenty of specimens. A

Figure 73: CASE 2 specimen 3D model

sharpie pen then marked the cutting lines and then the laminates returned to be the tile saw to be cut. At this point, the laminates and trapezoidal panels were ready for bonding. To get evenly distributed pressure when bonding these two pieces together, the female aluminum mold was used as a guide. The trapezoidal panel sat in the mold and then was lathered with structural adhesive. The plate was set directly on top in as perfect alignment as possible, and then placed back in the heated table press for another cure cycle. It was a quick cure: 30 minutes at 175 degrees Fahrenheit with 250 pounds of applied force. When using Magnolia 56 epoxy system and structural adhesive, it usually cures at room temperature for 24 hours. So being able to speed up the cure saved a lot of valuable time when bonding the faceplates to the panels. This process is visualized in Figure 74.

Figure 74: Cutting faceplates to size (top); bonding faceplate to trapezoidal panel (bottom)

After the two pieces were bonded together, the new part was measured and marked for cut lines based on the 3D CAD design of CASE 2. Before being cut into specimens, the CASE 2 newly bonded part was cut into columns and sanded for evenness. Sequentially, the columns were then cut into their final specimen sizes and measured again; see Figure 75. If any additional modifications were required, they were sent back to the sander. Lastly the samples' dimensions were recorded and labeled for testing.

Figure 75: Measuring and cutting CASE 2 specimen down to size

3.3.6 CASE 3 Specimens

Following in the footsteps of CASE 2, the same processes were executed to manufacture the third case's specimen. The only difference this time around was CASE 3's samples were the embodiment of two back to back CASE 1 specimens; see Figure 76.

Figure 76: CASE 3 specimen 3D model

Nevertheless, instead of bonding a faceplate to the front of the specimen, an entirely separate trapezoidal panel was bonded to the back. It was placed in the male mold this time and placed in the heated table press for a quicker cure. After the bond had completely cured, it was measured and marked for cutting. The cutting process was slightly different as well since a new tile saw was required. The Rigid Brand wet tile saw's blade was not tall enough to cut all the way through CASE 3's panel. Another wet tile saw was fortunately on hand that would cut all the way through the material. Once thoroughly cut and sanded to specification, the specimen's measurements were recorded and labeled for testing. These manufacturing steps are represented in Figure 76 and Figure 77.

Figure 77: Aligning and bonding trapezoidal panels together

Figure 78: Cutting CASE 3 specimen down to size

3.3.7 CASE 4 Specimens

Lastly CASE 4's specimen needed to be fabricated. CASE 4 was unique because it essentially uses two back to back CASE 2 specimens. Therefore the process to manufacture CASE 4 samples (Figure 79) was a combination of faceplate bonding from CASE 2's procedure and bonding from back to back parts from CASE 3.

Therefore, reading the previous procedures will give a good understanding on how CASE 4's specimens were manufactured. Nevertheless, it started off with two bonding two trapezoidal panels with faceplates together. The same structural adhesive and curing procedure was used to join the parts together. Once conjoined, the part was measured and marked for cutting. After cutting, the samples were sanded and then marked once more for cutting. If the samples required any additional work, they were put back on the sander and then measured for testing. It should be noted that the procedure to manufacture CASE 4 samples was duplicated. This is the only case that has samples made out of carbon fiber and bamboo, but also only carbon fiber samples. Everything was repeated twice to create samples with

Figure 79: CASE 4 specimen 3D model

bamboo and solely carbon fiber. The carbon fiber samples were labeled with 'CF' before their specimen number to avoid any confusion. It should be noted that for the CF only samples, the bamboo is replaced with a ply of carbon fiber. So regardless if the sample is labeled CF or CFBB, it will have a maximum of 3 plies. These steps are shown in Figure 80 and Figure 81. The final products are represented in Figure 82.

Figure 80: Bonding composite panels together for CASE 4

Eventually more CASE 4 specimens were required to be manufactured, to get more accurate data. The testing chapter will discuss the reasons for this in detail.

Figure 81: Final CASE 4 specimen (carbon fiber with bamboo and only carbon fiber)

Figure 82: Cutting the CASE 4 panels down to size

3.3.8 Final Products

After the manufacturing of all the test specimens was complete, they were given one last inspection. They were all assorted from each other and can be seen in Figure 83. The amount of time to fabricate 40+ samples took an enormous amount of time, but they were finally ready to be tested.

Figure 83: All specimen cases sized and ready for testing

3.4 Box Application Study

One important topic that this experiment acknowledges is the idea of application. Discovering the mechanical properties of biocomposite materials inside composite structures is exciting; but finding a realistic application can be just as intriguing. Fortunately after brainstorming different applications, the idea of a box structure kept surfacing. As discussed earlier, there was an older experiment in the same Composites and Structures Laboratory that utilized raw bamboo stalk and carbon fiber. The scope of the project was to build a light weight box that could handle high compressive loads; see Figure 84. This experiment was successful since the box held loads of 250,000 pounds and weighed less than 20 pounds; a much larger scale compared to this experiment's design. This older project was not the best of quality, but delivered surprising results. Box structures are surprisingly everywhere. Also, when boxes are stacked on top of each other it can create a vertical column. They can be used as a foundation for constructing commercial and residential buildings. They can be applied in almost any situation depending on the size. Shipping containers are a good example of structural boxes because they are corrugated and can accept high loads without any failure. Meanwhile smaller structures such as concert stages usually make use of metal bars or rods in specific patterns to distribute loads. But with small box shaped structures, concerts could be simpler to assemble and cheaper. Box structures are so useful and their use is so underestimated that it seemed like a good geometry application to explore.

Figure 84: Carbon fiber with raw bamboo stalk box project

3.4.1 Box Application Design

The box design for this experiment was influenced by the older carbon fiber box structure, in the sense that it only had four sides versus six. The top and bottom sides of the box were not manufactured as it wouldn't add any additional benefits to the overall structure. But the design was going to be a lot smaller than the older box design for a couple of limiting factors. For starters, the box height could only be as tall as the mold that the composite was laid upon; which happens to be less than 5.5 inches. But after factoring in the amount of excess material cut off after curing, the height was predetermined to be even smaller than 5.5 inches. Also to avoid any potential buckling failures, the height of the box dropped to 4.5 inches because it was under the ASTM C0364 recommended '4.8 inch maximum'. The box also couldn't be any longer than the length of the mold either (12 inches). This left the design perfectly constrained in terms of height and width. Therefore a SolidWorks model, Figure 85, was created to visualize the final product. The interior of the box was going to need surfaces to bond, while the outside edges would need to be some additional support as well. In order to fasten each side to one another, a combination of flat plates with small flanges was concocted. Meanwhile, the four corners of the exterior surface were going to be capped with small

‘L’ brackets to try and dissolve potential stress concentrations when testing. The box was going to be constructed twice as well; once with only carbon fiber, and once with carbon fiber and bamboo. This would give reference data once the box was tested; just like CASE 4’s specimen.

3.4.2 Manufacturing the Box Application

Once the model of the box was complete, the manufacturing process began promptly. Following the same layup procedures from earlier, many trapezoidal panels and laminates were manufactured. Once these two parts were manufactured they were brought to the tile saw to cut off the excess material. Sequentially the laminates were then measured and marked for cutting. Next, they were cut into smaller sized plates to be used as face sheets, and prepped for bonding. Using the same technique when manufacturing CASE 2’s specimen, the trapezoidal panels were bonded to face sheet laminates. Once enough panels and face sheets were bonded to create two boxes, each part was taken to the belt sander. This process was just as important before because any unevenness or sides that weren’t level could result in skewed test data and stress concentrations. After

Figure 85: Box application 3D SolidWorks models with dimensions

using a level to approve the specimen specifications, they were loosely assembled together for measurement. Figure 86 shows this initial production.

Figure 86: Box application external panel production

The panels would not hold together without internal bonding surfaces. Therefore after taking measurements of the box, laminates with flanges to bond the sides together were manufactured; shown in Figure 87. They were laid up on high density foam that was available in the lab. The foam is easily cut with a saw but can withstand the pressures and temperatures in the autoclave. By design two separate sets of interior laminates with flanges were required to accommodate the trapezoidal, interior geometries. These bonding surfaces underwent the same wet layup techniques and cure cycle as the face sheet laminates. After all the layups and cure cycles were completed, the composite parts were measured and then taken to the saw for cutting. Once all the parts appeared to fit, it was finally time for everything to bond together. The bonding surfaces were sanded and scratched before applying adhesive to increase the surface area. A higher surface area will allow more adhesive to bond to the surface of the composite and hopefully handle higher loads. Thankfully there was an excessive amount of clamps readily available in the lab. The parts were painted with adhesive and then clamped together in the respective manor. Once clamped, the autoclave was turned on to 175 degrees Fahrenheit. This had

to be done via manual override and is usually not recommended because the autoclave is not running a recipe. Nevertheless the autoclave was set to a temperature with no pressure so the chamber could be opened and closed at any time. Each box cured for about 45 minutes in the non-pressurized environment. Once taken out, the corner pieces of the boxes were bonded with adhesive, clamped, and sent back into the autoclave oven for another 45 minutes. At the end of this time, the boxes were removed and set aside for a final inspection.

Figure 87: Internal composite brackets manufactured for bonding surfaces and external corner protectors

The very last step before the boxes could be tested was to check for absolute flatness. If there was any rocking or unevenness, the boxes would not demonstrate their full capability when tested. It was recommended from another professor to have the edges faced with CNC mill. Unfortunately this procedure was not readily available and could even damage the box. Therefore a level and the belt sander were utilized to get the box as perfectly level as possible. The final result can be seen in Figure 88.

Figure 88: Bonding box panels together (left); using autoclave as heated oven to speed up curing cycle for structural adhesive (middle left); bonding external corner protectors (middle right); final box product (right)

4 EXPERIMENTAL TESTING AND RESULTS

This section will discuss the edgewise compression testing of the manufactured composite samples and their results. The extension versus the load graphs of each specimen will be presented. This graph should give a good understanding of the compression testing by displaying max load values.

4.1 Edgewise Compression Testing Details

The ASTM decidedly chosen to guide the compression tests in this experiment is ASTM C0364 (*Standard Test Method for Edgewise Compressive Strength of Sandwich Constructions*), but with slight variations. Figure 89 shows a common representation of this test. For example, very common test fixtures accompanied with this test are spherical bearing blocks and lateral ends supports [58]. But these test fixture supports are substituted for flat plate compression test fixtures. The flat compression test fixtures are a generous loan from a California Polytechnic State University professor: Dr. Blair London. By loaning these test fixtures to this effort, a large amount of machining and manufacturing time was saved. And as an added bonus, the test fixtures fit perfectly into the lab's Instron set up. The main different between the test fixtures mentioned in the ASTM and the text fixtures lent were the boundary conditions. The

Figure 89: Edgewise compression of a composite sandwich structure [58]

ASTM's test fixture actually fastens the specimens in place to avoid any potential rotations during testing.

Meanwhile the compression test fixtures loaned did not have any fasteners; which meant focus and patience was required to align the specimens perfectly when loading them onto the compression fixtures. Throughout the entire test, no wild rotations occurred or were noticeable to the naked eye. Also, another variation during the compression testing was the addition of a thin piece of cardboard (Figure 90). A small cardboard cutout was placed onto both ends of specimen before testing. This allowed higher loads to be applied to the specimens due to the distribution of the load across the cardboard

Figure 90: Cardboard pieces used during testing

strip. Originally used to protect the surface of the metal, the cardboard became an addition to the testing procedure throughout the entire experiment. Strangely enough, if rubber was used as a barrier between the specimen and the compression fixture, it would get cut up by the specimen's cross sectional area.

4.1.1 Compression Test Fixtures for Instron Machine

The test fixtures which can be seen in Figure 91 are basically a flat block of aluminum attached to a cylindrical, aluminum billet. The fixtures were reportedly used previously on extremely small objects in the materials engineering department. Therefore it was understood that the plates were designed to be extremely flat and symmetrical. A level was also used to validate the flatness of the aluminum blocks.

Figure 91: Compression head fixtures seen before and after installation

One interesting feature that the donated fixtures came with was a spherical aluminum ball. The aluminum ball would sit in between two aluminum plates during the compression test. Of course there was a machined out section of the block where the diameter of the ball rested. But this feature was never necessarily needed and therefore not used. Its purpose is to keep a specimen in uniaxial load if an edge is not perfectly flat. But after further investigation, it might be great for small material object tests but it was not very effective for larger structural specimens. Therefore the ball section was removed and the two bottom plates rested against one another during testing.

Another variation from the ASTM C0364 standards was the types of failures that were acceptable. The ASTM has a wide array of acceptable failure modes, but does not accept failures at the ends of the specimen because this is where they are clamped. But the specimens in this experiment were not clamped during testing, and

since bearing failure was desired, meant that crushing ends of the specimens were acceptable. This is because the interior bamboo likely failed first and pushed material outwards, deforming the carbon fiber at the ends.

4.1.2 Stress Calculations

As defined in a previous chapter, the ‘thickness’ value of these specimen is not the material thickness but rather the depth or length of the cross sectional area. But if this value is used, it will result in lower stress values than expected because the area input is clearly larger. In order to get an accurate representation of the cross sectional area of the specimen the cross sectional area of the physical specimens needed to be measured. Unfortunately this is not very easy to get accurate area values of complex shapes. Therefore, the average width of each CASE set was calculated. Width is the only inconsistent dimension across the physical specimens since the ply thickness does not change. So it seemed beneficial to average the width value. Then each CASE was modeled in NX10 CAD software with this calculated average width. Once modeled the in the CAD software it gave the cross sectional area of the shape. This is how the area was found for the physical samples. A caliper could have been used, but it would have been time consuming and not very accurate.

4.1.3 Compression Graph Explanation

An interesting fact to point out about all the graphs in this section is ‘Compressive Extension’ axis. This axis basically measures the distance that the cross head moved when compressing the samples. The cross head displacement, or movement, rate is related to the force exerted on the specimen. Since the machine has no way of knowing

what material it is compressing, the cross head movement rate is slow at first to anticipate for failure; which is characterized as a 40% drop in the applied load. But if the material being tested is very rigid and stiff, it will continue to resist the displacement change, resulting in higher applied loads.

But the addition of cardboard makes the machine think that the material it is compressing is soft. This results in a section undesired ‘noise’ usually characterized as a long horizontal line with low magnitudes of force at the start of the curve. This wouldn’t be an issue if the noise didn’t randomly translate the compression curves along the compressive extension axis. So once the graph is compiled, the noise is teared off in attempt to remove any cardboard compression data; and to align the curves with one other as best as possible. This noise is also known as ‘settling in’ displacements. The noise is removed by starting to graph the applied loads around 75 pounds. It should be noted, though, that by reorganizing the curves amongst the x-axis, the compressive extension net, or delta extension, per each specimen remains exactly the same.

4.1.4 Results Comparison and Analysis at a Specified Load

After testing the samples in each case, a good variety of data will be output. The data that will be displayed includes the ultimate applied load, the ultimate compressive strength, the ultimate load average, the compressive strength at the ultimate load average, the average cross sectional area of the specimens, and the average specimen weight. The deflection and stress at a specific load will also be calculated. This is for validating the results with the theoretical and numerical analyses in later chapters. For CASE 1, 1,000 pounds was the analysis point for displacement and stress calculations. CASE 2, 3, and both 4’s chose 2,000 pounds as the analysis point. And lastly the box

applications used 20,000 pounds as their analysis point. These points are decidedly chosen by examining the graph, then selecting a value in the elastic region but past the cardboard box noise.

4.1.5 Instron Crosshead Displacement Error

The best possible data was conceived from these tests by using the best equipment available. For example in the following tests the cross head displacement is used to calculate displacement of the material. Earlier in the report, the material properties section does not rely on the cross head displacement because they are inaccurate. A case study done by another graduate student named Mateja Andrejic discusses this study in his thesis [59]. But as he describes in his report, the internal measurement system for displacement does work, but gets disruptive at higher loads. But due to the capabilities of the lab equipment, the cross head displacement during the tests was the way the specimen displacement was going to be measured. This will be compared with numerical and theoretical values later.

4.2 CASE 1 Test and Results

As described in chapter 3, the CASE 1 was the smallest cross sectional area specimen manufactured. It is a good starting point to build up from since each case uses a combination of CASE 1 specimens. There were 8 specimens in CASE 1 and each were tested. Once the cardboard was placed down on both sides the bottom head was raised up to keep the specimen in place with interference contact. The load was then balanced and gauge length reset on the Bluehill 2 software that the Instron was connected to. At this point the test would begin and the Instron would slowly add load to the

structure by raising the bottom head upwards. Small fluctuations are recorded as the Instron initially works its way through the cardboard. As soon as the specimen was fully engaged, the rate of loading would increase significantly until failure; see Figure 92.

Figure 92: Testing a CASE 1 specimen

From the pictures, there are evident failures at the ends of the specimen. Usually more noticeable on the bottom end, the deformation can be seen because the edge is spread out and crinkled. After testing the ultimate applied load was 2364 lbf and an ultimate compressive strength of 34.17 ksi. Also the average weight of the specimen was 0.0114 lbs. Figure 93 shows the specimen results when the load is plotted against the net

Figure 93: CASE 1 Compression Test Results

compressive extension. Table 9 shows various result values from this data set.

Table 9: CASE 1 Experimental Results

	CASE 1
Ultimate Applied Load [lbf]	2365
Ultimate Compressive Strength [ksi]	17.86
Ultimate Load Average [lbf]	1627
Compressive Strength at Ultimate Load Average [ksi]	12.29
Cross Sectional Area [in ²]	0.1324
Average Specimen Weight [lbs]	0.0114
Stress at 1000 lbs [ksi]	7.553
Displacement at 1000 lbs [in]	0.0362

4.3 CASE 2 Test and Results

Moving on to CASE 2, the cross sectional area of the specimen from CASE 1 is increased with the addition of a faceplate attached. The same procedure was followed when loading the specimen from CASE 1, except this time the specimens were more stable to stand up on their own; shown in Figure 94.

Figure 94: Testing a CASE 2 specimen

The pictures denote roughly the same failures at the ends. Some specimen had some face plate deformations as well. After testing, the ultimate applied load was 5396

Figure 95: CASE 2 Compression Test Results

lbf and an ultimate compressive strength of 23.37 ksi. The average weight of the specimen was 0.028 lbs. The graph of this test is shown in Figure 95; while Table 10 contains results from CASE 2 testing.

Table 10: CASE 2 Experimental Results

	CASE 2
Ultimate Applied Load [lbf]	5396
Ultimate Compressive Strength [ksi]	23.37
Ultimate Load Average [lbf]	4457
Compressive Strength at Ultimate Load Average [ksi]	19.30
Cross Sectional Area [in ²]	0.2309
Average Specimen Weight [lbs]	0.0280
Stress at 2000 lbs [ksi]	8.662
Displacement at 2000 lbs [in]	0.0456

4.4 CASE 3 Test and Results

CASE 3 takes two back to back CASE 1 specimens and bonds them together; see Figure 96. The data output in this case was the most consistent when compared to the other cases.

Figure 96: Testing a CASE 3 specimen

This set consistently failed around the same load while experiencing the same failure locations. The flange tips furthest from the neutral axis were always damaged after testing. The ultimate applied load was 4600 lbf; and the ultimate compressive strength was 17.20 ksi. The average weight of the specimens was 0.0251 lbs. The graph of this test is shown in Figure 97; while Table 11 contains results from CASE 3 testing.

Figure 97: CASE 3 Compression Test Results

Table 11: CASE 3 Experimental Results

	CASE 3
Ultimate Applied Load [lbf]	4600
Ultimate Compressive Strength [ksi]	17.20
Ultimate Load Average [lbf]	4327
Compressive Strength at Ultimate Load Average [ksi]	16.17
Cross Sectional Area [in²]	0.2675
Average Specimen Weight [lbs]	0.0251
Stress at 2000 lbs [ksi]	7.477
Displacement at 2000 lbs [in]	0.0451

4.5 CASE 4 (Carbon Fiber with Bamboo) Test and Results

CASE 4 was the most heavily analyzed. Since its cross sectional area is the largest out of all of the cases, it is likely to handle the most load. It is also by far the most stable and overall realistic case manufactured. Therefore, in addition to the 8 specimens tested, 4 more specimens were manufactured and tested to capture as much data as possible. Also since there were some delamination issues with the faceplates while testing the first 8, the additional 4 were manufactured to not have these same defects. This was accomplished by increasing the surface area of the composites themselves by giving it texture during the layup process. A higher surface area allows more adhesive to bond to the two pieces.

This case was also given a control scenario for data comparison. CASE 4 includes carbon fiber with bamboo (CFBB) samples, and then purely carbon fiber (CF) samples. The purely carbon fiber samples are the ‘control’ case in a sense. Since the bamboo veneer is essentially replacing a ply of carbon fiber in the purely carbon fiber samples, comparing the results between the two would be interesting. Both CASE 4 scenarios were

tested with a full 12 specimens. Firstly, the bamboo veneer and carbon fiber samples were tested; seen in Figure 98.

Figure 98: Testing a CASE 4 (CFBB) specimen

These samples held up relatively well; and after testing the ultimate load applied to the carbon fiber with bamboo specimens was 9442 lbf. The ultimate compressive strength was 19.58 ksi. The average specimen weight was 0.0563 lbs.

As described above the same value of 2,000 pounds was chosen at an analysis point for both CASE 4 scenarios because it was a location in the elastic region on the graph, while being past the noise of the cardboard. The graph of this test is shown in Figure 99; while Table 12 contains results from CASE 4 testing.

Figure 99: CASE 4 (CFBB) Compression Test Results

Table 12: CASE 4 (CFBB) Experimental Results

	CASE 4 (CFBB)
Ultimate Applied Load [lbf]	9442
Ultimate Compressive Strength [ksi]	19.58
Ultimate Load Average [lbf]	7779
Compressive Strength at Ultimate Load Average [ksi]	16.13
Cross Sectional Area [in ²]	0.4823
Average Specimen Weight [lbs]	0.0563
Stress at 2000 lbs [ksi]	4.147
Displacement at 2000 lbs [in]	0.0465

4.6 CASE 4 (Only Carbon Fiber) Test and Results

Next specimens tested were the carbon fiber only group (Figure 100). This was the one of the most important group because it allows for data to be compared and contrasted with the usage of new materials.

Figure 100: Testing a CASE 4 (CF) specimen

The same failures were seen in the carbon fiber and bamboo test specimen; failures and deformations at the edges. Fortunately, no delamination issues occurred in the additional 4 coupons that were created. The ultimate applied load was 11731 lbf and the ultimate compressive strength was 40.43 ksi. The average specimen weight was 0.0585 lbs. The graph of this test is shown in Figure 101; while Table 13 contains results from CASE 4 (CF) testing. In the graph it is possible to tell that not only the spread of data good for accuracy, but Figure 101 is an expected result.

Figure 101: CASE 4 (CF) Compression Test Results

Table 13: CASE 4 (CF) Experimental Results

	CASE 4 (CF only)
Ultimate Applied Load [lbf]	11731
Ultimate Compressive Strength [ksi]	40.43
Ultimate Load Average [lbf]	9776
Compressive Strength at Ultimate Load Average [ksi]	33.69
Cross Sectional Area [in ²]	0.2902
Average Specimen Weight [lbs]	0.0585
Stress at 2000 lbs [ksi]	6.892
Displacement at 2000 lbs [in]	0.0440

4.7 Carbon Fiber and Bamboo (CFBB) Comparison to Only Carbon Fiber (CF)

After testing the carbon fiber bamboo specimen and carbon fiber specimens something important was discovered. This is one of the more important results throughout this experiment. After testing, the results showed that bamboo carbon fiber structures were comparable to a solely carbon fiber structure. This could be very important because it could have in the field of biocomposites in the future; assuming more tests are conducted in the future to quantify the bamboo biocomposite's contribution. The maximum applied load of the carbon fiber bamboo and the carbon fiber samples, 9442 lbs and 11731 lbs respectively, results in only a 22% difference. The average applied load, 9776 lbs and 7779 lbs respectively, results in an only 23% difference. So depending on the application of the structure, and the factor of safety in a structural scenario, the carbon fiber bamboo structure could be applicable. A roughly 23% difference in potential maximum loading conditions is relatively small. And only a single ply bamboo was used. Regardless, using a biocomposite material exhibits sustainability and is cheaper as well. The two structures discussed did not have a significant difference in weight; only a 3.8% difference. But regardless, the strength to weight ratio is quite impressive. The carbon fiber bamboo specimen averaged a maximum load of 9442 lbf while weighing in at 0.0563 lbs; resulting in a specific strength of 168000 lbf/lb. That's an increase of 168,000 times their own specimen weight. The carbon fiber samples could withstand load 200,000 times their own weight. Below is a graph, Figure 102, of the ultimate applied loads and the average ultimate loads of CASE 4's two specimen scenarios to give a better visualization of that 23% ultimate load difference.

Figure 102: CASE 4 Ultimate Load Comparison

4.8 Box Application Test and Results

After testing the entire specimen population, the manufactured boxes earlier were next. Using knowledge gained from the previously tested specimens, it was hypothesized that the boxes would hold 50,000 or more pounds. This meant that the Instron machine in the Cal Poly Structures and Composites Lab was not sufficient enough. The Instron in the composites lab can only apply loads up to 22,000 pounds. To test the boxes it would require a special machine only available in Cal Poly's Civil Engineering labs. The machine used was a SATEC Systems compression testing machine; commonly used to test the compression characteristics of concrete blocks. Its maximum applied load capability was around 200,000 pounds which seemed sufficient enough for the testing the boxes.

Once the approval was given that the boxes could be tested, random materials were gathered for this test. This included cardboard pieces large enough to cover the

box's cross sectional area and metal slabs. The metal slabs are used because the head of the SATEC compression machine is not large enough in diameter to compress the entire box. So therefore the plates act as a medium for the head to transfer the load across the entire box specimens. And the cardboard layer's roll is the same as it was when testing the case specimens; to protect the compression machine's fixtures and distribute load slightly more uniform. Once the materials were gathered, the first box being the carbon fiber with bamboo was placed into the machine and measured for exact alignment; as shown in Figure 103.

Figure 103: Testing box application samples

After testing the carbon fiber bamboo box's ultimate applied load was 78,824 lbf and had an ultimate compressive strength of 11.59 ksi. The carbon fiber box's ultimate applied load was 85,267 lbf with an ultimate compressive strength of 21.98 ksi. The

carbon fiber bamboo box and carbon fiber box weighed only 1.45 lbs and 1.547 lbs, respectively. Refer to Figure 104 for a graph of the results.

While these numbers are quite impressive for a box that doesn't even weigh more than two pounds, there was some unfollowed advice that could have led to even higher applied loads for this test. The advice being that the end edges of the boxes should be faced with a CNC mill to create a completely level edge. When there is even a slight difference in the edges during testing at high loads, the loads will all concentrate on the surface that is the highest in height and break it down unevenly. This can be seen in the testing of the carbon fiber box, how one of the faceplates is completely bowing outwards because it most likely was taller than the surrounding sides. But unfortunately due to time constraints and processes available, using a CNC machine to face the edges was replaced with a hand held belt sander. Therefore the edges were most likely not as flat as they could have been if a CNC was used.

Figure 104: Box Application Compression test Results

The results can be seen below in Table 14 displayed below. 20,000 pounds was chosen as an analysis point because it appeared on the graph to be in the elastic region, but past the noise from the cardboard box, as described earlier.

Table 14: Box Application Experimental Results

	CFBB BOX	CF BOX
Ultimate Applied Load [lbf]	78824	85267
Ultimate Compressive Strength [ksi]	11.59	21.98
Cross Sectional Area [in²]	4.52	2.92
Weight of Specimen [lbs]	1.45	1.547
Stress at 20,000 lbs [ksi]	2.941	5.155
Displacement at 20,000 lbs [in]	0.0495	0.056

5 THEORETICAL ANALYSIS

The theoretical analysis can be used to help understand if the experimental data makes sense. This section will explore the mathematical equations used to calculate stress and displacement for the experiment.

5.1 Theoretical Equations

Theoretical formulas, which are usually used in finite element programs, can be used to calculate variables like stress and displacement by hand. When taking a theoretical look at this experiment, it was important to classify it as purely uniaxial compression. This is because compression can easily get mixed in with buckling and bending analyses. But since this experiment abided by the specimen compression standards in ASTM C0364 the samples were almost too small to show any signs of bending or local buckling. The word ‘almost’ is used because there still might have been an uncertain amount of very small bending or buckling during the tests; but regardless this is ignored.

Nevertheless, when dealing with orthotropic materials, especially composite materials, mechanical properties are analyzed a little bit differently than isotropic materials. For example, a very common tool used to calculate theoretical strains and stresses is the Classical Laminate Theory (CLT). But while CLT is very good for examining the stress-strain relationships of the material, it’s a good representation of information for a just that: a laminate or a flat plate. If the composite examined has a complex shape or contour other than a flat plate, things can get even more complicated. That is why CLT is helpful in determining certain variables, like elastic moduli of the

entire laminate; but due to its lack of inertia or area terms, it doesn't do a very good job of representing anything other than a flat plate. But by using the outputs from CLT as inputs in finite element analysis software, the data can be manipulated to represent different shapes. In this experiment the CLT was used to calculate the young's modulus of the entire laminate that is to be used in the finite element analysis section. First CLT starts off with building the reduced stiffness matrix Q from the equations (eqn. 7-10) below [60].

$$Q_{11} = \frac{E_{11}^2}{(E_{11} - \nu_{12} \cdot E_{22})} \quad (7)$$

$$Q_{12} = \frac{\nu_{12} E_{11} E_{22}}{(E_{11} - \nu_{12}^2 \cdot E_{22})} \quad (8)$$

$$Q_{22} = \frac{E_{11} E_{22}}{(E_{11} - \nu_{12}^2 \cdot E_{22})} \quad (9)$$

$$Q_{66} = G_{12} \quad (10)$$

The different Q_{ij} variables are used to build the reduced stiffness matrix (eqn. 11). Notice all the equations are with respect to young's modulus, ' E ', the shear modulus, ' G ', and Poisson's ratio [60].

$$Q_{ij} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \quad (11)$$

Once that matrix has been built, the reduced stiffness matrix needs to account for any orientations of the plies. This is calculated by using the following equations (eqn. 12-17) [60].

$$\bar{Q}_{11} = Q_{11} \cos(\theta)^4 + 2(Q_{12} + 2Q_{66}) \cos(\theta)^2 \sin(\theta)^2 + Q_{22} \sin(\theta)^4 \quad (12)$$

$$\bar{Q}_{12} = \bar{Q}_{21} = Q_{12} (\cos(\theta)^4 + \sin(\theta)^4) + (Q_{11} - Q_{22} - 4Q_{66}) \cos(\theta)^2 \sin(\theta)^2 \quad (13)$$

$$\begin{aligned} \bar{Q}_{16} = \bar{Q}_{61} = (Q_{11} - Q_{12} - 2Q_{66}) \cos(\theta)^3 \sin(\theta) - (Q_{22} - Q_{12} \\ - 2Q_{66}) \cos(\theta) \sin(\theta)^3 \end{aligned} \quad (14)$$

$$\bar{Q}_{22} = Q_{11} \sin(\theta)^4 + 2(Q_{12} + 2Q_{66}) \cos(\theta)^2 \sin(\theta)^2 + Q_{22} \cos(\theta)^4 \quad (15)$$

$$\begin{aligned} \bar{Q}_{26} = \bar{Q}_{62} = (Q_{11} - Q_{12} - 2Q_{66}) \cos(\theta) \sin(\theta)^3 - (Q_{22} - Q_{12} \\ - 2Q_{66}) \cos(\theta)^3 \sin(\theta) \end{aligned} \quad (16)$$

$$\bar{Q}_{11} = (Q_{11} + Q_{22} + 2Q_{12} - 2Q_{66}) \cos(\theta)^2 \sin(\theta)^2 + Q_{66} (\cos^4 \theta + \sin^4 \theta) \quad (17)$$

These variables are then used to produce the transformed reduced stiffness matrix. In this experiment most of the plies orientation is zero, so that cancels out a lot of the sine terms [60].

$$Q_{ij} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \quad (18)$$

At this point the A, B, and D matrices can be built using the following formulas (eqn. 19-21) [60]; where z is the thickness location of a ply with respect to the neutral axis.

$$A_{ij} = \sum_{k=1}^n \{Q_{ij}\}_n (z_k - z_{k-1}) \quad (19)$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^n \{Q_{ij}\}_n (z_k^2 - z_{k-1}^2) \quad (20)$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^n \{Q_{ij}\}_n (z_k^3 - z_{k-1}^3) \quad (21)$$

$$\mathbf{ABD} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \quad (22)$$

At this point the inverse of the ABD matrix (eqn. 22) is taken to give values that have physical representation. For example, the laminate elastic constants can be found using the following equations (eqn. 23-26) [60]; where ‘a’ is the inverse of the A matrix.

$$E_x = 1/a_{11} * t \quad (23)$$

$$E_y = 1/a_{22} * t \quad (24)$$

$$G_{12} = 1/a_{66} * t \quad (25)$$

$$\nu_{12} = -a_{12}/a_{11} \quad (26)$$

Fortunately there are programs like Autodesk Helious, where the program runs through the CLT and gives the inverse ABD matrices with a click of a button; after inputting each lamina’s properties of course. This was used to check the calculated Young’s moduli, shear modulus, and Poisson’s ratio of the CFBB laminate: $E_x = 2.911 \times$

10^6 psi; $E_y = 2.435 \times 10^6$ psi; $G_{12} = 3.682 \times 10^5$ psi; $\nu_{12} = 7.517 \times 10^{-2}$ psi. Meanwhile, the CF composite modulus was already found earlier; since it's just one material. These values will be used in the numerical analysis later.

Normally the CLT would continue through its calculations and a load would be applied to the system of equations which outputs strain, and eventually stress values. But as discussed earlier this is not so necessary because of the lack of geometry terms that are needed for the trapezoidal case specimens (only represents flat laminate).

Meanwhile there is another universal stress equation that does account for specimen geometry. The stress equation (eqn. 27) that is used in this experiment is as follows:

$$\sigma = \frac{F}{A} \quad (27)$$

One of the simplest equations in mechanics of materials applies to this experiment. The equation reads stress, ' σ ', is equivalent to the force, ' F ', divided by the area, ' A '; in this case the cross sectional area. There are no inertia or modulus terms, which is strange because the formula has no idea what the material are made out of. Another theoretical analysis equation used was the displacement formula. Displacement of compression samples is somewhat important because it is beneficial to understand how far a material will displace under load. The displacement formula (eqn. 28) used is:

$$\delta = \sum_{i=1}^n \frac{P_i L_i}{E_i A_i} \quad (28)$$

Since the materials used are not isotropic, this specific version of the displacement formula must be used. It is the summation of the load, ' P ', times the length of the specimen, ' L ', divided by the elastic modulus, ' E ', and the area, ' A '; which again is

the cross sectional area. For example the elastic modulus, or Young's Modulus, of carbon fiber and bamboo veneer are different. So this is important to use to get accurate results. Below in Table 15 are the theoretical analyses of each case at its respective and specific load. These will be compared to the experimental and numerical values in another chapter.

Table 15: Theoretical Analysis Results

	Stress [ksi]	Displacement [in]	Theoretical Cross Sectional Area Sizes [in ²]
CASE 1 at 1,000 lbs	7.225	0.0361	0.1384
CASE 2 at 2,000 lbs	8.389	0.021	0.2384
CASE 3 at 2,000 lbs	7.444	0.0372	0.2687
CASE 4 (CFBB) at 2,000 lbs	4.267	0.0213	0.4687
CASE 4 (CF) at 2,000 lbs	6.452	0.0253	0.3099
BOX (CFBB) at 20,000 lbs	2.899	0.0274	6.9
BOX (CF) at 20,000 lbs	5.051	0.0214	3.96

6 NUMERICAL ANALYSIS AND RESULTS

In this section the same loaded structures discussed earlier are analyzed using a numerical analysis. Experimental and theoretical data are sometimes not always reliable. Therefore a third analysis can provide more useful data which will be compared later.

6.1 Finite Element Analysis (FEA) Software Introduction

It is very important to use more than one method to try and validate experimental results. Theoretical analysis results are idealized and sometimes almost impossible in the physical world. Therefore another tool used to get a better understanding of results in a specific loading scenario is numerical analysis via finite element analysis (FEA). FEA software also has its own downsides as it tends to lean more on the idealized world as well. And understanding FEA solvers can take a lot of time and practice. But nevertheless, the scenarios discussed in this experiment are relatively simple when compared to non-linear modes of analysis. In fact, the type of mode used for modeling the finite element models detailed below is linear static. That is, a load is applied linearly to a structure without any dynamic interference. The FEA solver used in this report is Siemens' UniGraphics NX10 Simulation solver. Many academic publications rely on the use of Ansys, FEMAP, or ABAQUS as their choice for FEA software, but NX10 Simulation uses the same solvers, namely NASTRAN. Therefore the results should be the same, but the user interface is slightly different. There is a push in the Aerospace industry to update structural and stress engineering FEA software. For example, ABAQUS, though continuously updated, was released in 1978 [61]. Siemens' NX10 software is one of the newer modeling software available today. Not all companies have selected NX to

be their main tool used by designers, but there are a handful of large corporations that are beginning to shift in this direction.

One of the most beneficial characteristics of using NX10 as a finite element solver is its seamless transition from modeling into analysis. It has a great 3D modeler that is easily switched into analysis software with the click of a button. The first step in creating a successful finite element analysis is the design of your finite element model (FEM). This section will go through the steps from the design of the model, to the material selection, mesh, boundary conditions, loads, and lastly results by using a CASE 1 specimen as the example.

6.2 Geometry and Modeling FEM

The geometry of CASE 1 starts by drawing out the cross sectional area. The exact dimensions are required because this is what gives the specimen its shape. Once the cross section has been drawn, and given the correct thickness, the shape can be extruded.

Extruding a 2D shape turns it into a 3D shape. In this example the cross sectional shape is extruded symmetrically along the z axis. The default material that is given to a model in NX10 is aluminum, but this can always be changed. Figure 105 and Figure 106 show the model from different perspectives.

Figure 105: Extruded FEM specimen

Figure 106: CASE 1 FEM cross sectional geometry

6.3 Meshing Convergence and Element Type

After the model had been generated, it can then be transferred into the finite element analysis simulation environment. The system renames the 3D model file type as a '.FEM'; classifying it as a Finite Element Model. Then after selecting the analysis

mode, 'linear static', the model is ready for analysis operations. Now, usually the next step is to add the material properties to the model. But since the material in this experiment is not isotropic, a couple additional steps are required before assigning material properties. For FEA programs like Ansys, FEMAP, and NX simulation there is a built in orthotropic, composite ply/matrix build up. Therefore it is one of the first steps in the simulation process after meshing the model; see Figure 107.

Figure 107: FEM with 2D shell elements applied

The model is meshed using 2D shell elements for simplicity and to give a good representation of the stiffness. To find the optimal mesh size, a mesh convergence study was conducted on CASE 1's data while watching the change in the displacement. It was found that .075 inch elements were more than sufficient to represent the most accurate data. It was a good size to use because it wouldn't crash the laptop computer used to run

the results. Therefore CASE 1's model is meshed with .075 inch elements resulting in 2200 elements. The mesh convergence graph can be seen in Figure 108.

Figure 108: Mesh Convergence (Using CASE 1 Data)

6.4 Material Property Assignment

Once the model was meshed, the next steps were to build up the plies of carbon fiber and bamboo in the software. The mathematical algorithm card used in NX is 'PCOMP' which is used for composite material ply layups. Within each material type are the inputs of the elastic moduli, the shear moduli, and Poisson's ratio for an orthotropic material. These are the values of each material calculated in the material properties section of this report. The software then takes this data and applies it to the mesh. Figure 109 shows some of the input fields from the software.

Figure 109: Material assignment using NX Simulation’s built in ply builder

6.5 Boundary Conditions

Once the mesh and material have been assigned the next step is to apply the load and boundary conditions. For the load, since CASE 1 is analyzed at 1000 pounds, this will be the force applied to the top edge; which is imposing a displacement on the specimen. The boundary conditions are similar to a pinned support because during the testing there was nothing to stop rotation. Only the translation was fixed on the model. The boundary conditions (BC’s) for this scenario were as followed: the translation was fixed but rotation was left free for on the bottom edge; see Figure 110 where the blue line

is the BC's and the red line is the force. These were the only boundary conditions applied needed because the force was assumed to be purely uniaxial.

Figure 110: FEM model with boundary conditions applied

6.6 Linear Static Solution

Once all of the steps to set up the FEM model were complete (material assignment, mesh, loads, boundary conditions), it was ready to be solved. Since this is a linear static model, it is not as intensive on the machine processor when compared to nonlinear solutions. Once the model was solved, the displacement and the stresses were analyzed. Figure 111 shows displacement while Figure 112 shows stress values.

Figure 111: Linear static displacement solution of CASE 1

CASE 1's FEM results showed a 0.0418 inch displacement. This is not terribly far off of the theoretical results, but it is also not exact. The deformed model also looks somewhat realistic since the edges were mostly damaged. A deformed model in an FEA solver is almost always exaggerated; this exaggeration percentage can be changed but is allowable in this circumstance. It does still look similar to the specimens tested.

Figure 112: Linear static stress solution of CASE 1 (left); average stress calculation (right)

Meanwhile the stress of the model requires one additional step. The stresses are solved per element, just like the displacement, but the stresses need to be averaged. The displacement values are fine as is because it is representing the maximum change in location at the edge where a force was applied; which is realistically correct. Meanwhile the stresses need to be averaged because it is this is the total stress of the specimen. After averaging all the elements, the stress comes out to be 7.463 ksi when a 1000 pound force is applied.

For the rest of the cases models and box models, the screen shots of the models after FEA solving will be available in the appendix for further inspection. But each model follows these same steps as described above. The only detail that is not evident in this section was the addition of a surface contact (glue) command when modeling CASE 2 through 4 and the boxes. It's a way to represent the structural adhesive that was used to glue the faceplates to the trapezoidal flanges. CASE 1 just simply does not need this feature. The results of all of the models displacements and stresses at specific loads, and the number of elements are detailed below in Table 16.

Table 16: Numerical Analysis Results

	Stress [ksi]	Displacement [in]	Number of Elements
CASE 1 at 1,000 lbs	7.463	0.0418	2200
CASE 2 at 2,000 lbs	9.616	0.0195	2610
CASE 3 at 2,000 lbs	7.341	0.0363	4400
CASE 4 (CFBB) at 2,000 lbs	4.074	0.052	6020
CASE 4 (CF) at 2,000 lbs	5.937	0.0528	
BOX (CFBB) at 20,000 lbs	3.3810	0.0537	129100
BOX (CF) at 20,000 lbs	5.669	0.050	

7 EXPERIMENTAL, THEORETICAL, AND NUMERICAL RESULTS COMPARISON

After running through each test experimentally, theoretically, and numerically it is important to compare the results. This section will display all of the results found in this experiment and then compare each result.

7.1 Experimental, Theoretical, and Numerical Results

By comparing the final results, it will help to validate and give credibility to the experimental outcomes. Not always do the results from each analysis method come out equivalent. This is why a percent error is calculated between each method for the displacement and the stress values. Originally displacement was chosen as the variable to calculate experimentally, theoretically, and numerically. But upon learning that the Instron machine's internal sensors are not very accurate, it seemed best to reinforce the displacement values with the stress values. Table 17 displays all of the results found. The similarities, differences, and common sense check are described in the next two tables below. Table 17 is just a global view of all the data obtained in this experiment.

Table 17: Experimental, Theoretical, and Numerical Results

	EXPERIMENTAL RESULTS		THEORETICAL RESULTS		NUMERICAL (FEA) RESULTS	
	Stress [ksi]	Displacement [in]	Stress [ksi]	Displacement [in]	Stress [ksi]	Displacement [in]
CASE 1 at 1,000 lbs	7.5530	0.0362	7.2254	0.0361	7.4630	0.0418
CASE 2 at 2,000 lbs	8.6618	0.0456	8.3893	0.0210	8.3970	0.0504
CASE 3 at 2,000 lbs	7.4766	0.0451	7.4441	0.0372	7.3410	0.0363
CASE 4 (CFBB) at 2,000 lbs	4.1468	0.0465	4.2674	0.0213	4.0740	0.0520
CASE 4 (CF) at 2,000 lbs	6.8918	0.0440	6.4524	0.0253	5.9370	0.0528
BOX (CFBB) at 20,000 lbs	2.9412	0.0495	2.8990	0.0274	3.3810	0.0537
BOX (CF) at 20,000 lbs	5.1546	0.0560	5.0505	0.0214	5.6690	0.0504

7.2 Results Comparison and Percent Error

In the next tables, the percent error comparison of each result method is displayed. One thing that may be obvious is that the stress value percent errors are much lower than the displacement percent errors. As described earlier this may be due to the fact that the experimental displacement data is not very accurate due to lab equipment. The main differences in error for the displacement values are the comparison to the theoretical values. This might be derived from the fact that the theoretical equations used are too ideal; and therefore it did not represent the realistic system very well. However, the numerical to experimental results seem to be relatively close in comparison which is very positive. Nevertheless, the stress and displacement comparisons are detailed below in Table 18 and in Table 19.

Table 18: Stress Results Comparison and Percent Error

	EXPERIMENTAL	THEORETICAL	NUMERICAL	% ERROR COMPARISONS		
	Stress [ksi]	Stress [ksi]	Stress [ksi]	Experimental & Theoretical	Experimental & Numerical	Theoretical & Numerical
CASE 1 at 1,000 lbs	7.5530	7.2254	7.4630	4.43%	1.20%	3.23%
CASE 2 at 2,000 lbs	8.6618	8.3893	8.3970	3.20%	3.10%	0.09%
CASE 3 at 2,000 lbs	7.4766	7.4441	7.3410	0.44%	1.83%	1.39%
CASE 4 (CFBB) at 2,000 lbs	4.1468	4.2674	4.0740	2.87%	1.77%	4.64%
CASE 4 (CF) at 2,000 lbs	6.8918	6.4524	5.9370	6.58%	14.89%	8.32%
BOX (CFBB) at 20,000 lbs	2.9412	2.8990	3.3810	1.44%	13.91%	15.35%
BOX (CF) at 20,000 lbs	5.1546	5.0505	5.6690	2.04%	9.50%	11.54%

Table 19: Displacement Results Comparison and Percent Error

	EXPERIMENTAL	THEORETICAL	NUMERICAL	% ERROR COMPARISONS		
	Displacement [in]	Displacement [in]	Displacement [in]	Experimental & Theoretical	Experimental & Numerical	Theoretical & Numerical
CASE 1 at 1,000 lbs	0.0362	0.0361	0.0418	0.30%	14.33%	14.63%
CASE 2 at 2,000 lbs	0.0456	0.0210	0.0504	73.93%	9.94%	82.35%
CASE 3 at 2,000 lbs	0.0451	0.0372	0.0363	19.11%	21.54%	2.45%
CASE 4 (CFBB) at 2,000 lbs	0.0465	0.0213	0.0520	74.34%	11.16%	83.77%
CASE 4 (CF) at 2,000 lbs	0.0440	0.0253	0.0528	54.06%	18.09%	70.42%
BOX (CFBB) at 20,000 lbs	0.0495	0.0274	0.0537	57.48%	8.14%	64.86%
BOX (CF) at 20,000 lbs	0.0560	0.0214	0.0504	89.26%	10.53%	80.62%

7.3 Sources of Error

Aside from equipment errors, another possible source of error for the specimens was the possibility of an uneven edge. This could have led to stresses and displacements distributed differently than what a uniaxial compression should display. This was known to be an error that affected the box specimen. If the box specimens had been machined flat on their testing edges, there might have been a smaller percent error. The same might have been able to be said for the ‘case’ specimens as well.

One thing that should be pointed out is the box specimens used an entirely different compression machine than the ‘case’ specimen. Because this machine was not completely analyzed, there is a possibility that the machine could be just as inaccurate as the composite lab’s Instron machine. This could lead to cross head displacement errors and a reason why the comparison for the boxes are high; when compared to the theoretical.

8 CONCLUSION

This experiment's main focus was to explore the mechanical characteristics of using a biocomposite material inside a composite structure. Bamboo fibers in the form of a unidirectional veneer sheet were chosen as the biocomposite material. The bamboo veneer was then surrounded by carbon fiber composite and the structure took the shape of a trapezoidal stiffener. The newly formed structure was to be then tested in uniaxial compression for a better look at its mechanical strength and resistance to deformation. Since uniaxial compression was the main focus, bending and buckling failure modes were ignored. After running the experiment, tested carbon fiber with bamboo sample results were compared to that of only carbon fiber samples. The carbon fiber samples resulted in a maximum compressive load difference of only 23% higher loads (9776 lbs CFBB and 7779 lbs CF) when compared to the carbon fiber with bamboo, on average. The use of bamboo veneer could be embedded inside carbon fiber specimens as a substitution for core material or plies of carbon fiber. It would also enhance sustainability for the environment, reduce weight slightly, and reduce cost for the overall structure. Depending on an engineer's calculated factor of safety decision, carbon fiber with bamboo could be a very realistic building material in all engineering industries.

Meanwhile, displacement, which showed higher percent errors when compared to the theoretical analysis, still presented credible information. The data showed that no CASE specimen or box recorded any displacement higher than 0.06 inches. This result was expected, because the samples were too small to buckle or bend significantly; thus they did not have any direction to displacement except into themselves vertically. This would give way to failure quickly, thus resulting in very small displacement values.

And another interesting observation from the test data was how much more consistent the data was for CASE 3 and CASE 4, when compared to CASE 1 and CASE 2. This is most likely due to the geometric and local stability CASE 3 and CASE 4 display.

Another great conclusion from this experiment is the scalability of these materials. When the box applications were tested, the CFBB box's ultimate load was 78824 lbs while the CF box's was 85267 lbs. Essentially, by keeping couple corrugations together as opposed to cutting them into individual specimens, the maximum allowable load was exponentially increased which was expected. All while both boxes still weighed less than two pounds. And this still takes into account the inconsistent manufacturing process described earlier. If more machines, instruments, tooling and time were available, the edges could have been processional leveled; which would have most likely resulted in the boxes accepting higher ultimate loads. Regardless, with those kinds of results it is very intriguing to see what kind of other opportunities the combination of these two materials might have.

8.1.1.1 Future Considerations

A closer look at conventional compositions paired with internal biocomposites should be given more focus. Specifically, carbon fiber with bamboo structures would probably show amazing results if used in flexural experiments like three or four point bending tests. Compression testing is just one of many ways in which the structure could be analyzed and utilized.

Also, the future of biocomposites is not fully realized across engineering industries because there is not yet enough research available. There are many different kinds of natural fibers that all exhibit different mechanical properties. Once industry

leaders realize that biocomposites and composite hybrids are just as useful as conventional composites, there will be a shift in the industry followed by a high demand. Also in this experiment, 'green' epoxies were ruled out due to poor mechanical properties. But if the recipe for these types of epoxy can be mastered, they will be very significant to biocomposites, and composites, in the future. Already in the state of California green building materials are welcomed and highly suggested. All while attempting to reduce the carbon footprint from humanity on Earth by using nature's materials.

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APPENDIX

Below entails the FEA screenshots of each case including the box applications.

CASE 2:

Figure 113: CASE 2 model and mesh

Figure 114: CASE 2 displacement (left) and stress (right) results

CASE 3:

Figure 115: CASE 3 model and mesh

Figure 116: CASE 3 displacement (left) and stress (right) results

CASE 4:

Model and mesh

Figure 117: CASE 4 model and mesh

CFBB Results:

Figure 118: CASE 4 CFBB displacement (left) and stress (right) results

CF Results:

Figure 119: CASE 4 CF displacement (left) and stress (right) results

Box Application Model and mesh

Figure 120: Box application drawing and model

Figure 121: Box application mesh

CFBB Box:

Figure 122: CFBB box displacement (top) and stress (bottom) results

CF Box:

Figure 123: CF box displacement (top) and stress (bottom) results