MECHANICAL OPTIMIZATION AND BUCKLING ANALYSIS OF BIO-COMPOSITES

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Abstract

Mechanical Optimization and Buckling Analysis of Bio-composites

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Today's environmental concerns have led a renewed search in industry to find new sustainable materials to replace non-renewable resources. President Barack Obama also quoted in the recent 2012 Presidential Debate "that there is a need to build the energy sources of the future and invest in solar, wind, and bio-fuels." Bio-composites are believed to be the future and the new substitute for non-renewable resources. Bio-composites are similar to composites in that they are made up of two constituent materials; however the main difference is that bio-composites are made from natural fibers and a biopolymer matrix. This research investigates the buckling behavior of bamboo and will analyze and determine the slender ratio that will induce buckling when bamboo is used as a column. Along with the investigation of the bamboo under buckling, this study will also show the potential of bio-composites to replace non-renewable resources in industry through experimental and numerical analysis. However, in order to study the buckling behavior of the bamboo, the mechanical characteristics of the bamboo and optimal curing treatment first had to be established. This is because, in order for bamboo to acquire proper strength characteristics, the bamboo must first be treated.

Due to the scarcity of bamboo material in the lab, the obtainment of the mechanical properties of the bamboo as well as the optimal curing treatment was done in collaboration with Jay Lopez. In order for bamboo to acquire proper strength characteristics, the bamboo must be treated. In the first study, a total of four different types of natural treatments were analyzed to optimize the mechanical characteristics of bamboo. To assess each curing method, tensile and compression tests were performed to obtain the mechanical properties. Due to each bamboo culm having different thicknesses and cross sections, the specific strength property is used to normalize the data and allow for easy comparison and assessing of each curing method equally. The specific strength parameter is defined as the ultimate stress divided by the density of the material. These curing treatments consisted of four thermo-treatments, three different percentages of salt treatments, one lime treatment, and one oil treatment. The thermo-treatments consisted of heating the bamboo internodes in an autoclave with no pressure at 150°F, 180°F, 200°F, and 220°F. The experimental results of the thermo-treatments determined that bamboo obtains higher mechanical properties as well as reduced weight when heated at higher temperatures. This is explained by the increasing bound water extracted from the bamboo material at higher temperatures. In addition to finding the optimal heat treatment, the internodes of bamboo were soaked in natural additives that included a 3%, 6%, and 9% Instant Ocean sea salt solution, a Bonide hydrated lime solution, and a Kirkland canola oil solution for approximately five days and then heat treated at the optimal temperature of 220°F. The experimental results showed that all of the different additives had a significant effect on the mechanical properties.

After determining the mechanical properties of each curing method, the results were then analyzed through a trade study. The trade study parameters consisted of weight-drop of the material, the specific strength, and the ultimate stress for both compression and tension. Each parameter of the trade study is kept unbiased as the weighting of each parameter is set equal to each other. The results of the trade study indicated that the 3% salt solution was the optimal curing treatment, yielding a higher specific strength value for both compression and tension, along with a significantly lower weight-drop after curing.

After we came up with the optimal treatment, the buckling behavior of bamboo was investigated. The buckling analysis was investigated to determine at what slenderness ratio the bamboo would buckle when used as a column. A total of seven cases were investigated using different lengths, that ranged from 1.5" to 10". Through experimental results, it was determined that a slenderness ratio above approximately 34.7 would induce global buckling to the bamboo column.

The last investigation of this study consisted of building a small prototype wall structure using bio-composites. The prototype wall structure was manufactured using a combination of bamboo and a bi-directional woven hemp fabric. The dimensions of the prototype were 15.13" long and 7.75" tall. The wall structure was tested under compression in the Aerospace Structures/Composites Lab and the Architectural Engineering Department's high bay laboratory. The results of the experimental test on the wall showed great potential for bio-composites, as the structure withstood a force of 46,800 pounds.

A numerical analysis technique was also employed through the finite element method using the Abaqus software. The purpose of the finite element method was to validate the experimental results by comparing the buckling behavior of the tests. The numerical analysis showed very good agreement with the experimental results.

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Nomenclature

		<u>Units</u>
A	= Area	in^2
D	= Internode diameter	in
E	= <i>Elastic modulus</i>	<i>KSI</i>
F	= Force	lb_f
I	= Second moment of area	in^4
V	= Volume	in^3
c	= Non-prismatic parameter	
h	= Height	in
l	= Length	in
m	= Mass	lb_m
r	= Radius of gyration	in
t	= Wall thickness	in
w	= Width	in
Δ	= Delta	
∂	= Displacement	
ε	= <i>Strain</i>	<i>in/in</i>
Γ	= Area shrinkage	
λ	= Slenderness ratio	
ν	= Poisson's ratio	
ρ	= Density	lb_f/in^3
σ	= Stress	psi
MC	= Moisture content	

Subscripts

E = Elastic

I = Inelastic

g = Gage

l = Longitudinal

o = After heat treatment

t = Transverse

avg = Average

cr = Critical

eff = Effective

ult = Ultimate

1 = Larger cross section

2 = Smaller cross section

Chapter 1. Introduction

The following section will discuss what bio-composites are in general and why it is necessary to investigate bio-composites. With the main focus of this study on bamboo, general information on bamboo will also be discussed. Previous research will then be discussed on bio-composites from different resources, and lastly the scope and the objectives of this research will be addressed.

1.1 What is a Bio-Composite

A composite is a mixture made from two or more constituent materials with significantly different physical or chemical properties. The composite behavior is a combination of the properties of its constituents.¹ One of the main advantages to composites is its tailorability, which allows for custom strength to be built into a variety of shapes for

Figure 1.1 Composite Composition

practically any structural design. This high tailorability of composites (glass-fibre-reinforced plastics) has made composites become the popular choice in manufacturing small components up to entire systems. With a composite structure having the ability to be specified and designed to a particular load, more often than not that structure will consist of high strength and low weight. The high strength and low weight properties make it especially advantageous to aerospace applications, as weight savings can reduce energy needs, such as fuel. However, synthetic plastics are not environmentally friendly. Instead, composites, such as Glass-Fiber Reinforced Plastics are made from non-renewable resources, emit significant greenhouse gases during fabrication, and are sent to landfills to be incinerated, or recycled, usually by heavy energy intensive methods, to materials of lesser quality at the end of their life cycle.² These

composite products are unsustainable and have a huge environmental impact in today's world. With the potential shortage of fossil fuel reserves, such as carbon fiber, future economies will be forced to utilize raw materials from renewable resources, such as bio-composites.³

Figure 1.2 Lifecycle of bio-composites

As a result of the world's growing environmental awareness and the depletion of petroleum resources, principles of sustainability and industrial ecology are being investigated. Green chemistry and engineering are being integrated into the development of the next generation of materials, products, and processes. Bio-composites, also known as “green composites”, fit well into this new

paradigm shift and are believed to be the new substitute for non-renewable synthetic plastics.⁴ Bio-composites are similar to composites in that they are made up of two or more constituent materials; however, the main difference is that bio-composites are made from natural fibers and a biopolymer matrix, which are renewable and more sustainable than the synthetic fibers and polymers that are traditionally used in composites. Being a renewable resource, bio-composites possess a life that is envisioned to be a never ending cycle—as they continually can be disposed of and recreated. When the useful service life of a particular material ends, it is conceived that the material can be disassembled and transformed into the feedstock needed to create a second generation of equal quality.² A diagram of the continued lifecycle of bio-composites can be seen in Figure 1.2.

Like traditional composites, bio-composites also have great tailorability, as they can be engineered to give unique structural properties for structural and non-structural applications. Although bio-composites may not possess the high structural strength of the synthetic polymers and fibers, recent research suggests that natural fibers do demonstrate competitive performance to traditional composite materials.⁴

1.2 Natural Fibers

Natural fibers are fibers that are formed by nature and are derived from both plants and animals.⁵ These fibers are primarily composed of binding materials: cellulose, hemi-cellulose, and lignin. Natural fibers offer a number of advantages, with the most important being its economical/environmental advantage.

Natural fibers play a major role in the emerging “green” economy based on energy efficiency with its use of renewable feed stocks in bio-based polymer products, industrial processes that reduce carbon emissions, and

Figure 1.3 Flax and hemp are two types of natural fibers

recyclable materials that minimize waste.⁶ Natural fibers are a renewable resource and are considered to be carbon-positive as they have the potential to deliver an overall reduction in global warming by sequestering atmospheric carbon dioxide in the fibers and binding materials. However, the thing that sets natural fibers from the rest is the disposal stage of their lifecycle. With natural fibers being 100% biodegradable, natural fiber products can be composted to improve the soil structure or incinerated with no emission of carbon dioxide greater than the fibers and binding materials absorbed over their lifetime. Synthetic fibers create a huge economical problem due to a large range of disposal issues. Recycling of synthetic fibers requires costly separation, while incineration of synthetic fibers produces large volumes of

pollutants, and in the case of polyethylene, three tons of carbon dioxide emissions are released for every ton of polyethylene burnt.⁶

Along with the economical advantages, natural fibers also contain numerous advantages in terms of the specific material properties. The advantages of natural fibers include low cost, low density, acceptable specific strength properties, ease of separation, non-irritating, great damping characteristics, and can also improve flexural strength, stiffness, and ductility. For lightweight purposes, the substitution of synthetic fibers with natural fibers can reduce the weight of a composite structure by approximately 40%, offering substantial gains in overall efficiency to the aerospace and automotive industries.⁵ In addition to saving money through fuel costs, natural fibers can also cut the production costs of car manufacturers by approximately 30%, as the molding process of natural fibers consumes less energy than synthetic fibers.⁶ Natural fibers also produce less wear and tear on machinery, making natural fibers a more attractive choice for car manufacturers, and leading to a more “green” economy. In terms of the overall strength properties of natural fibers, they still lag behind the strength of synthetic fibers. However, there are some natural fibers that can approach the tensile modulus of E-glass. The advantages that the intrinsic properties of natural fibers carry over their synthetic counterparts have made natural fibers more appealing in all industries, and are the reason there has been a large increase in usage in recent years.

1.3 Bio-Composite Potential Applications

Figure 1.5 De Havilland DH-88 comet was first to utilize bio-composites in aerospace industry

There is a long history of bio-composites that dates all the way back to the 1500s B.C when early Egyptian and Mesopotamian settlers made strong and durable buildings out of straw, reinforced with clay. Over time, natural fibers have continually grown into many industries, such as the goods, automotive, and aerospace industries. An example of

bio-composites being utilized in the Aerospace field can be seen in Figure 1.5, which shows a picture of the deHavilland DH-88 used in World

War II. The deHavilland DH-88 was the first aircraft to implement bio-composites with the fuselage being made of unidirectional, unbleached flax yarn impregnated with phenolic resin cured under

pressure.⁷ However, with the birth of the “plastic era” and many designers demanding higher strength properties, the use of bio-composites suffered depletion from 1950 to 1996.⁸ However, with the scarcity of petroleum resources and with the World’s growing environmental awareness, bio-composites have made a strong recovery registering a significant increase in usage from 2000 to 2010, as seen in Figure 1.4. The Biomass Research and Development Act of 2000 played a major role in this large increase in usage of bio-composites, as it called for tripling America’s use of bio-based products by 2010 and greening the government through recycling and waste prevention. The 2002 Farm Bill is also creating an environment where there is an economic incentive to consider bio-based alternatives to petroleum based materials—reducing the United States’ dependence on foreign oil.⁴ Worldwide, the construction industry is moving to natural fibers for a variety of products

Figure 1.4 There has been a large increase in the use of natural fibers from 2000-2010

that include insulation materials, roofing, truss systems, and structural walls and floors, which will be investigated in a later section. Along with the construction industry, the automotive industry has also made a huge push in utilizing natural fibers, as more car manufacturers are producing more mats, seat backs, headrests, engine shields, parcel shelves, panels for door liners, and body panels out of natural fiber materials, such as hemp.⁶ Bio-composites have shown amazing potential with newly found applications happening every day.

Figure 1.6 Bio-composites have the potential to replace many aircraft structural frames, ala the F-22 Raptor

1.4 Bamboo

Bamboo is one of the most useful, abundant, natural, and renewable resources, characterized by high strength and low weight and is greatly appreciated by many all over the world. Not only is bamboo appreciated by humans, but it also plays a major role for all living organisms. The bamboo forest is a habitat for many animals and for some animals it is their only source of food. There are over 1300 species of bamboo that grow predominantly in the World's tropical and subtropical regions, but also have the ability to grow in almost any geographic location, providing easy accessibility to all.⁹

1.4.1 Chemical Structure of Bamboo

Although botanically not wood, the chemical composition of bamboo is almost an exact duplicate of wood with approximately the same proportions. As alluded to before, the main constituents of bamboo are cellulose, hemicellulose, lignin, and water. Depending on the

species, the chemical composition of bamboo is made up of 50-70% cellulose, 20-30% hemicellulose, and 20-30% lignin.¹⁰

Cellulose, $[(C_6H_{10}O_5)_n]$ is an organic linear polymeric polysaccharide carbohydrate of beta glucose with lengths ranging from 1000 to 4000 units. This organic compound is known to be the structural component of the primary cell wall of green plants, which include bamboo. The cellulose

Figure 1.7 A molecular diagram of three glucose monosaccharides that make up cellulose

structure is responsible for providing the strength in the bamboo because of its high degree of polymerization and linear orientation. The reason that the cellulose is able to provide the strength of the bamboo is because of the covalent bonding between individual glucose units, which also establish cellulose as a strong crystalline structure. The cellulose aggregates shape the microfibrils that make up the reinforced fibers in the matrix, which give the bamboo structure its high tensile strength property.¹⁰

Hemicellulose is very similar to that of cellulose, but is less ordered. Instead of containing one long polysaccharide, hemicellulose can be any of several heteropolymers, which is a polymer derived from two or more different types of monomer. Hemicellulose is present in almost all cell walls along with cellulose

Figure 1.8 Hemicellulose acts as a matrix for the cellulose

and its main function is to act as a matrix for the cellulose and increase the packing density of the cell wall, providing very little strength to the bamboo structure.

Figure 1.9 Molecular diagram of lignin

The last major constituent of bamboo is lignin, which is a chemical compound that is an integral part of the cell walls in plants. Lignin acts as a matrix to the bamboo structure as it fills the spaces in the cell wall between the cellulose and hemicellulose components and confers mechanical strength to the cell wall and, therefore, the entire plant. In simpler terms, the main function of the lignin is to hold the fibers and cellulose molecules within the fiber wall. Lignin is an encrusting agent that gives the bamboo cell wall its rigidity, which also is responsible for the compressive strength of bamboo.¹⁰

Along with the three major constituents, water is also very much present and plays a huge role in the strength of bamboo, which will be discussed in section 2.1. Along with wood, bamboo is a hygroscopic material, which gains or loses moisture to reach equilibrium with its immediate environment.¹⁰ The equilibrium moisture content is particularly dependent on the temperature and humidity that the bamboo is in. There are two types of water contained inside of the bamboo structure. The first type of water is the free water, which is water obtained from the moisture in the air. This type of water is constantly moving in and out of the bamboo structure as it constantly changes with the current environmental conditions of the bamboo. The second type of water is the bound water, which is the water that is bound by the cellulose molecules. The bound water remains constant until enough energy is inputted into the bamboo to break the bonds and draw out the moisture.¹⁰

1.4.2 Bamboo Physical Structure

The common misconception of bamboo is that it is of the tree species because of its similar chemical structure to wood.¹¹ However, bamboo is actually a giant grass-like plant that belongs to the family of Bambusoideae.¹² The bamboo culm in general is a smooth, hollow, cylindrical shape that is divided at intervals by transversal

Figure 1.10 Anatomy of Bamboo culm

diaphragms from which the branches arise. These intervals are called nodes and completely separate the cavity of one internode from the next, making the bamboo culm not a complete hollow structure. Figure 1.10 shows a diagram of a typical bamboo culm.

A key separator of bamboo from wood is the orientation of the fibers inside each structure. Wood has anisotropic properties and contains grains oriented in the same direction throughout the whole structure. However, bamboo is an orthotropic material, as its fibers and grains are oriented in multiple directions at the node locations.¹²

Figure 1.11 Distribution of fibers vary along the thickness of the bamboo

Figure 1.12 Cross-sectional view of node displays both the axial and transverse fibers

By looking at a cross sectional view of a bamboo culm in Figure 1.11 one can see that the distribution of the fibers is non-uniform, varying along its thickness. Figure 1.11 also illustrates how the axial aligned fiber density increases towards the outer edge of the diameter, which may be a result of the bamboo adapting to its environment, as it is highly subjected to large wind

forces.¹² One thing that Figure 1.11 does not show however, is the transverse aligned fibers located in the nodes of the bamboo. To analyze the transversal fibers, Figure 1.12 shows the cross sectional view of a node section. The first thing one may notice by looking at this Figure is that fibers are reinforced along the transverse direction towards the inner diameter of the bamboo culm. Throughout the bamboo pole in the node sections, these transverse fibers to some extent are aligned parallel to one another, providing a circular shape which is outlined in the Figure 1.12. This suggests that the ratio of the fiber density to its surrounding matrix increases with decreases in diameter. This signifies an increase in strength with an increase in thickness. This also explains the correlation between strength and the fibers of bamboo, as the optimal strength would result in a mixture of having a thicker culm along with a small diameter. This is because the smaller the diameter, the greater the ratio the fiber density is to the surrounding lignin matrix.¹² In knowing this, to achieve the best mechanical properties of the bamboo, one would want to choose the top of the bamboo culm. The reason for this is because the diameter of the bamboo decreases in length and also because the fiber concentration is the highest in the top portion, due to the maturity of the fibers.¹³

1.5 Bamboo as a Building material

Bamboo has a long and well established tradition as a building material throughout the world's tropical and subtropical regions. It is known to be one of the chief building materials in rural areas and villages around the world, as over one billion people live in a bamboo house. The reason that bamboo is very attractive for home and villages is

Figure 1.13 Bamboo is the chief building material for many rural areas and villages

because the material is plentiful and also inexpensive. Bamboo housing holds many advantages in comparison to other building materials, as bamboo houses are easy to build, easy to repair, well ventilated, sturdy, and earthquake resistant due to its great damping characteristics. However, deterioration by insects and rot fungi is one of its drawbacks, as untreated bamboo must be replaced every two or three years. Narayanamurti states that improving the mechanical properties and the construction techniques of bamboo houses/building would be a giant step towards improving the quality of life for millions of rural dwellers in the world's developing countries.¹⁴ This research will explore different techniques in increasing the mechanical properties of bamboo as well as looking at different construction techniques in hopes of improving the quality of life of millions of rural dwellers.

1.6 Environmental Advantages of Bamboo

One of the major problems of the construction industry is that it is one of the most polluting on earth, due to the manufacturing of steel, raising many environmental concerns. The environmental problems of the construction industry have caused irreparable damage, as the

Figure 1.15 Display of the embodied energy for bamboo and steel

consequences become more and more evident with droughts, heat waves, polluted air and waters, failed crops, lack of water in the reservoirs for energy generation, etc. By substituting steel for bamboo, there are countless advantages. Not only will bamboo

save time, money, and energy, but it will also help the environmental issues in this world. When wanting a material for sustainable development, bamboo is the clear choice, offering minimum energy consumption. It was found that for steel, it is necessary to spend approximately 71 times more energy than for bamboo to produce one unit of building material with the same

performance, as seen in Figure 1.15.¹² In the production of one ton of steel, two tons of carbon dioxide is produced, while bamboo plants absorb carbon dioxide by sequestering up to 12 tons of carbon dioxide per hectare, which is approximately 15.5 million square

Figure 1.14 Display of carbon footprint for both bamboo and steel

inches. Not only can bamboo sequester carbon dioxide, it can also produce 35% more oxygen than trees.¹⁰

Other advantages that bamboo provides for construction are its impressive physico-chemical properties. Compared to Douglas fir, bamboo has exceptional mechanical properties, which

include compression, tensile, shear, and bending. Once the bamboo reaches its mature age, approximately three to six years old, it is 30% harder than oak and more resistant to insects and mold compared to traditional wood used for construction. Another important advantage of bamboo is its high yield characteristic. When compared to wood, the yield of bamboo in production of raw material for construction is approximately 20 times greater for the same amount of surface and time. This is largely due to bamboo being able to be harvested yearly compared to 40 to 100 years for trees.¹¹ However, according to the owner of Jungle Supply Company, it is very important that the amount of bamboo harvested is equal to the number of new bamboo shoots cultivated in order to sustain its supply.

1.7 Rapid Growth

One of the reasons that bamboo can be harvested almost yearly is because of its phenomenal rapid growth and maturity. Bamboo is the fastest growing woody plant in the world, as some species can grow up to 40 inches per day, and can produce up to 50,000 feet of usable pole in its lifetime. The rapid growth rate and abundance of bamboo have led it to be considered as the ultimate “green” material for all applications. Along with its rapid growth rate, bamboo is also quick to mature, as individual bamboo shoots complete their growth within a four to six month period. Once the bamboo has reached maximum height, it then goes through a lignification process for the ensuing two to three years. The lignification process of the bamboo solidifies the matrix of the bamboo by increasing the amount of lignin in the cell walls. This lignification process is responsible for making the bamboo wood-like and the end of this process marks when the bamboo has reached its mature stage.¹² As a general rule, bamboo culms should be grown for a minimum of three years and no more than a maximum of six years in order to obtain the highest mechanical properties of the bamboo.

1.8 Growth Factors

Although bamboo can grow in almost any geographical location besides Antarctica, optimal growth rates and mechanical properties of bamboo require certain conditions. The growth rate and mechanical properties of bamboo can be influenced by many factors during the growth period of the bamboo. These factors include the location, the climate, the soil, and post-harvest treatment.

1.9 Climate

Climate plays a huge factor in the growth rate of bamboo and its mechanical properties. With bamboo preferring to be in more tropical and subtropical regions, weather outside of this may damage the bamboo. For example, if the bamboo is in very cold weather or it is dehydrated, the bamboo can be damaged and the growth will be stunted. The amount of moisture content inside of the bamboo is one of the critical factors in the growth rate and mechanical properties of bamboo, so dehydration can be an issue. As mentioned earlier, bamboo frequently gains and loses moisture to gain equilibrium with its environment. This absorbing and releasing of the moisture causes the internal strength of the structure to decrease, and in turn causes the ratio of fiber density to the matrix to diminish.

1.10 Soil

Although bamboo is not picky and can grow in different types of soil, in order to achieve the optimal mechanical properties of bamboo, the bamboo needs rich soil that will provide all the nutrients needed to maintain a healthy structure. The amounts of Nitrogen(N), Potassium(K), Phosphorous (P), and the amount of acid in the soil can have a great effect on the growth of bamboo. With slightly acidic soil, a healthy amount of water, and partial shade, bamboo can grow on average approximately 1.5" per hour, which is 36 inches per day.

1.11 Post-Harvesting

With new growth of the bamboo occurring during the wet seasons, it is important not to disturb the clump of shoots during this time of year. For this reason, once the bamboo has reached its mature age of three to six years old, the bamboo should be harvested at the end of the dry season when saps are at their lowest and damage to the shoots is less likely. Also when harvesting the bamboo at the end of the dry season, it is highly advised to be done during dawn or dusk. The reason for this is because photosynthesis is at its peak during the heat of the day and sap levels are highest, making harvesting more difficult. Once the bamboo is harvested, it can be treated immediately.¹⁵

1.12 Applications and Potential of bamboo

Although bamboo is appreciated all over the world, it is still a natural resource that is one of the most least used and studied, as its value has been largely ignored. However, with new legislative laws placing tighter constraints on conventional manufacturing techniques, there has been a general increasing surge of usage and research on bamboo and bio-composites in general. Not only is bamboo used as a building material, but it has more than 1,500 other documented uses today. Today bamboo is used as a paper pulp resource, and in scaffolding, medicine, light bulbs, fuel wood, bicycles, small aircraft applications, etc. With resource management and technical improvements this fast-growing grass can easily be converted to be used for higher load construction purposes as well as a wide range of semi-industrialized products. By dedicating a little more time to the research and development of bamboo, it has the potential to replace various carbon-fiber applications as well as high-strength steel

Figure 1.16 Bamboo has the potential to be used in shipping containers

applications, ridding the world of highly toxic materials. A material this powerful should not just be used for houses, but it should be used for larger structural applications in the car industry, the shipping industry, and the aerospace industry. Although there are 1,500 documented uses for bamboo today, there are probably over 10,000 more that have yet to be discovered.¹⁶

1.13 Previous Research

As mentioned earlier, there is a long history of bio-composites that dates back all the way to the 1500's B.C, but they have fallen out of use with the introduction of synthetic fibers, such as carbon fiber. Since the 1950's, bio-composites have been underappreciated. However, with many environmental regulations being put into place since 2000, there has been a large surge in research on bio-composites to be utilized for structural services. Therefore, a handful of references from previous works are investigated to provide guidance as well as give validation to this research. This collection is comprised of research focusing on the mechanical properties of bio composites, specifically bamboo, as well as bamboo's various treatment/curing methods.

Chalet and Bamboo, is a Thailand based company whose mission is "to be socially and ecologically responsible while also being economically successful." The principal of sustainability has been a guideline that Chalet and Bamboo utilizes for long-term strategic and day-to-day decisions and activities, specializing in the manufacturing and design of bamboo products. Chalet and Bamboo provides great insight of why it is important to treat bamboo as well as various methods of treatments of the bamboo. These treatments are divided into chemical and non-chemical treatments. Chemical treatments are defined as toxic substances that pose a hazard to working personnel or the environment and non-chemical treatments are defined as 100% eco-friendly methods, which pose no threat to the environment or personnel. However, because Chalet and Bamboo does not give data on the curing treatments, this

resource is only used to help generate ideas for curing methods. For this study, because we want to be 100% eco-friendly, only non-chemical treatments were applied.⁹

Bamboo in the Lab by Wolfram Schott¹⁰ was found to be one of the few studies available specifically studying the relationship between the strength and the moisture content of bamboo. Schott's studies consist of curing the bamboo by performing various heat treatments ranging from 300°F to 400°F in a conventional oven up to 25 minutes. Through experimental tests, Schott did discover that the strength of the bamboo is dependent on the moisture content. However, this trend was found to be only valid until the bamboo material reached thermal degradation. Once the bamboo reaches thermal degradation, the material properties of the bamboo significantly decrease as it produces too brittle of a material to be used in any structural applications. However, there are two key notes that must be made concerning Schott's experiments. The first note is that Schott performed the heat treatments on parallel planed triangular shapes that measured approximately a quarter inch in height and two inches in length; Schott did not perform any tests on full bamboo internodes. Another note is that Schott only investigated heat treating the bamboo at high temperatures for a short period of time. However, heat treating the bamboo with this method can cause thermal shock to the bamboo, and it is understood that lower and longer heat treatments provide the best mechanical properties.

Column Buckling of Structural bamboo by W.K. Yu, K.F. Chung, and S.L. Chan²⁸ is another paper that was reviewed. With bamboo scaffolding being very popular in the South East Asia, and column buckling being one of the critical modes of failure in bamboo scaffolds, the authors investigated the column buckling behavior of two structural bamboo species: Kao Jue and Mao Jue. A total of 72 column buckling tests were performed in this research with specimens ranging

from approximately 15.75 inches in length to 78.74 inches in length with an average diameter of approximately 1.5". All buckling tests were performed on mature bamboo specimens that ranged from three to six years of age. In this study, bamboo specimens for each test were also cured by air-drying. Through their analysis, it was found that the column buckling of bamboo adhered very closely to the modern structural design philosophy of Euler, with the slight difference of a non-prismatic factor.

1.14 Scope and Objectives

The purpose of this research has been inspired by today's current environmental awareness policies and the trend to promote more sustainable materials. The push for a greener environment, where more products are created from renewable sources is an eminent one. Although, synthetic fibers allow the creation of lighter and stronger structures, these material do not decompose and negatively impact the environment.

This study investigated the mechanical behavior of bio-composites through both experimental and numerical analysis and had four primary objectives. The first two primary objectives of this research included obtaining the mechanical properties of the yellow groove bamboo species, as well as optimizing its mechanical properties through different curing treatments. The third objective of this study was to investigate the buckling behavior and mechanical stability of bamboo to develop design column buckling guidelines for bamboo. The last primary objective was to evaluate whether bio-composites have the potential to replace current non-renewable materials used on higher strength applications in the aerospace, automotive, and construction industries.

The following provides a glance at the body of work completed in this study. Chapter 2 will discuss the different curing methods utilized in an attempt to find the optimal curing method.

This section will discuss the preparation of each specimen including the different recipes used for each curing method. Along with the preparation of each specimen, the thermo-treatment curing cycles are also discussed in detail. Lastly, the moisture content and area shrinkage associated with each curing treatment will be discussed and analyzed.

Chapter 3 investigates the tensile and compressive mechanical properties for the yellow groove bamboo. Within this section, the preparation and the manufacturing method is discussed for each mechanical tests, as well as the testing procedure to obtain the mechanical characteristics of the bamboo for both compression and tension. This section will then discuss the results of the experimentally investigated bamboo under both compression and tension for each of the curing treatments. The investigated mechanical properties will include the classical material properties: the elastic modulus, the yield stress and strain, and the ultimate stress and strain. Additionally, another variable specific strength is utilized to normalize the different curing treatments for simple comparison.

Chapter 4 will then discuss how all of the experimental data was analyzed and formed into a trade study to determine the optimal curing treatment of the bamboo. This section will discuss how the parameters and the weightings of each parameter were chosen in order to determine the optimal curing treatment. The results of the trade study are also reported in this section. Along with finding the optimal treatment in this section, the optimal treatment is also compared to non-recyclable materials that are currently used in high strength applications for the aerospace, automotive, and construction industry.

Chapter 5 first presents an overview of the experimental methodology used to analyze the buckling behavior of the bamboo. To investigate the buckling behavior of bamboo, a total of seven different specimen lengths will be analyzed to determine at what slenderness ratio, the

buckling of bamboo is experienced. Along, with analyzing the buckling behavior of bamboo, this section will also develop design rules against column buckling.

Chapter 6 will show the potential and feasibility of bio-composites through a small structural prototype of a wall application made of a combination of hemp and bamboo. This section will discuss the manufacturing methods for the wall application, as well as the testing procedures of the wall application. Lastly, the results and the analysis of the wall application will be discussed.

Chapter 7 discusses the methodology and approach in developing the analytical results to verify the experimental results of both the buckling behavior of bamboo, as well as the wall application. In this section, the material properties, the boundary conditions, the mesh, and the results will be discussed for the 8" buckling specimen, as well as the wall application. Lastly, this section will compare the numerical and experimental results.

Chapter 8 will address the conclusions resulting from this research.

Chapter 2. Exploring Different Curing Methods

In order for bamboo to obtain the proper structural characteristics, the bamboo must first be cured. The reason for this is because the structural properties of bamboo are dependent on the amount of moisture that is inside of the bamboo, which will be discussed further in this chapter. A total of four different curing methods will be explored within this research in an attempt to find an optimal curing method for the bamboo. Not only will the optimal curing method for the bamboo provide the best structural properties, but it shall also reduce the weight of the material, creating a stronger and lighter structure. Not only will this chapter address the preparation of each curing method, as well as the preparation of the bamboo internodes before treatment, it will also discuss the geometric changes associated with each curing treatment. This is very important for the designer to estimate how the structure of the bamboo will change to apply to an application. This part of the project was done in a team effort with Jay Lopez.

2.1 Why Treat Bamboo?

The natural durability of untreated bamboo is substantially lower than any conventional structural material, such as aluminum, steel, or wood.¹⁷ The expected lifetime of untreated bamboo ranges between one to fifteen years, and is dependent on the environmental conditions.¹⁷ Humid conditions will yield a lower life expectancy, as it is more subject to attacks by biological agents, such as fungi and insects because it is a ready source of food. To avoid the bamboo being attacked by biological agents, such as fungi and insects, the bamboo must be treated.

Bamboo must also be treated because the strength of bamboo is dependent on the amount of moisture that is inside of the bamboo fiber cell wall. The moisture in bamboo is divided into two categories: free water and bound water. The moisture in bamboo is analogous to that of a sponge as one can squeeze out the free water, but the sponge will remain moist with the bound

water, as the bound water is directly involved with the structure of bamboo.¹⁸ The fiber saturation identifies the point between the free and bound water, which is approximately 20% for bamboo.¹⁰ For moisture contents that are below the fiber saturation point there is no tangible strength effects associated with the changing of moisture content. However, at moisture contents between oven dry and the fiber saturation point, the bamboo experiences significant strength effects. This is because increased amounts of bound water interfere with and reduce the hydrogen bonding between the organic polymers of the cell walls, ultimately decreasing the strength of the bamboo.¹⁰ By decreasing the amount of bound water in the bamboo, the strength of the bamboo increases.

2.2 Topography of Bamboo

It is very important throughout this study to maintain consistency when analyzing each method, which is why each curing method will use the Yellow Groove bamboo species supplied by Jungle Supply Co, which is a bamboo nursery located in Newcastle, CA. To follow the general rule for bamboo culm age, each Yellow Groove bamboo that was obtained from the Jungle Supply Co. met the three year minimum requirement, and were all approximately four years old. Also to maintain consistency in the bamboo, each bamboo species was hand-picked to try and keep the geometric dimensions of each bamboo culm uniform. The diameters of each bamboo pole ranged from 1.4" to 2". For this study, 34 nine foot yellow groove bamboo poles were obtained from the Jungle Supply Co, as seen in Figure 2.2

Figure 2.1 Jungle Supply Co. is a leading supplier of bamboo located in Newcastle, CA.

Figure 2.2 34 bamboo culms were handpicked from Jungle Supply Co.

2.3 Curing Methods

There are various methods to cure bamboo, and these are split into two categories: chemical methods and non-chemical methods. Chemical methods include treating the bamboo with toxic substances and non-chemical methods include treating the bamboo with non-toxic substances. Common chemical methods include soaking the bamboo in a boric acid solution and another is the tanalised method, which impregnates the bamboo under pressure with highly toxic substances. For this study, chemical methods were avoided to retain the bamboo's environmental friendly characteristic, which is why only non-chemical methods were explored.¹⁷

Traditional non-chemical methods include smoking, white washing, and storing in water. However, because part of this study optimizes the structural characteristics of the bamboo along with decreasing the susceptibility of bamboo to biological agents, a thermo treatment was applied to each of the solutions to decrease the amount of bound water inside of the bamboo culm. The non-chemical methods that were explored in this study will include thermo treatments with no additives, salt solutions, a slaked lime solution, and an oil solution.

2.3.1 Preparation of Bamboo

To prepare the bamboo specimens for each curing method, initial measurements were made for each bamboo pole, measuring the weight and the outer diameters of each end of the pole to determine the tapering of the pole. After the initial measurements were made, each bamboo internode was marked to identify the culm that each internode originated from. The internodes of the bamboo were then cut using a Rigid wet diamond tile saw, as shown in Figure 2.3 and Figure 2.4. After the internodes were cut, each internode was measured in accordance with ISO/TR 22157 to determine the area shrinkage of the bamboo and the moisture content after the curing treatment. To maintain consistent traceability of each measurement, each bamboo internode was marked in 12 different spots to ensure that each thickness and outer diameter measurement was made on the exact same spot before and after treatment.¹⁹ This is significant because bamboo is a natural product that does not grow uniformly, meaning that the bamboo has varying diameters as well as varying thicknesses. The measurements were taken in accordance with ISO 22157 and can be seen in Figure 2.5. Each measurement was taken using an electronic caliper to ± 0.001 " accuracy and the weight of each internode was measured using an Adam Equipment electronic scale to within ± 0.0005 lb.

Figure 2.3 Bamboo internodes were cut using Rigid tile saw

Figure 2.4 Bamboo internodes

Figure 2.5 Measurements of bamboo were taken in accordance with ISO 22157

Figure 2.6 Bamboo internodes are marked to maintain consistent traceability of each measurement

Figure 2.7 Diameter and thicknesses of internode are measured using an electronic caliper

2.3.2 Heat Treatment Weight Reduction and Geometric Changes

With all of the curing methods including a thermo treatment, one of the most important parts of this study is to determine the optimal heat treatment cycle. For this reason, thermo treatment was the first method considered. To heat-treat the bamboo, the bamboo was heated inside of the American Autoclave Co. autoclave at the Cal Poly's Structures/Composites laboratory at varying rates and temperatures to

Figure 2.8 American Autoclave Co. autoclave

determine the optimal heat treatment. Figure 2.8 displays the autoclave used for this study. The autoclave curing chamber measures two feet in diameter and four feet in length. It must be noted that during the curing cycles inside of the autoclave, no pressure was applied to prevent the bamboo from catastrophically failing. A total of six different heat treatments were performed on the bamboo: 150°F at a rate of 5°F/min, 180°F at a rate of 5°F/min and 1°F/min, 200°F at a rate of 5°F/min and 1°F/min, and 220°F at a rate of 1°F/min. The reason that the first thermo-treatment of 150°F was chosen was because it was desired to choose a temperature that was well under the boiling temperature of water to ensure there was no thermal degradation. Small increments in the temperatures, such as the 180°F, 200°F, and 220°F were then chosen to determine when thermal degradation of the bamboo occurs. Heat treatments were not explored above 220°F due to the autoclave being incapable of performing at such a high level. For each thermo-treatment, once the target temperature was reached, the temperature was sustained for four hours and then cooled back down to room temperature (70°F) at a rate of 0.2°F. Figure 2.10 illustrates the bamboo internodes after heat treatment, changing from their original green color to a golden brown color. Figure 2.9 illustrates the heat treatment curing cycle of the bamboo.

Figure 2.10 Internodes after heat treatment

Figure 2.9 Heat treatment cure cycle of bamboo

After each curing method was complete the moisture content and the area shrinkage were measured for each internode. In this research, the moisture content is used to calculate the water extracted from the bamboo after each curing treatment. The moisture content parameter is counter-intuitive as higher moisture content results in a higher volume of water being extracted from the bamboo. The moisture content (MC) of the bamboo is taken in accordance with ISO 22157 and is determined utilizing equation 2.1

$$MC = \frac{m - m_o}{m_o} \quad (2.1)$$

where m is the mass of the original internode and m_o is the mass of the internode after the heat treatment. In addition, the area shrinkage (Γ) of the bamboo was determined by equation 2.2

$$\Gamma = \frac{\frac{\pi}{4} [D_{avg}^2 - (D_{avg} - 2t_{avg})^2] - \frac{\pi}{4} [D_{oavg}^2 - (D_{oavg} - 2t_{oavg})^2]}{\frac{\pi}{4} [D_{avg}^2 - (D_{avg} - 2t_{avg})^2]} \quad (2.2)$$

Where D_{avg} is the average outer diameter of the original internode, t_{avg} is the average thickness of the original internode, D_{oavg} is the average outer diameter of the internode after the heat treatment, and t_{oavg} is the average thickness of the internode after the heat

treatment. Due to the internode length having minimal changes after being treated, the volume shrinkage is precisely the same as the area shrinkage.

2.3.2.1 150°F (5°F/min)

The first heat treatment consisted of heating the bamboo from room temperature to 150°F at a rate of 5°F/min. A total of four different internodes were cured using this method of treatment, as Table 2.1 shows the moisture content and the area shrinkage of the internode. The average moisture content that resulted from this curing method is an 18.1% moisture content and a area shrinkage of 5.56%

Table 2.1 150°F (5°F/min) Geometric Changes

Specimen	Weight Before (<i>lb</i>)	Weight After Treatment (<i>lb</i>)	Moisture Content (%)	Average Area Before (<i>in</i> ²)	Average Area After (<i>in</i> ²)	Area shrinkage (%)
11.6	0.281	0.229	18.5	.976	.916	6.14
11.7	0.274	0.223	18.6	1.01	.957	5.69
11.8	0.253	0.207	17.9	1.03	.974	5.22
11.9	0.203	0.168	17.5	1.01	.953	5.18
Average			18.1			5.56

2.3.2.2 180°F (5°/min) and (1°/min)

The second and third thermo treatments that were applied to the bamboo consisted of heating the bamboo to a temperature of 180°F, but at different rates. The first rate that was explored at 180°F was a 5°F/min rate and the second rate was at 1°F/min. Three total specimens were cured using the five degree rate and four different specimens were cured using the one degree rate. The results of the moisture content and area shrinkage measurements for each rate can be seen in Table 2.2 and

Table 2.3. The average moisture content for the five degree and one degree are 27.39% and 26.15% respectively, and the average area shrinkage for the five degree and one degree rate are 9.07% and 7.70% respectively. The results for the 180°F treatments were very similar to each

other in moisture content and area shrinkage resulting in a significant increase when compared to the 150°F curing treatment at a rate of five degrees. This shows that a higher percentage of the bound water was removed from the bamboo.

Table 2.2 180°F (5°/min) geometric changes

Specimen	Weight Before (<i>lb</i>)	Weight After Treatment (<i>lb</i>)	Moisture Content	Area Before (<i>in</i> ²)	Area After (<i>in</i> ²)	Area shrinkage
11.3	0.308	0.222	27.90%	.931	.844	9.31%
11.4	0.272	0.198	27.14%	.979	.888	9.22%
11.5	0.286	0.208	27.12%	.971	.887	8.68%
Average			27.39%			9.07%

Table 2.3 180°F (1°/min) geometric changes

Specimen	Weight Before (<i>lb</i>)	Weight After Treatment (<i>lb</i>)	Moisture Content	Area Before (<i>in</i> ²)	Area After (<i>in</i> ²)	Area shrinkage
10.5	0.288	0.214	25.54%	.907	.840	7.45%
12.8	0.169	0.120	28.72%	.845	.769	9.01%
13.6	0.267	0.197	26.07%	.880	.816	7.31%
13.8	0.194	0.147	24.26%	.910	.846	7.04%
Average			26.15%			7.70%

2.3.2.3 200°F @ (5°/min) and (1°/min)

The fourth and fifth thermo treatments consisted of heating the bamboo internodes to 200°F at a rate of 5°F/min and 1°F/min. A total of four different internodes were cured using both curing cycles, and the results of moisture change and area shrinkage for each internode can be seen in Table 2.4 and Table 2.5. The average moisture content for the five degree rate and one degree rate are 28.35% and 27.0% respectively and the average area shrinkage was 6.56% and 10.72%. The resultant moisture content and area shrinkage values for these tests were very similar to both 180°F curing methods.

Table 2.4 200°F (5°/min) geometric changes

Specimen	Weight Before (<i>lb</i>)	Weight After Treatment (<i>lb</i>)	Moisture Content	Area Before (<i>in</i> ²)	Area After (<i>in</i> ²)	Area shrinkage
14.1	0.194	0.135	30.23%	.924	.867	6.18%
14.2	0.318	0.235	26.28%	1.11	1.04	5.65%
14.3	0.365	0.258	29.28%	.988	.920	6.87%
14.4	0.378	0.273	27.62%	1.04	.964	7.53%
Average			28.35%			6.56%

Table 2.5 200°F (1°/min) geometric changes

Specimen	Weight Before (<i>lb</i>)	Weight After Treatment (<i>lb</i>)	Moisture Content	Area Before (<i>in</i> ²)	Area After (<i>in</i> ²)	Area shrinkage
14.6	0.357	0.258	27.62%	1.02	.926	9.09%
15.4	0.477	0.353	26.06%	1.02	.888	12.84%
15.6	0.491	0.354	27.85%	1.05	.939	10.51%
Average			27.0%			10.72%

2.3.2.4 220°F @ (1°/min)

The sixth and final curing method that was applied to the bamboo heated the bamboo from room temperature to a temperature of 220°F at a rate of 1°F/min. The reason that the five degree rate was not done was because the autoclave was incapable of heating the bamboo to a high temperature at a high rate, signaling the alarm every five minutes while running. Four different specimens were cured using this method and the moisture content and area shrinkage results can be seen in Table 2.6. The average moisture content for this curing method was 26.42% and the average shrink was 9.57%. The results of this curing method was very similar to the other curing methods above 180°F

Table 2.6 220°F (1°/min) geometric changes

Specimen	Weight Before (<i>lb</i>)	Weight After Treatment (<i>lb</i>)	Moisture Content	Area Before (<i>in</i> ²)	Area After (<i>in</i> ²)	Area shrinkage
15.1	0.48752	0.35728	26.71%	.906	.814	10.20%
15.2	0.47828	0.35332	26.13%	.967	.880	8.99%
15.3	0.49456	0.36696	25.8%	.970	.878	9.54%
16.1	0.30844	0.22506	27.03%	.726	.657	9.52%
Average			26.42%			9.57%

Table 2.7 shows the resultant moisture content and area shrinkage averages for all of the curing methods. From this table, one can see that there are significant increases in moisture content for all of the curing methods compared to the 150°F at a rate of five degrees. The 150°F at a rate of five degrees curing cycle yielded an average of only 18.1%, failing to increase the moisture content above the expected fiber saturation point of 20%. However, all of the other curing cycles did succeed in raising the moisture content above the expected fiber saturation point, ranging from 26% to 28%, decreasing a small percentage of the bound water inside of the bamboo, and increasing the strength of the bamboo. There were no distinct advantages in the physical properties of the bamboo for any of the heat treatments above 180°F yielding the same geometric changes. However, it is important to note that the 220°F sample began with a higher mass value before treatment; this fact may have skewed the final differences. It is theoretically known that a higher temperature treatment yields higher moisture content levels and improved mechanical characteristics, so it was decided that the 220°F thermo treatment would be used at a rate on 1°F/min for all of the heat treatment cures with additives. The reason that the rate of five degrees was not chosen is because it would signal the alarm of the autoclave every five minutes and there were thoughts that heating the bamboo at a higher rate would cause thermal shock to the bamboo, and lead to thermal degradation, ultimately decreasing the structural strength of the bamboo.

Table 2.7 Comparison of all heat treatments for weight and area reduction

Curing Treatment	Moisture Content	Area Area shrinkage
Green	0	0
150deg (5 deg/min)	18.15%	5.56%
180deg (5 deg/min)	27.39%	9.07%
180deg (1 deg/min)	26.15%	7.70%
200deg (5 deg/min)	28.35%	6.56%
200deg (1 deg/min)	27.00%	10.72%
220deg (1 deg/min)	26.21%	9.57%

2.3.3 Thermo Treatment with Additives

Due to the various micro-gaps (holes) in the cross section of the bamboo fiber, bamboo has outstanding moisture absorption qualities.²⁰ However, to increase the strength of bamboo, the moisture needs to be removed from the bamboo. The strength of bamboo is also dependent on specific gravity. As the specific gravity of the bamboo material increases, the strength properties also increase because the internal stresses are distributed among more molecular material.¹⁰ In order to fill the voids in the cross sections and increase the specific gravity of the bamboo, a variety of additives will be introduced to the bamboo. The additives in this study include salt, slaked lime, and oil.

2.3.3.1 Salt Treatments

The first additive that was introduced was salt. The salt that was used for this study was Instant Ocean Sea Salt Mix purchased at

Figure 2.12 Bamboo internodes were soaked in salt solutions for five days

Petsmart, seen in Figure 2.11. For this study we wanted to purchase marine salt that would replicate sea conditions. Saltwater is used because

Figure 2.11 placeholder Instant ocean Sea Salt mix

it allows the introduction of salt inside of the bamboo in its dissolved state to fill the voids inside the cross section of the

bamboo fibers. The average salinity of the ocean is approximately 30-35 parts per thousand. This means that for every 1000 grams of seawater, 30-35 of those grams are composed of salt, which is equivalent to 3.0%-3.5% salt to water. The 3% salt recipe consists of 20.58 Kg of water and .62 Kg of salt inside a large tub purchased at Costco. Once the 3% salt recipe was made, the solution was mixed and 11 bamboo internodes were randomly selected from various poles and placed into the solution for approximately five days, as seen in Figure 2.12. After the five days in the salt solution, the bamboo was then taken out and weighed to determine the amount of mass gained from the saltwater bath. Once all measurements were taken, the internodes were then thermo-treated in the autoclave at the 220°F, 1°F/min rate. The moisture content and area shrinkage of each bamboo was then recorded using the same method as the thermo-treatments as mentioned earlier. Table 2.8 shows the moisture contents and area shrinkage for each bamboo internode cured with the 3% salt solution. It is important to note that the moisture content of the additive treatments was calculated for the bamboo in relation to its green condition and not after the additive baths. This was done to keep the moisture content similar to the heat treatments, as the moisture content of the heat treated specimens were calculated using the bamboo at its untreated condition. The average area shrinkage of the 3% salt was 13.02% and moisture content was 37.14% higher, which is an approximate 10% increase from the thermo-treatments with no additives. The reason that there is a 10% increase in the moisture content of the bamboo is because the heat capacity of salt water is lower than pure water meaning that it takes less energy to raise the temperature of water.²² This means that salt water heats up faster and eventually gets to its boiling points first, so when in the autoclave, the temperature that the bamboo experiences inside of the autoclave may be higher than the 220°F. This may be the reason that there is such a large increase in the moisture content with salt added.

Table 2.8 3% Salt 220°F geometric changes

Specimen	Weight Before (<i>g_f</i>)	Weight After Treatment (<i>g_f</i>)	Moisture Content	Area Before (<i>in</i> ²)	Area After (<i>in</i> ²)	Area shrinkage
1.2	0.328	0.196	40.27%	.594	.504	15.15%
1.4	0.359	0.225	37.18%	.681	.563	17.37%
2.1	0.284	0.177	37.77%	.589	.515	12.58%
2.2	0.304	0.191	37.34%	.653	.580	11.24%
2.3	0.318	0.199	37.48%	.580	.610	10.42%
2.4	0.320	0.207	35.44%	.752	.692	8.02%
3.1	0.364	0.225	38.26%	.684	.593	13.38%
3.2	0.378	0.238	37.21%	.720	.594	17.53%
3.3	0.392	0.246	37.26%	.719	.617	14.26%
4.6	0.362	0.230	36.37%	1.03	.903	12.07%
4.9	0.379	0.239	36.82%	.947	.841	11.20%
Average			37.14%			13.02%

Two other salt solutions were also fabricated to find a trend to see if the addition of more salt would be beneficial or not. To do this a 6% salt solution and a 9% salt solution was fabricated in the exact same way the 3% salt solution was fabricated. The 6% saltwater recipe consisted of 18.52Kg of water and 1.11Kg of salt and the 9% salt water recipe consisted of 29.67Kg of water along with 2.67Kg of salt. The average moisture content and area shrinkage for the 6% was 36.35% and 12.37% respectively. The average moisture content and area shrinkage for the 9% salt solution was 28.92% and 11.14% respectively. Table 2.9 shows the moisture contents and area shrinkage for all of the internodes cured in the 6% solution and Table 2.10 shows the moisture content and area shrinkage for the 9% solution internodes.

Table 2.9 6% Salt 220°F geometric changes

Specimen	Weight Before (g_f)	Weight After Treatment (g_f)	Moisture Content	Area Before (in^2)	Area After (in^2)	Area shrinkage
1.1	0.315	0.192	39.05%	.567	.497	12.29%
1.3	0.347	0.212	38.91%	.682	.550	19.38%
1.6	0.393	0.241	38.63%	.830	.643	15.74%
2.5	0.297	0.198	33.56%	.787	.750	9.68%
2.6	0.333	0.221	33.60%	.860	.786	8.61%
4.7	0.386	0.249	35.46%	1.01	.877	12.81%
Average			36.35%			12.37%

Table 2.10 9% Salt 220°F geometric changes

Specimen	Weight Before (g_f)	Weight After Treatment (g_f)	Moisture Content	Area Before (in^2)	Area After (in^2)	Area shrinkage
5.1	0.342	0.239	29.99%	.665	.559	15.94%
5.4	0.387	0.271	30.03%	.781	.695	10.96%
6.3	0.298	0.205	31.31%	.669	.623	6.94%
8.2	0.386	0.285	26.22%	.812	.675	16.90%
8.3	0.400	0.294	26.4%	.859	.753	12.35%
8.4	0.422	0.312	26.17%	.897	.801	9.71%
8.6	0.442	0.328	25.87%	.974	.904	7.21%
8.7	0.424	0.312	26.35%	.984	.892	9.36%
9.1	0.450	0.311	30.89%	.869	.791	8.92%
9.2	0.433	0.299	31.0%	.826	.724	12.25%
9.6	0.349	0.241	30.90%	.909	.804	12.02%
Average			28.92%			11.14%

2.3.3.2 Lime Treatment

The following additive that was introduced to bamboo to help cure the material was a hydrated lime solution. Lime has been known for many centuries with its earliest uses being in buildings and agriculture. The hydrated lime is a 100% natural product, and some of its properties include being antifungal, disinfectant, insect repellent, good thermal and sound insulation, and is anti-humidity, as it is excellent in adapting to changes in temperature and freezing. The hydrated lime solution provides a 100% eco-friendly

Figure 2.13 Hydrated lime

and non-toxic treatment of the bamboo. The hydrated lime that was used in this study was a Bonide Hydrated Lime purchased at Miner's Ace Hardware in San Luis Obispo as seen in Figure 2.13. The composition of the hydrated lime solution consisted of 30.85Kg of water and 1.54Kg of the hydrated lime solution. To prepare the lime water, the slaked lime was mixed until a white solution appeared, called the milk of lime, which is a suspension of the calcium hydroxide particles in the water. After the milk of lime solution appeared, the mixing of the lime water was stopped, allowing the milk of lime solution to settle at the bottom. A board was then placed on top of the milk of lime solution and the bamboo internodes were then placed inside of the solution on the board, so that the internodes were only in the clear solution of the lime water. The internodes were then soaked in the lime solution for approximately five days and went through the same processes that the salt solution internodes went through, which consisted of measurements and a thermo-treatment to obtain the moisture content and area shrinkage. The average moisture content and area shrinkage for the lime solution was 33.45% and 15.50% respectively. Table 2.11 shows the moisture content and area shrinkage of each internode cured using the slaked lime solution.

Table 2.11 Lime, 220°F geometric changes

Specimen	Weight Before (<i>g_f</i>)	Weight After Treatment (<i>g_f</i>)	Moisture Content	Area Before (<i>in</i> ²)	Area After (<i>in</i> ²)	Area shrinkage
10.2	0.334	0.222	33.47%	.848	.739	12.88%
10.3	0.342	0.227	33.72%	.851	.744	12.62%
10.4	0.346	0.233	32.70%	.882	.777	11.97%
11.2	0.306	0.201	34.39%	.916	.764	16.6%
12.2	0.345	0.230	33.42%	.814	.659	18.99%
12.3	0.340	0.227	33.29%	.842	.693	17.67%
12.4	0.316	0.211	33.15%	.849	.676	20.41%
12.6	0.214	0.140	34.7%	.846	.684	19.36%
12.7	0.198	0.129	34.81%	.864	.724	16.24%
11.10	0.176	0.117	33.33%	1.03	.907	12.07%
13.2	0.194	0.279	32.73%	.882	.759	13.94%
13.3	0.374	0.250	33.14%	.873	.735	15.72%
13.5	0.290	0.197	32.17%	.858	.746	13.02%
Average			33.45%			15.50%

2.3.3.3 Oil treatment

Figure 2.14 Kirkland Canola Oil was used for the oil solution

The final curing treatment that was considered was oil. For this recipe, Kirkland Canola was purchased from Costco and used for this curing treatment, which is shown in Figure 2.14. Approximately three liters of canola oil was poured into a large container, where the bamboo internodes were then placed. The bamboo internodes were then soaked

for five days inside of the oil and were then taken out of the solution to sit

out for a day in an attempt to get the excess oil off of each bamboo internode reducing the potential fire hazard the oily bamboo might present, when heat-treating. After the oil solution bamboos were left to sit out for a day, each internode was then measured and heat-treated inside of the autoclave. The average moisture content and the area shrinkage of the bamboo for the oil cured internodes was 29.68% and 7.82% respectively. Although, the bamboo had a high moisture content, the bamboo looked dehydrated when coming out of the autoclave, as the skin of each internode consisted of a brown grayish tone, compared to the golden brown tone of the heat-treat only and salt solutions. Table 2.12 shows the moisture contents and the area shrinkage for each bamboo internode cured in the oil solution.

Table 2.12 Oil, 220°F geometric changes

Specimen	Weight Before (g_f)	Weight After Treatment (g_f)	Moisture Content	Area Before (in^2)	Area After (in^2)	Area shrinkage
5.5	0.39116	0.2706	29.13%	.785	.743	5.32%
6.1	0.32692	0.22792	30.28%	.743	.654	12.01%
6.3	0.29788	0.2046	31.31%	.669	.623	6.95%
6.4	0.2838	0.198	30.23%	.636	.584	8.06%
6.5	0.27104	0.19008	29.87%	.610	.552	9.48%
6.6	0.25476	0.176	30.92%	.576	.531	7.84%
6.7	0.2376	0.16368	31.11%	.542	.528	2.59%
7.2	0.30932	0.2222	28.17%	.720	.642	10.81%
7.4	0.28116	0.20328	27.70%	.667	.621	6.90%
7.5	0.26576	0.19096	28.15%	.647	.604	6.75%
7.6	0.2574	0.18128	29.57%	.608	.551	9.33%
Average			29.68%			7.82%

Table 2.13 shows the average resultant moisture content and area shrinkage of each curing method including the heat only treatments. One can see that the highest change in moisture content was produced by the salt specimens, with three percent leading the way with an average of 37.14%. This is believed to be because salt water has a lower heat capacity than pure water, which allows the salt subjects to experience a higher temperature than the other bamboo, extracting a higher percentage of the bound water inside of the bamboo fibers. However, it was concluded that soaking the bamboo in a higher salinity solution does not yield higher moisture content, as the moisture content decreases with increased salinity. This could be caused by an excess of salt inside of the bamboo, and because salt has a higher density, it does not lose as much mass as the lower salinity solution.

Table 2.13 Comparison of geometric changes for all treatments

Curing Treatment	Moisture Content	Area shrinkage
Green	0	0
150deg (5 deg/min)	18.15%	5.56%
180deg (5 deg/min)	27.39%	9.07%
180deg (1 deg/min)	26.15%	7.70%
200deg (5 deg/min)	28.35%	6.56%
200deg (1 deg/min)	27.00%	10.72%
220deg (1 deg/min)	26.21%	9.57%
3% salt 200deg (1 deg/min)	35.33%	11.67%
3% salt 220deg (1 deg/min)	37.62%	14.574%
6% salt 200deg (1 deg/min)	33.2%	11.458%
6% salt 220deg (1 deg/min)	35.99%	14.47%
9% salt 220deg (1 deg/min)	28.65%	10.96%
Oil 220deg (1 deg/min)	30.49%	8.19%
Lime 220deg (1 deg/min)	33.45%	15.76%

Chapter 3. Bamboo Mechanical Characteristics

To assist the designer in selecting the correct material for his/her application, understanding the mechanical properties of the material is very important. Determining the mechanical characteristics of a material allows the material to be evaluated and compared against others. With one of the principal objectives of this research being to find the optimal treatment of bamboo, the mechanical characteristics of the yellow grove bamboo were explored for the different curing treatments listed in Section 2.3. The following aspect of the project was done in a team effort with my fellow aerospace colleague, Jay Lopez.

The following sections will present an overview of the experimental methodology used to obtain the mechanical properties of the yellow groove bamboo for both compression and tension. This section will then discuss the results of the experimentally investigated bamboo under both compression and tension for each of the curing treatments. The key mechanical properties that will be investigated in this study include the classical material properties: the elastic modulus, the yield stress and strain, ultimate stress and strain. Additionally, another variable specific strength is utilized to normalize the different curing treatments for simple comparison.

3.1 Compression Testing

3.1.1 Preparation of Compression Testing Coupons

The compressive properties of the yellow groove bamboo were determined for each curing method by utilizing standard ISO 22157- “Bamboo Determination of Physical and Mechanical Properties”.⁵ The standard indicates that “there is no significant difference between compressive test results of nodes and internodes”. However, to validate this statement, additional testing of compression specimens with nodes and no nodes were performed and the results of these tests confirm the statement made in ISO 22157. In knowing that there are no significant differences in the compressive mechanical properties of bamboo between nodes and

internodes, to maximize the number of compression test specimens only the internodes were used. The standard requires a minimum of 12 compression specimens to determine the mechanical properties of the bamboo.

Each compression specimen is carefully handcrafted at the Cal Poly San Luis Obispo, Aerospace Composites/ Structures Lab to meet the standards of ISO 22157. With the standard requiring that the length of each compressive specimen tested be equal to the diameter of the internode of the bamboo, the length of each compressive specimen was cut to the average diameter of the originating culm. To begin manufacturing of the compressive specimens, first each bamboo internode was carefully inspected to ensure that there were no significant defects, such as cracks or deformities. Once the internodes were selected the internodes' maximum and minimum diameters were measured at both ends of the internode to determine the average diameter of the internode, as noted in section 2.3.1. The average diameter of each internode was then used to mark sections along the length of the internodes.

Once the internodes were marked, the internode was then cut using a Rigid diamond tile saw as seen in Figure 3.2. After the compressive specimens were cut to length, the specimens were inspected and checked with a leveler to ensure that the end planes of each specimen were perpendicular to the length of the bamboo. If the end planes of the compressive specimen were not found to be perpendicular to the length, the end planes of each specimen were thoroughly sanded using a belt sander, as shown in Figure 3.3. After each specimen was sanded down with the belt sander, a final inspection of each specimen was performed using the leveler. Any imperfections caused by the belt sander were then sanded by hand with a 120 grit sand paper. Manufacturing the compressive specimens so that the end planes were perpendicular to the length proved to be the most difficult task when preparing each compressive specimen.

Figure 3.2 Compression specimens were cut to average diameter of internode

Figure 3.3 A belt sander is used to make end planes of the specimens perpendicular to the length

Figure 3.1 Example of preparation of compression specimens

3.1.2 Experimental test setup (design)

Figure 3.5 Instron 8801 testing

All compression testing was conducted using the Instron 8801 machine located at the Cal Poly SLO Aero Composites/Structures Lab, shown in Figure 3.5. All compressive testing was controlled by the Instron's Bluehill 2 software using an attached controller along with a data acquisition computer. The compression testing procedure first began by manufacturing special compression fixtures to the Instron machine. The first compression fixtures were

manufactured using steel. However, preliminary tests showed that the steel material caused significant bearing stress on the specimens, and had a huge impact on the results of the tests. To address the bearing stress of the specimens, a buffer was added to the compression fixtures in the form of a composite fiberglass laminate

Figure 3.4 Compression test fixtures

between the bamboo and the compression plates as seen in Figure 3.4. This proved to have a significant impact, providing more accurate results.

Figure 3.6 Compression specimens were preloaded to ensure end planes were in full contact with fixtures

Before the compressive specimens were loaded into the Instron machine, the dimensions of each compressive specimen were measured identically to the measurements of the bamboo internodes described in Section 2.3.1. Once the measurements and averages were obtained they were then inputted into the Bluehill 2 testing software to compute the stress and strain of each specimen. After the measurements of each specimen were recorded and

inputted into the Bluehill 2 software, the compression specimen was then loaded into the Instron machine with the appropriate fixtures in place. The ISO standard dictates the specimen must be set in the center of the compression plates and pre-loaded only to create contact between the specimen end plane and compression plate. All compression specimens were pre-loaded to approximately 10 lbf to ensure contact between the specimen and plate, as shown in Figure 3.6. Once the specimen was pre-loaded correctly, the test was then conducted using a cross-head speed of 0.0004 in/min and concluded when a 40% drop in the applied load occurred. This procedure was repeated for all compression specimens.

3.1.3 Compression Tests, Results, and Discussion

A total of 12 different treatments were tested and analyzed under compression including “green” bamboo, which is used as the control case. With the standards requiring a minimum of 12 test specimens, each group contained 12 or more specimens as in ISO-22157. The test groups consisted of the control case, six heat treatments, and five heat treatments with additives, which consisted of the 3%, 6%, and 9% salt, oil, and a lime solution. The results of the compression tests were grouped into six categories to analyze the structural properties of each bamboo curing method. The six categories consisted of the ultimate stress and strain, the yield stress and strain, the elastic modulus, and the specific strength. The specific strength mechanical property is particularly important in this study because it normalizes the data and allows for simple comparison of each curing method.

3.1.3.1 *Green Bamboo Experimental Tests*

The “green” compression group, in which no treatments were done to the bamboo served as the control case to compare the results of the different treatments. In this way, any improvements in its mechanical properties could be noted and optimized for commercial application. All “green” compressions specimens were manufactured in accordance with

Section 3.1.1. A total of 12 compression specimens were manufactured to test and analyze the mechanical properties of the control case. Table 3.1 summarizes the geometries of compression specimens in the control group to account for any anomalies that may exist in the results of the tests. As mentioned all measurements were obtained in accordance with Section 2.3.1 to determine the average height, diameter, and thickness of each specimen. Once the average diameter and thickness was computed, the cross-sectional area (A) of each specimen was calculated using the Equation 3.1

$$A = \pi \left(\frac{D_{avg}^2}{4} - \frac{(D_{avg} - 2t_{avg})^2}{4} \right) \quad (3.1)$$

where D_{avg} is average diameter and t_{avg} is the average wall thickness. Subsequently, the volume (V) of each specimen is calculated by Equation 3.2

$$V = Ah \quad (3.2)$$

where h is the height. The density (ρ) of each specimen is determined using Equation 3.3

$$\rho = \frac{m}{V} \quad (3.3)$$

where, m is the mass of the specimen.

Table 3.1 Green specimen testing geometry

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in. ³)
1		1.596	1.682	0.176	0.833	0.0525	1.329	0.0395
2		1.531	1.650	0.166	0.774	0.0500	1.185	0.0422
3		1.530	1.637	0.167	0.770	0.0490	1.178	0.0416
4		1.528	1.664	0.164	0.773	0.0485	1.181	0.0411
5		1.481	1.659	0.165	0.774	0.0480	1.146	0.0419
6		1.450	1.659	0.168	0.787	0.0489	1.141	0.0429
7		1.477	1.393	0.206	0.767	0.0495	1.133	0.0437
8		1.473	1.475	0.197	0.790	0.0495	1.164	0.0425
9		1.459	1.482	0.191	0.775	0.0485	1.131	0.0429
10		1.471	1.479	0.196	0.790	0.0490	1.162	0.0422
11		1.480	1.482	0.194	0.785	0.0488	1.161	0.0420
12		1.496	1.498	0.192	0.787	0.0482	1.178	0.0408
Mean		1.498	1.563	0.182	0.784	0.0492	1.174	0.0419
Standard Deviation		0.041	0.103	0.016	0.018	0.0012	0.052	0.0011
Maximum		1.596	1.682	0.206	0.833	0.0525	1.329	0.0437
Minimum		1.450	1.393	0.164	0.767	0.0480	1.131	0.0395

Due to bamboo being a natural growing material, finding a standard deviation of anything less than 5% is extremely difficult. For this reason, a standard deviation goal of 15% was set for the geometries and mechanical properties of the specimens in each group. By looking at Table 3.1, one can see that the specimens within the control group were very similar to each other, as the geometric dimensions differed by less than a standard deviation of 9%.

After the completion of each test, the Bluehill 2 software generated the load-extension curve, and subsequently generated a stress-strain curve using the dimensions inputted into the Bluehill 2 software. The Bluehill 2 software computed the stress and strain data using Equations 3.4 and 3.5

To compute the stress (σ) of each specimen, Equation 3.4 was employed

$$\sigma = \frac{F}{A} \quad (3.4)$$

where F is the load applied to the compression specimen and A is the cross sectional area of the specimen. The ultimate stress for each test specimen was obtained by taking the maximum stress value after Bluehill 2 computed the stress values. The yield stress for each specimen was determined by utilizing the threshold –slope method. This method takes the yield point to be the location where the slope of the stress-strain curve falls below a set percentage of the linear elastic region. In this study, a 10% set percentage of the linear elastic region was utilized, which is a large enough percentage to detect an inflection point and determine where the stress-strain curve begins to enter the plastic region.

The strain (ϵ) of each test was calculated utilizing Equation 3.5

$$\epsilon = \frac{\Delta h}{h} \quad (3.5)$$

where Δh is the change in the height of each compression specimen and h is the original height of the compression specimen. The ultimate strain and yield strain were found by determining the strain at the corresponding ultimate and yield stress values.

Along with the stress and strain values, two other key important mechanical properties obtained from each test specimen were the elastic modulus and the specific strength. To compute the elastic modulus of each test specimen, the slope of the linear elastic region of the stress-strain curves was used. The elastic modulus (E) is calculated using Equation 3.6.

$$E = \frac{\Delta \sigma}{\Delta \epsilon} \quad (3.6)$$

To verify the calculated elastic modulus, a line fitting of the linear elastic region was used. All curve –fits to calculate the modulus yielded an average R^2 value of 0.999.

To calculate the specific strength (ζ) value for each specimen, Equation 3.7 was utilized

$$\zeta = \frac{\sigma_{ult}}{\rho} \quad (3.7)$$

where ρ is the density of the yellow groove bamboo using its specified curing treatment.²⁹

Figure 3.7 displays the stress-strain curve of the green bamboo group. When looking at the curves of the stress-strain plot, it is easily noticed that the curves follow a very precise path, which shows how consistent geometries can have an effect on the results of the data. However, one thing to note on the plot is the nonlinear portion of the curve at the very beginning of the test. This may be explained by the end planes not being completely perpendicular to the heights of each specimen when manufacturing each specimen.

Figure 3.7 Stress-strain curve for “green” bamboo compression specimens

The average elastic modulus calculated by the Bluehill 2 testing software was 441.97 KSI with a standard deviation of 8.87%. The average ultimate stress was computed to be 9.36KSI with a standard deviation of 5.37% and the corresponding ultimate strain was 3.85% with a standard deviation of 11.63%. The average yield stress and strain was calculated to be 9.36 KSI and 3.85% with a standard deviation of 10.36% and 5.28%. The last mechanical property calculated was the specific strength of the “green” compression group, which was calculated to be 222.63

$\frac{\text{kips-in}}{\text{lbm}}$ with a standard deviation of 4.71%. The results of the “green” compression specimens were very accurate as the standard deviation of each specimen was within the 15% standard set. Table 3.2 summarizes the mechanical properties of the “green” compression specimens. Figure 3.8 shows the failure modes of the green compression specimens.

Table 3.2 Mechanical properties of green compression specimens

Specimen	Label	Compressive Modulus (ksi)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb _m)
1	1.1G	488.741	3.318	8.677	3.318	8.677	219.679
2	1.2G	375.385	4.083	9.027	4.176	9.017	213.686
3	1.3G	422.998	3.289	8.688	3.289	8.688	208.856
4	1.4G	394.306	3.702	9.2431	3.702	9.243	224.895
5	1.5G	429.095	3.611	9.440	3.611	9.440	225.300
6	1.6G	439.746	3.276	8.607	3.276	8.607	200.634
7	1.7G	493.865	4.379	10.061	4.409	10.021	229.335
8	1.8G	483.770	4.718	9.653	4.246	9.632	226.657
9	1.9G	472.701	4.106	9.902	4.142	9.900	230.769
10	1.10G	450.968	4.001	9.681	4.001	9.681	229.429
11	1.11G	398.687	3.762	9.567	3.995	9.389	223.557
12	1.12G	453.412	3.981	9.734	4.046	9.742	238.788
Mean		441.973	3.852	9.357	3.851	9.336	222.632
Standard Deviation		39.188	0.448	0.502	0.398	0.492	10.488
Maximum		493.865	4.718	10.061	4.409	10.021	238.788
Minimum		375.381	3.276	8.607	3.276	8.607	200.634

Figure 3.8 Failure modes of green compression specimens after compression test

3.1.3.2 *Thermo-Treatment Compression Experimental Tests*

Initial experiments began with the thermo-treated groups. This group is comprised of heat treatments of 150°F, 180°F, 200°F, and 220°F—with varying heat rates.

3.1.3.2.1 150°F at 5°F/min Experimental Tests

The first heat treatment considered was the 150°F at a rate of 5°F/min. A total of 12 specimens were tested under compression to determine the compressive mechanical properties of this group. Table 3.3 provides the geometries of each specimen within this group. From this table it can be seen that the geometries of the testing group are exceptionally accurate with all of the geometric standard deviations less than 5%.

Table 3.3 150°F compression specimen testing geometry

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in ³)
1	11.6.1	1.738	1.738	0.170	0.837	0.0530	1.455	0.0364
2	11.6.2	1.763	1.733	0.173	0.848	0.0555	1.495	0.0371
3	11.6.3	1.760	1.740	0.181	0.888	0.0550	1.563	0.0352
4	11.6.4	1.750	1.724	0.173	0.841	0.0550	1.472	0.0374
5	11.7.1	1.753	1.712	0.183	0.880	0.0565	1.543	0.0366
6	11.7.2	1.748	1.724	0.177	0.860	0.0570	1.504	0.0379
7	11.7.3	1.752	1.720	0.177	0.856	0.0570	1.499	0.0380
8	11.8.1	1.700	1.692	0.186	0.878	0.0570	1.493	0.0382
9	11.8.2	1.689	1.718	0.192	0.920	0.0585	1.553	0.0377
10	11.9.1	1.559	1.664	0.202	0.927	0.0520	1.445	0.0360
11	11.9.2	1.587	1.641	0.194	0.883	0.0530	1.401	0.0378
12	11.9.3	1.588	1.646	0.205	0.926	0.0540	1.470	0.0367
Mean		1.699	1.704	0.184	0.879	0.0553	1.491	0.0371
Standard Deviation		0.077	0.035	0.012	0.032	0.0020	0.047	0.0009
Maximum		1.763	1.740	0.205	0.927	0.0585	1.563	0.0382
Minimum		1.559	1.641	0.170	0.837	0.0520	1.401	0.0352

Figure 3.9 displays the resulting stress-strain curve for the group generated by the Bluehill 2 software. Again the trends of the stress-strain curves are accurate, which is largely due to the preciseness in the geometries of each specimen. The elastic modulus of this curing method was computed to be 446.21 KSI with a standard deviation of 10.09%. The average yield stress was calculated to be 8.85 KSI with a deviation of 4.39% and the corresponding yield strain values was

3.69% with a standard deviation of 11.49%. The ultimate stress and strain values were calculated to be almost identical to the ultimate values of the stress and strain. The average ultimate stress and strain was calculated to be 8.87 KSI and 3.77% respectively. The standard deviations of the ultimate stress and strain were 465% and 12.68% respectively. Table 3.4 displays the complete summary of the mechanical properties for the 150°F at a rate of 5°F per minute. Figure 3.10 shows the failure modes of the 150°F compression specimens.

Table 3.4 Mechanical Properties of 150°F compression specimens

Specimen	Label	Compressive Modulus (ksi)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb _m)
1	11.6.1	484.529	3.391	9.072	3.391	9.072	249.251
2	11.6.2	435.725	3.130	7.926	3.130	7.926	213.661
3	11.6.3	439.077	3.471	8.504	3.471	8.504	241.594
4	11.6.4	481.921	3.056	8.889	3.056	8.889	237.678
5	11.7.1	408.890	3.814	8.882	3.814	8.882	242.693
6	11.7.2	519.082	3.893	8.888	3.893	8.888	234.533
7	11.7.3	366.151	4.113	9.040	4.113	9.040	237.897
8	11.8.1	487.845	3.905	9.116	4.377	9.179	240.305
9	11.8.2	420.455	3.345	8.421	3.345	8.421	223.371
10	11.9.1	388.838	4.518	8.957	4.518	8.957	248.806
11	11.9.2	470.202	3.750	9.299	4.192	9.470	250.535
12	11.9.3	451.874	3.877	9.207	3.8775	9.207	250.877
Mean		446.215	3.688	8.850	3.765	8.869	239.267
Standard Deviation		45.036	0.424	0.388	0.484	0.412	11.305
Maximum		519.082	4.518	9.299	4.518	9.470	250.877
Minimum		366.151	3.056	7.926	3.056	7.926	213.661

Figure 3.10 Failure modes of 150°F compression specimens after compression test

3.1.3.2.2 180°F at 5°F/min. Experimental Tests

Second among the heat treatment group is the 180°F at 5°F/min set. A total of 12 specimens were manufactured and tested to find the compressive mechanical properties of the specified bamboo cure. Again, great care was given to each specimen when manufacturing, to try and keep each specimen uniform. Table 3.5 provides the geometries for the 180°F, 5°F/min group and from this table it can be seen that the standard deviations for all geometries are all under 10.5%, well below the 15% standard.

Table 3.5 180°F, 5°F/min compression specimen testing geometry

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in. ³)
1	11.3.1	1.743	1.713	0.154	0.754	0.0450	1.315	0.0342
2	11.3.2	1.708	1.713	0.142	0.701	0.0450	1.197	0.0376
3	11.3.3	1.725	1.730	0.145	0.722	0.0450	1.245	0.0361
4	11.3.4	1.703	1.718	0.148	0.730	0.0455	1.243	0.0366
5	11.4.1	1.681	1.697	0.151	0.733	0.0435	1.233	0.0353
6	11.4.2	1.732	1.703	0.145	0.710	0.0460	1.229	0.0374
7	11.4.3	1.726	1.740	0.159	0.789	0.0480	1.362	0.0352
8	11.4.4	1.628	1.785	0.156	0.797	0.0460	1.297	0.0355
9	11.5.1	1.785	1.701	0.155	0.754	0.0485	1.346	0.0360
10	11.5.2	1.726	1.695	0.156	0.752	0.0460	1.298	0.0354
11	11.5.3	1.746	1.708	0.149	0.731	0.0470	1.276	0.0368
12	11.5.4	1.642	1.731	0.158	0.780	0.0450	1.280	0.0352
Mean		1.708	1.775	0.159	0.808	0.0445	1.381	0.0322
Standard Deviation		0.060	0.033	0.013	0.072	0.0042	0.143	0.0012
Maximum		1.858	1.829	0.182	0.932	0.0510	1.658	0.0339
Minimum		1.588	1.720	0.143	0.709	0.0365	1.184	0.0297

Figure 3.11 displays the resulting stress-strain curve of the compressive specimens cured under 180°F at a rate of 5°F per minute. When looking at the stress-strain plot it is clearly evident that the trends are very consistent, as each curve is overlaid on top of one another. Also by looking at the plot, one may also notice that the mechanical properties of this curing method yield better results than the curing treatment of 150°F at a rate of 5°F per minute. This may be due to the increased amount of water extracted from the bamboo. The elastic modulus for this group was calculated to be 544.05 KSI with a standard deviation of 12.92%. The average yield stress was computed to be 10.26KSI with a standard deviation of 4.16%. The average yield strain for this group was 3.31% with a deviation of 7.44%. The ultimate stress and strain values were 10.26KSI and 3.32% respectively with a standard deviation of 4.16% and 7.54%. The specific strength of the 180°F at 5°F/min group was calculated to be $285.60 \frac{\text{kips-in}}{\text{lbm}}$ with a standard

deviation of 3.76%. A complete summary of the mechanical properties of each compression specimen within this specified group can be seen in

Table 3.6. Figure 3.12 also shows the failures of the 180°F, 5°F/min compression specimens.

Table 3.6 Mechanical Properties of 180°F, 5°F/min compression specimens

Specimen	Label	Compressive Modulus (ksi)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb _m)
1	11.3.1	541.5953	2.97872	10.16788	3.0065	10.16788	297.40702
2	11.3.2	620.2979	3.16162	10.52523	3.16162	10.52523	279.92633
3	11.3.3	521.0134	3.35317	10.29214	3.40601	10.29214	285.51607
4	11.3.4	490.7574	3.43256	10.04681	3.43256	10.04681	274.50301
5	11.4.1	637.4228	3.01246	10.68601	3.01246	10.68601	302.71983
6	11.4.2	659.1031	3.08417	11.13354	3.08417	11.13354	297.68824
7	11.4.3	477.9027	3.39783	9.82334	3.39783	9.82334	279.07216

Figure 3.11 placeholder Stress-strain curve of 180°F, 5°F/min compression specimens

8	11.4.4	444.6369	3.72747	9.4255	3.70951	9.4255	266.13521
9	11.5.1	532.4614	3.38759	10.0707	3.38759	10.0707	279.74167
10	11.5.2	604.2418	3.07765	10.29056	3.07765	10.29056	290.69379
11	11.5.3	474.8445	3.66338	10.35276	3.72524	10.35276	282.04022
12	11.5.4	524.3334	3.41409	10.26809	3.41409	10.26809	291.70710
Mean		544.0509	3.307559	10.25688	3.317936	10.25688	285.5959
Standard Deviation		70.28525	0.246027	0.426642	0.250042	0.426642	10.72672
Maximum		659.1031	3.72747	11.13354	3.72524	11.13354	302.7198
Minimum		444.6369	2.97872	9.4255	3.0065	9.4255	266.1352

Figure 3.12 Failure modes of 180°F, 5°F/min compression specimens after compression test

3.1.3.2.3 180°F at 1°F/min. Results Experimental Tests

Third among the heat treatment group is the 180°F at 1°F/min set. Table 3.7 provides the geometries for the 180°F at 1°F/min test group. A total of 14 specimens were manufactured and cured using the specified treatment. By looking at the table, one may notice that each specimen was manufactured to detail, as all of the geometries are below a standard deviation of 10%.

Table 3.7 180°F, 1°F/min rate compression testing specimens

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in. ³)
1	10.5.1	1.505	1.522	0.189	0.79	0.039	1.188	0.032
2	10.5.2	1.503	1.526	0.155	0.668	0.039	1.003	0.038
3	12.8.1	1.512	1.536	0.183	0.777	0.039	1.165	0.033
4	12.8.1	1.410	1.421	0.184	0.714	0.032	1.004	0.032
5	12.8.2	1.403	1.415	0.170	0.665	0.033	0.933	0.035
6	12.8.3	1.397	1.409	0.169	0.658	0.033	0.919	0.036
7	13.6.1	1.588	1.508	0.185	0.769	0.039	1.22	0.032
8	13.6.2	1.379	1.484	0.172	0.708	0.034	0.976	0.034
9	13.6.3	1.474	1.496	0.172	0.716	0.035	1.055	0.033
10	13.6.4	1.429	1.468	0.171	0.692	0.035	0.989	0.035
11	13.8.1	1.264	1.387	0.213	0.787	0.033	0.994	0.033
12	13.8.2	1.352	1.377	0.199	0.737	0.036	0.997	0.036
13	13.8.3	1.347	1.388	0.201	0.745	0.036	1.003	0.035
14	13.8.4	1.376	1.405	0.215	0.803	0.036	1.104	0.032
Mean		1.423	1.453	0.184	0.731	0.035	1.039	0.034
Standard Deviation		0.084	0.058	0.018	0.049	0.002	0.094	0.001
Maximum		1.588	1.536	0.215	0.803	0.0395	1.220	0.038
Minimum		1.264	1.377	0.155	0.658	0.0325	0.919	0.032

Figure 3.13 displays the resulting stress-strain curve for the specimens cured at a temperature of 180°F and at a rate of 1°F/min. As seen from the figure, the trend of the curves is fairly consistent, as they all follow the same path. However, by looking at the plot one may also identify that there is some deviation within the linear elastic region of some of the specimens, and a specific deviation in the elastic modulus. The elastic modulus calculated by the Bluehill 2 software was 479.68 KSI with a standard deviation of 13.93%. The deviation of the elastic modulus was greatest among all the mechanical properties. An explanation of the high

deviation may be because the end planes of the specimens were not completely level or may be due to the large bearing stress on some of the specimens, causing the elastic modulus to decrease for some of the specimens. The average yield stress was computed to be 10.28KSI with a standard deviation of 7.49% and the average ultimate stress for this group was 10.45KSI with a deviation of approximately 6.96%. The average specific strength parameter for this test group was calculated to be $302.6 \frac{\text{kips-in}}{\text{lbm}}$ and a standard deviation of 7.71% from the average. Table 3.8 summarizes the mechanical properties for the compressive specimens cured at 180°F and at a rate of 1°F/min. Figure 3.14 also shows the failures of the 180°F, 1°F/min compression specimens.

Figure 3.13 Stress-strain curves of 180°F, 1°F/min compression specimens

Table 3.8 Mechanical properties of 180°F, 1°F/min compression specimens

Specimen	Label	Compressive Modulus (ksi)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb _m)
1	10.5.1	499.9524	3.99168	10.3994	3.99168	10.39946	317.05671
2	10.5.2	558.4104	3.56456	11.28261	3.56456	11.28254	290.03959
3	12.8.1	547.7586	10.28185	10.28184	3.99671	10.28185	303.29941
4	12.8.1	488.7949	9.61192	9.611979	3.15313	9.61192	295.75138
5	12.8.2	382.6215	9.3527	9.020678	4.69727	9.3527	260.52089
6	12.8.3	486.0019	9.09606	8.889351	4.60117	9.09606	249.20712
7	13.6.1	477.5094	10.05276	10.05276	3.49699	10.05276	310.27037
8	13.6.2	497.0739	11.32789	11.32791	4.12378	11.32789	325.51408
9	13.6.3	548.5519	10.9895	10.70005	4.34245	10.9895	327.06845
10	13.6.4	556.4418	11.13571	10.59693	4.34017	11.13571	314.56808
11	13.8.1	356.5443	10.15834	9.568019	4.76364	10.15834	305.97410
12	13.8.2	375.262	10.79764	10.57351	4.9262	10.79764	299.10360
13	13.8.3	465.8887	11.12508	11.07048	4.67607	11.12508	309.89081
14	13.8.4	474.7666	10.698	10.53856	4.50542	10.698	328.15951
Mean		479.6842	9.441692	10.27958	4.227089	10.45068	302.6017
Standard Deviation		66.80072	2.497173	0.769463	0.53258	0.727295	23.35592
Maximum		558.4104	11.32789	11.32791	4.9262	11.32789	328.1595
Minimum		356.5443	3.56456	8.889351	3.15313	9.09606	249.2071

Figure 3.14 Failure modes of 180°F, 1°F/min compression specimens after compression test

3.1.3.2.4 200°F at 5°F/min Results

The fourth heat-treatment test conducted was heat-treated to 200°F at a rate of 5°F/min set. A total of 22 specimens were manufactured and tested to obtain the compressive mechanical properties of the specified bamboo cure. Table 3.9 summarizes the geometries for each specimen as well as the averages of the group. It is important to note that the geometries all of the specimens in this test group are very accurate as all standard deviations are below 10.5%, well below the 15% deviation standard.

Table 3.9 200°F, 5°F/min compression specimen testing geometry

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in. ³)
1	14.1.1	1.707	1.762	0.145	0.737	0.0420	1.257	0.0334
2	14.1.2	1.690	1.739	0.144	0.719	0.0395	1.215	0.0325
3	14.1.3	1.615	1.726	0.150	0.741	0.0365	1.196	0.0305
4	14.2.1	1.735	1.829	0.180	0.932	0.0510	1.617	0.0315
5	14.2.3	1.706	1.800	0.180	0.917	0.0500	1.564	0.0320
6	14.2.4	1.630	1.804	0.170	0.872	0.0470	1.420	0.0331
7	14.3.1	1.742	1.819	0.170	0.880	0.0455	1.534	0.0297
8	14.3.2	1.704	1.751	0.148	0.745	0.0410	1.269	0.0323
9	14.3.3	1.588	1.730	0.162	0.798	0.0385	1.268	0.0304
10	14.3.4	1.718	1.720	0.143	0.709	0.0405	1.218	0.0332
11	14.3.5	1.676	1.737	0.145	0.723	0.0395	1.211	0.0326
12	14.3.6	1.660	1.730	0.143	0.714	0.0390	1.184	0.0329
13	14.4.1	1.732	1.793	0.158	0.813	0.0465	1.408	0.0330
14	14.4.2	1.650	1.795	0.158	0.812	0.0440	1.340	0.0328
15	14.4.3	1.693	1.788	0.177	0.897	0.0470	1.519	0.0310
16	14.4.4	1.713	1.800	0.155	0.800	0.0465	1.371	0.0339
17	14.4.5	1.705	1.798	0.161	0.829	0.0470	1.414	0.0332
18	14.5.1	1.749	1.777	0.157	0.801	0.0460	1.400	0.0329
19	14.5.2	1.749	1.777	0.157	0.801	0.0460	1.400	0.0329
20	14.5.3	1.858	1.797	0.157	0.811	0.0485	1.506	0.0322
21	14.5.4	1.774	1.784	0.155	0.794	0.0465	1.409	0.0330
22	14.5.5	1.786	1.808	0.182	0.929	0.0500	1.658	0.0302
Mean		1.708	1.775	0.159	0.808	0.0445	1.381	0.0322
Standard Deviation		0.060	0.033	0.013	0.072	0.0042	0.143	0.0012
Maximum		1.858	1.829	0.182	0.932	0.0510	1.658	0.0339
Minimum		1.588	1.720	0.143	0.709	0.0365	1.184	0.0297

Figure 3.15 displays the resulting stress-strain curve for the group heat treated at 200°F at 5°F/min. Similarly to the curing cycle of the 180°F at a rate of 1°F/min compression specimens, the trend of the curves is reasonably consistent, but again the deviation in the elastic modulus is also visible in the plot. The elastic modulus of the bamboo compression specimens treated under a heat treatment of 200°F with a 5°F/min rate was calculated to be 487.37 KSi with a standard deviation of 14.06%. Again the deviation of the elastic modulus is greatest among all of the mechanical properties in this group, falling just under the 15% standard. The average yield stress was calculated to be 10.81 KSi with a standard deviation of 6.42% and the corresponding average yield strain was 3.73% with a standard deviation of 8.36%. The average ultimate compressive stress of this test group was 10.82 KSi with a standard deviation of 6.41% and the corresponding ultimate strain was calculated to be 3.74% with a standard deviation of 8.18%. The last mechanical property calculated was the specific strength property. The specific strength of the bamboo compressive specimens cured under a temperature of 200°F and a rate of 5°F/min was computed to be $335.76 \frac{\text{kips-in}}{\text{lbm}}$ with a standard deviation of 6.13%. A summary of the mechanical properties of this testing group can be seen in Table 3.10. Figure 3.16 also shows the failures of the 200°F, 5°F/min compression specimens.

Figure 3.15 Stress-strain curves of 200°F, 5°F/min compression specimens

Table 3.10 Mechanical Properties of 200°F, 5°F/min compression specimens

Specimen	Label	Compressive Modulus (ksi)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb _m)
1	14.1.1	462.9025	3.59822	11.36637	3.62433	11.37666	340.61856
2	14.1.2	495.9209	3.73168	11.70218	3.62468	11.72677	360.82369
3	14.1.3	593.3323	3.62632	12.09952	3.62632	12.09952	396.70557
4	14.2.1	442.375	3.97947	10.12696	3.91819	10.14184	321.96317
5	14.2.3	377.8028	4.47557	10.21399	4.49012	10.23235	319.76094
6	14.2.4	522.9106	3.87477	11.00257	3.87477	11.00257	332.40393
7	14.3.1	468.1434	4.01702	9.73118	4.04601	9.73313	327.71481
8	14.3.2	538.4969	3.87326	11.36353	3.90569	11.36744	351.93313
9	14.3.3	532.6716	3.46203	10.91134	3.50099	10.92111	359.24704
10	14.3.4	614.436	3.22259	11.60094	3.22259	11.60094	349.42590
11	14.3.5	568.7562	3.46389	11.71319	3.5857	11.71422	359.33190
12	14.3.6	391.3656	4.19383	10.71366	4.21814	10.73939	326.42523
13	14.4.1	449.5842	3.52423	10.96812	3.49477	10.97015	332.42879
14	14.4.2	470.127	3.44806	10.46007	3.44806	10.46007	318.90457
15	14.4.3	393.2859	3.68559	9.50776	3.68559	9.50776	306.70194
16	14.4.4	569.3053	3.56384	11.40017	3.4682	11.41138	336.61888
17	14.4.5	447.1463	4.18417	10.42346	4.24481	10.44892	314.72651
18	14.5.1	421.9223	3.75121	10.27672	3.75121	10.27672	312.36231
19	14.5.2	446.3392	3.84251	10.74474	3.84251	10.74474	326.58784
20	14.5.3	547.67	3.28383	10.85839	3.31671	10.86018	337.27267
21	14.5.4	537.8423	3.68253	10.8188	3.6087	10.83061	328.20030
22	14.5.5	429.7918	3.68994	9.84982	3.62727	9.86383	326.61689
Mean		487.3695	3.735207	10.81152	3.732971	10.81956	335.7625
Standard Deviation		68.51784	0.305383	0.693931	0.312155	0.693278	20.57338
Maximum		614.436	4.47557	12.09952	4.49012	12.09952	396.7056
Minimum		377.8028	3.22259	9.50776	3.22259	9.50776	306.7019

Figure 3.16 Failure modes of 200°F, 5°F/min compression specimens after compression test

3.1.3.2.5 200°F at 1°F/min Experimental Tests

The fifth heat treated group was cured at 200°F at a rate of 1°F/min set. A total of 24 compression specimens were fabricated and tested to identify the compressive properties of the cure. Again, great attention was given to each specimen to try and make all of the specimens uniform to obtain accurate results. Table 3.11 presents all of the geometries for each specimen within this group and from this table it can be seen that the geometries are precise with each deviation being below a value of 10%.

Table 3.11 200°F, 1°F/min compression testing specimen geometry

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in ³)
1	14.6.1	1.763	1.771	0.151	0.769	0.0440	1.355	0.0325
2	14.6.2	1.696	1.815	0.167	0.862	0.0440	1.462	0.0301
3	14.6.3	1.723	1.770	0.144	0.733	0.0420	1.263	0.0333
4	14.6.4	1.714	1.763	0.149	0.753	0.0420	1.291	0.0325
5	14.6.5	1.697	1.769	0.157	0.793	0.0420	1.345	0.0312
6	15.4.1	1.733	1.809	0.162	0.840	0.0535	1.454	0.0368
7	15.4.2	1.686	1.784	0.154	0.790	0.0485	1.331	0.0364
8	15.4.3	1.680	1.779	0.151	0.773	0.0495	1.299	0.0381
9	15.4.4	1.697	1.783	0.153	0.782	0.0500	1.328	0.0377
10	15.4.5	1.651	1.792	0.151	0.778	0.0480	1.285	0.0374
11	15.4.6	1.661	1.793	0.147	0.761	0.0480	1.264	0.0380
12	15.4.7	1.676	1.776	0.147	0.752	0.0485	1.261	0.0385
13	15.5.2	1.724	1.809	0.146	0.761	0.0515	1.312	0.0392
14	15.5.3	1.763	1.788	0.146	0.752	0.0530	1.325	0.0400
15	15.5.4	1.742	1.810	0.149	0.779	0.0525	1.356	0.0387
16	15.5.1	1.752	1.798	0.150	0.778	0.0530	1.362	0.0389
17	15.5.5	1.875	1.800	0.172	0.880	0.0590	1.649	0.0358
18	15.5.6	1.729	1.798	0.153	0.788	0.0530	1.362	0.0389
19	15.6.1	1.860	1.806	0.171	0.878	0.0570	1.632	0.0349
20	15.6.2	1.788	1.824	0.148	0.777	0.0555	1.389	0.0400
21	15.6.3	1.713	1.841	0.157	0.831	0.0525	1.423	0.0369
22	15.6.4	1.733	1.856	0.162	0.862	0.0525	1.494	0.0351
23	15.6.5	1.797	1.851	0.159	0.846	0.0550	1.519	0.0362
24	15.6.6	1.779	1.826	0.158	0.825	0.0560	1.468	0.0381
Mean		1.734	1.800	0.154	0.798	0.0504	1.385	0.0365
Standard Deviation		0.056	0.026	0.008	0.044	0.0049	0.108	0.0028
Maximum		1.875	1.856	0.172	0.880	0.0590	1.649	0.0400
Minimum		1.651	1.763	0.144	0.733	0.0420	1.261	0.0301

Figure 3.17 shows the stress-strain curves generated by the Bluehill 2 testing software. When viewing the stress-strain curves in the plot; it is clearly evident that the trend is consistent, with

one clear visual outlier. However, it is also clearly visible that the values of the ultimate stress are somewhat sporadic, ranging from approximately 12KSI to 15 KSI. Although, it is visible that there is a high deviation between the ultimate stress values of the specimens, the Bluehill 2 software calculated the average ultimate stress to be 13.59 KSI with a standard deviation of only 9%, which still meets the 15% standard deviation mark. The complementary average ultimate strain was calculated to be 3.9% with a standard deviation of 10.34%.

Other key mechanical properties worth noting consist of the elastic modulus, yield stress and strain, and the specific strength. The average elastic modulus determined for this test group was 623.39 KSI with a standard deviation of 11.59%, which is the highest among the mechanical properties. The average yield stress was 13.58KSI with a standard deviation of 8.96%, and the corresponding yield strain was 3.85% with a deviation of 7.89%. The specific strength of this test group was calculated to be $372.6 \frac{\text{kips-in}}{\text{lbm}}$ with a standard deviation of 4.47%. When compared to the curing cycle of the 200°F at a rate of 5°F/min, the mechanical properties of this testing group yields superior mechanical properties, which may be because the 5°F/min rate causes a thermal shock to the bamboo in the autoclave. Table 3.12 summarizes the mechanical properties of this test group. Figure 3.18 also shows the failures of the 200°F, 1°F/min compression specimens.

Figure 3.17 Stress-strain curves of 200°F, 1°F/min compression specimens

Table 3.12 Mechanical Properties of 200°F, 1°F/min compression specimens

Specimen	Label	Compressive Modulus (ksi)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb _m)
1	14.6.1	582.7547	3.88878	12.14775	3.83087	12.14875	373.80769
2	14.6.2	567.6067	3.60129	11.53257	3.60129	11.53257	383.14186
3	14.6.3	636.6509	3.65813	12.75297	3.65813	12.75297	382.97207
4	14.6.4	545.3654	3.23561	11.57813	3.35481	11.62401	357.66185
5	14.6.5	512.8695	3.7429	11.62266	3.7429	11.62266	372.52115
6	15.4.1	667.4928	3.49386	13.57058	3.52518	13.58075	369.04212
7	15.4.2	613.401	4.23834	14.25445	4.27222	14.27344	392.12747
8	15.4.3	605.4596	4.01898	14.07776	4.01898	14.07776	369.49501
9	15.4.4	757.1809	3.62206	14.83797	3.70918	14.84376	393.73369
10	15.4.5	652.1429	3.99279	14.459	4.11559	14.49117	387.46444
11	15.4.6	607.2278	4.03564	14.80181	4.15256	14.82465	390.12237
12	15.4.7	654.0022	4.20828	14.82193	4.24479	14.83393	385.29688
13	15.5.2	747.9152	3.74274	15.01912	3.76783	15.02637	383.32577
14	15.5.3	693.0045	3.98702	15.04254	4.01749	15.05631	376.40775
15	15.5.4	605.1033	4.07633	14.55023	4.07633	14.55023	375.97494
16	15.5.1	707.5408	3.73881	14.44923	3.7943	14.4773	372.16710
17	15.5.5	708.3847	3.29562	13.33006	3.37781	13.33342	372.44190
18	15.5.6	549.8044	3.99478	14.02984	3.96894	14.03934	360.90848
19	15.6.1	719.0024	3.46239	13.54265	3.54842	13.55353	388.35330
20	15.6.2	570.0618	4.16544	14.59318	4.22654	14.60246	365.06150
21	15.6.3	512.1999	4.07824	13.03482	4.07824	13.03482	353.24715
22	15.6.4	528.8627	5.24504	11.21965	3.22092	11.16859	318.19345
23	15.6.5	623.9629	4.14768	13.29782	4.14768	13.29782	367.34309
24	15.6.6	593.3316	4.01362	13.39755	4.01362	13.39755	351.64173
Mean		623.3887	3.903515	13.58184	3.852693	13.58934	372.6022
Standard Deviation		72.27014	0.40364	1.216554	0.304163	1.223284	16.63821
Maximum		757.1809	5.24504	15.04254	4.27222	15.05631	393.7337
Minimum		512.1999	3.23561	11.21965	3.22092	11.16859	318.1935

Figure 3.18 Failure modes of 200°F, 1°F/min compression specimens after compression test

3.1.3.2.6 220°F at 1°F/min Experimental Tests

The last heat treated group was cured at a temperature of 220°F at a rate of 1°F/min. a total of 21 specimens were manufacture for this group. Table 3.13 provides the dimensions of all specimens within this testing group. By looking at the table, it is clearly visible that the specimens are fairly accurate, as the standard deviation of all geometries is well below the 15% mark, with the highest deviation being the volume of the specimens at 10.43%.

Table 3.13 220°F, 1°F/min compression testing specimen geometry

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in ³)
1	15.1.1	1.685	1.682	0.146	0.704	0.0410	1.187	0.0346
2	15.1.2	1.650	1.678	0.140	0.678	0.0400	1.118	0.0358
3	15.1.3	1.568	1.677	0.140	0.676	0.0390	1.059	0.0368
4	15.1.4	1.620	1.666	0.152	0.721	0.0400	1.167	0.0343
5	15.1.5	1.561	1.677	0.144	0.692	0.0395	1.081	0.0366
6	15.1.6	1.787	1.740	0.156	0.776	0.0485	1.387	0.0350
7	15.1.7	1.737	1.669	0.141	0.678	0.0425	1.178	0.0361
8	15.1.8	1.655	1.679	0.142	0.685	0.0400	1.134	0.0353
9	15.2.1	1.786	1.718	0.164	0.801	0.0465	1.430	0.0325
10	15.2.3	1.749	1.715	0.154	0.755	0.0455	1.320	0.0345
11	15.2.4	1.737	1.741	0.150	0.748	0.0445	1.300	0.0342
12	15.2.5	1.684	1.754	0.160	0.800	0.0450	1.346	0.0334
13	15.2.6	1.720	1.737	0.151	0.750	0.0440	1.291	0.0341
14	15.2.7	1.489	1.487	0.153	0.642	0.0445	0.956	0.0466
15	15.2.8	1.759	1.735	0.151	0.753	0.0450	1.324	0.0340
16	15.3.1	1.715	1.756	0.172	0.856	0.0465	1.468	0.0317
17	15.3.2	1.690	1.764	0.157	0.790	0.0460	1.335	0.0345
18	15.3.3	1.715	1.766	0.156	0.788	0.0445	1.352	0.0329
19	15.3.4	1.657	1.757	0.155	0.781	0.0435	1.294	0.0336
20	15.3.5	1.781	1.753	0.156	0.781	0.0480	1.391	0.0345
21	15.3.6	1.577	1.764	0.157	0.791	0.0440	1.247	0.0353
Mean		1.489	1.487	0.140	0.642	0.0390	1.256	0.0351
Standard Deviation		0.082	0.063	0.008	0.055	0.0028	0.131	0.0029
Maximum		1.737	1.669	0.141	0.678	0.0425	1.468	0.0466
Minimum		1.655	1.679	0.142	0.685	0.0400	0.956	0.0317

Figure 3.19 displays the resulting stress-strain curves for the group heat treated at 220°F and a 1°F/min rate. Confidence in the data is established with the consistent trend of the curves, and only one visible outlier in Specimen 21. The average elastic modulus calculated for the 220°F curing cycle was 579.01KSI with a standard deviation of 10.18%. Again, this high deviation in the elastic modulus may be due to the end planes not being completely perpendicular to the height of the specimen or may also be caused by the large bearing stress due to the compression fixtures of the Instron machine. The average yield stress and strain was calculated to be 17.14KSI and 5.35% respectively. The average ultimate stress of the test group was calculated to be 17.16KSI with a standard deviation of 9.52%. The corresponding average ultimate strain was 5.36% with a standard deviation of 11.32%. The specific strength of the 220°F compression specimens was calculated to be $489.43 \frac{\text{kips-in}}{\text{lbm}}$ with a standard deviation of 7.14%. This is a significant increase when compared to the rest of the heat treatment curing cycles, as it is approximately 31.36% higher than the 200°F curing cycle at a rate of 1°F/min.

In summary, the mechanical properties of the 220°F heat treatment at a rate of 1°F/min yields the highest mechanical properties compared to the rest of the heat-only treatments. Along with the higher specific strength characteristic, the 220°F heat treatment also yields a higher ultimate stress, approximately 26% better than the next highest average of all the heat-only treatments. These higher mechanical properties may be explained by the reduction of bound water inside of the bamboo. Overall, the 220°F heat treatment was found to be the optimal heat treatment. Table 3.14 summarizes the mechanical properties of the 220°F compression specimens. Figure 3.20 also shows the failures of the 220°F, 1°F/min compression specimens.

Figure 3.19 Stress-strain curves of 220°F, 1°F/min compression specimens

Table 3.14 Mechanical properties 220°F, 1°F/min specimens

Specimen	Label	Compressive Modulus (ksi)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb _m)
1	15.1.1	476.4273	5.39544	16.47995	5.39544	16.47995	476.29913
2	15.1.2	618.9094	5.99524	18.11174	6.21066	18.11174	505.91453
3	15.1.3	607.6609	5.99313	18.24714	6.12069	18.24714	495.84620
4	15.1.4	640.6734	5.58506	18.48615	5.71894	18.48615	538.95481
5	15.1.5	574.9817	6.28574	18.50267	6.26701	18.50267	505.53743
6	15.1.6	592.3021	4.85881	16.36852	4.9401	16.36852	467.67200
7	15.1.7	635.2098	4.83655	17.16311	4.83655	17.16311	475.43241
8	15.1.8	640.6692	5.21838	18.03543	5.31324	18.10006	512.74958
9	15.2.1	631.0517	5.1199	16.80677	5.1199	16.80677	517.13138
10	15.2.3	624.2022	5.88682	17.97443	5.88682	17.97443	520.99797
11	15.2.4	591.5572	5.75267	17.77319	5.90145	17.81851	521.00906
12	15.2.5	506.514	4.89644	16.24594	4.89644	16.24594	486.40539
13	15.2.6	647.6529	5.18045	17.82356	5.18045	17.82356	522.68504
14	15.2.7	599.429	6.30932	20.9062	6.41649	20.93095	449.16202
15	15.2.8	538.5198	4.72442	15.4815	4.72442	15.4815	455.33824
16	15.3.1	506.6291	4.9893	15.95252	4.9893	15.95252	503.23407
17	15.3.2	540.0218	4.93765	15.69759	4.93765	15.69759	455.00261
18	15.3.3	519.6997	5.21284	14.37132	5.21284	14.37132	436.81824
19	15.3.4	452.966	5.00896	14.13197	4.15462	13.46971	400.88423
20	15.3.5	629.0684	4.71361	17.7084	4.71361	17.7084	513.28696
21	15.3.6	585.0229	5.3539	18.17654	5.57583	18.27007	517.56572
Mean		579.008	5.345459	17.16403	5.357736	17.14336	489.4251
Standard Deviation		58.96164	0.508641	1.559997	0.606541	1.638223	34.93959
Maximum		647.6529	6.30932	20.9062	6.41649	20.93095	538.9548
Minimum		452.966	4.71361	14.13197	4.15462	13.46971	400.8842

Figure 3.20 Failure modes of 220°F, 1°F/min compression specimens after compression test

3.1.3.3 *Heat-Treatments with Additives Compression Results*

The final set of investigative treatments to improve the mechanical characteristics of bamboo consisted of a thermo-treatment with additives, as described in section 2.3.3. As mentioned earlier, these groups consist of different concentrations of salt, lime, and an oil recipe. Also, with the limited number of bamboo culms available to us, only the optimal 220°F heat-treatment was utilized for the curing of the bamboo with additives.

3.1.3.3.1 3% Salt at 220°F (1°F/min) Experimental Tests

Initial heat treatment with additives group consisted of bamboo being soaked in a 3% salt solution, which is described in Section 2.3.3. A total of 13 compression specimens were manufactured within this group to determine the effects of the 3% salt solution on the mechanical properties of the bamboo. Table 3.15 provides the geometries of all the specimens manufactured for this test group, along with group's average. From this table, it may seem that the dimensions of the specimens in this test group are not very accurate. However, this is due to the fact that two different internodes from different culms were used within this group. With the standard stating that the compression specimens must be equal to the diameter of the internodes and the average diameter for internode 1.2 and 4.6 were 1.41in^2 and 1.7in^2 respectively, there was a large deviation in the weight of the 3% salt group. The standard deviation of the weight was 32.76%.

Table 3.15 3% salt 220°F, 1°F/min compression testing specimens geometry

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in ³)
1	1.2.1	1.362	1.407	0.108	0.441	0.0190	0.600	0.0317
2	1.2.3	1.344	1.416	0.109	0.446	0.0190	0.599	0.0317
3	1.2.4	1.306	1.408	0.108	0.440	0.0180	0.575	0.0313
4	1.2.5	1.340	1.415	0.113	0.461	0.0195	0.618	0.0316
5	1.2.6	1.352	1.411	0.108	0.440	0.0190	0.595	0.0319
6	1.2.7	1.344	1.386	0.110	0.440	0.0185	0.591	0.0313
7	1.2.8	1.358	1.394	0.110	0.443	0.0185	0.601	0.0308
8	1.2.9	1.388	1.404	0.107	0.436	0.0185	0.605	0.0306
9	1.2.10	1.366	1.405	0.121	0.488	0.0190	0.667	0.0285
10	4.6.1	1.647	1.707	0.164	0.794	0.0430	1.308	0.0329
11	4.6.2	1.706	1.664	0.173	0.808	0.0435	1.379	0.0316
12	4.6.3	1.694	1.700	0.174	0.834	0.0440	1.412	0.0312
13	4.6.4	1.648	1.714	0.181	0.870	0.0435	1.434	0.0303
14	4.6.5	1.603	1.717	0.173	0.839	0.0420	1.345	0.0312
Mean		1.461	1.511	0.133	0.584	0.0275	0.881	0.0312
Standard Deviation		0.156	0.148	0.031	0.190	0.0122	0.384	0.0010
Maximum		1.706	1.717	0.181	0.870	0.0440	1.434	0.0329
Minimum		1.306	1.386	0.107	0.436	0.0180	0.575	0.0285

Although compression specimens were manufactured from two different internodes, the results of the tests still show a very consistent trend, as seen in the stress-strain plot of Figure 3.21.

The average elastic modulus calculated for the 3% salt solution bamboo was 513.54KSI with a standard deviation of 5.57%. The average yield stress calculated was 14.9KSI with a standard deviation of 7.40% and the corresponding average yield strain was calculated to be 5.22% with a standard deviation of 6.13%. The average ultimate stress and strain of this group was 15.28KSi and 5.32% respectively. The ultimate stress and strain also had a standard deviation of 5.58% and 5.93% respectively. The specific strength of this test group was found to be $490.21 \frac{\text{kips-in}}{\text{lbm}}$ with a deviation of 5.57%. The results of the test are exceptional considering that bamboo is an organic material, and all deviations within this test are all below 7.5%. This also shows that the mechanical properties of two different internodes do not differ at all, as all of the curves are consistent with respect to one another. Table 3.16 displays a summary of the mechanical

properties of this test group. Figure 3.22 also shows the failures of the 3% salt compression specimens.

Figure 3.21 Stress-strain curves for 3% salt compression specimens

Table 3.16 Mechanical properties of 3% salt compression specimens

Specimen	Label	Compressive Modulus (KSI)	Yield Strain (%)	Yield Stress (KSI)	Ultimate Strain (%)	Ultimate Stress (KSI)	Specific Strength (kips-in./lb _m)
1	1.2.1	538.3765	5.25367	13.40388	5.25367	13.40388	422.83533
2	1.2.3	579.1647	5.51025	16.49306	5.472	16.51182	520.87760
3	1.2.4	511.0243	5.47631	16.3432	5.47631	16.3432	522.14696
4	1.2.5	538.3398	4.68776	14.91403	4.68776	14.91403	471.96297
5	1.2.6	496.6778	5.20686	15.3537	5.20686	15.3537	481.30721
6	1.2.7	509.215	5.12561	15.38222	5.79615	15.73316	502.65687
7	1.2.8	502.2903	4.78221	12.37501	5.08378	14.7344	478.38961
8	1.2.9	529.5094	5.00528	14.79383	5.18686	16.06686	525.06078
9	1.2.10	498.4794	5.09224	13.97301	5.09224	13.97301	490.28105
10	4.6.1	466.2423	5.95384	15.5249	5.95384	15.5249	471.88146
11	4.6.2	506.0284	5.49355	14.96671	5.49355	14.96671	473.63006
12	4.6.3	521.8249	5.27939	15.24205	5.19278	15.27479	489.57660
13	4.6.4	471.6939	5.08456	14.32329	5.43287	15.58514	514.36106
14	4.6.5	520.639	5.1821	15.53694	5.1821	15.53694	497.97885
Mean		513.5361	5.22383	14.90184	5.3222	15.28018	490.21046
Standard Deviation		28.5817	0.32033	1.10223	0.31578	0.85281	27.282171
Maximum		579.1647	5.95384	16.49306	5.95384	16.51182	525.06078
Minimum		466.2423	4.68776	12.37501	4.68776	13.40388	422.83533

Figure 3.22 Failure modes of 3% salt compression specimens after compression test

3.1.3.3.2 6% Salt at 220°F (1°F/min) Experimental Tests

The second heat treatment with additives consisted of a 6% salt solution. Again, large deviations are seen in the testing specimens because two different internodes are used. A total of 13 compression specimens were manufactured for this test group. Table 3.17 provides the geometries for the compression group.

Table 3.17 6% salt compression specimen geometries

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in ³)
1	1.3.2	1.479	1.444	0.144	0.589	0.0225	0.872	0.0258
2	1.3.3	1.495	1.451	0.115	0.481	0.0225	0.719	0.0313
3	1.3.4	1.505	1.493	0.111	0.483	0.0225	0.726	0.0310
4	1.3.5	1.503	1.459	0.112	0.475	0.0230	0.714	0.0322
5	1.3.6	1.503	1.463	0.113	0.479	0.0225	0.720	0.0312
6	1.3.7	1.496	1.466	0.114	0.484	0.0225	0.724	0.0311
7	1.3.8	1.567	1.505	0.129	0.556	0.0250	0.871	0.0287
8	1.3.9	1.468	1.471	0.116	0.492	0.0225	0.723	0.0311
9	4.10.1	1.735	1.731	0.164	0.807	0.0420	1.400	0.0300
10	4.10.2	1.671	1.719	0.151	0.746	0.0405	1.245	0.0325
11	4.10.3	1.694	1.731	0.148	0.734	0.0415	1.243	0.0334
12	4.10.4	1.675	1.723	0.147	0.726	0.0415	1.216	0.0341
13	4.10.5	1.660	1.737	0.151	0.751	0.0420	1.247	0.0337
Mean		1.573	1.569	0.132	0.600	0.0300	0.955	0.0313
Standard Deviation		0.098	0.132	0.019	0.131	0.0095	0.268	0.0022
Maximum		1.735	1.737	0.164	0.807	0.0420	1.400	0.0341
Minimum		1.468	1.444	0.111	0.475	0.0225	0.714	0.0258

Figure 3.23 displays the resulting stress-strain curve for the group treated with 6% salt. Again, although two different internodes from different culms are used, the data is still very consistent as there is a clear trend, with Specimen 1 being the only visible outlier in the plot. The elastic modulus of the 6% salt group was calculated to be 518.22KSI with a standard deviation of 6.55%. The average yield stress and strain calculated for this curing method was 14.13KSI and 4.9% respectively along with a deviation of 9.97% and 7.67%. The average ultimate stress and strain was 14.72KSI and 5.17% respectively with a standard deviation of 7.85% and 5.65%. The specific strength which normalizes the each curing method for easy comparison was calculated to be $471.65 \frac{\text{kips-in}}{\text{lbm}}$ with a standard deviation of 6.19%. When compared to the 3% salt

solution there is a slight decrease in the specific strength, indicating that an excess of salt may be trapped inside of the bamboo with the 6% salt solution, decreasing its strength. **Table 3.18** summarizes the mechanical properties of the 6% salt treatment for the compression specimens.

Figure 3.24 also shows the failures of the 6% salt compression specimens.

Figure 3.23 Stress-strain curves of 6% salt compression specimens

Table 3.18 Mechanical properties of 6% salt compression specimens

Specimen	Label	Compressive Modulus (KSI)	Yield Strain (%)	Yield Stress (KSI)	Ultimate Strain (%)	Ultimate Stress (KSI)	Specific Strength (kips-in./lb _m)
1	1.3.2	453.7123	4.35578	11.12639	5.20255	11.56429	448.22829
2	1.3.3	526.6109	4.51139	13.56203	5.06839	14.31027	457.19712
3	1.3.4	573.9645	4.49359	13.45953	4.83532	15.08807	486.71194
4	1.3.5	526.1362	4.39642	12.24137	4.90176	13.67977	424.83758
5	1.3.6	558.6998	4.69332	13.2393	5.12503	14.71557	471.65288
6	1.3.7	491.2636	5.24577	14.74894	5.08191	14.81531	476.37653
7	1.3.8	520.3932	5.19639	14.73517	5.19639	14.73517	513.42056
8	1.3.9	524.1514	4.91069	15.72624	4.91069	15.72624	505.66688
9	4.10.1	558.4187	4.87198	15.15994	4.87198	15.15994	505.33133
10	4.10.2	520.2003	5.4001	15.81519	5.66365	16.13648	496.50708
11	4.10.3	503.4455	4.89767	13.67666	5.34549	14.87565	445.37874
12	4.10.4	485.4998	5.35094	14.7748	5.72118	15.09767	442.74692
13	4.10.5	494.4146	5.34361	15.4134	5.34361	15.4134	457.37092
Mean		518.2239	4.89751	14.12915	5.17446	14.71675	471.64821
Standard Deviation		33.26957	0.38375	1.40298	0.28432	1.12595	28.257388
Maximum		573.9645	5.4001	15.81519	5.72118	16.13648	513.42056
Minimum		453.7123	4.35578	11.12639	4.83532	11.56429	424.83758

Figure 3.24 Failure modes of 6% salt compression specimens after compression test

3.1.3.3.3 9% Salt at 220°F (1°F/min) Experimental Tests

The last group among the salt treated sets was the bamboo soaked in the 9% salt solution. A total of 14 specimens were manufactured to determine the mechanical properties of the 9% salt treatment. Although, two different internodes were used for these tests the geometries of the specimens are still very accurate with all geometries under the 15% standard deviation mark. Table 3.19 provides a summary of the geometries for the 9% salt compression specimens.

Table 3.19 9% salt compression specimen geometries

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lbf)	Volume (in. ³)	Density (lb _m /in ³)
1	5.4.2	1.551	1.510	0.138	0.596	0.0315	0.924	0.0341
2	5.4.3	1.503	1.517	0.133	0.577	0.0310	0.867	0.0358
3	5.4.4	1.536	1.530	0.138	0.603	0.0310	0.925	0.0335
4	5.4.5	1.531	1.538	0.141	0.620	0.0320	0.948	0.0337
5	5.4.6	1.551	1.519	0.137	0.595	0.0310	0.922	0.0336
6	5.4.7	1.526	1.520	0.135	0.587	0.0310	0.896	0.0346
7	5.4.8	1.489	1.557	0.147	0.651	0.0320	0.970	0.0330
8	8.2.1	1.731	1.615	0.136	0.633	0.0403	1.095	0.0368
9	8.2.2	1.663	1.595	0.125	0.579	0.0380	0.962	0.0395
10	8.2.3	1.662	1.602	0.126	0.586	0.0390	0.973	0.0401
11	8.2.4	1.642	1.602	0.130	0.603	0.0390	0.990	0.0394
12	8.2.5	1.613	1.620	0.133	0.622	0.0390	1.004	0.0388
13	8.2.6	1.665	1.587	0.127	0.581	0.0385	0.967	0.0398
14	8.2.7	1.664	1.596	0.124	0.573	0.0375	0.953	0.0394
Mean		1.595	1.565	0.134	0.600	0.0351	0.957	0.0366
Standard Deviation		0.076	0.041	0.007	0.023	0.0039	0.054	0.0028
Maximum		1.731	1.620	0.147	0.651	0.0403	1.095	0.0401
Minimum		1.489	1.510	0.124	0.573	0.0310	0.867	0.0330

Figure 3.25 shows the resulting stress-strain curves calculated from the Bluehill 2 testing software. From this plot it is seen that the trends of the stress-strain curves are very consistent. The average elastic modulus of the 9% salt solution was 585.03KSI with a standard deviation of 7.23%. However, visually looking at the graph one can see that Specimen 9 is a clear outlier for the elastic modulus outperforming the rest. By excluding the elastic modulus data for Specimen 9, the average elastic modulus would be 575.27KSI with a standard deviation of 6.56%. The

average yield stress and strain were 17.04KSI and 5.44% respectively with a standard deviation of 13.93% and 5.05%. The average ultimate stress calculated for this test group was 17.21KSI with a standard deviation of 15.97% and the corresponding ultimate strain was 5.44 with a standard deviation of 5.17%. The specific strength value calculated for the 9% salt solution was $471.58 \frac{kips-in}{lbm}$ with a standard deviation of 5%. Figure 3.26 also shows the failures of the 9% salt compression specimens.

Figure 3.25 Stress-strain curves of 9% salt compression specimens

Table 3.20 Mechanical properties of 9% salt compression specimens

Specimen	Label	Compressive Modulus (KSI)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb _m)
1	5.4.2	563.2668	5.32167	16.69827	5.32167	16.69827	489.68534
2	5.4.3	554.4088	5.0545	13.92982	5.3089	15.97262	446.16257
3	5.4.4	591.5635	5.20704	16.09925	5.33983	16.259	485.34328
4	5.4.5	588.1623	5.34618	16.47529	5.34618	16.47529	488.88101
5	5.4.6	566.6646	5.67974	16.72575	5.67974	16.72575	497.79018
6	5.4.7	572.7606	5.79896	16.8663	5.79896	16.8663	487.46532
7	5.4.8	499.7694	5.44523	16.54197	5.44523	16.54197	501.27182
8	8.2.1	524.1916	5.17229	16.08087	5.17229	16.08087	436.98016
9	8.2.2	711.9053	5.1723	18.80064	5.1723	18.80064	475.96557
10	8.2.3	577.9169	5.35098	17.44553	5.35098	17.44553	435.05062
11	8.2.4	614.8897	5.59852	17.61967	5.5356	17.67105	448.50381
12	8.2.5	565.0349	5.88739	17.15695	5.67289	17.21734	443.74588
13	8.2.6	631.0634	5.71488	18.67147	5.57628	18.78008	471.86131
14	8.2.7	628.8448	5.4696	19.43921	5.4696	19.43921	493.38096
Mean		585.0316	5.444234	17.03936	5.442175	17.21242	471.5777
Standard Deviation		51.44112	0.257916	1.367836	0.190222	1.093466	24.20571
Maximum		711.9053	5.88739	19.43921	5.79896	19.43921	501.2718
Minimum		499.7694	5.0545	13.92982	5.17229	15.97262	435.0506

Figure 3.26 Failure modes of oil compression specimens after compression test

3.1.3.3.4 Lime at 220°F (1°F/min) Experimental Tests

The following additive used to cure the bamboo was a 5% Bonide hydrated lime solution.

Details of the recipe of this solution can be seen in Section 2.3.3. A total of 12 compression specimens were manufactured to find the mechanical properties of the specified cure. Table 3.21 shows the geometries for the lime compression samples. The standard deviation of all geometries within this group was kept below 6%, well below the 15%.

Table 3.21 Lime compression specimen testing geometries

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in. ³)
1	10.3.2	1.418	1.514	0.151	0.647	0.0330	0.917	0.0360
2	10.3.3	1.504	1.450	0.145	0.595	0.0350	0.895	0.0391
3	10.3.4	1.495	1.500	0.140	0.598	0.0335	0.894	0.0375
4	10.3.5	1.382	1.547	0.149	0.654	0.0335	0.904	0.0371
5	10.3.6	1.492	1.515	0.152	0.651	0.0330	0.972	0.0340
6	13.2.1	1.623	1.605	0.147	0.673	0.0355	1.091	0.0325
7	13.2.2	1.518	1.587	0.136	0.621	0.0325	0.942	0.0345
8	13.2.3	1.587	1.598	0.133	0.612	0.0340	0.971	0.0350
9	13.2.4	1.561	1.598	0.133	0.611	0.0335	0.953	0.0351
10	13.2.5	1.570	1.597	0.129	0.596	0.0340	0.935	0.0364
11	13.2.6	1.474	1.604	0.136	0.628	0.0325	0.926	0.0351
12	13.2.7	1.538	1.613	0.141	0.654	0.0345	1.005	0.0343
Mean		1.513	1.561	0.141	0.628	0.0337	0.946	0.0355
Standard Deviation		0.069	0.054	0.008	0.027	0.0009	0.056	0.0018
Maximum		1.623	1.613	0.152	0.673	0.0355	1.091	0.0391
Minimum		1.382	1.450	0.129	0.595	0.0325	0.894	0.0325

Figure 3.27 displays the resulting stress-strain curves for the compression specimens cured in the lime solution. When looking at the stress-strain curves one may notice that the curves exhibit sporadic behavior throughout with one clearly defined visible outlier in Specimen 1. The reason for this sporadic behavior may be explained by the non-precise geometries of this test group with the end planes not being completely parallel to the compression fixtures or may also be due to the natural curvature in the bamboo specimens. Although, it is clearly visible that the data of the lime specimens was not as consistent as the other curing treatmentstests, the data

was not far off from being considered great data. The elastic modulus of the test specimens was calculated to be 555.54KSI with a standard deviation of 16.55%, which is just outside the 15% mark. The ultimate stress values yielded more consistent results as the Bluehill 2 software calculated the ultimate stress to be 15.59KSI with a standard deviation of only 8.42%, which is well under the 15% standard. The corresponding ultimate strain was determined to be 5.42% with a standard deviation of 8.35%. The yield stress and strain were calculated to be 15.54KSI and 5.22% respectively and also had a 8.42% and 15.85% standard deviation. The large standard deviation of the yield strain is due to the Specimen 1 outlier. Excluding specimen 1 the yield strain would be 5.03% with a standard deviation of 10.49%. The specific strength of the lime compression group was calculated to be $439.31 \frac{\text{kips-in}}{\text{lbm}}$ with a standard deviation of 10.49%. Table 3.22 summarizes the mechanical properties of the lime compression group. Figure 3.28 also shows the failures of the lime compression specimens.

Figure 3.27 Stress-strain curves of lime compression specimens

Table 3.22 Mechanical properties of lime compression specimens

Specimen	Label	Compressive Modulus (ksi)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb _m)
1	10.3.2	418.0487	7.29808	13.48884	6.80477	13.66308	379.53000
2	10.3.3	523.3095	5.58948	16.4525	5.91422	16.64937	425.81509
3	10.3.4	585.5738	5.78474	16.85254	5.78474	16.85254	449.40107
4	10.3.5	463.5909	5.7525	15.63458	5.93619	15.7239	423.82480
5	10.3.6	619.6666	4.92339	16.17901	4.92339	16.17901	475.85324
6	13.2.1	590.8437	4.71359	16.77202	4.71359	16.77202	516.06215
7	13.2.2	532.5172	4.07358	13.23209	6.68456	13.26378	384.45739
8	13.2.3	754.2402	4.71964	16.53153	4.55702	16.65955	475.98714
9	13.2.4	568.97	4.70177	15.19159	4.70177	15.19159	432.80883
10	13.2.5	597.8939	5.22538	15.71463	5.22538	15.71463	431.72060
11	13.2.6	581.5028	5.08982	16.5304	5.08982	16.5304	470.95157
12	13.2.7	430.3171	4.70806	13.90352	4.70806	13.90352	405.35044
Mean		555.5395	5.215003	15.54027	5.420293	15.59195	439.3135
Standard Deviation		91.948	0.826483	1.307956	0.787425	1.302073	40.37552
Maximum		754.2402	7.29808	16.85254	6.80477	16.85254	516.0622

Figure 3.28 Failure modes of lime compression specimens after compression test

3.1.3.3.5 Oil at 220°F (1°F/min) Experimental Tests

The last additive used to cure the bamboo in addition with the heat-treatment was oil. A total of 13 compression specimens were manufactured to obtain the mechanical properties of the oil curing treatment. Table 3.23 provides the geometries of the specimens tested for the specified cure. Each specimen was manufactured with great precision as all standard deviations of the geometries are below 6%.

Table 3.23 Oil compression specimen testing geometries

Specimen	Label	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Area (in. ²)	Weight (lb _f)	Volume (in. ³)	Density (lb _m /in. ³)
1	6.1.1	1.475	1.506	0.127	0.550	0.0280	0.812	0.0345
2	6.1.2	1.456	1.509	0.121	0.529	0.0275	0.770	0.0357
3	6.1.3	1.481	1.581	0.127	0.578	0.0285	0.856	0.0333
4	6.1.4	1.398	1.508	0.125	0.541	0.0265	0.756	0.0350
5	6.1.5	1.454	1.519	0.124	0.545	0.0275	0.792	0.0347
6	6.1.6	1.449	1.504	0.125	0.542	0.0280	0.785	0.0357
7	7.2.1	1.448	1.470	0.136	0.570	0.0280	0.825	0.0339
8	7.2.2	1.492	1.537	0.149	0.648	0.0285	0.967	0.0295
9	7.2.3	1.447	1.485	0.133	0.566	0.0275	0.819	0.0336
10	7.2.4	1.400	1.487	0.138	0.586	0.0275	0.820	0.0335
11	7.2.5	1.369	1.482	0.136	0.575	0.0265	0.786	0.0337
12	7.2.6	1.445	1.498	0.140	0.595	0.0280	0.860	0.0326
13	7.2.7	1.438	1.520	0.143	0.617	0.0280	0.888	0.0315
Mean		1.442	1.508	0.133	0.572	0.0277	0.826	0.0336
Standard Deviation		0.035	0.029	0.008	0.034	0.0006	0.057	0.0017
Maximum		1.492	1.581	0.149	0.648	0.0285	0.967	0.0357
Minimum		1.369	1.470	0.121	0.529	0.0265	0.756	0.0295

Figure 3.29 displays the resulting stress-strain curve for the group treated with oil. The slopes of the curves all appear to be very consistent with the exception of the Specimen 2, colored in green. The figure displays a consistent linear elastic region across all specimens, yielding an elastic modulus value of 535.04KSI and a 8.42% standard deviation. The ultimate stress and strain values were calculated to be 15.30KSI and 5.86% respectively, along with a standard deviation of 7.49% and 6.10%. The yield stress was equated to be 14.90KSI with a standard deviation of 9.38% and the corresponding yield strain value was 5.63% with a 7.21% deviation.

The specific strength of the oil cured bamboo was determined to be $455.32 \frac{\text{kips-in}}{\text{lbm}}$ with a

standard deviation of 6.34%. Overall, the data of the oil compression specimens was very accurate with all deviations of the mechanical properties being under 10%. Table 3.24 displays the mechanical properties of each specimen within this group along with its averages. Figure 3.29 also shows the failures of the oil compression specimens.

Table 3.24 Mechanical Properties of oil compression specimens

Specimen	Label	Compressive Modulus (KSI)	Yield Strain (%)	Yield Stress (KSI)	Ultimate Strain (%)	Ultimate Stress (KSI)	Specific Strength (kips-in./lb_m)
1	6.1.1	538.928	5.48296	14.08805	6.10653	15.64575	453.50000
2	6.1.2	536.4895	6.45591	13.15043	6.5627	13.64993	382.35098
3	6.1.3	510.237	5.41333	14.38515	5.97735	14.86475	446.38889
4	6.1.4	551.7009	5.19545	15.95165	5.37045	16.00398	457.25657
5	6.1.5	505.8645	5.63611	15.96006	5.63611	15.96006	459.94409
6	6.1.6	612.94	5.90703	17.3885	5.90703	17.3885	487.07283
7	7.2.1	588.8467	5.48389	15.67257	5.48389	15.67257	462.31770
8	7.2.2	501.5958	5.25395	14.26256	5.25395	14.26256	483.47661
9	7.2.3	539.9849	5.21641	14.1916	5.88012	15.15181	450.94673
10	7.2.4	585.3551	5.94414	16.22204	5.94414	16.22204	484.24000
11	7.2.5	512.908	6.27325	16.08798	6.19961	16.14377	479.04362
12	7.2.6	532.7865	5.6376	13.67982	5.82252	14.77157	453.11564
13	7.2.7	437.896	5.29121	12.69128	6.05636	13.21563	419.54381
Mean		535.041	5.630095	14.90244	5.861597	15.30407	455.3229
Standard Deviation		45.02889	0.405937	1.397586	0.357286	1.145556	28.84699
Maximum		612.94	6.45591	17.3885	6.5627	17.3885	487.0728
Minimum		437.896	5.19545	12.69128	5.25395	13.21563	382.351

Figure 3.29 Failure modes of oil compression specimens after compression test

3.1.4 Failure Analysis Under Compression

As seen from all of the figures, the different type of failures that were identified for all of the compression tests were both due to compression loading. These failure modes are displayed in Figure 3.30 and Figure 3.31. As mentioned earlier, the compression specimens experienced a large bearing stress due to the compression fixtures. This large bearing stress accounted for the first material failure as seen in Figure 3.30. The second material failure of the compression specimens was due to the longitudinal splitting of the compression specimens, as seen in Figure 3.31. More often times than not the longitudinal splitting of the compression specimens were concentrated on one side of the bamboo. This suggests that the end faces of the specimens are not completely perpendicular to the heights of each specimen.

Figure 3.30 Failure due to bearing stress

Figure 3.31 Failure due to longitudinal splitting

Figure 3.32 Bearing stress of green compression specimen

In analyzing the failures of each compression group it was apparent that the failure of each specimen was dependent on two things; the height of the specimen and the curing treatment. Short compression specimens (1.4"-1.55") predominantly experienced a large bearing stress, as larger specimens failed more due to longitudinal splitting. Not only did the height matter, but the curing treatment also played a large role in how the specimen would fail. For the green bamboo tests, which had an average height of 1.498" mainly experienced significant bearing

stress. However, the bearing stress of the green compression specimens differed slightly from the bearing stress of the heat treated groups, as the wall of the green compression specimens would begin to peel back instead of compressing within itself. This splitting of the green compression specimens' exterior wall may be due to the moisture inside of the bamboo.

Figure 3.33 shows the bearing stress of the green compression specimens. Another trend seen in analyzing the failures is that longitudinal splitting is more evident in the higher thermo treatments. This may be due to the higher temperatures making the bamboo material more brittle, causing the bamboo to fail from longitudinal splitting. However, the additive compression groups that were cured under 220°F all failed due to significant bearing stress, which may be due to micro-voids inside of the fiber being filled and increasing the structural density of the material.

3.1.5 Mechanical Behavior Comparison Between The Different Treatments

To find the optimal treatment, the first step was to analyze all of the data. Table 3.25 summarizes the mechanical properties of the control bamboo along with the heat treatments without any additives. By looking at the table, one can easily see that there are significant advantages to heat treating the bamboo when wanting to increase the structural performance of the bamboo material. Barring the 150°F, 5°F/min heat-treatment, all heat-treatments significantly raised the mechanical properties of the bamboo compared to the control group. A possible explanation of the poor performance of the 150°F curing treatment may be because the moisture content of the specified cure did not reach the fiber saturation point, where the extraction of the bound water occurs. As mentioned earlier, the mechanical properties of the bamboo are dependent on the moisture that is inside the bamboo material, and is particularly dependent on the amount of bound water in the bamboo. If the bound water is not extracted

from the bamboo, it is understood that the mechanical properties of the bamboo material will not change.

Table 3.25 Summary of thermo treated test results

Test Group	Compressive Modulus (ksi)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb_m)
Green (control)	441.9733	3.852648	9.357038	3.851406	9.336893	222.6326
150°F (5°F/min)	446.2145	3.68899	8.850476	3.765179	8.869971	239.2672
180°F (5°F/min)	544.0509	3.307559	10.25688	3.317936	10.25688	285.5959
180°F (1°F/min)	479.6842	9.441692	10.27958	4.227089	10.45068	302.6017
200°F (5°F/min)	487.3695	3.735207	10.81152	3.732971	10.81956	335.7625
200°F (1°F/min)	623.3887	3.903515	13.58184	3.852693	13.58934	372.6022
220°F (1°F/min)	579.008	5.345459	17.16403	5.357736	17.14336	489.4251

A trend in the table also shows that heat treating the bamboo at higher temperature yields better mechanical properties, as there is a steady increase in all mechanical properties, excluding the modulus. The reason that the elastic modulus does not follow the same trend and are more sporadic may be because higher heat treatments make the bamboo more brittle, or the end planes of the specimens are not completely parallel with the compression fixtures. However, it must be noted that these trends will only stay true until the thermal degradation point is reached, which in this study is never reached due to the autoclave being incapable to sustain a heat treatment higher than 220°F. Compared to the “green” control group, the 220°F at 1°F/min increased the specific strength and ultimate stress by 120% and 84% respectively.

Another trend noticed within this table is that heat treating the bamboo at lower rates increases the mechanical properties at the specified temperature. Although, there is not significant

increases in the mechanical properties, results have shown that bamboo that is cured at a rate of 1°F/min yields better results than bamboo cured at 5°F/min. When comparing the specific strength of the bamboo cured at 200°F with a rate of 1°F/min and 5°F/min, the 1°F/min rate outperforms the higher rate by 11%. When comparing the ultimate stress, the 1°F/min rate yields a 25.6% increase when compared to the 5°F/min rate. This trend may imply that curing the bamboo at higher rates will cause a thermal shock to the bamboo and ultimately lead to a form of thermal degradation.

As mentioned earlier, due to the limited bamboo, the heat treatment with additives were all cured at the optimal heat treatment of 220°F at a rate of 1°F/min. Table 3.26 summarizes the results of all thermo treatments with additives along with a comparison to the control and the no additive 220°F heat treatment.

Table 3.26 Summary of additive test results

Test Group	Compressive Modulus (ksi)	Yield Strain (%)	Yield Stress (ksi)	Ultimate Strain (%)	Ultimate Stress (ksi)	Specific Strength (kips-in./lb _m)
Green (control)	441.9733	3.852648	9.357038	3.851406	9.336893	222.6326
3% salt	513.5361	5.22383	14.90184	5.3222	15.28018	490.21046
6% salt	518.2239	4.89751	14.12915	5.17446	14.71675	471.64821
9% salt	585.0316	5.444234	17.03936	5.442175	17.21242	471.5777
Lime	555.5395	5.215003	15.54027	5.420293	15.59195	439.3135
Oil	535.041	5.630095	14.90244	5.861597	15.30407	455.3229

From Table 3.26, one can see that there are some pros and cons to curing the bamboo with additives. When evaluating the three salt solutions, the trends are not as straightforward as the trend seen when comparing the different heat treatments. In analyzing the elastic modulus

of the three salt treatments, it is understood from the results that curing the bamboo under a higher concentration of salt yields higher elastic modulus, signifying that the material becomes stiffer. However, when analyzing the specific strength of the salt solutions, there is an opposite trend to the elastic modulus, with 3% having the highest values. Although for the ultimate stress and yield stress there is no trend when comparing the three salt solutions. This may be because the bamboo in the 6% salt solution was tainted slightly by the mold of the weights that were placed in the curing solution to help submerge the bamboo internodes under the solution. In comparison to all of the additives the 9% solution outperformed the rest in almost every single category except for the specific strength. Compared to the control the 9% salt solution raised the elastic modulus by over 32% and raised the ultimate stress by over 84%. For the specific strength, the 3% salt solution was victorious as the modulus increased by 120% compared to the control group.

3.2 Tension Parallel to Grain

3.2.1 Preparation of Tensile Test Coupons

The tensile properties of the yellow groove bamboo were determined for each curing method utilizing the ISO 22157 standard test- “Bamboo- Determination of Physical and Mechanical Properties”.⁵ Each tensile specimen was carefully handcrafted to meet the standards of ISO 22157.

One of the most difficult procedures in obtaining the tensile properties was the manufacturing of

each test piece. Due to the natural roundness of the bamboo, it was almost impossible to cut the bamboo to the suggested specimen dimensions of the ISO 22157 standard. For this reason, a smaller scaled version of the suggested specimen dimensions was fabricated. For the tensile tests a dog-bone shape coupon is suggested, as seen in Figure 3.33.

Preparation of the tensile test pieces began by cutting the bamboo pole parallel to the grain with a Rigid wet tile saw in eight identical strips, as seen in Figure 3.34. Once the eight identical strips were made from each bamboo pole, the strips were then cut down to a length of six inches as seen in Figure 3.35 and Figure 3.36.

Figure 3.33 Tensile specimens were manufactured into dog-bone specimens

Figure 3.34 Internodes were first cut into eight identical strips

Figure 3.35 Specimens were cut down to 6 inches with Rigid Tile saw.

Figure 3.36 Results of specimens after cut by tile saw

Once the test coupons were cut to length, the test coupons were then taken to the belt sander, where they were sanded down in an attempt to make all of the test coupons uniform and achieve a length, width, and thickness of 6 in. X 0.6 in. X 0.12 in. respectively. Once the test pieces were cut into rectangular coupons, the middle section of the specimen was then necked down with the belt sander and Dremel to a width of 0.2in. as seen in Figure 3.37, resembling a dog bone shape.

Figure 3.37 Specimens were sanded to obtain a dog-bone shape

The gage length of each tensile specimen was approximately 2in. An important note is that when sanding the test pieces to obtain a uniform shape, only the inside of the fiber wall should be sanded, as the strength of the inner side of the bamboo is significantly weaker than the outer skin of the bamboo. Figure 3.38 illustrates the dimensions of each tensile testing coupon. Figure 3.39 shows the results of the tensile coupons tested.

Figure 3.38 Dimension of tensile test specimens

Figure 3.39 Actual experimental test specimens

3.2.2 Testing Procedures

A minimum of 12 testing coupons were prepared for each bamboo curing method to remain within the standards of ISO 22157. Tensile tests were performed using the Instron 8801 Servohydraulic Fatigue Testing System in the Cal Poly Aerospace Structures/Composites Laboratory and is controlled by Instron's Bluehill 2 software on an attached controller and data acquisition computer. The test fixture applies pressure to the coupon using wedge grips that provide a shear contacting force. Due to the low crushability of the bamboo, the pressure of the wedge grips was set to its minimal setting of 100 psi to prevent

the bamboo test coupon from splitting near the grips and influence the failure of the test coupon at the neck. The test coupons were then loaded into the machine, perpendicular to the grips as seen in Figure 3.40. Before testing began the dimensions of each specimen was inputted into the Bluehill 2 software to calculate the stress and strain from the load and extension data provided by the Instron 8801 machine. The test was then conducted using a

Figure 3.40 Tensile test specimens were loaded perpendicular to the grips

cross-head speed of .0004 in/min and the testing ended when a 40% drop in applied load occurred.

3.2.3 Tensile Tests, Results, and Discussion

This research presents a study of the mechanical properties of the bamboo without any treatment, with heat treatments, and with additives. A total of nine different tensile groups were tested to try and find the optimal curing treatment. With the standard ISO 22157 necessitating a minimum of 12 specimens due to the natural characteristics of bamboo, each group contains a range of 15 to 30 test coupons. Due to the costs of the bamboo, the 150°F and 5°F/min rate heat treatments mentioned in section 2.3 were omitted from tensile testing and were only evaluated under compression loads.

3.2.3.1 *Green Bamboo Experimental Tests*

Initial tensile tests began with the control case, in which no treatments were done to the bamboo, maintaining its “green” state. The “green” testing coupons were prepared following the method discussed in section 3.2.1. A total of 15 specimens were manufactured to test and determine the mechanical tensile properties of the “green” control case. Table 3.27 summarizes all of the specimens’ dimensions prior to testing to account for any anomalies that may exist in the results of the tensile tests. It must be noted that all dimensions listed in Table 3.27 except the weight corresponds to the gage area of the test specimen and not the full specimen. The average gage length, width, and thickness was each measured using an electronic caliper that had a tolerance of ± 0.001 ". The weight of each specimen was measured using an Adam Equipment electronic scale that had a tolerance of ± 0.0005 lb_f.

Table 3.27 Green tensile specimen geometries

Specimen	Label	Length (in)	Width (in)	Thickness (in)	Area (in^2)	Weight (lbf)	Volume	Density
1	1.1.1	1.202	0.231	0.165	0.038	0.0135	0.0457	0.2956
2	1.1.2	1.230	0.195	0.147	0.029	0.0120	0.0357	0.3364
3	1.1.3	1.217	0.243	0.148	0.036	0.0130	0.0438	0.2967
4	1.1.4	1.231	0.250	0.155	0.039	0.0135	0.0480	0.2812
5	1.1.5	1.227	0.223	0.146	0.033	0.0120	0.0405	0.2964
6	1.1.6	1.206	0.247	0.140	0.035	0.0125	0.0422	0.2961
7	1.1.7	1.241	0.255	0.164	0.042	0.0130	0.0521	0.2494
8	1.1.8	1.206	0.240	0.142	0.034	0.0120	0.0410	0.2927
9	1.1.9	1.224	0.241	0.144	0.035	0.0120	0.0428	0.2801
10	1.1.10	1.201	0.241	0.155	0.037	0.0130	0.0444	0.2925
11	1.1.12	1.235	0.201	0.153	0.031	0.0115	0.0383	0.3004
12	1.1.13	1.205	0.200	0.157	0.031	0.0125	0.0374	0.3346
13	1.1.14	1.187	0.210	0.145	0.030	0.0125	0.0356	0.3510
14	1.1.15	1.220	0.223	0.143	0.032	0.0115	0.0390	0.2946
15	1.1.16	1.225	0.165	0.157	0.026	0.0125	0.0319	0.3925
Mean		1.217	0.224	0.151	0.034	0.0125	0.0412	0.0125
Standard Deviation		0.015	0.025	0.008	0.004	0.00064	0.0052	0.0006
Maximum		1.241	0.255	0.165	0.042	0.0135	0.0521	0.0135
Minimum		1.187	0.165	0.142	0.026	0.0115	0.0319	0.0115

The cross sectional gage area (A_g) of each specimen was calculated using Equation 3.8

$$A_g = w_g * t_g \quad (3.8)$$

Where w_g is the width of the gage length and t_g is the thickness of the gage length.

Subsequently, the gage volume (V_g) is calculated utilizing Equation 3.9

$$V_g = A_g * l_g \quad (3.9)$$

Where l_{gage} is the gage length. The density (ρ) for each tensile specimen is then calculated using Equation 3.10

$$\rho = \frac{m}{V_g} \quad (3.10)$$

where m is the total mass of each specimen. However, it must be noted that the density calculated is not definite. This is because the mass pertains to the whole specimen, while the

volume only applies to the gage. The reason that density had to be calculated this way is because there was not a way to measure the weight of the gage area without cutting the specimen and losing mass.

As seen in Table 3.27, the geometric dimensions of the “green” tensile group differ by less than 12%, not including the weight of each specimen. As mentioned earlier, because bamboo is an organic material, a standard deviation of anything less than 5% is extremely difficult.

Each testing coupon yielded a load-extension curve, and subsequent stress-strain curve were generated using the dimensions inputted in the Bluehill2 software. The stress (σ) was determined by utilizing Equation 3.11

$$\sigma = \frac{F}{A_g} \quad (3.11)$$

in which F is the load and A is the measured cross sectional gage area of the tensile coupon.

Strain(ϵ) is determined utilizing Equation 3.12

$$\epsilon = \frac{\Delta L}{L} \quad (3.12)$$

Where ΔL is the change in length of the necking portion of the coupon specimen and L is the original length of the necking portion of the coupon.

To generate stress-strain plots, the stress and strain were measured throughout the test. Following the obtainment of the stress-strain plots after each test, the elastic tensile modulus of the test specimens was then calculated by finding the slope of the first linear region on the stress-strain curve.

Figure 3.41 Typical stress-strain curves for ductile and brittle material

Figure 3.41 shows the response of a brittle material compared to the response of a ductile material. One can see from the figure that the red line shows the ductile material and the blue line represents the stress strain curve for a brittle material. With a conventional ductile material, like a metal, the linear portion of the curve is the

elastic region and the slope is the modulus of elasticity. After the curve reaches the yield stress, the curve enters the plastic region, decreasing slightly and then increasing again on account of strain hardening, until reaching the ultimate strength. After reaching the ultimate strength, there is then a necking portion that forms where the cross sectional area decreases quickly until the material becomes unstable and ruptures. Brittle materials, on the other hand do not have a yield point or show any plastic deformation, and instead fail while the deformation is elastic. Figure 3.42 shows the stress-strain curve of the control specimens. By looking at the stress-strain curves of the bamboo, one can see that the stress-strain curves that the tensile specimens generate do not follow the conventional stress strain plot nor do they follow the stress-strain plots of the brittle material and instead represent a combination of both. In the elastic portion of the tensile stress-strain curve, it follows the trends of both the brittle and ductile stress-strain plots. The average modulus of elasticity calculated for the 15 “green” tensile specimens was 812.86KSI with a standard deviation of 15.40%, which is slightly out of the 15% mark, but is still respectable considering that bamboo is a natural product. After the curve exits the elastic portion, it peaks and then has a slight decrease in strength, shooting straight down like a brittle material. This peak is considered to be where the yield stress or first failure occurs for the bamboo material. The average yield stress or average first failure of the “green bamboo” was

23.23KSI and had a standard deviation of 8.44%. The corresponding average first failure or yield strain was 3.82%. Following the slight decrease of the stress-strain curve, the curve then does something unique, as it begins to increase, which is uncommon for a brittle material. However, it does not act like a conventional curve either as the bamboo material does not experience any type of strain hardening, as it increases linearly until reaching the ultimate failure mode. After reaching the ultimate failure mode, the load drops straight down similar to how a brittle material would fail. The average ultimate stress of the “green” bamboo tensile specimens was 26.04KSI with a standard deviation of 11.67%. The corresponding ultimate failure or second failure strain was 5.21%.

Figure 3.42 Stress-strain curves of "green" tensile tests

In addition to the mechanical properties that are obtained from the stress-strain curve, an additional variable specific strength is added in order to normalize data and compare the data among all of the curing methods. The specific strength is calculated in the same fashion as compression with equation 3.7. However, it must be noted that the density used in this calculation for the tensile samples was taken from the same specified cure of the compression specimens, because the density calculation of the tensile specimens was very difficult because

of the dog-bone shape. The average specific strength for the green bamboo was 621.64

$\frac{\text{Kips-in}}{\text{lbm}}$, with a standard deviation of 11.67%. **Table 3.28** presents the complete mechanical properties of the “green” bamboo loaded under axial loading. Figure 3.43 and Figure 3.44 also show the failures of the green tensile coupons.

Table 3.28 Mechanical properties of green tensile specimens

Specimen	Label	Tensile Modulus (KSI)	Yield Stress (<i>First Failure</i>) (KSI)	Yield Strain (%)	Ultimate Tensile Stress (KSI)	Ultimate Strain (%)	Specific Strength (kips-in./lb _m)
1	1.1.1	578.100	22.660	5.340	25.110	6.910	599.284
2	1.1.2	785.860	24.400	3.680	25.740	4.560	614.320
3	1.1.3	718.200	24.930	4.480	30.000	6.760	715.990
4	1.1.4	699.250	21.760	3.920	26.070	6.030	622.196
5	1.1.5	614.760	24.440	4.870	23.120	6.700	551.790
6	1.1.6	778.380	24.390	3.990	28.160	5.960	672.076
7	1.1.7	717.390	19.470	3.210	20.400	3.870	486.874
8	1.1.8	943.130	21.140	2.800	23.300	3.540	556.086
9	1.1.9	949.430	25.250	3.510	30.630	5.250	731.026
10	1.1.10	854.180	23.630	3.530	25.800	5.030	615.752
11	1.1.12	885.780	26.700	5.570	26.580	5.190	634.368
12	1.1.13	858.320	21.120	3.490	21.400	3.330	510.740
13	1.1.14	931.580	22.740	2.850	29.370	5.750	700.955
14	1.1.15	912.510	21.410	2.740	28.440	4.710	678.759
15	1.1.16	966.080	24.380	3.370	26.580	4.600	634.368
Mean		812.863	23.228	3.823	26.047	5.213	621.639
Standard Deviation		125.206	1.958	0.886	3.036	1.141	72.464
Maximum		966.080	26.700	5.570	30.630	6.910	731.026
Minimum		578.100	19.470	2.740	20.400	3.330	486.874

Figure 3.43 Failure modes of green tensile coupons after tensile test

Figure 3.44 Failure modes of green tensile coupons after tensile test

3.2.3.2 ***Thermo-Treatment Tensile Experimental Tests***

Similar to the compression tests, the first group of curing methods to improve the mechanical characteristics of the bamboo is the heat treated groups. This first set of specimens will have no additives added to the structure of the bamboo and will be cured solely by heat. Unlike the compression tests however, only three different temperature cures will be investigated due to the scarcity of bamboo present in the Cal Poly Structures/Composites Lab. The thermo-treatments that will be investigated are 180°F, 200°F, and 220°F with all temperatures being cured at a rate of one degree per minute, because anything higher than this rate may cause thermal shock to the bamboo.

3.2.3.3 ***180°F (1°F/min) Experimental Tests***

The opening heat treatment tested was at 180°F at a rate of one degree per minute. A total of 12 tensile specimens were tested to determine the mechanical properties of this method of cure. Table 3.29 shows the complete dimensions of each specimen. From the table, it can be seen that the geometric dimensions are fairly accurate, differing only by less than 12%, with some dimensions being as low as 3%. Although 12% may sound high, because bamboo is a natural material, any standard deviation below 15% is considered good.

Table 3.29 180°F, 1°F/min Tensile compression specimen geometries

Specimen	Label	Length (in)	Width (in)	Thickness (in)	Area (in ²)	Weight (lbf)	Volume	Density
1	16.3.1	1.991	0.1566	0.11733	0.01838	0.007	0.036599	0.19126
2	16.3.2	1.998	0.197	0.12	0.02364	0.0075	0.047233	0.15879
3	16.3.3	1.994	0.166	0.113	0.01876	0.0075	0.037403	0.20052
4	16.3.4	2.002	0.208	0.108	0.02246	0.007	0.044973	0.15565
5	16.3.5	1.998	0.18967	0.119	0.02257	0.007	0.045096	0.15523
6	16.3.6	1.998	0.1896	0.119	0.02257	0.0075	0.045096	0.16631
7	16.3.7	1.989	0.19034	0.11267	0.02144	0.0065	0.042655	0.15239
8	16.3.8	1.988	0.181	0.115	0.02082	0.0065	0.04138	0.15708
9	16.3.9	2.001	0.204	0.116	0.02366	0.007	0.047352	0.14783
10	16.3.10	2.01	0.23	0.12	0.0276	0.0075	0.055476	0.13519
11	16.3.11	1.981	0.18633	0.112	0.02087	0.0075	0.041341	0.18141
12	16.3.12	1.99	0.17233	0.12133	0.02091	0.007	0.041609	0.16823
Mean		1.995	0.18925	0.11611	0.02197	0.00713	0.043838	0.16416
Standard Deviation		0.00775	0.01967	0.00406	0.00244	0.00038	6.19E-07	0.01871
Maximum		2.01	0.23	0.12133	0.0276	0.0075	0.056091	0.20052
Minimum		1.996	0.18967	0.11667	0.02195	0.007	0.044169	0.15793

Figure 3.45 shows the stress-strain curves from the Bluehill 2 software, which is generated by using the dimensions of each specimen along with their corresponding force-extension curves. One may observe that the curves do follow a precise trend, very similar to the force-extension curves. However, there are a couple visible outliers in this data, as a couple of specimens seemed to fail prematurely. An explanation of these outliers could be because there were minor deficiencies in the test specimens such as small cracks near the jaw because of the clamping force or can also be because of the non-uniform geometries.

The average elastic modulus calculated by the Bluehill 2 testing software was 1356 KSI with a standard deviation of 12.67%. The average yield stress was 27.16 KSI with a standard deviation of 17.38 % and the corresponding yield strain was 2.32% with a deviation of 21.12 %. The average ultimate stress of the bamboo was 30.69 KSI with a standard deviation of 16.62%. The corresponding ultimate strain was 2.76% and a standard deviation of 18.48%. Table 3.30 summarizes the mechanical properties of the 180°F tensile specimens. The specific strength property of the specified treatment was calculated to be $887 \frac{\text{Kips-in}}{\text{lbm}}$ with a standard deviation of

16.60%. This high deviation may be caused by the non-uniform geometries of the test specimens within this group. The 180°F thermo-treatment showed a significant increase in the mechanical properties lending confidence that a thermo treatment is necessary when optimizing the structural properties of bamboo. Figure 3.46 also shows the failures of the 180°F tensile coupons.

Figure 3.45 Stress-strain curves of 180°F tensile specimens

Table 3.30 Mechanical properties of 180°F tensile specimens

Specimen	Label	Tensile Modulus (KSI)	<i>Yield Stress</i> (KSI)	Yield Strain (%)	Ultimate Tensile Stress (KSI)	Ultimate Strain (%)	Specific Strength (kips-in./lb _m)
1	16.3.1	1692.520	25.670	1.570	35.704	2.399	1031.912
2	16.3.2	1211.922	28.804	2.862	30.095	3.153	869.801
3	16.3.3	1468.033	30.596	2.319	38.856	3.456	1122.992
4	16.3.4	1261.158	21.692	1.909	29.121	2.822	841.634
5	16.3.5	1295.812	24.923	2.683	32.432	3.498	937.333
6	16.3.6	1458.417	31.831	2.404	34.653	2.849	1001.542
7	16.3.7	1396.177	35.645	2.932	35.645	2.932	1030.214
8	16.3.8	1183.938	25.600	2.633	25.856	2.760	747.292
9	16.3.9	1285.038	30.571	2.790	30.571	2.790	883.553
10	16.3.10	1066.965	21.071	2.147	21.192	2.449	612.492
11	16.3.11	1530.771	29.088	2.065	29.088	2.065	840.692
12	16.3.12	1423.569	20.475	1.469	25.069	1.924	724.533
Mean		1356.193	27.164	2.315	30.690	2.758	886.999
Standard Deviation		171.774	4.719	0.493	5.096	0.513	147.289
Maximum		1692.520	35.645	2.932	38.856	3.498	1122.992
Minimum		1066.965	20.475	1.469	21.192	1.924	612.492

Figure 3.46 Failure modes of 180°F tensile coupons after tensile test

3.2.3.4 200°F (1°F/min) Experimental Tests

The following thermo-treatment test conducted was heat-treated to 200°F at a rate of one degree per minute. A total of 12 specimens were manufactured and tested to find the tensile mechanical properties of the specified bamboo cure. Great care was given to each specimen when manufacturing each tensile test specimen, in efforts to try and keep each tensile test piece uniform. Table 3.31 shows the dimensions of each specimen tested and by looking at the table, one can see that the dimensions of the test specimens were accurate as all dimensions yielded a standard deviation of less than 12%.

Table 3.31 200°F tensile specimen geometries

Specimen	Label	Length (in)	Width (in)	Thickness (in)	Area (in ²)	Weight (lbf)	Volume	Density
1	16.2.1	1.987	0.185	0.129	0.02386	0.0075	0.04742	0.15816
2	16.2.2	1.988	0.18133	0.121	0.02194	0.008	0.043619	0.18341
3	16.2.3	2	0.19033	0.11	0.02094	0.0075	0.041873	0.17911
4	16.2.4	1.968	0.18467	0.119	0.02198	0.008	0.043248	0.18498
5	16.2.5	1.992	0.2	0.129	0.0258	0.008	0.051394	0.15566
6	16.2.6	1.982	0.221	0.116	0.02564	0.007	0.050811	0.13777
7	16.2.7	2.007	0.20433	0.116	0.0237	0.0075	0.04757	0.15766
8	16.2.8	2.009	0.15133	0.12	0.01816	0.0075	0.036483	0.20557
9	16.2.9	1.998	0.195	0.114	0.02223	0.008	0.044416	0.18012
10	16.2.10	2.016	0.17833	0.119	0.02122	0.0085	0.042782	0.19868
11	16.2.11	1.98	0.208	0.11	0.02288	0.0075	0.045302	0.16555
12	16.2.12	1.992	0.18167	0.117	0.02126	0.0065	0.042341	0.15352
Mean		1.99325	0.19008	0.11833	0.02247	0.00763	0.044833	0.17168
Standard Deviation		0.01359	0.0177	0.0061	0.00212	0.00053	1.47E-06	0.02016
Maximum		2.016	0.221	0.129	0.0258	0.0085	0.057474	0.20557
Minimum		1.992	0.18767	0.118	0.0221	0.0075	0.044113	0.17233

Figure 3.47 shows the stress-strain curves generated by the Bluehill 2 software, and by looking at the curves, one can see that the curves do follow a fairly precise trend and seem to fracture at a strain of approximately 2.9%, given a standard deviation of less than 6%. However, there is some sporadic behavior of the curve, as the average ultimate stress calculated by the Bluehill 2 software was 32.79KSI, and had a standard deviation of approximately 17.4%, higher than the 15% standard. An explanation of this irregular high standard deviation can be due to the non-uniform wall thickness or the natural notches grown on some of the bamboo material. The

natural notches may have caused stress concentration points on the tensile coupons, causing a couple of the specimens to fail prematurely.

Other important material properties to note consist of the elastic modulus, the yield stress, the yield strain, and the specific strength. The average elastic modulus determined was 1390.22KSI with a standard deviation of 13.75%. The average yield stress was 30.46KSI with a standard deviation of 21.14%, and the corresponding yield strain was 2.52% with a deviation of 19.84%. The reason that the average yield stress is so high is because of the inconsistent failures of the test specimens, as some of the test specimens never experience a yield stress failure, and instead proceeds straight to an ultimate stress. Examples of this can be seen in specimens three, four, and 10. If these were to be excluded from the yield stress data, the average yield stress would result to be 27.57KSI with a standard deviation of 13.02%. The average specific strength of the 200°F thermo-treatment, which normalizes the data for all of the curing methods for comparison, was calculated to be $898.25 \frac{\text{Kips-in}}{\text{lbm}}$ with standard deviation of 17.38%. This is a slight increase compared to the 180°F thermo treatment, providing a small advantage to the increased thermo-treatment temperature. Table 3.32 summarizes the mechanical properties of the 200°F tensile specimens. Figure 3.48 and Figure 3.49 also show the failures of the 200°F tensile coupons.

Figure 3.47 Stress-strain curves of 200°F tensile specimens

Table 3.32 Mechanical properties of 200F tensile specimens

Specimen	Label	Tensile Modulus (KSI)	<i>Yield Stress</i> (KSI)	Yield Strain (%)	Ultimate Tensile Stress (KSI)	Ultimate Strain (%)	Specific Strength (kips-in./lb _m)
1	16.2.1	1158.723	23.998	2.351	24.911	2.794	682.501
2	16.2.2	1480.460	28.965	2.041	34.081	3.086	933.722
3	16.2.3	1371.652	34.375	2.959	34.375	2.959	941.780
4	16.2.4	1512.289	38.695	3.098	38.695	3.098	1060.131
5	16.2.5	1195.571	28.189	3.010	28.189	3.010	772.312
6	16.2.6	1129.802	21.048	1.977	25.148	2.715	688.982
7	16.2.7	1319.111	30.610	2.729	31.475	2.998	862.343
8	16.2.8	1703.196	26.746	1.646	37.481	2.792	1026.881
9	16.2.9	1462.659	32.292	2.428	34.723	3.024	951.300
10	16.2.10	1707.443	44.391	3.165	44.391	3.165	1216.191
11	16.2.11	1336.698	30.669	2.674	30.669	2.674	840.242
12	16.2.12	1304.997	25.575	2.105	29.298	2.708	802.672
Mean		1390.217	30.463	2.515	32.786	2.919	898.255
Standard Deviation		191.098	6.439	0.500	5.716	0.172	156.611
Maximum		1707.443	44.391	3.165	44.391	3.165	1216.191
Minimum		1129.802	21.048	1.646	24.911	2.674	682.501

Figure 3.48 Failure modes of 200°F tensile coupons after tensile test

Figure 3.49 Failure modes of 200°F tensile coupons after tensile test

3.2.3.5 220°F (1°F/min) Experimental Tests

The final thermo-treatment was conducted at 220°F at a rate of one degree per minute. A total of 32 tensile test specimens were manufactured to determine the mechanical properties of this curing method. Table 3.33 shows the dimensions of each specimen using the 220°F cure. When looking at the table of the dimensions of each specimen, it is clearly visible that the group of specimens had a very high standard deviation. Although, much care was given to each specimen, because of the naturalness, it is very difficult to make each specimen uniform. In this case the reason that the standard deviation was high was because of the natural thickness of the different bamboos poles tested under this curing method.

Table 3.33 220°F tensile specimen geometries

Specimen	Label	Length (in)	Width (in)	Thickness (in)	Area (<i>in</i> ²)	Weight (lbf)	Volume	Density
1	17.2	1.982	0.224	0.12566	0.02815	0.0105	2.680952	0.055789
2	17.3	1.853	0.24267	0.105	0.02548	0.01	2.548	0.047215
3	17.4	2.041	0.214	0.10733	0.02297	0.009	2.552222	0.046879
4	17.5	1.927	0.22767	0.11067	0.0252	0.01	2.52	0.048553
5	17.6	1.994	0.24167	0.117	0.02828	0.0105	2.693333	0.056381
6	xx.1	1.934	0.21067	0.125	0.02633	0.009	2.925556	0.050929
7	XX.3	1.925	0.19667	0.102	0.02006	0.008	2.5075	0.038616
8	XX.6	1.936	0.20367	0.126	0.02566	0.009	2.851111	0.049682
9	XX.7	1.928	0.191	0.127	0.02426	0.009	2.695556	0.046767
10	XX.8	1.875	0.229	0.114	0.02611	0.0085	3.071765	0.048949
11	16.4.1	1.986	0.23	0.119	0.02737	0.0115	2.38	0.054357
12	16.4.2	1.978	0.197	0.142	0.02797	0.012	2.330833	0.055333
13	16.4.3	1.983	0.213	0.129	0.02748	0.0125	2.1984	0.054487
14	16.4.4	1.962	0.212	0.128	0.02688	0.0125	2.1504	0.052739
15	16.4.5	1.978	0.197	0.142	0.02797	0.012	2.330833	0.055333
16	16.4.6	1.964	0.207	0.123	0.02546	0.0095	2.68	0.050005
17	16.4.7	1.96	0.193	0.133	0.02567	0.0105	2.444762	0.050311
18	16.4.8	1.994	0.216	0.125	0.027	0.0115	2.347826	0.053838
19	17.3.1	1.994	0.205	0.0953	0.01954	0.008	2.4425	0.038956
20	17.3.2	1.962	0.183	0.103	0.01885	0.0065	2.912	0.036982
21	17.3.3	1.956	0.202	0.108	0.02182	0.0075	2.909333	0.042672
22	17.3.4	1.977	0.196	0.106	0.02078	0.0065	3.196923	0.041074
23	17.3.5	1.981	0.19467	0.106	0.02063	0.0065	3.173846	0.040878
24	17.3.6	1.976	0.19267	0.107	0.01927	0.008	2.40875	0.038072
25	17.3.7	1.976	0.192	0.113	0.0192	0.007	2.742857	0.037939
26	17.3.8	1.977	0.18333	0.103	0.01888	0.0075	2.517333	0.037332
27	17.3.9	1.966	0.19033	0.099	0.01884	0.007	2.691429	0.037045
28	17.3.11	1.963	0.196	0.09967	0.01953	0.006	3.255	0.038348
29	17.3.12	1.977	0.19967	0.10434	0.02083	0.008	2.60375	0.041188
30	17.3.13	1.996	0.19867	0.10167	0.0202	0.007	2.885714	0.040317
31	17.3.14	1.968	0.182	0.11267	0.02051	0.0075	2.734667	0.040356
32	17.3.15	1.987	0.19	0.09367	0.0178	0.007	2.542857	0.035363
Mean		1.96425	0.20467	0.11353	0.02328	0.00892	2.653563	0.045642
Standard Deviation		0.03549	0.01635	0.01352	0.00357	0.00196	0.283714	7.85E-06
Maximum		2.041	0.24267	0.142	0.02828	0.0125	3.255	0.070331
Minimum		1.976	0.19917	0.10933	0.02361	0.00875	2.1504	0.043028

Figure 3.50 shows the stress-strain curves of the bamboo treated under a 220°F thermo-treatment. When looking at the stress-strain curves for the 220°F bamboo specimens, it is

evident that the trends are consistent. However, with the inconsistent dimensions of each specimen in this group, the yield stress and strain resulted in high deviations as the yield stress and strain were 29.65KSI and 1.71% respectively with a standard deviation of 18.75% and 19.30%. Other explanations of this high deviation may be because of the inconsistent failures of the specimens, as some of the specimen experience a couple of drops in load, instead of having one defined drop on the load to determine where the yield is. Another reason of the high deviation may also be because of the pre-mature failures of the tensile specimens caused by the clamping forces of the grips. The 220°F thermo-treatment also yielded an average ultimate stress and strain value of 40.19KSI and 2.88% respectively, with a standard deviation of 12.62% and 17.71%. The average tensile elastic modulus calculated for the 220°F group was 1866.09KSI with a standard deviation of only 5.67% and the average specific strength was calculated to be $1146.53 \frac{\text{Kips-in}}{\text{lbm}}$ with a standard deviation of 12.62%. Table 3.34 illustrates the mechanical properties of each 220°F specimen tested and its averages. Figure 3.51 also shows the failures of the 220°F tensile coupons.

Figure 3.50 Stress-strain curves of 220°F tensile specimens

Table 3.34 Mechanical properties of 220°F tensile specimens

Specimen	Label	Tensile Modulus (KSI)	<i>Yield Stress</i> (KSI)	Yield Strain (%)	Ultimate Tensile Stress (KSI)	Ultimate Strain (%)	Specific Strength (kips-in./lb _m)
1	17.2	1708.043	36.631	2.268	42.324	3.400	1207.540
2	17.3	1866.615	24.797	1.390	37.568	2.526	1071.832
3	17.4	2079.091	32.412	1.729	41.886	1.692	1195.051
4	17.5	1819.839	22.053	1.274	39.596	3.067	1129.690
5	17.6	1729.595	35.341	2.167	41.349	3.217	1179.721
6	xx.1	1740.888	25.224	1.495	40.288	3.384	1149.432
7	XX.3	2131.902	37.569	1.858	50.271	3.220	1434.263
8	XX.6	1803.145	26.017	1.692	28.300	2.138	807.411
9	XX.7	1935.495	29.120	1.592	37.262	2.873	1063.112
10	XX.8	1903.371	12.609	0.717	34.150	2.345	974.333
11	16.4.1	1947.361	33.677	1.860	47.506	3.710	1355.392
12	16.4.2	1779.063	31.544	1.959	31.544	1.959	899.981
13	16.4.3	1899.999	28.761	1.601	34.744	2.530	991.262
14	16.4.4	1905.164	34.145	1.938	43.442	3.377	1239.421
15	16.4.5	1864.301	36.221	2.245	36.221	2.245	1033.400
16	16.4.6	1890.045	22.563	1.311	33.791	2.453	964.091
17	16.4.7	1793.349	21.963	1.299	35.273	2.293	1006.372
18	16.4.8	2009.851	37.006	1.995	44.732	3.221	1276.224
19	17.3.1	1995.976	36.209	2.122	43.668	3.023	1245.891
20	17.3.2	1831.377	26.852	1.571	37.450	2.425	1068.462
21	17.3.3	1760.318	27.830	1.648	37.861	2.887	1080.213
22	17.3.4	1626.069	23.091	1.522	36.953	3.102	1054.304
23	17.3.5	1850.051	33.780	2.021	45.942	3.520	1310.751
24	17.3.6	1827.642	33.613	2.074	40.586	2.858	1157.942
25	17.3.7	1860.596	27.879	1.544	43.970	3.269	1254.513
26	17.3.8	1905.540	30.109	1.640	42.898	3.222	1223.912
27	17.3.9	1930.626	32.961	1.802	42.452	3.001	1211.193
28	17.3.11	1776.872	29.364	1.712	39.014	3.009	1113.102
29	17.3.12	1912.623	30.323	1.668	45.586	3.210	1300.593
30	17.3.13	1878.265	30.772	1.977	37.180	2.353	1060.762
31	17.3.14	1799.113	27.280	1.581	42.938	2.921	1225.061
32	17.3.15	1952.675	31.237	1.661	49.199	3.376	1403.681
Mean		1866.089	29.655	1.707	40.186	2.868	1146.53
Standard Deviation		105.895	5.558	0.333	5.073	0.508	144.74
Maximum		2131.902	37.569	2.268	50.271	3.710	1434.26
Minimum		1626.069	12.609	0.717	28.300	1.692	807.41

Figure 3.51 Failure modes of 220°F tensile coupons after tensile test

3.3 Thermo Treatment with Additives Tensile Results

The final group of investigative treatments to improve the mechanical characteristics of the bamboo consisted of a thermo-treatment with additives, described in section 2.3.3. Due to the costs of the bamboo, it was decided that the thermo treatment with additives would be done using only the optimal thermo-treatment, instead curing the bamboo with additive at different treatments. With the 220°F heat treatment far exceeding the other two thermo-treatments mentioned in the last section, the 220°F was chosen for all additives, which include a 3%, 6%, and 9% salt solution, an oil solution, and a hydrated lime solution.

3.3.1 3% Salt Experimental Tests

The first thermo-treatment group with additives consisted of bamboo being soaked in a 3% salt solution described in 2.3.3. A total of 29 specimens were fabricated to determine the effect that the 3% salt solution might have on the mechanical properties of the bamboo. Table 3.35 shows the dimensions of each tensile specimen cured with the 3% salt solution. Looking at the table, one can see that the measured dimensions of each test specimen are fairly accurate, disregarding the weight, as it has a deviation of approximately 16% and may be caused by a combination of the deviation in width and thickness.

Table 3.35 3% salt tensile specimen geometries

Specimen	Label	Length (in)	Width (in)	Thickness (in)	Area (<i>in</i> ²)	Weight (lbf)	Volume	Density
1	3.2.1	2.00	0.21067	0.118	0.02486	0.008	0.049718	0.16091
2	3.2.2	2.00	0.20633	0.134	0.02765	0.0075	0.055296	0.13563
3	3.2.3	2.005	0.199667	0.113	0.02256	0.007	0.045238	0.15474
4	3.2.5	2.002	0.201	0.114	0.02291	0.0075	0.045874	0.16349
5	3.2.6	2.017	0.197	0.121	0.02384	0.0075	0.048079	0.15599
6	3.2.7	2.00	0.189	0.114	0.02155	0.008	0.043092	0.18565
7	3.2.8	2.00	0.201	0.116	0.02332	0.0075	0.046632	0.16083
8	3.2.9	2.00	0.193	0.117	0.02258	0.009	0.045162	0.19928
9	3.2.10	2.025	0.226	0.121	0.02735	0.008	0.055376	0.14447
10	3.2.11	1.978	0.212	0.13133	0.02784	0.009	0.055071	0.16342
11	3.2.12	2.013	0.23	0.11867	0.02729	0.0085	0.054943	0.15471
12	3.2.13	2.00	0.206	0.121	0.02493	0.0075	0.049852	0.15045
13	3.2.14	1.995	0.20333	0.112	0.02277	0.0075	0.045432	0.16508
14	3.2.15	2.00	0.168	0.11667	0.0196	0.005	0.039201	0.12755
15	3.2.16	2.00	0.18467	0.119	0.02198	0.0065	0.043951	0.14789
16	2.2.1	1.987	0.208	0.108	0.02246	0.008	0.044636	0.17923
17	2.2.2	1.989	0.193	0.112	0.02162	0.0075	0.042994	0.17444
18	2.2.3	2.008	0.20267	0.11	0.02229	0.008	0.044766	0.17871
19	2.2.4	1.995	0.208	0.10667	0.02219	0.0075	0.044264	0.16944
20	2.2.5	1.998	0.18167	0.113	0.02053	0.008	0.041016	0.19505
21	2.2.6	1.991	0.186	0.10067	0.01872	0.0075	0.037281	0.20118
22	4.9.1	2.023	0.234	0.12967	0.03034	0.0105	0.061383	0.17106
23	4.9.2	2.018	0.199	0.14	0.02786	0.011	0.056221	0.19565
24	4.9.3	1.994	0.18133	0.13	0.02357	0.01	0.047004	0.21274
25	4.9.4	1.993	0.19667	0.125	0.02458	0.0105	0.048995	0.21431
26	4.9.5	2.004	0.19567	0.13967	0.02733	0.01	0.054768	0.1826
27	4.9.6	2.035	0.19067	0.138	0.02631	0.0095	0.053546	0.17742
28	4.9.7	1.991	0.19767	0.128	0.0253	0.009	0.050376	0.17866
29	4.9.8	2.013	0.183	0.138	0.02525	0.0095	0.050836	0.18687
Mean		2.00255	0.19948	0.12087	0.02412	0.00829	0.048284	0.17198
Standard Deviation		0.01243	0.01462	0.01062	0.00279	0.00133	1.93E-06	0.02174
Maximum		2.035	0.234	0.14	0.03034	0.011	0.066667	0.21431
Minimum		2	0.199	0.11867	0.02357	0.008	0.047231	0.17106

Figure 3.52 shows the stress strain curves of the bamboo treated with the 3% salt solution. The stress-strain curves shown in Figure 3.52 illustrate a persistent trend, with only a couple of pre-mature failures caused by small cracks in the bamboo due to the clamping force of the grips near the test. These pre-mature failures could have been because of the high standard deviation seen in the mechanical properties of the 3% salt solution.

The average elastic modulus calculated for the 3% salt solution was 1612.68KSI with a standard deviation of 8.12%. The yield stress and strain calculated for this cure was 32.11KSI and 2.18% respectively, along with a deviation of 11.52% and 17.89% and the ultimate stress and strain were calculated to be 36.99KSI and 2.86% respectively with a standard deviation of 13.90% and 19.58%. The specific strength variable, which normalizes each curing method for comparison was calculated to be $1186.47 \frac{\text{Kips-in}}{\text{lbm}}$ with a standard deviation of 13.80%. Table 3.36 shows the mechanical properties of the 3% salt solution. Figure 3.53 also shows the failures of the 3% salt tensile coupons.

Figure 3.52 Stress-strain curves of 3% salt tensile specimens

Table 3.36 Mechanical properties of 3% salt tensile specimens

Specimen	Label	Tensile Modulus (KSI)	<i>Yield Stress</i> (KSI)	Yield Strain (%)	Ultimate Tensile Stress (KSI)	Ultimate Strain (%)	Specific Strength (kips-in./lb _m)
1	3.2.1	1639.970	1.638	31.629	2.307	0.161	1014.411
2	3.2.2	1345.020	3.019	35.201	3.019	0.136	1128.962
3	3.2.3	1690.820	1.785	28.753	1.785	0.155	922.161
4	3.2.5	1507.390	2.186	34.937	2.677	0.163	1120.480
5	3.2.6	1527.420	1.956	35.509	2.738	0.156	1138.831
6	3.2.7	1627.670	1.697	27.764	2.073	0.186	890.442
7	3.2.8	1595.580	1.868	32.739	2.674	0.161	1050.011
8	3.2.9	1666.500	1.826	36.769	2.804	0.199	1179.252
9	3.2.10	1436.990	2.297	31.442	2.634	0.144	1008.401
10	3.2.11	1382.610	2.369	35.021	3.014	0.163	1123.202
11	3.2.12	1472.090	2.632	42.168	3.452	0.155	1352.401
12	3.2.13	1552.220	2.215	41.271	3.491	0.150	1323.633
13	3.2.14	1665.950	1.910	31.297	2.824	0.165	1003.744
14	3.2.15	1440.120	2.357	36.237	2.907	0.128	1162.184
15	3.2.16	1378.370	3.303	43.398	3.854	0.148	1391.862
16	2.2.1	1698.360	1.798	37.464	2.391	0.179	1201.542
17	2.2.2	1672.870	2.275	35.942	2.526	0.174	1152.712
18	2.2.3	1732.900	2.457	42.497	3.139	0.179	1362.954
19	2.2.4	1706.090	1.755	36.174	2.643	0.169	1160.183
20	2.2.5	1732.760	2.281	40.913	2.915	0.195	1312.172
21	2.2.6	1832.640	1.926	37.683	2.527	0.201	1208.560
22	4.9.1	1724.670	2.348	45.172	3.843	0.171	1448.730
23	4.9.2	1629.140	2.008	31.130	2.008	0.196	998.391
24	4.9.3	1719.510	2.015	47.997	4.136	0.213	1539.352
25	4.9.4	1823.020	2.329	45.814	3.331	0.214	1469.340
26	4.9.5	1548.020	2.240	38.515	3.244	0.183	1235.242
27	4.9.6	1616.000	1.973	38.939	3.145	0.177	1248.832
28	4.9.7	1691.710	1.958	32.548	2.127	0.179	1043.880
29	4.9.8	1711.390	2.684	37.906	2.684	0.187	1215.723
Mean		1612.683	2.182	36.994	2.859	0.172	1186.469
Standard Deviation		131.011	0.394	5.135	0.564	0.022	164.704
Maximum		1832.640	3.303	47.997	4.136	0.214	1539.352
Minimum		1345.020	1.638	27.764	1.785	0.128	890.442

Figure 3.53 Failure modes of 3% salt tensile coupons after tensile test

3.3.2 6% Salt Experimental Tests

The second thermo treatment with additives solution consists of a 6% salt solution. A total of 15 tensile specimens were manufactured to determine the tensile mechanical properties of the bamboo using this method of cure. Table 3.37 provides the geometries of the specimens tested in the 6% salt solution. Looking at the table, one can see that the tensile specimens tested for the 6% solution were made with precision as the standard deviation for all geometries is less than 10%, which is very good when considering a natural material.

Table 3.37 6% salt tensile specimen geometries

Specimen	Label	Length (in)	Width (in)	Thickness (in)	Area (in^2)	Weight (lbf)	Volume	Density
1	1.1.1	2.01	0.213	0.11	0.02343	0.0065	0.047094	0.13802
2	1.1.2	1.975	0.206	0.11	0.02266	0.007	0.044754	0.15641
3	1.1.3	1.998	0.195	0.105	0.02048	0.007	0.040909	0.17111
4	1.1.4	2.009	0.217	0.115	0.02496	0.007	0.050135	0.13962
5	1.1.5	2.07	0.226	0.114	0.02576	0.007	0.053331	0.13125
6	1.1.6	1.982	0.22293	0.119	0.02653	0.007	0.05258	0.13313
7	1.1.7	1.964	0.212	0.109	0.02311	0.0065	0.045384	0.14322
8	1.1.8	1.995	0.238	0.11333	0.02697	0.0075	0.05381	0.13938
9	1.1.9	2.002	0.23	0.1063	0.02445	0.0065	0.048947	0.1328
10	1.1.10	1.984	0.21	0.109	0.02289	0.0065	0.045414	0.14313
11	1.1.12	1.954	0.23533	0.11	0.02589	0.0075	0.050582	0.14827
12	1.1.13	2.006	0.218	0.1133	0.0247	0.007	0.049547	0.14128
13	1.1.14	1.989	0.24833	0.11833	0.02938	0.008	0.058447	0.13688
14	1.1.15	1.99	0.211	0.111	0.02342	0.007	0.046608	0.15019
15	1.1.16	2.00	0.263	0.11	0.02893	0.007	0.05786	0.12098
Mean		1.9952	0.22304	0.11155	0.0249	0.007	0.049641	0.14171
Standard Deviation		0.02624	0.01762	0.00396	0.00241	0.00042	1.83E-06	0.01177
Maximum		2.07	0.263	0.119	0.02938	0.008	0.064785	0.17111
Minimum		1.995	0.218	0.11	0.0247	0.007	0.04784	0.13962

Figure 3.54 illustrates the stress-strain curves of the 6% salt solutions. Evaluating the stress-

strain curves, it is evident that all of the specimens are very consistent. The average elastic modulus calculated for the 6% salt solution was 1355.43KSI with a standard deviation of 7.03%.

The yield stress and strain calculated for this cure was 26.37KSI and 2.08% respectively, along with a deviation of 11.15% and 8.65% and the ultimate stress and strain were calculated to be 29.78KSI and 2.58% respectively with a standard deviation of 8.16% and 7.75%. The specific

strength variable, was calculated to be $953.04 \frac{\text{Kips-in}}{\text{lbm}}$ with a standard deviation of 8.16%. Table 3.38 shows the mechanical properties of the 3% salt solution. The persistent trends of the stress-strain curve are also evident in the standard deviations of the mechanical properties, as each deviation is below 12%, under the desirable 15%. Compared to the 3% salt solution cure there is a slight decrease in the mechanical properties, which may be caused by the immersion of too much salt trapped inside the bamboo, decreasing the strength. Figure 3.55 also shows the failures of the 6% salt tensile coupons.

Figure 3.54 Stress-strain curves of 6% salt tensile specimens

Table 3.38 Mechanical properties of 6% salt tensile specimens

Specimen	Label	Tensile Modulus (KSI)	<i>Yield Stress</i> (KSI)	Yield Strain (%)	Ultimate Tensile Stress (KSI)	Ultimate Strain (%)	Specific Strength (kips-in./lb _m)
1	1.1.1	1399.241	26.636	2.084	30.487	2.500	975.571
2	1.1.2	1441.173	32.367	2.423	35.732	2.854	1143.420
3	1.1.3	1495.087	28.140	1.969	33.521	2.622	1072.673
4	1.1.4	1367.715	26.981	2.125	29.255	2.528	936.162
5	1.1.5	1415.534	24.732	1.896	28.756	2.432	920.191
6	1.1.6	1412.295	27.998	2.146	29.689	2.475	950.040
7	1.1.7	1544.389	31.235	2.187	31.235	2.187	999.501
8	1.1.8	1353.803	25.883	2.005	29.372	2.542	939.912
9	1.1.9	1331.818	26.109	2.234	31.433	2.872	1005.861
10	1.1.10	1234.264	22.670	1.937	30.114	3.035	963.630
11	1.1.12	1221.823	25.914	2.249	27.639	2.628	884.452
12	1.1.13	1298.946	22.721	1.841	27.607	2.578	883.421
13	1.1.14	1306.723	22.305	1.796	25.821	2.463	826.260
14	1.1.15	1308.251	28.831	2.376	28.831	2.376	922.592
15	1.1.16	1200.425	23.044	2.003	27.248	2.651	871.940
Mean		1355.432	26.371	2.085	29.783	2.583	953.042
Standard Deviation		95.354	2.940	0.181	2.431	0.205	77.803
Maximum		1544.389	32.367	2.423	35.732	3.035	1143.420
Minimum		1200.425	22.305	1.796	25.821	2.187	826.260

Figure 3.55 Failure modes of 6% salt tensile coupons after tensile test

3.3.2.1 9% Salt Experimental Tests

The final salt solution consisted of treating the bamboo with a 9% salt solution. Fourteen total tensile specimens were manufactured to determine the tensile mechanical properties using this method of cure. Table 3.39 provides the geometries of the specimens tested using the 9% salt solution. Looking at the table, one can see that the tensile specimens tested for the 9% solution were made with precision as the standard deviation for all geometries is 13%, much less than the 15% standard.

Table 3.39 9% salt tensile specimen geometries

Specimen	Label	Length (in)	Width (in)	Thickness (in)	Area (in ²)	Weight (lbf)	Volume	Density
1	5.1.2	2.008	0.221	0.121	0.02674	0.009	0.053696	0.16761
2	5.1.4	1.989	0.243	0.12467	0.03029	0.009	0.060256	0.14937
3	5.1.5	1.903	0.18367	0.118	0.02167	0.0085	0.041244	0.20609
4	5.1.6	2	0.195	0.117	0.02282	0.0075	0.04563	0.16437
5	5.1.7	2.007	0.209	0.13	0.02717	0.009	0.05453	0.16505
6	5.1.8	2.009	0.20933	0.123	0.02575	0.008	0.051727	0.15466
7	5.1.9	1.992	0.211	0.12	0.02532	0.008	0.050437	0.15861
8	5.1.10	1.988	0.183	0.12867	0.02355	0.008	0.046811	0.17091
9	5.1.11	1.98	0.201	0.119	0.02392	0.0085	0.04736	0.17948
10	5.1.12	1.993	0.19	0.12	0.0228	0.009	0.04544	0.19806
11	5.1.13	2.02	0.213	0.135	0.02876	0.0095	0.058085	0.16355
12	5.1.14	2	0.23467	0.125	0.02933	0.009	0.058668	0.15341
13	5.1.15	1.996	0.21067	0.126	0.02654	0.0085	0.052983	0.16043
14	5.1.16	2.003	0.175	0.111	0.01943	0.007	0.038908	0.17991
Mean		1.992	0.20567	0.12274	0.02529	0.00846	0.050286	0.16939
Standard Deviation		0.02761	0.01946	0.00609	0.00311	0.00069	3.27E-06	0.01649
Maximum		2.02	0.243	0.135	0.03029	0.0095	0.066266	0.20609
Minimum		1.998	0.20917	0.122	0.02553	0.0085	0.050986	0.16471

Figure 3.56 displays the stress-strain curves from the 9% salt tensile group calculated by the Bluehill 2 software. From the data, one can see that the curves do follow a consistent trend. After obtaining the stress-strain curves for the 14 test specimens, the elastic tensile modulus, the yield stress and strain, the ultimate stress and strain, and the specific strength were calculated for each specimen. The average elastic tensile modulus calculated was 1458.01KSI with a standard deviation of 6.4%. The yield stress and strain calculated for this cure was

25.78KSI and 2.29% respective, along with a deviation of 9.74% and 14.41% and the ultimate stress and strain were calculated to be 33.8KSI and 2.65% respectively with a standard deviation of 11.54% and 11.70%. The specific strength variable, which is calculated by dividing the ultimate stress by the density of the specimen, was calculated to be $913.15 \frac{\text{Kips-in}}{\text{lbm}}$ with a standard deviation of 12.97%. **Table 3.40** summarizes the mechanical properties of the 9% salt tensile specimens. Figure 3.57 also shows the failures of the 9% salt tensile coupons.

Figure 3.56 Stress-strain curves of 9% salt tensile specimens

Table 3.40 Mechanical properties of 9% salt tensile specimens

Specimen	Label	Tensile Modulus (KSI)	<i>Yield Stress</i> (KSI)	Yield Strain (%)	Ultimate Tensile Stress (KSI)	Ultimate Strain (%)	Specific Strength (kips-in./lb _m)
1	5.1.2	1418.294	26.636	2.195	33.419	2.896	913.841
2	5.1.4	1290.107	32.367	1.944	27.622	2.929	755.320
3	5.1.5	1461.820	28.140	2.340	38.469	3.225	1051.931
4	5.1.6	1468.228	26.981	1.687	32.426	2.480	886.683
5	5.1.7	1466.828	24.732	2.464	32.812	2.464	897.244
6	5.1.8	1441.581	27.998	1.991	26.990	1.991	738.041
7	5.1.9	1521.632	31.235	2.411	32.754	2.596	895.651
8	5.1.10	1454.681	25.883	2.414	35.437	2.738	969.012
9	5.1.11	1565.368	26.109	2.176	31.822	2.429	870.163
10	5.1.12	1572.570	22.670	2.734	39.018	2.734	1066.934
11	5.1.13	1306.966	25.914	2.417	28.400	2.417	776.602
12	5.1.14	1388.555	22.721	2.203	30.014	2.442	820.731
13	5.1.15	1435.246	22.305	3.002	38.543	3.002	1053.952
14	5.1.16	1620.226	23.044	2.023	39.788	2.794	1087.983
Mean		1458.007	26.195	2.286	33.394	2.653	913.149
Standard Deviation		93.403	3.079	0.335	4.330	0.313	118.416
Maximum		1620.226	32.367	3.002	39.788	3.225	1087.983
Minimum		1290.107	22.305	1.687	26.990	1.991	738.041

Figure 3.57 Failure modes of 9% salt tensile coupons after tensile test

3.3.2.2 *Lime Experimental Tests*

The fourth additive used to treat the bamboo was a hydrated lime solution described in 2.3.3. A total of 31 specimens were manufactured to find the mechanical properties of the bamboo using the lime treatment. Table 3.41 displays the geometries of the specimens tested for the lime solution. With each manufactured with care to keep each test specimen uniform, the standard deviation for all geometries was kept under 12%.

Table 3.41 Lime tensile specimen geometries

Specimen	Label	Length (in)	Width (in)	Thickness (in)	Area (in^2)	Weight (lbf)	Volume	Density
1	10.2.1	2.002	0.201	0.142	0.0281	0.011	0.056056	0.17839
2	10.2.3	1.980	0.194	0.138	0.02686	0.0095	0.053192	0.1786
3	10.2.4	1.994	0.204	0.140	0.02879	0.0105	0.057409	0.18291
4	10.5.5	1.994	0.189	0.139	0.02627	0.009	0.052384	0.17181
5	10.2.6	1.925	0.199	0.146	0.02905	0.012	0.055929	0.1788
6	10.2.7	1.992	0.225	0.141	0.0317	0.011	0.063141	0.17422
7	10.2.8	1.996	0.210	0.141	0.0297	0.0115	0.05929	0.19396
8	13.5.1	1.994	0.194	0.136	0.02649	0.009	0.052827	0.17036
9	13.5.2	1.991	0.202	0.145	0.02939	0.0105	0.05851	0.17946
10	13.5.3	1.991	0.210	0.148	0.02967	0.013	0.059035	0.16939
11	13.5.4	1.998	0.178	0.141	0.0251	0.0105	0.050146	0.20939
12	13.5.5	1.985	0.192	0.141	0.02717	0.011	0.053925	0.20399
13	13.5.6	2.022	0.189	0.139	0.02649	0.014	0.053565	0.1867
14	13.5.7	1.968	0.190	0.153	0.0292	0.0105	0.05746	0.18274
15	13.5.8	2.031	0.198	0.142	0.02825	0.0105	0.057373	0.18302
16	12.2.1	2.012	0.209	0.107	0.02236	0.009	0.044726	0.20123
17	12.2.2	1.998	0.212	0.113	0.02366	0.009	0.047274	0.20096
18	12.2.3	1.992	0.215	0.111	0.02365	0.009	0.047111	0.19104
19	12.2.4	1.988	0.194	0.118	0.02289	0.015	0.045509	0.21974
20	12.2.5	1.994	0.201	0.111	0.02231	0.008	0.044488	0.17982
21	12.2.6	1.949	0.196	0.105	0.02061	0.0085	0.040178	0.21156
22	12.2.7	1.989	0.214	0.104	0.02184	0.0085	0.04344	0.19567
23	12.2.8	1.993	0.201	0.106	0.02131	0.008	0.042463	0.1884
24	13.3.1	1.987	0.208	0.123	0.02551	0.009	0.050699	0.17752
25	13.3.2	1.880	0.197	0.117	0.02305	0.009	0.043332	0.2077
26	13.3.3	2.125	0.196	0.128	0.02509	0.013	0.050176	0.1993
27	13.3.4	1.997	0.211	0.126	0.02659	0.0095	0.053092	0.17893
28	13.3.5	2.002	0.200	0.122	0.02444	0.009	0.048929	0.18394
29	13.3.6	1.999	0.189	0.119	0.02257	0.0085	0.045119	0.18839
30	13.3.7	1.989	0.201	0.125	0.02521	0.009	0.05014	0.1795
31	13.3.8	1.998	0.196	0.128	0.02515	0.012	0.050255	0.19898
Mean		1.98765	0.20015	0.12886	0.02575	0.00961	0.051264	0.18859
Standard Deviation		0.02714	0.00932	0.01476	0.00289	0.0009	3.73E-06	0.01319
Maximum		2.031	0.22533	0.15367	0.0317	0.0115	0.070326	0.21974
Minimum		1.994	0.2	0.12833	0.02551	0.0095	0.051178	0.18394

Figure 3.58 shows the stress-strain curves of the lime treatment group and displays consistent data among the test specimen within the specified curing treatment. The elastic region of the stress-strain curve is very consistent, yielding an elastic modulus of 1783.25KSI and only a standard deviation of 8.3%. The yield stress and strain calculated from the stress strain curve were 35.58KSI and 2.25% respectively with a standard deviation of 12.37% and 16.44%. The ultimate stress and strain were calculated to be 41.20KSI and 2.98% respectively with a standard deviation of 9.32% and 9.40%. The average specific strength of the bamboo when cured with the lime treatment was calculated to be $1159.37 \frac{\text{Kips-in}}{\text{lbm}}$ with a standard deviation of 9.32%. Table 3.42 displays the mechanical properties of the lime tensile specimens. Figure 3.59 also shows the failures of the lime tensile coupons.

Figure 3.58 Place holder Force-extension curves of lime tensile specimens

Table 3.42 Mechanical properties of lime tensile specimens

Specimen	Label	Tensile Modulus (KSI)	<i>Yield Stress</i> (KSI)	Yield Strain (%)	Ultimate Tensile Stress (KSI)	Ultimate Strain (%)	Specific Strength (kips-in./lb _m)
1	10.2.1	1577.200	33.001	2.421	34.898	2.959	981.921
2	10.2.3	1567.557	31.412	2.140	35.552	2.717	1000.342
3	10.2.4	1652.200	31.951	2.132	31.946	2.849	898.870
4	10.5.5	1667.510	34.401	2.281	40.938	2.974	1151.901
5	10.2.6	1434.964	39.921	2.911	41.595	2.956	1170.373
6	10.2.7	1580.038	38.681	2.862	38.683	2.896	1088.432
7	10.2.8	1514.374	37.382	2.251	37.382	2.855	1051.824
8	13.5.1	1898.694	35.663	2.380	37.738	2.574	1061.842
9	13.5.2	1686.234	35.411	2.093	37.488	2.896	1054.803
10	13.5.3	1684.005	32.074	2.541	41.697	3.353	1173.242
11	13.5.4	1933.639	39.943	1.500	45.069	3.150	1268.134
12	13.5.5	1850.506	26.392	2.431	41.656	3.190	1172.094
13	13.5.6	1878.555	37.071	2.152	43.746	3.383	1230.902
14	13.5.7	1714.199	32.484	1.973	38.983	3.334	1096.871
15	13.5.8	1849.047	33.672	2.281	41.623	3.124	1171.160
16	12.2.1	1784.039	37.131	2.962	42.357	2.828	1191.811
17	12.2.2	1826.503	43.274	2.001	43.274	2.959	1217.602
18	12.2.3	1742.171	32.152	2.264	42.153	2.815	1186.081
19	12.2.4	1794.211	36.882	2.622	45.038	3.008	1267.262
20	12.2.5	1744.397	39.931	2.042	40.794	2.891	1147.840
21	12.2.6	1767.946	33.612	2.423	39.952	2.551	1124.143
22	12.2.7	1795.525	36.813	3.034	42.197	3.123	1187.322
23	12.2.8	1867.667	46.862	2.421	47.190	3.102	1327.801
24	13.3.1	1901.053	40.973	2.111	44.218	3.136	1244.182
25	13.3.2	1956.331	37.244	1.502	50.889	3.646	1431.883
26	13.3.3	1925.397	27.472	1.783	36.304	2.981	1021.500
27	13.3.4	1885.734	31.071	1.841	42.971	2.862	1209.101
28	13.3.5	1874.391	31.871	2.222	42.411	3.074	1193.322
29	13.3.6	2082.509	39.432	2.233	45.565	2.975	1282.070
30	13.3.7	1904.639	33.000	1.894	41.866	3.104	1178.002
31	13.3.8	1939.553	35.780	2.252	41.149	2.249	1157.823
Mean		1783.251	35.579	2.257	41.204	2.981	1159.370
Standard Deviation		147.944	4.402	0.374	3.839	0.282	108.016
Maximum		2082.509	46.862	3.034	50.889	3.646	1431.883
Minimum		1434.964	26.392	1.500	31.946	2.249	898.870

Figure 3.59 Failure modes of lime tensile coupons after tensile test

3.3.2.3 Oil Experimental Tests

The fifth and final additive used to treat the bamboo was an oil solution described in section

2.3.3. A total of 16 specimens were manufactured to find the mechanical properties of the bamboo using the oil treatment. Table 3.43 displays the geometries of the specimens tested for the oil solution. The standard deviation for all geometries was kept under 12%.

Table 3.43 Oil tensile specimen geometries

Specimen	Label	Length (in)	Width (in)	Thickness (in)	Area (in ²)	Weight (lbf)	Volume	Density
1	5.5.1	1.991	0.25367	0.137	0.03475	0.01	0.069193	0.14453
2	5.5.2	2.00	0.227	0.13467	0.03057	0.01	0.06114	0.16356
3	5.5.3	1.973	0.18333	0.143	0.02622	0.01	0.051725	0.19333
4	5.5.4	2.005	0.189	0.114	0.02155	0.008	0.0432	0.18519
5	5.5.5	2.016	0.21167	0.128	0.02709	0.0095	0.054621	0.17393
6	5.5.6	2.003	0.236	0.138	0.03257	0.0115	0.065234	0.17629
7	5.5.7	2.008	0.20667	0.136	0.02811	0.0095	0.056439	0.16832
8	5.5.8	1.987	0.17233	0.131	0.02258	0.0095	0.044857	0.21178
9	5.5.9	2.012	0.201	0.129	0.02593	0.01	0.052169	0.19168
10	5.5.10	2.008	0.196	0.138	0.02705	0.0105	0.054312	0.19333
11	5.5.11	1.988	0.20667	0.144	0.02976	0.0105	0.059164	0.17747
12	5.5.12	1.975	0.231	0.151	0.03488	0.011	0.06889	0.15967
13	5.5.13	2.004	0.22867	0.138	0.03156	0.0105	0.063239	0.16604
14	5.5.14	2.012	0.22633	0.142	0.03214	0.0115	0.064663	0.17784
15	5.5.15	1.976	0.20033	0.131	0.02624	0.0095	0.051857	0.18319
16	5.5.16	1.998	0.19367	0.133	0.02576	0.0105	0.051465	0.20403
Mean		1.99725	0.21021	0.13548	0.02855	0.01012	0.05688	0.17939
Standard Deviation		0.01397	0.02185	0.00833	0.00397	0.00087	2.54E-06	0.01721
Maximum		2.016	0.25367	0.151	0.03488	0.0115	0.077221	0.21178
Minimum		2.0015	0.20667	0.1365	0.0276	0.01	0.056463	0.17766

Figure 3.60 displays the stress-strain curves of the oil treatment group and is shown to contain very consistent trends. The elastic region of the stress-strain curve is also very consistent, yielding an elastic modulus of 1486.22KSI and only a standard deviation of 7.55%. The yield stress and strain calculated from the stress strain curve were 32.41KSI and 2.45% respectively with a standard deviation of 8.89% and 13.06%. The ultimate stress and strain were calculated to be 37.52KSI and 3.41% respectively with a standard deviation of 7.30% and 12.32%. The average specific strength of the bamboo when cured with the oil treatment was calculated to be

$1115.55 \frac{\text{Kips-in}}{\text{lb}_m}$ with a standard deviation of 7.30%. Table 3.44 summarizes the mechanical properties of the oil tensile specimens. Figure 3.61 also shows the failures of the oil tensile coupons.

Figure 3.60 Stress-strain curves of oil tensile specimens

Table 3.44 Mechanical properties of oil tensile specimens

Specimen	Label	Tensile Modulus (KSI)	<i>Yield Stress</i> (KSI)	Yield Strain (%)	Ultimate Tensile Stress (KSI)	Ultimate Strain (%)	Specific Strength (kips-in./lb _m)
1	5.5.1	1334.375	32.231	2.721	37.302	3.787	1109.191
2	5.5.2	1530.273	28.260	2.152	34.484	2.894	1025.402
3	5.5.3	1586.697	37.311	2.570	39.117	3.271	1163.161
4	5.5.4	1605.404	29.050	1.921	41.836	3.366	1244.004
5	5.5.5	1455.550	29.700	2.282	37.176	3.245	1105.440
6	5.5.6	1453.828	31.7910	2.813	34.942	3.395	1039.012
7	5.5.7	1447.540	32.411	2.401	37.336	3.847	1110.193
8	5.5.8	1712.464	31.723	1.950	36.930	2.591	1098.131
9	5.5.9	1605.928	37.044	2.601	42.025	3.584	1249.622
10	5.5.10	1494.724	33.821	2.461	37.683	3.749	1120.522
11	5.5.11	1475.466	33.611	2.860	37.967	3.876	1128.960
12	5.5.12	1294.612	27.210	2.253	31.344	3.047	932.031
13	5.5.13	1341.483	34.890	2.914	40.039	3.986	1190.570
14	5.5.14	1400.982	33.663	2.771	35.218	3.033	1047.222
15	5.5.15	1479.180	31.514	2.182	39.639	3.338	1178.680
16	5.5.16	1561.052	34.322	2.393	37.218	3.145	1106.691
Mean		1486.222	32.410	2.453	37.516	3.412	1115.552
Standard Deviation		112.269	2.885	0.315	2.738	0.417	81.423
Maximum		1712.464	37.311	2.914	42.025	3.986	1249.622
Minimum		1294.612	27.210	1.921	31.344	2.591	932.031

Figure 3.61 Failure modes of oil tensile coupons after tensile test

3.3.3 Tensile Failure Modes

Bamboo is a very unique material in that it can have multiple failures before reaching complete fracture at its ultimate strength. This suggests that the bamboo acts more like a weaved carbon fiber composite than a unidirectional carbon fiber composite. The reason that the bamboo acts more like a bi-directional composite may be because of the molecular bonding inside of the bamboo. Due to the cellulose inside of the bamboo, bamboo is extremely resistant to tensile stress because of

the covalent bonding between individual units. These preceding failures before the ultimate may be caused by some of the breaking of the cellulose bonds and the ultimate is when all of the bonds have failed. In addition to the multiple failures under tension, bamboo also holds various types of modes of failure. After each tensile test, each testing coupon was photographed and the failure modes were analyzed in accordance with the type and the location of the damages attending the ASTM D3039-00. Typical failure modes of weaved composites given in ASTM D3039-00 are shown in Figure 3.62.²³ To facilitate the interpretation of the typical failure modes they are codified in sequence based on characteristics of type, area, and locale, as shown in Figure 3.62. The most common failure mode in bamboo when tensile testing was SGM, which refers to a long splitting failure in the middle of the gage area as seen in Figure 3.63. Other failure modes that were exhibited during tensile tests were XGM, LGM, and occasionally SAT and SAB. However, the long splitting near the tab area on both top and bottom

Figure 3.62 Tensile typical failure modes of weaved composites

was mainly due to the gripping forces of the jaws, which caused the bamboos to have minor cracks before running the test.

Figure 3.63 Most common failure of tensile specimens was long splitting on the middle of gage area

Figure 3.64 Typical failure modes of tensile specimens

3.3.4 Mechanical Behavior Comparison Between The Different Treatments

To perform a final comparison of the bamboo under tension Table 3.45 summarizes the mechanical properties of the control bamboo (“green”) and the thermo-treatments without any additives. One can see that there are significant advantages to heat treating bamboo when wanting to increase the material’s structural performance. It can also be concluded that curing the bamboo at higher temperatures yields better results, as there is a steady increase in each of the mechanical properties excluding the yield stress. The reason that the yield stress does not follow suit with the other mechanical properties listed is because in some cases there was not a yield for the tensile specimens, only exhibiting an ultimate stress, which significantly increased the average yield stress. However, the trend of an increase in strength with an increase in temperature will only hold true until the thermal degradation point of the bamboo is reached. Due to the autoclave being incapable of performing at a higher temperature than the 220°F, thermal degradation of the bamboo was never reached, which signifies the point where heating the bamboo is no longer beneficial to the structural performance of the bamboo. One of the

largest increases when comparing the three thermo-treatments was in the modulus as there was a 37.6% increase from the 180°F to the 220°F thermo-treatment. Compared to the control, the 220°F thermo-treatment cure increased the tensile modulus by over 129.6%. Other mechanical properties worth noting are the ultimate tensile stress and the specific strength. The ultimate tensile stress is very significant as it is a predictor to when the specimen will fail and the specific strength is the most critical because it normalizes all of the curing treatments for the bamboo to allow for easy comparison. The 220°F thermo-treatment cure outperformed both the 200°F, 180°F, and the green for the ultimate tensile stress, increasing by 54.3% when compared to the control, while the 200°F and 180°F increase the ultimate tensile stress by 25.9% and 17.9 % respectively. When analyzing the specific strength of the thermo-treatments, one will also find a steady increase as the curing temperature increases. The 220°F thermo-treatment yields the highest results of $1146.53 \frac{\text{Kips-in}}{\text{lbm}}$, which is 84.44% higher than the green bamboo. The steady increase of the mechanical properties with each succeeding higher temperature is a result of the amount of bound water that is taken out of the bamboo.

As mentioned earlier, due to the limited amount of bamboo, the thermo-treatment cures with additives were conducted using only one temperature instead of all three thermo-treatment temperatures. With the 220°F thermo-treatment producing the best results, the 220°F thermo-treatment was selected for all additives. Table 3.45 also summarizes the results of all thermo-treatments with additives along with a comparison to the control. From this table, one can conclude that there are advantages and disadvantages to all of the additive treatments. When analyzing the 3%, 6%, and 9% salt treatments, the 3% salt clearly outperformed the rest, yielding the highest mechanical properties. It was concluded from these results that a higher concentrated solution will not increase the stiffness of the material, and instead will cause the bamboo to become more brittle. This brittleness may be a result of the crystallization of the

large excess of salt inside the bamboo when thermo-treated. Similarly to the salt treatments, the oil and lime both greatly increased the mechanical properties of the bamboo when compared to the “green” material.

When compared to the standard 220°F thermo-treatment, all of the additives had both good and bad trade-offs. Analyzing the modulus, the 220°F thermo-treatment obtained the highest modulus compared to all cures as the additives made the bamboo material more brittle. However, for the ultimate tensile stress, the lime solution was victorious with the 3% salt solution slightly trailing. The specific strength was the exact opposite of the trend of the ultimate stress as the 3% salt solution was the best, with the lime solution trailing slightly. The lime solution increases the ultimate tensile stress by approximately 58.22% and the 3% salt solution increases the specific strength by 90.86% when compared to the control “green” bamboo. Table 3.45 shows the complete summary of all tensile groups.

Table 3.45 Summary of the mechanical properties for all tensile groups

Curing Treatment	Tensile Modulus (KSI)	<i>Yield Stress</i> (KSI)	Yield Strain (%)	Ultimate Tensile Stress (KSI)	Ultimate Strain (%)	Specific Strength (kips-in./lb _m)
Green	812.86	23.23	3.82	26.04	5.21	621.63
180°F (1°/min)	1356.19	27.16	2.32	30.69	2.76	887.00
200°F (1°/min)	1390.22	30.46	2.52	32.79	2.92	898.25
220°F (1°/min)	1866.09	29.66	1.707	40.18	2.868	1146.53
3% salt	1612.68	32.11	2.18	36.99	2.86	1186.47
6% Salt	1355.43	26.37	2.08	29.78	2.58	210.69
9% Salt	1458.01	25.78	2.29	33.80	2.65	913.15
Lime	1783.25	35.58	2.25	41.20	2.98	1159.37
Oil	1486.22	32.41	2.45	37.52	3.41	1115.55

Chapter 4. Optimal Curing Treatment

Once all of the data were collected for all curing treatments for compression and tensile testing, the data then had to be analyzed to determine overall which curing treatment performed the best. To correctly determine which treatment was optimal, a trade study was conducted to compare all of the curing treatments. To begin the development of the trade study the initial step was to define the objectives and requirements of the study. The primary objective of this study is to identify methods to improve the mechanical properties of bamboo to evaluate its potential to be used on higher strength to weight ratio applications and become a substitute for non-sustainable toxic materials such as steel, aluminum, and carbon fiber.

The following step was to define the criteria for how to judge the performance of each curing treatment. In knowing the primary objective is to increase the mechanical properties of the bamboo, as well as decrease the weight, the normalized parameter specific strength was utilized for both compression and tension. The reason that the specific strength was chosen is because not only will it identify the ultimate stress of the material, but it will also identify the weight reduction of each treatment, as it is essentially the strength to weight ratio. The next criteria chosen to evaluate the curing treatments were the compressive and tensile moduli. The compressive and tensile moduli were chosen because unlike the specific strength, the modulus describes the material's response to linear strain in the elastic region, as well as determining the stiffness of the material. With current bamboo applications consisting of framed structures and potential applications being applied to the aerospace and automotive industry, a high elastic modulus is desired to keep a rigid structure and resist any deformities of the material under high loads. The last criterion chosen for this trade study was weight, which describes the weight drop of the material after treatment compared to its natural green condition.

The ensuing step was to define the relative weights for the trade study. The weighting of each criterion for this trade study were all set to an equivalent of 20%. The weighting factors were chosen to be equal to keep the results of the trade study unbiased.

The fourth and final step was to do a complete analysis of the materials through an objective trade study, which means that the performance of each curing treatment was evaluated based upon the experimental results done in the Cal Poly Aerospace Structures/Composites Lab. To compare the results from each curing treatment using the trade study, the results of all the curing treatments were normalized to the curing treatment that yielded the best results per criterion. For example, the compressive specific strengths for 3% salt, 6% salt and lime were $490.21 \frac{\text{kips-in}}{\text{lbm}}$, $471.65 \frac{\text{kips-in}}{\text{lbm}}$, and $439.31 \frac{\text{kips-in}}{\text{lbm}}$ respectively. Due to the 3% salt yielding the highest values, each curing treatment would be normalized to the specific strength value of 3% salt. To normalize all of the curing treatments' specific strength values to 3% salt, each specific strength value would be divided by the specific strength of 3% salt to find each curing treatment's proportion to the 3% salt value. For this example, after normalizing the data, the 3% salt, 6% salt, and lime values would be 1.0, 0.962, and 0.896 respectively. Then after the results are normalized these values are used to enter into the trade study by multiplying the normalized values by the weighting factor of the criterion, which for this trade study will always be 20%. Going back to our example, the 3% salt, 6% salt, and lime would have values of 20%, 19.24%, and 17.92% respectively. Once all of the criteria are normalized, the total for each curing treatment is then summed up, with the best performance being that of the curing treatment that has the highest sum.

By looking at Table 4.1 with the five different criteria and different treatments, one can see that the 3% salt solution was found to be the optimal curing treatment for bamboo as it performed

best in this trade study, outperforming the rest of the curing treatments in three out of the five categories. One of the most significant reasons that the 3% salt curing method was shown to be best was because of the weight drop associated with the cure. As explained in Section 2.3.3, the reason that 3% salt has a significantly higher weight drop is because the salt lowers the heat capacity of the moisture or water inside the bamboo. The average weight drop of the 3% curing treatment was 37.2% compared to its natural green condition.

Table 4.1 trade study to find optimal curing treatment

	Green	220deg	3% salt	6% salt	9% salt	Oil	Lime
Compressive Specific Strength	9.08	19.97	20	19.24	19.24	18.58	17.92
Compressive Modulus	15.52	19.79	17.56	17.72	20	18.29	18.99
Tensile Specific Strength	1.43	19.33	20	16.07	15.39	18.80	19.54
Tensile Modulus	8.70	20	17.28	14.52	15.63	15.93	19.11
Weight-drop	0	14.09	20	19.34	15.40	16.34	17.98
TOTAL	34.74	93.18	94.84	86.89	85.66	87.94	93.55

Once it was determined that the 3% salt solution was the optimal curing treatment for bamboo, the potential of the bamboo was analyzed against non-sustainable materials currently used for higher strength applications in the aerospace and automotive industry. The non-renewable materials that were included in this analysis of bamboo were carbon fiber (AS4), titanium, stainless, steel, and also aircraft structural grade aluminum which consists of 2024-T3 and 7075-T6. To evaluate the bamboo using the 3% salt curing treatment, the specific strengths of each material were compared in Table 4.2. By looking at Table 4.2, it is shown that bamboo does have great potential to be used on future aerospace, automotive, and construction applications, as it has a higher tensile specific strength than stainless steel, titanium, and both structural grade aluminums. However, the bamboo material does not pass the specific strength of AS4 carbon fiber, which was expected due to AS4 being one of the premier aerospace grades of

carbon fiber. This table shows that bamboo has the potential to replace non-sustainable materials used in industry. This table in no way means that all aluminum, stainless steel, and titanium should be replaced by bamboo for all applications, as it merely shows the potential of bamboo to replace non-renewable materials. Additional research is needed as one must look at the design requirements of each system to assess if the bamboo material is a viable option.

Table 4.2 Tensile specific strength comparison of building materials

Material	Specific Strength ($\frac{Kips-in.}{lbm}$)
AISI 4130 Steel, normalized at 1600°F	342.25
Aluminum 2024-T3	700
Aluminum 7075-T6	813.73
Titanium Ti-6Al-4V (Grade 5), Annealed	862.5
Bamboo-3% Salt Treatment	1186.47
AS4 Carbon Fiber	9,938.18

4.1 Poisson's Ratio

To determine the Poisson's ratio of the bamboo material, testing coupons were prepared similarly to the testing coupons used for tensile testing. However, instead of making the testing coupons into a dog bone shape the testing coupons were kept rectangular, but were manufactured to the same geometry as the tensile coupons. The reason that the testing coupons were not prepared using a dog bone shape is because a larger area is needed to attach the strain gage to the bamboo. The geometric dimensions of the bamboo testing coupons are 6" X 0.6" X 0.12". With no real standard to follow for determining Poisson's ration for bamboo material, ASTM E0132-04 was utilized for the tests, which uses a constant crosshead rate of 0.004 inches per minute. The main difference between a Poisson's ratio test and a standard tensile test is that a strain gage is affixed to the testing coupon in the transverse direction to measure the lateral changes in the test specimen when being longitudinally loaded by the Instron 8801 machine. With the Instron machine capable of measuring the strain in the

longitudinal direction there is no need to place another strain gage in the longitudinal directions. Also, for all of the Poisson tests, the maximum applied load was 500lbf because there was no need to go to failure.

To apply the strain gages to the testing coupons, directions outlined in the Student Strain Gage Application Manual were followed, as written by Vishay.²⁵ The first step in applying the strain gage is to clean the area where the strain gage will be applied using acetone and a base cleaner that is provided by Vishay Micro measurements. The next step is to then apply a cleaner to the area where the strain gage will be applied and then wipe the area down with a cotton swab. It is important that the swabs run only once in a single direction to avoid picking up any debris and re-depositing in the application area. After cleaning the strain gage area carefully, an M-Bond 200 adhesive is utilized to attach the strain gage to the testing coupon. M-Bond 200 is a two part adhesive, which consists of an epoxy and a catalyst, shown in Figure 4.2. Before applying the M-Bond 200 adhesive, the strain gage is positioned on the clean surface of the testing specimen.

Figure 4.1 Strain gage mounted onto test specimen

Figure 4.2 M-bond 200

Scotch tape is then placed on the top of the strain gage and pressed down on top of the strain gage. The scotch tape is then peeled back until the strain gage is not in contact with the testing specimen. After the scotch tape is peeled back, the catalyst is then applied onto the strain gage and then allowed to dry for approximately one minute. The catalyst is very important when bonding the strain gage to the test specimen as it accelerates the chemical reaction of the epoxy. Once the catalyst has dried, a small drop of epoxy is then placed on the testing specimen

where the strain gage is applied and the tape is then pressed down in one sweeping motion to avoid any air bubbles and to force the adhesive outward in a thin layer. Pressure is then applied to the strain gage for approximately one minute and the scotch tape is then carefully removed to avoid any dislodging of the strain gage. Finally, once the strain gage is mounted to the test specimen, electrical wires are then soldered to the strain gage and the specimen is ready to test. The prepared strain gage is shown in Figure 4.1

Figure 4.3 Poisson test specimen loaded perpendicular to the grips of the Instron machine

strain gage reading to be directly measured and read by the testing software using the Versa Channel in Bluehill2. Instructions on how to use the versa channel option including the instructions on how to calibrate the strain gages were followed from Ahmad Amini's thesis.³⁰ Figure 4.3 and Figure 4.4 show the complete set-up of a Poisson test for the bamboo material.

To record the strain in the lateral direction for the bamboo material, Vishay Micro-Measurements EA-13-250BG-120 strain gages were implemented. The strain gage was then connected to a Wheatstone bridge strain indicator box, which was then connected to a National Instrument BNC-2111 External Connector Box attached to a data acquisition PC running the Bluehill2 software. This

allowed the

Figure 4.4 Schematic of Poisson test set-

A total of seven different curing treatments were tested to find the Poisson's ratio for each curing method. The curing methods that were tested included the "green" control case, the 220°F thermo-treatment, the 3%, 6%, and 9% salt 220°F thermo-treatment, the lime 220°F thermo-treatment, the oil 220°F thermo-treatment, and the 3% salt 220°F thermo-treatment loaded in the direction perpendicular to the fibers. To determine an average strain for each testing group, ten coupons are tested. Upon completion of the tests, each test outputted an average-strain vs. applied load curve for both the longitudinal strain and the lateral strain from the Bluehill 2 testing software. Figure 4.5 shows an example of the average-strain vs. applied load curves for the 3% salt group, where the steeper slope is the longitudinal strain and the shallower slope is the transverse strain.

Figure 4.5 3% salt strain-load curve

To calculate the Poisson's ratio, the slope of the average longitudinal strain is divided by the average slope of the transverse strain as seen in Equation 4.1

$$\nu = \frac{\left(\frac{d\epsilon_t}{dF}\right)}{\left(\frac{d\epsilon_l}{dF}\right)} \quad (4.1)$$

where ν is Poisson's ratio, F is the applied load, and ϵ_t and ϵ_l are the transverse strains and longitudinal strains respectively. The measured Poisson's ratio for each of the curing treatments were all correlative to one another as the Poisson's ratio ranged from 0.260 to 0.311 for specimens loaded in the longitudinal direction. The Poisson's ratio for the specimen loaded transversely to the fiber direction is 0.571. The Poisson's ratio calculated are very close to the expected Poisson's ratio referred by Janssen and Laemlaksakul—their experiments yield values ranging from 0.31 to 0.35.

Table 4.3 displays a summary of the Poisson's ratios determined in this study. The majority of the groups have a Poisson's ratio within the range established by the previous works. An exception, however, may be seen in the green bamboo group. The ratio determined from this experiment is higher than the rest of the sample groups. As of now, there are no references to the Poisson's ratio for green bamboo. Both references discovered for this mechanical property only investigated the value for construction-grade bamboo—implying the bamboo is a few years old and already air-dried for several months. Green bamboo is much more flexible than treated bamboo, so intuitively, an increase in both longitudinal/transversal strains is possible. This is seen in the strain-load curve provided in the appendix; the strains are higher than the other treated groups. Nonetheless, slight hesitation remains in stating with unwavering confidence that the determined value is accurate. If any errors could have possibly occurred during the test, they would be found in the grip jaws. The moisture from the green bamboo may have produced slippage at the contact surfaces of the grip jaws and specimens.

Table 4.3 Poisson's Ratio for the various curing treatments

	Green	220deg	3% salt	6% salt	9% salt	Oil 220deg	Lime	Transverse
Poisson's Ratio	0.48	0.30	0.26	0.30	0.30	0.30	0.31	0.052

Figure 4.6 Transverse Poisson ratio test specimen

Similarly to the green bamboo, no references exist—to the knowledge of the author—as to the Poisson’s ratio for bamboo loaded perpendicular to the fiber direction. Consequently, a method had to be devised for this particular experiment. Since the diameter of the culm makes it exceptionally difficult to provide flat surfaces for the jaws of the Instron machine to attach, the Instron machine was quickly ruled out as a potential testing apparatus. A small specimen was taped to the edge of a table and at its center for loading. Due to the

enormous amount of work required to perform this test, only one specimen was prepared.

The procedure initiates by cutting a culm out of the specified bamboo pole. Very much like the tension specimens, the culm is split radially into several sections to produce a nearly flat specimen in its thickness. Unlike the tension specimens, however, a larger width is required to allow proper anchorage to the table. The specimen is then prepared in the same aforementioned manner to apply a strain gage oriented in the direction perpendicular to the fiber; the orientation of the strain gage is the only contrast to the previous tests. Once the strain gage is on the coupon, the specimen is taped at its flanks up to the table and left to hang. Next, a string is then taped directly below the strain gage. The test begins by tying small weights to the string and letting them hang while recording the value on the strain indicator. A total of six weights, and therefore six strains, make up the data for this test. Figure 4.6 and Figure 4.8 illustrate the experiment set-up for this test.

Figure 4.8 Transverse Poisson ratio test set up

The value for the Poisson's ratio under transverse loading is the highest among all the groups as expected. As mentioned earlier, bamboo is a naturally unidirectional material that has fibers running in the axial direction. During a transverse load applied to the fibers, the only substance carrying most of the stress is the lignin and hemicellulose matrix. The matrix is not meant to withstand the majority of a tensile load—much like conventional composite structures. As a result, greater longitudinal-to-transversal strains are noted from the strain-load curve provided.

Figure 4.7 shows the strain-load curve used to calculate the transverse Poisson's ratio.

Figure 4.7 Transverse Poisson strain-load curve

Chapter 5. Buckling Characteristics

After finalizing the optimal curing treatment, the mechanical properties of 3% salt bamboo were then investigated under buckling. With many modern bamboo structures utilizing bamboo as structural columns, such as in houses, it is very important to study the buckling behavior of bamboo. Normally when structural members are in compression it is considered a good thing, as the members will only fail by material failure once the ultimate strength is surpassed. However, if the geometry of the member is a column, buckling may occur, and is particularly dangerous because when a member buckles, it can catastrophically fail without any warning. For this reason, designers must be constantly aware of the buckling failure of the member.

Not only is it essential to provide design data for both physical and chemical properties, but it is also necessary to provide design rules against various types of failure in accordance with modern design theory. After establishing the compressive mechanical properties for bamboo, which include analysis of strength and modulus of elasticity, it was necessary to develop design rules against column buckling of bamboo.

5.1 Preparation of Buckling Specimens

To develop the design rules against column buckling, seven different testing groups were prepared with each group consisting of a different height, ranging from 1.5" to 10". The reason that a maximum height of 10" was chosen was because 10" was approximately the average length of the internodes from the bamboo culms. Once again, the preparation of each buckling specimen was carefully done at the Cal Poly's Aerospace/Composite Structures Lab. However, before any preparation could be begun, bamboo internodes were first cut using the Rigid diamond tile saw and then inspected for any irregularities, which included internodes that were warped or had non-circular cross-sections. These internodes were then excluded from any testing.

Once the bamboo internodes were cured, the bamboo internodes were then arranged according to height and then were marked accordingly for the specified heights to obtain the optimal amount of test pieces. Once the internodes were marked, the internodes were cut with the Rigid diamond tile saw at the marked locations. The cuts were then inspected to be flat and perpendicular to the direction of the bamboo fibers. If any end planes were not perpendicular to the length of the specimen, the end planes were then sanded preliminarily using a belt sander and then by hand using a 120 grit sand paper, similar to the compression specimens. To insure that the planes were perpendicular, a leveler was employed to each specimen.

5.2 Buckling Testing Procedures

All testing was done at the Cal Poly Structures/Composites lab using the Instron 8801 machine.

With no exact buckling testing procedures referenced for bamboo, all of the buckling testing was done in accordance with the compression testing standard stated in ISO 22157, ignoring the requirement of the height of each specimen equaling the diameter of the internode. Like the compression tests, special compression fixtures were used for each test. Once the specimens were ready for testing, each buckling specimen was loaded into the middle of the

Figure 5.1 Buckling specimen test set-up

testing area of the Instron with the appropriate testing fixtures in place, as shown in . All of the buckling specimens were pre-loaded to within $10lb_f$ to ensure contact between the specimen and plate. The same program that was used for compression was applied to each test, which consists of a 0.0004 in/min loading rate as recommended by the standard. After pre-loading of the specimen, the test initiates and concludes when there is a 40% drop in the load or at complete failure. Procedures were repeated for each buckling specimen.

5.3 Buckling Tests, Results, and Discussion

There are two distinguishable categories that lead to sudden failure when performing buckling analysis. The first category is material failure and the second is structural instability, which is also known as buckling. For material failure there are two types of analysis; one for ductile materials, which is analyzed using the yield stress and another for brittle, which uses the ultimate stress. With bamboo being a more brittle material, the ultimate stress was assessed when looking at material failure. The load at which buckling occurs depends solely on the stiffness of the material.²⁶ Buckling refers to the loss of stability primarily characterized by a loss of structural stiffness and is usually independent of the material strength. For buckling, there are also two modes of failure; local buckling and overall buckling. Local buckling is characterized by a distorted longitudinal axis of the member and in overall buckling, the axis of the member is not distorted, but the strength of the cross section is compromised by the buckling component of the cross section. The force that is necessary to cause a buckling motion varies by a factor of four depending on how the end planes are restrained. In knowing this, it is very important that the end planes of the bamboo internodes are parallel to the testing fixtures, as buckling studies are much more sensitive to the component restraints compared to a normal stress analysis. Steele²⁷ has done the analysis of several different end conditions, and show that each set of different end conditions has a different effect on the effective length. Table 5.1 displays the different end conditions and their corresponding “effective” length. The buckling experimental tests conducted at Cal Poly’s Aerospace Structures/Composites Lab were confined at the ends to be round and free, giving an effective length twice the original length of the specimen. However, for this study because some of the end planes were not completely parallel with the end planes of the fixture in the Instron and also with some irregularities in the bamboo, it has

been chosen that the conservative effective length will be 2.4 times the original length of each specimen.

Table 5.1 End Conditions

End Condition	Theoretical Value	AISC Value	Conservative Value
Round-Round	$L_{eff} = L$	$L_{eff} = L$	$L_{eff} = L$
Pinned-Pinned	$L_{eff} = L$	$L_{eff} = L$	$L_{eff} = L$
Round-Free	$L_{eff} = 2L$	$L_{eff} = 2.1L$	$L_{eff} = 2.4L$
Fixed-Pinned	$L_{eff} = 0.707L$	$L_{eff} = 0.80L$	$L_{eff} = L$
Fixed-Fixed	$L_{eff} = 0.5L$	$L_{eff} = 0.65L$	$L_{eff} = L$

A total of 42 specimens were tested to study the column buckling behavior of bamboo. As mentioned earlier the 42 specimens were split into seven different groups, and were grouped according to the height of each specimen. These groups consisted of 1.5", 2", 3", 4", 6", 8", and 10". Similar to the compression and tensile tests, a table will be showcased for each group summarizing the geometric dimensions of each specimen. The only reason that this table is shown is for reassuring purposes that all testing samples were within the same geometric dimensions. Along with the table showing the geometries of the specimens, each group's load-deflection curve and stress-strain curve will be illustrated. Lastly, a strength to slenderness ratio curve will be illustrated to compare the analysis of all testing groups and also assist in determining where buckling occurs.

5.3.1 1.5-Inch Long Experimental Tests

The first group tested under buckling was 1.5", which is very similar to the dimensions of the initial compression testing. A total of seven compression specimens were tested in this group and Table 5.2 summarizes the geometries of this test group. Also, to keep things consistent, the following geometries were recorded in accordance to section 2.3.1. By looking at the table one can see that the geometries of the specimens are very consistent with the highest deviation being the weight at 10.58%, far below the 15% standard deviation acceptable range.

Table 5.2 1.5 inch buckling specimen geometries

Specimen	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Weight (lb _f)	Density (lb _m /in ³)
1	1.471	1.699	0.146	0.031	0.029
2	1.502	1.685	0.146	0.031	0.029
3	1.493	1.491	0.130	0.027	0.032
4	1.481	1.485	0.120	0.025	0.033
5	1.494	1.497	0.127	0.026	0.031
6	1.495	1.476	0.119	0.025	0.033
7	1.492	1.699	0.146	0.031	0.031
Mean	1.49	1.56	0.13	0.03	0.031
Standard Deviation	0.01	0.11	0.01	0.00	0.002
Maximum	1.50	1.70	0.15	0.03	0.033
Minimum	1.47	1.48	0.12	0.03	0.029

Figure 5.2 shows the stress-strain curves of the 1.5" buckling specimens. By looking at the plot one can see that the trend of the graph is fairly consistent with the average critical stress being 15.86KSI with a standard deviation of 2.19%. The reason that there is some variation in the ultimate stress is because of the varying thickness of each specimen, which is due to the bamboo's natural growth. Also from this Figure, one can see that some major deviations with the Specimen 3. This deviation may be caused by deficiencies with the end planes of the bamboo specimens not being completely parallel to the testing fixtures. This is an example of how small deficiencies can cause large discrepancies to the data. The elastic modulus was computed to be 553.58KSI, with a standard deviation of 10.25%.

Figure 5.2 Stress-strain curves of 1.5" buckling specimens.

To analyze the buckling characteristics of a material, one of the key parameters is the slenderness ratio of the test specimen. However, before one can compute the slenderness ratio, the basic section properties of a bamboo column must be evaluated first. The first section property of the bamboo specimen that must be evaluated is the cross-sectional area, which can be computed using equation 3.1. Although, bamboo culms do have taper to them, to simplify things, it is assumed that the cross sectional areas of the bamboo specimens are identical. Once the cross-sectional area is calculated the second moment of area is computed using Equation 5.1

$$I = \left[\frac{\pi}{64} \left(D_{avg}^4 - (D_{avg} - 2 * t_{avg})^4 \right) \right] \quad (5.1)$$

where D is the average diameter and t is the average thickness of the bamboo specimen.

Once the second moment of area is calculated, the radius of gyration is then calculated. The radius of gyration describes the way in which the area of the cross section is distributed around its centroidal axis. If the area is concentrated far from the centroidal axis, the radius of gyration

will be greater and also have a higher resistance to buckling. The radius of gyration is calculated using Equation 5.2

$$r = \sqrt{\frac{I}{A}} \quad (5.2)$$

After the three sectional properties of the bamboo specimen have been calculated, the slenderness ratio can then be calculated by Equation 5.3

$$\lambda = \frac{l}{r} \quad (5.3)$$

The average slenderness ratio computed for the 1.5" test specimens was 7.11 with a standard deviation of 5.78%. Table 5.3 displays the key sectional properties of the 1.5" buckling specimens, including the critical stress values.

Table 5.3 Sectional properties of the 1.5-inch buckling specimens

Specimen	Effective Length (in.)	Area (in ² .)	Second Moment of Area (in ⁴ .)	Radius of Gyration (in.)	Slenderness Ratio (-)	Critical Stress (KSI)
1	3.600	0.710	0.216	0.552	6.53	16.21
2	3.630	0.706	0.211	0.546	6.64	15.67
3	3.574	0.557	0.130	0.483	7.39	17.30
4	3.583	0.514	0.121	0.485	7.39	15.93
5	3.551	0.547	0.129	0.486	7.30	16.30
6	3.567	0.508	0.118	0.481	7.41	14.86
7	3.600	0.710	0.216	0.552	7.11	15.53
Mean	3.584	0.591	0.154	0.506	7.11	15.97
Standard Deviation	0.028	0.093	0.046	0.034	0.411	0.35
Maximum	3.630	0.710	0.216	0.552	7.409	17.30
Minimum	3.551	0.508	0.118	0.481	6.527	14.86

The failures for the 1.5" buckling specimens did not experience any type of buckling, signifying that the slenderness ratio was not large enough to cause the bamboo to become unstable. The two typical failures that were identified were significant end bearing and longitudinal splitting, which is shown in respectively Figure 5.3 and Figure 5.4. The reason that the specimens did not experience buckling is because at small slenderness ratios, the buckling stress is quite large. So

at these levels of slenderness, the critical buckling stress exceeds the capacity of the material to handle it so the limiting strength becomes the material strength instead of buckling.

Figure 5.3 Material failure due to bearing stress

Figure 5.4 Material failure due to splitting

Figure 5.5 1.5" buckling specimens after tests

Figure 5.6 1.5" buckling specimens after tests

5.3.2 2-Inch Long Experimental Tests

The second group that was tested for buckling analysis was the 2" group. This group contained seven test specimens with Table 5.4 summarizing the geometries of each. Similarly to the 1.5" the geometries were very consistent with the length of the specimens holding a standard deviation of 1.62%. The highest geometric deviation again was the weight of the specimens at 12.14%, which is exceptional for a natural material.

Table 5.4 2-inch buckling specimen geometries

Specimen	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Weight (lb _f)	Density (lb _m /in ³)
1	1.946	1.684	0.146	0.040	0.029
2	1.940	1.633	0.140	0.039	0.031
3	1.923	1.536	0.127	0.035	0.032
4	1.944	1.472	0.119	0.032	0.032
5	1.965	1.454	0.121	0.032	0.032
6	1.867	1.491	0.124	0.030	0.030
7	1.922	1.467	0.123	0.031	0.030
Mean	1.929	1.534	0.129	0.034	0.031
Standard Deviation	0.031	0.090	0.010	0.004	0.001
Maximum	1.965	1.684	0.146	0.040	0.032
Minimum	1.867	1.454	0.119	0.030	0.029

Figure 5.7 illustrates the stress-strain curve respectively. One can see by looking at the figure that the trend is very consistent with all the curves following the same path. Also, one may notice that the critical stress of this group has dropped significantly, which is expected with an increase in length, as the specimen becomes less stable with an increase in length. The average critical stress obtained from the stress-strain plots was 15.48KSI with a standard deviation of 10.08%. The average elastic modulus of the 2" specimen was also obtained from the stress-strain plot, yielding a value of 704.00KSI with a standard deviation of 13.41%, which is good as it is below the 15% standard deviation mark. Table 5.5 shows a summary of the sectional properties along with the critical stress of the 2" buckling specimens.

Figure 5.7 Stress-Strain curves of 2" buckling specimens

Table 5.5 Sectional properties of the 2-inch buckling specimens

Specimen	Effective Length (in.)	Area (in ² .)	Second Moment of Area (in ⁴ .)	Radius of Gyration (in.)	Slenderness Ratio (-)	Critical Stress (KSI)
1	4.671	0.706	0.210	0.546	8.554	14.77
2	4.655	0.657	0.185	0.530	8.780	12.64
3	4.614	0.562	0.141	0.500	9.226	14.76
4	4.665	0.504	0.116	0.480	9.714	17.16
5	4.715	0.506	0.113	0.473	9.965	16.81
6	4.480	0.534	0.126	0.485	9.236	15.81
7	4.612	0.521	0.119	0.477	9.668	16.37
Mean	4.630	0.570	0.144	0.499	9.306	15.48
Standard Deviation	0.075	0.080	0.038	0.029	0.514	1.56
Maximum	4.715	0.706	0.210	0.546	9.965	17.16
Minimum	4.480	0.504	0.113	0.473	8.554	12.64

The failures identified for the 2" specimens were exactly identical to the 1.5" specimens. The most typical failure that the 2" specimen experienced was end bearing with some occasional splitting. A typical test of the 2" specimens would show a high amount of end bearing stress on the top of each specimen, followed by splitting. The splitting of the fibers is caused by instability of the matrix.

Figure 5.8 2" buckling specimens after experimental test

5.3.3 3-Inch Long Experimental Tests

The next group of specimens that were tested was the 3" case, which contained a total of seven specimens. The geometries of each specimen within the 3" can be seen in Table 5.6. By looking at the table, one can see that they are exceptionally accurate with the standard deviation of all geometries below 5%.

Table 5.6 3-inch buckling specimen geometries

Specimen	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Weight (lb _f)	Density (lb _m /in ³)
1	2.966	1.553	0.125	0.053	0.032
2	2.967	1.529	0.126	0.052	0.032
3	2.963	1.542	0.124	0.052	0.032
4	2.970	1.517	0.123	0.051	0.032
5	2.971	1.503	0.121	0.049	0.031
6	2.974	1.498	0.125	0.051	0.031
7	2.944	1.491	0.134	0.050	0.029
Mean	2.965	1.519	0.125	0.051	0.031
Standard Deviation	0.010	0.023	0.004	0.001	0.001
Maximum	2.974	1.553	0.134	0.053	0.032
Minimum	2.944	1.491	0.121	0.049	0.029

Figure 5.9 displays the stress strain curves respectively. It is evident by looking at the graph, that the precision of the geometries plays a huge role in the consistency of the tests, as the curves follow the same trend. As mentioned with bamboo being a brittle material, one parameter that should be focused on is the critical stress. The average critical stress for this test group was 13.52KSI, with a standard deviation of 10.15%, which is very good for being a natural material. This is a significant decrease when compared to the 2" group, as the average critical stress dropped by 14.41%. The average elastic modulus was also calculated using the stress-strain plot, and was found to be 907.25KSI with a standard deviation of 2.75%. **Table 5.7** shows a summary of the sectional properties as well as the critical stress of each specimen in this test group.

Figure 5.9 Stress-strain curves of 3" buckling specimens

Table 5.7 Sectional properties of the 3" buckling specimens

Specimen	Effective Length (in.)	Area (in ² .)	Second Moment of Area (in ⁴ .)	Radius of Gyration (in.)	Slenderness Ratio (-)	Critical Stress (KSI)
1	7.119	0.560	0.144	0.507	14.045	11.4
2	7.120	0.553	0.137	0.498	14.297	13.47
3	7.111	0.551	0.140	0.503	14.133	14.42
4	7.128	0.538	0.132	0.495	14.406	14.21
5	7.129	0.526	0.127	0.491	14.534	14.64
6	7.137	0.540	0.128	0.487	14.640	47.7
7	7.064	0.572	0.133	0.482	14.657	11.82
Mean	7.116	0.549	0.134	0.495	14.387	13.52
Standard Deviation	0.024	0.015	0.006	0.009	0.241	1.362
Maximum	7.137	0.572	0.144	0.507	14.657	14.7
Minimum	7.064	0.526	0.127	0.482	14.045	11.4

The failure for the 3" case were very similar to the 1.5" and 2" buckling specimens with the failures of all specimens being due to significant bearing stress as well as longitudinal splitting. However, by looking at Figure 5.10, one can see that the bearing stress was not as significant as the 1.5" and 2" long buckling specimens. Most specimens within this group failed mostly due to longitudinal splitting.

Figure 5.10 3" buckling specimens after experimental tests

5.3.4 4-Inch Long Experimental Tests

The fourth group of specimens tested for buckling analysis was a 4" case study. This group contained a total of seven specimens. The first table that is presented for this specific case study is Table 5.8, which shows the geometries of each specimen including the averages. By looking at this table, one can see that the geometries of each specimen are exceptionally accurate as all the deviation are well below the standard of 15%, as all are geometries are under a 7% standard deviation.

Table 5.8 4-inch buckling specimen geometries

Specimen	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Weight (lb _f)	Density (lb _m /in ³)
1	3.990	1.647	0.137	0.079	0.030
2	3.900	1.677	0.158	0.081	0.027
3	3.942	1.635	0.145	0.079	0.029
4	3.948	1.564	0.134	0.073	0.031
5	3.957	1.597	0.134	0.074	0.030
6	3.982	1.577	0.136	0.075	0.030
7	3.958	1.588	0.133	0.074	0.030
Mean	3.954	1.612	0.140	0.076	0.030
Standard Deviation	0.029	0.041	0.009	0.003	0.001
Maximum	3.990	1.677	0.158	0.081	0.031
Minimum	3.900	1.564	0.133	0.073	0.027

Figure 5.11 shows the stress-strain curves of the 4" buckling specimens. Once again, it is clear that the preciseness of the geometries lead both plots to become very consistent. Also, by looking at the stress-strain curve, in comparison to the 3" specimens, there is only a 1.73% drop in the critical stress of the specimens, far from the critical stress percentage drops that were seen from the other groups compared to their preceding group. The average critical stress for the 4" test group was 13.29KSI with a standard deviation of 10.11%. The average elastic modulus for this test group was 1146.96KSI with a standard deviation of 7.07%. Table 5.9 illustrates the sectional properties and the critical stress of the 4" buckling specimens.

Figure 5.11 Stress-strain curves of 4" buckling specimens

Table 5.9 Sectional properties of the 4-inch buckling specimens

Specimen	Effective Length (in.)	Area (in ² .)	Second Moment of Area (in ⁴ .)	Radius of Gyration (in.)	Slenderness Ratio (-)	Critical Stress (KSI)
1	9.577	0.650	0.187	0.536	17.862	13.92
2	9.360	0.754	0.220	0.540	17.335	14.3
3	9.460	0.677	0.190	0.529	17.876	14.12.
4	9.475	0.601	0.155	0.508	18.653	11.54
5	9.497	0.617	0.167	0.519	18.288	14.06
6	9.556	0.616	0.161	0.512	18.681	14.34
7	9.498	0.609	0.163	0.517	18.387	11.6
Mean	9.489	0.646	0.177	0.523	18.154	13.29
Standard Deviation	0.071	0.054	0.023	0.012	0.489	1.34
Maximum	9.577	0.754	0.220	0.540	18.681	14.34
Minimum	9.360	0.601	0.155	0.508	17.335	11.54

The primary failures of each specimen in the 4" case study for the bamboo were local buckling. It was apparent in the early parts of the tests that there was not significant bearing stress on the specimens, however the end bearing stress was not the cause for the failure of the bamboo. The instability of the matrix and individual fibers would cause the bamboo to first buckle locally, which then leads to critical failure. A typical failure of the 4" specimen can be seen in Figure 5.13.

Figure 5.13 Local buckling of 4" specimen

Figure 5.12 4" buckling specimens after experimental tests

5.3.5 6-Inch Long Experimental Tests

The next group of specimens that were tested under buckling analysis was a 6" case study that contained a total of five specimens. Table 5.10 presents the geometries for each specimen in this test group. From Table 5.10, one may notice substantially large deviations between each specimen, most notably with the weight and thickness of each specimen at 31% and 21.64% respectively. The reason for this deviation is because unlike the preceding test groups, the 6" test specimens were obtained from different internodes because of the length of each specimen. With the average internode length being approximately 10", many times only one testing specimen could be obtained from each internode. With bamboo being a natural product, it is not possible to control the thickness of each specimen, which is the explanation of the large deviations.

Table 5.10 6-inch buckling specimen geometries

Specimen	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Weight (lb _f)	Density (lb _m /in ³)
1	5.688	1.698	0.175	0.141	0.030
2	5.875	1.727	0.253	0.206	0.030
3	5.984	1.525	0.165	0.110	0.026
4	5.906	1.619	0.206	0.149	0.027
5	5.630	1.482	0.149	0.093	0.026
Mean	5.816	1.610	0.189	0.140	0.028
Standard Deviation	0.151	0.106	0.041	0.043	0.002
Maximum	5.984	1.727	0.253	0.206	0.030
Minimum	5.630	1.482	0.149	0.093	0.026

Although, there are very large deviations within the geometry the trend of the stress-strain curve, which can be seen in Figure 5.14 is still consistent. However the critical stresses are not very consistent, as the values range from approximately 10 KSI to approximately 15KSI. The average critical stress for this testing group was 11.54KSI with a standard deviation of 14.57%. With the consistent trends of the stress-strain curves, the elastic modulus was calculated to be

very consistent yielding a value of 1111.06KSI and a standard deviation of 6.61%. The average slenderness ratio of the 6" test group was 27.61 with a standard deviation of 6.27%. Table 5.11 summarizes the sectional properties of the 6" buckling specimens.

Figure 5.14 Stress-strain curves of 6" buckling specimens

Table 5.11 Sectional properties of the 6-inch buckling specimens

Specimen	Effective Length (in.)	Area (in ² .)	Second Moment of Area (in ⁴ .)	Radius of Gyration (in.)	Slenderness Ratio (-)	Critical Stress (KSI)
1	13.650	0.835	0.245	0.542	25.177	13.19
2	14.100	1.170	0.327	0.529	26.655	12.10
3	14.362	0.704	0.165	0.484	29.647	11.12
4	14.173	0.915	0.233	0.505	28.069	14.22
5	13.512	0.624	0.140	0.474	28.493	10.56
Mean	13.959	0.850	0.222	0.507	27.608	12.08
Standard Deviation	0.362	0.212	0.074	0.029	1.730	1.25
Maximum	14.362	1.170	0.327	0.542	29.647	13.42
Minimum	13.512	0.624	0.140	0.474	25.177	10.56

The failure modes that were evident in this test group were very similar to the 4" testing group.

However, for the 6" test group, the instability of the specimens was much more evident visually than the 4" test group.

Figure 5.15 6" buckling specimens after experimental test

5.3.6 8-Inch Long Experimental Tests

The sixth group that was analyzed to study the buckling characteristics consisted of specimens with an approximate length of 8". Four total specimens were tested within the 8" group. Table 5.12 shows the geometries of each specimen within the testing group. From this table, one can see that the geometries are very consistent with each geometric parameter being under 9%. Table 5.12 provides the geometries of the 8" buckling specimens.

Table 5.12 Sectional properties of the 8-inch buckling specimens

Specimen	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Weight (lb _f)	Density (lb _m /in ³)
1	8.071	1.687	0.187	0.184	0.026
2	8.071	1.784	0.175	0.223	0.031
3	8.032	1.746	0.197	0.196	0.025
4	7.992	1.658	0.193	0.193	0.027
Mean	8.041	1.719	0.188	0.199	0.027
Standard Deviation	0.038	0.057	0.010	0.017	0.003
Maximum	8.071	1.784	0.197	0.223	0.031
Minimum	7.992	1.658	0.175	0.184	0.025

Although the geometries are very consistent, this is not shown in the data of the stress-strain curves, as the curves are very irregular. The stress-strain curve for the 8" buckling specimens can be seen in Figure 5.16. The cause of this sporadic behavior seen on the curves may be due to the lengths of the bamboo as well as some natural curvature to the bamboo specimens.

Although, all of the warped and irregular internodes were removed from all testing groups, it is almost impossible to obtain specimens that are perfectly straight due to the natural growth of bamboo. In knowing this, some of the specimens may have failed before the critical load was reached due to the influence of the curvature on the bamboo. The average critical stress for the 8" testing group was 11.60KSI with a standard deviation of 9.18%. The average elastic modulus and slenderness ratio were 1229.48KSI and 35.43 with a standard deviation of 10.05% and 3.70% respectively. Table 5.13 displays the sectional properties of the 8" buckling specimens.

Figure 5.16 Stress-strain curves of 8" buckling specimens

Table 5.13 Sectional properties of the 8-inch buckling specimens

Specimen	Effective Length (in.)	Area (in ² .)	Second Moment of Area (in ⁴ .)	Radius of Gyration (in.)	Slenderness Ratio (-)	Critical Stress (KSI)
1	19.370	0.881	0.252	0.534	36.251	12.24
2	19.370	0.883	0.289	0.572	33.847	11.22
3	19.276	0.958	0.292	0.552	34.919	10.58
4	19.181	0.889	0.242	0.522	36.724	12.65
Mean	19.299	0.903	0.269	0.545	35.435	11.67
Standard Deviation	0.091	0.037	0.025	0.022	1.306	1.06
Maximum	19.370	0.958	0.292	0.572	36.724	12.65
Minimum	19.181	0.881	0.242	0.522	33.847	10.28

The primary failure mode of the 8" test group was overall buckling, signifying that the bamboo

has reached its elastic stability limit. The compression forces applied to the bamboo specimens

caused the long slender specimen to move lateral to the force causing a bend in the specimen,

which led to catastrophic failure. However, it may be that the reason that the bamboo

specimens did reach their elastic stability limit could be because of the natural curvature as

mentioned. Figure 5.17 shows the 8" buckling test specimens after catastrophic failure.

Figure 5.17 8" buckling specimens after experimental test

5.3.7 10-Inch Long Experimental Tests

The seventh and final group that was analyzed consisted of five total specimens that were approximately 10" in length. Table 5.14 summarizes the geometries of the specimens inside this test group. By looking at the table, one may notice that there is a large deviation for some of the geometries with weight and thickness having the highest deviations at 16.67% and 26.92% respectively. However, as mentioned earlier because of the naturalness of bamboo, there is no way to correct this.

Table 5.14 10" buckling specimen geometries

Specimen	Height (in.)	Outer Diameter (in.)	Wall Thickness (in.)	Weight (lb _f)	Density (lb _m /in ³)
1	10.002	1.460	0.132	0.171	0.031
2	9.961	1.693	0.188	0.221	0.025
3	9.961	1.853	0.205	0.324	0.031
4	9.961	1.862	0.205	0.322	0.030
5	9.921	1.699	0.195	0.286	0.031
Mean	9.961	1.713	0.185	0.265	0.030
Standard Deviation	0.028	0.163	0.031	0.067	0.003
Maximum	10.000	1.862	0.205	0.324	0.031
Minimum	9.921	1.460	0.132	0.171	0.025

Figure 5.18 illustrates stress-strain curve respectively. Knowing that there are large deviations in the errors, the stress-strain curves are still fairly consistent with exception to the critical stresses. The average critical stress for the 10" specimen was 11.12KSI, with a standard deviation of 5.18%. The calculated average elastic modulus and slenderness ratio for the 10 test group was 1449.34KSI and 44.21 with a standard deviation of 16.06% and 9.48% respectively. Table 5.15 displays a summary of the sectional properties of each specimen and the averages of the 10" buckling specimens.

Figure 5.18 Stress-strain curves of 10" buckling specimens

Table 5.15 Sectional properties of 10" buckling specimens

Specimen	Effective Length (in.)	Area (in ² .)	Second Moment of Area (in ⁴ .)	Radius of Gyration (in.)	Slenderness Ratio (-)	Critical Stress (KSI)
1	24.000	0.550	0.122	0.472	50.856	12.24
2	23.906	0.888	0.255	0.536	44.567	10.22
3	23.906	1.059	0.365	0.587	40.698	11.34
4	23.906	1.068	0.372	0.590	40.514	11.34
5	23.811	.923	0.276	0.544	44.410	11.12
Mean	23.906	0.898	0.276	0.544	44.209	11.25
Standard Deviation	0.067	0.210	0.102	0.048	4.193	1.06
Maximum	24.000	1.068	0.372	0.590	50.856	12.65
Minimum	23.811	0.550	0.122	0.472	40.514	10.28

The failure mode that was exhibited during the testing of the 10" specimens was again overall

buckling, very similar to the 8" test specimens, indicating that the material is in the elastic range of buckling. The buckling behavior of the 10" specimen was however predicted with the 10" group having a larger slender ratio that the 8" specimen, which also experienced overall buckling. Figure 5.19 shows the catastrophic failure of the 10" buckling specimens after experiencing general buckling during the experimental tests.

Figure 5.19 10" buckling specimens after experimental test

5.4 Buckling Theoretical and Experimental Analysis

The classical analysis of buckling comes from the Swiss mathematician Leonhard Euler, who developed an equation that predicts the critical buckling load and strength for a straight pinned end column.²⁸ The elastic critical buckling strength developed by Euler is given by Equation 5.4

$$\frac{P_{cr}}{A} = \frac{\pi^2 E}{\lambda_{eff}^2} \quad (5.4)$$

Where E_c is the elastic modulus and λ is the slender ratio.

Although the critical strength is subject to Euler's equation, there are many other factors that go into determining the predicted buckling strength. As mentioned earlier, one factor that has a large influence on the buckling strength is how the ends of the column are attached. Another factor that can influence the critical strength of the bamboo is the geometry and the natural curvature of the bamboo. With bamboo being a natural product, more times than not the bamboo will not be straight, which may increase the chances of failure before reaching the critical load.

Through studies found by Chung and Chan, it was found that the modern structural design philosophy of column buckling follows very closely to the structural design philosophy of Euler. As a natural non-homogeneous organic material, Chung and Chan found that it is apparent that there are large variations of the physical properties along the length of the bamboo culms.²⁸ These large variations are seen in both the external diameter, the thickness of the bamboo, as well as curvature in the bamboo. To incorporate the natural large geometric variations of the bamboo, Chung and Chan proposed to add a non-prismatic parameter, β to the elastic Euler buckling load of bamboo columns. The non-prismatic parameter (β) is calculated using Equation 5.5

$$\beta = 1.005 + .4751c - .011c^2 \quad (5.5)$$

where c is defined by Equation 5.6

$$c = \frac{I_2 - I_1}{I_1} \quad (5.6)$$

where I_1 and I_2 denote the larger and smaller second moment of areas.

It is recommended by ISO 22156 Bamboo Structural Design that there be at least a 10% reduction to be applied to the second moment of area of bamboo culms. To be conservative, in this study, a 15% reduction was applied to the second moment of area, which supplied a c value of 0.414 and a β value of 1.20.

The modified elastic critical buckling strength (σ_{cr}) of the bamboo column is then given Equation 5.7

$$\sigma_{cr} = \beta \frac{\pi^2 E}{\lambda_{eff}^2} \quad (5.7)$$

There are three distinct regions on a strength curve when evaluating column buckling. These three distinct regions are known as the plastic, inelastic, and elastic regions. When the slenderness of the column is relatively low, plastic behavior is expected, as the column is limited to its material strength. When the member slenderness transitions from plastic to elastic, the region is known as the inelastic range. The inelastic range is when a material experiences a combination of both plastic and elastic strength, where local buckling occurs. When the slenderness is large enough to exit the inelastic range, elastic buckling behavior is expected, and the strength is controlled by the Euler buckling behavior. Figure 5.20 shows a typical strength curve associated with both local and overall buckling behavior.

Figure 5.20 Typical strength curve showing the three distinct regions

Figure 5.21 and Figure 5.22 show the predicted stress values obtained from the modified Euler's equation as well as the experimental results respectively. It is very important to note that the predicted stress values from the modified Euler's equation only predict the critical strengths of the specimens that buckle, and are not a predictor to specimens that do not experience buckling. This is why the critical stresses of the earlier slenderness ratios may seem to be a bit high, but this is because specimens with low slenderness ratio did not experience buckling. By looking at Figure 5.21, one may notice that the transition phases from plastic to inelastic and inelastic to plastic are not very clear and easy to visualize.

Figure 5.21 Predicted strength curve using a modified Euler's equation only predicts the critical strength of specimens that experience buckling and not a predictor of strength of specimens that do not buckle.

Figure 5.22 Experimental strength curve

To help identify the regions within the graph, the experimental results of the bamboo are also shown in Figure 5.23. By looking at Figure 5.23, one can see that within the plastic region, the predicted critical strength is substantially higher than the experimental results. As mentioned earlier, this is because the critical buckling stress exceeds the capacity of the material to handle it, which is why the failure mode of the small slenderness values is due to the material strength and not buckling. From the experimental results, all of the 1.5", 2", and 3" specimens failed due to material strength. From these experimental results it was estimated that the end of the plastic region and beginning of the inelastic range is approximately at a slender ration of approximately 18.12. This transition point is denoted on Figure 5.23 by λ_I . Also by looking at the graph, the beginning of the elastic region is marked by the intersection of the predicted Euler results and the experimental results. The beginning of the elastic region was determined to be a slender ratio of 34.7 and is denoted by λ_E . When comparing the experimental results with the analytical results, there are some discrepancies. The reason for this could be the geometric deformities, as the bamboos were not all completely straight or cylindrical.

Figure 5.23 Experimental strength curve overlaid on predicted stress curve

Based on the extensive and systematic experimental testing, a design rule has been developed for column buckling of bamboo. From the theoretical and experimental results, it is suggested that the slenderness ratios of bamboo when in compression should be kept below 34.7 to avoid global buckling. A slender ratio above 34.7 can severely deplete the strength of the bamboo material, causing the bamboo to fail at a premature load due to buckling. However, to avoid any form of buckling for bamboo, including local buckling, a slender ratio below 18.2 is suggested.

As mentioned earlier, bamboo has great potential to be used on real world high strength applications. Although, bamboo is most popularly used in housing, as over one billion live in bamboo houses, I believe there is much more potential for use of bamboo. With these houses, the bamboo is not used to its potential, as many of the bamboo housing applications never have to experience the high loads that the bamboo is suitable for. This section is about exploring new possibilities for bio-composites in general and to test the feasibility of the bio-composites in a typical application. The only limit to bamboo is the imagination.

Chapter 6. Wall Application

One of the main objectives of the wall application is to show the feasibility of bio-composites being applied to real life applications. To show the feasibility of bio-composites, a small structural wall prototype was built using hemp and bamboo and tested under compression in the Architectural Engineering high bay laboratory at Cal Poly, San Luis Obispo. The dimensions of the wall prototype were 15.13" long, 7.75" tall, and 2.375" wide.

6.1 Manufacturing of Wall Application

All manufacturing of the wall application was done in the Cal Poly Structures/Composites Lab. The wall was constructed using bamboo and a bi-directional hemp fabric. The first step in manufacturing the wall application was to first cure the bamboo internodes using the 3% optimal treatment. The guidelines of the 3% salt treatment were followed in section 2.3.3. After the curing of the bamboo was complete,

Figure 6.1 Placeholder half Internode bamboos

a total of six internodes were cut longitudinally into two equal half internodes using the Rigid Tile saw, as seen in Figure 6.1. Once the internodes were cut, a leveler was employed to ensure that the bamboo specimens were perpendicular to the faces of the testing fixtures. If the bamboo was not level, the bamboo was sanded by hand until level. The next step was to manufacture two-ply laminates using the bi-directional hemp fabric. To do this, two 16" X 8" pieces are cut from the hemp fabric. Once the 16" X 8" hemp pieces are cut, the fibers of the first cutout piece are directly aligned on top of the other hemp cutout. After the fibers were aligned a ECOPOXY EH-725hardener/ER-500 resin system is

Figure 6.2 ECOPOXY EH-725hardener/ER-500 resin system

used to wet the hemp fibers. This system was mixed using a 4:1 resin to hardener ratio. After wetting the fibers, a porous release media was applied to both sides of the laminate, and a non-porous media was applied over the porous material on both sides of the laminate. The part and release media was then placed inside of the vacuum bag and the bag was sealed using sealant tape. Along with the laminate, release media, vacuum bag, vacuum, and sealing tape, a breather is also used to squeeze out all of the air without taking in any resin. Figure 6.3 shows the general layout of the vacuum bag materials. After the laminate was set into the vacuum bag, the laminate was cured for 12 hours inside the vacuum bag to allow the laminate to fully cure and harden. Two laminates were manufactured in this way.

Figure 6.3 Vacuum Bag Lay-up of Materials

Once the laminate cured, the sliced bamboo internodes were then carefully placed and aligned on the laminates, as shown in Figure 6.4. The sliced cross-sections of the internodes were then glued onto the laminate using the same Ecopoxy EH-725 hardener/ER-500 resin system, and was allowed an hour to cure. Once the bamboo internodes were cured onto the laminate two 16" by 8" pieces of hemp fabric were cut out again. After the hemp fabric was cut, the ECOpox system was used to wet the fibers, and then was placed over the bamboo, sandwiching the bamboo internodes as seen in Figure 6.6. Release media was then applied on top of the hemp fabric and the part was vacuumed for 12 hours to allow for curing. This method was applied to both laminates. Figure 6.7 shows two composite bamboo sandwiches manufactured.

Figure 6.4 Half bamboo internodes are aligned and glued onto hemp laminate

Figure 6.6 Composite bamboo sandwich is cured using the vacuum on the table

Figure 6.7 Composite bamboo sandwich after cure

The next step is to then build the frame of the wall. To build the frame four U-channels were made out of the bi-directional hemp fabric. The first step in fabricating the U-Channels was to first make a mold. The mold, seen in Figure 6.5 was manufactured from a 2" X 4" piece of wood, thanks to Mr. Robby Nielsen of Mustang 60₁. The measurements of the mold consisted of 17.125" X 2.375" X .923". The first step in using the mold was to apply a vacuum bag over the mold. This is to prevent from any epoxy seeping into the mold and also allow the cured part to easily be removed after curing. Once the vacuum bag was set onto the mold, eight pieces of hemp were cut out to match the configuration of the mold. The epoxy system was then applied to the hemp fabric, and each ply was carefully placed on top of one another, aligning the fibers of each ply. The release media was then applied on both sides of the hemp fabric and was then placed on the mold. A vacuum bag was then applied to the part and was cured for 12 hours. This process was done four times to make the frame of the wall.

Figure 6.5 The mold was used to manufacture U-channel frames

Figure 6.8 Curing of the U-channel frames

Once the wall pieces were cured, the U-channels were then cut down to size. The horizontal pieces of the frame were measured out to 15.13" in length and the longitudinal members of the frame were measured out to be 7.75" in height. After each piece was cut to size, finger joints were manufactured to join the sides of the frame together.

To do this, the flanges of the vertical U-channel beams are cut to the depth of the horizontal beams, creating small finger joints. However, because it was extremely hard to accurately cut the flanges to the depth of the horizontal U-channels, the side flanges of the horizontal members were sanded down using a dremel until there was a proper fit.

Figure 6.9 Finger joints were used to join the U-channel frames

Figure 6.9 displays the finger joints used to construct the wall frame.

After all of the finger joints were manufactured and all joints had a good fit, the side walls and the bottom frame member were assembled with the two sandwich bamboo laminates as seen in Figure 6.12. After fitting the frame the finger joints were then tack together using the ESFR 200 fast set adhesive system from Ecopoxy Systems. The adhesive system was mixed using a 2:1 resin to hardener ratio was applied to the joints. After the hardening of the adhesive, EP 400 putty filler from Ecopoxy was used to cover each of the joints to provide more stiffness to the

joints and also induce failure of the wall away from the joints. The EP 400 putty system was mixed using a 4:1 resin to hardener ratio. Once the putty was applied to the wall application, the wall was then left overnight to cure. Figure 6.14 shows the final outcome of the wall application.

Figure 6.10 EP 400 putty system

Figure 6.11 Ep400 putty system applied to joints

Figure 6.12 Wall application

Figure

Figure 6.14 Final wall application

6.2 Testing of Wall Application

The testing of the wall application was done in the

Architecture Structures Laboratory in the

Engineering West building of Cal Poly, San Luis

Obispo. The wall application was tested in

compression using two different machines. The first

test of the wall application was conducted using the

Tinius Olsen H50K-s UTM benchtop tester, which is

capable of handling up to 10,000lbf. The Tinius

Olsen H50K-s UTM benchtop tester can be seen in

Figure 6.15. To distribute the load across the

length of the wall application, two hollow metal

box beams are placed on the top and bottom of the

wall application inside the testing area of the

machine, as seen in Figure 6.16. Once the wall

application was centered inside the testing area,

the application was then preloaded by

approximately 1lbf. Once preloaded, the test was

then conducted using a cross head speed of .5

in/min and was set to test until failure.

The second test performed was conducted in the Architecture High Bay Structures Laboratory.

This test was a repeat of the first test, but was conducted using the Riehle testing machine that

has a higher capacity load and is commonly used to test wall applications. This machine is

capable of handling loads up to 300,000 lbf. Load versus deformation data is collected through

Figure 6.15 Tinius Olsen H50K-s UTM benchtop tester

Figure 6.16. Wall experimental test set-up for first test

the National Instruments 8 data acquisition system. Figure 6.17 and Figure 6.18 show a photograph of the machine. Once again to distribute the load along the length of the wall structure, two hollow box beams were placed on the top and bottom of the wall application. The test set-up of the wall application can be seen in Figure 6.17. The application was then preloaded to approximately 10 lbf, and the test was performed at a cross head of approximately 0.5 in/min until complete failure of the application.

Figure 6.17 Experimental test set-up for test 2

Figure 6.18 Riehle testing machine

6.3 Results of Wall Application

The first test that was conducted on the wall application using the Tinius Olsen benchtop tester never reached complete failure, as it exceeded the 10,000lbf testing limit of the machine. Figure 6.20 shows the load extension curve of the test performed using the Tinius Olsen machine. By looking at this curve, one can see a small spike at approximately 4900 lbf. This identifies the point where there was some minor cracking in the finger joints of the frame, seen in Figure 6.19. The cracking of the joints in the bonded area is a result of not having tight tolerances for the finger joints. With no complete failure of the wall application, a second test was conducted.

Figure 6.19 Cracking of joints due to

Figure 6.20 Force-extension curve of first test on wall application

For the second test, the wall application did fail, as it reached complete failure at approximately 46,800 pounds. The force-displacement curve of the wall application is shown in Figure 6.21.

Initial failures of the wall application initiated at approximately 18,000 lbf at the finger joints of the wall, similar to the cracking of the joints during the first experimental tests. The cracking of the adhesive first developed in the corners of the joints and then slowly propagated throughout the whole joint as testing continued. The initial failure and cracking of the joints is hypothesized to be from the vertical joints not completely matching the width and depth of the U-channel slot. This caused little gaps around the edges of the joints, which were then filled using the ecopoxy adhesive. The filling of the edges of the joints with adhesives induced high loading on the adhesives, causing it to crack.

Figure 6.21 Force-extension curve of 2nd test on wall application

Although small cracking was evident along the joints, it did not have much effect on the ultimate strength of the bamboo. The bamboo that were inside the wall structure held up very well, as it provided stiffness to the wall structure. It was not until a load of approximately 35,000 pounds that the the bamboo inside the wall began to lose stiffness and the bonding between the hemp and

Figure 6.22 The bamboo specimens of the wall structure began to buckle at an approximate force of 40,000lbs.

bamboo began to become undone, as the bamboo began to locally buckle against the laminate on both sides of the wall. The local buckling inside of the wall structure can seen in Figure 6.22. This local buckling of the bamboo caused crimping of the laminate, depreciating the stability of the structure. Once the stability of the structure was diminished, it could no longer support the load that was applied by the Riehle testing machine causing complete failure at an approximate load of 46,800 pounds. Figure 6.23 shows an inside look at the damage after the experimental testing of the wall application.

Figure 6.23 Aftermath of experimental test of wall application

6.4 Wall application Results, Analysis, and Discussion

The response of the bamboo in the wall application was very similar to the earlier buckling tests done performed on the bamboo, which is discussed in Section Chapter 5. Along with the fact that the wall application used bamboo poles that were cut in half, another main difference between the bamboo specimens in the wall application and the bamboo used for buckling analysis is how the ends of the bamboo are confined. In the buckling tests, the ends of the bamboo are confined as a fixed and free, giving an effective length twice the size of the original specimen length. However, for the wall application, the ends of the bamboo were fixed to the top and bottom frames, which made the effective length of the bamboo equal to the specimen length. With a length of approximately 7.75" and an average diameter of approximately 1.5", the slenderness ratio of the bamboo inside the wall is calculated to be approximately 21, using the equations discussed in section Chapter 5. With earlier buckling analysis determining that local buckling begins at a slenderness ratio of 14.4 and global buckling beginning at an approximate slenderness ratio of 34.7, it was expected that the bamboo would fail due to local buckling.

Overall, the experimental testing of the wall prototype proves that bio composites have great potential to be used in future structural applications. However, there is still more research needed make the potential of bio-composites to become a reality, which is discussed in Section Chapter 9.

Chapter 7. Numerical Analysis

With today's engineering product world driven primarily by cost and quality, the finite element method has become widely established in all engineering industries. With the finite element method able to analyze general problems in solid, structural, and fluid mechanics, as well as heat and mass transfer, by finding approximate solutions to partial differential equations the finite element method is frequently employed in the preliminary design stages before the manufacturing of a project. Not only can the finite element method reduce costs significantly, but it also can identify critical areas that carry a large portion of the load as well as identify area where material may be able to be saved. The intent of this section will be to verify the deflections found experimentally through a numerical method. The buckling specimens and the application are both numerically verified in this section. The numerical method utilized in this section is the finite element method using the Abaqus software.

7.1 Buckling FEA

The first test that was modeled numerically in the finite element method was the buckling specimens. When building the buckling finite element model, three key assumptions were made to ease the analysis. The first assumption of the finite element model was that the bamboo specimen did not have any curvature to the specimen, and was completely straight. The second assumption made includes the bamboo specimens having a uniform thickness. The final assumption made in the modeling of the bamboo is that the cross-section is completely circular. However, knowing that bamboo is a natural growing material, there is no way to control the bamboo's growth, and for this reason, the majority of the bamboo culms, if not all will always have some deformities in their geometries. With no bamboo having identical geometry, it would be almost impossible to model the bamboo without forming these key assumptions.

7.1.1 Material Properties

With only wanting to verify the results of the experimental tests, only the 8" buckling case is analyzed. The reason that the 8" buckling case is chosen is because the 8" group was the first to experience global buckling. The 8" buckling case specimen is modeled using the continuum shell/conventional shell function in Abaqus and the dimensions of the specimens were made to be 8" long , 1.5" diameter, and a thickness of 0.12". The material properties of the bamboo shell were assigned using the engineering constants obtained from the experimental tests of this study, described in Chapter 3. The engineering constants used to model the bamboo are shown in Table 7.1. These material properties are applied to the whole bamboo specimen. Along with the material properties, the global coordinate system was replaced with a local coordinate system, as seen in Figure blank. The local coordinate system is defined as the 1 being the x axis, 2 the y axis, and 3 the z axis.

Table 7.1 Engineering constants used to model bamboo in the finite element model

E_1 (KSI)	E_2 (KSI)	E_3 (KSI)	ν_{12}	ν_{23}	G_{12} (KSI)	G_{23} (KSI)
1355	7.31	7.31	0.26	0.57	537.53	2.33

7.1.2 Load and Boundary Conditions

After the material properties were inputted into the Abaqus software, the load and boundary conditions were defined in the Abaqus software. The first thing that was accomplished was the boundary conditions of the buckling specimen. To try and match the end conditions of the experimental tests, the translation in the z-direction is fixed on the bottom end plane of the bamboo buckling specimen and the top end has no constraints, as seen in Figure 7.1. Once the boundary conditions were established, the load was then applied to the top free end of the bamboo. The load used for this analysis was a shell edge load and the applied load was approximately 6000 lbf.

Figure 7.1 Load and boundary conditions applied to the 8" buckling specimen for numerical analysis

7.1.3 Mesh

The meshing of the buckling specimen was generated with the help of the Abaqus software. For the model, an 8-node linear brick element with reduced integration is chosen for the shell. A total of 10,000 elements were generated for the mesh, with an approximate global size seeding of .05". Each element generated for the mesh of the bamboo resembled a square. The reason for this is because when elements get too elongated or distorted the accuracy of the model decreases. Once the mesh was created, the mechanical properties of the bamboo were assigned to each element. Figure 7.2 shows the meshing of the 8" buckling specimen.

Figure 7.2 Mesh of the bamboo used for numerical analysis

7.1.4 Results

After meshing of the bamboo buckling specimen was complete, the post processing analysis of the sandwich beam is conducted statically under the specified loads. Once the analysis is complete a displacement contour plot is then plotted within the Abaqus software and can then be compared to the experimental results. The numerical value for the deflection of the buckling specimen at the specified load of 6000lb_f was 0.0549 inches. The average value for the experimental specimens was 0.0599 inches at this load. In comparison of the two, the numerical value found through the Abaqus software agrees very closely to the experimental values, as they differ by only 8.35%, providing much confidence to the data. Figure 7.3 shows the displacement contour plot of the buckling specimen.

Figure 7.3 Displacement contour plot of 8" buckling specimen

Along with verifying the deflection of the buckling specimen, the stresses of the specimen are also analyzed numerically to compare to the experimental values and evaluate where the critical stresses are being applied. Figure blank displays the stress contours of the buckling specimen. The numerical value obtained from the Abaqus software using a load of 6000lb_f was 6.745KSI, which was seen throughout the structure, excluding the top portion of the specimen, where

high bearing stress was exhibited. In the region where high bearing stress was exhibited, a stress of 8.986KSI is produced by the load, which is 33.22% higher than the load seen throughout most of the structure. The stress obtained from experimental testing of the 8" buckling specimens was 6.829KSI. When compared to the numerical stress that is seen throughout most of the structure, the experimental stresses show precise agreement with the numerical analysis. The experimental values differ from the numerical values by only 1.25%.

Figure 7.4 Stress contour plot of 8" buckling specimen

7.2 Wall Application FEA

The second test modeled numerically to verify experimental results using finite element analysis was the wall application. Like the finite analysis performed for buckling, there were many assumptions that were made when building the finite element model. The assumptions made for the buckling analysis still hold true for the wall application. However, with the wall structure two additional key assumptions have been made when building the finite element model of the wall. The first additional key assumption of the finite element model does not account for the epoxy used to make the joints of the wall frame nor any deformities in the finger joints of the U-channel frame. Instead the joints of the wall frame are perfectly bonded together. The last assumption made for the wall application finite element model is that all parts of the wall, including the bamboo and hemp were perfectly bonded together.

7.2.1 Material Properties of Wall Application

One of the main differences of the wall and the buckling specimen is that the wall utilizes a hemp fabric for the outside structure. The material properties of the hemp fabric were extracted out of the senior project of Ms. Tery Muy, who analyzed hemp fabric under different curing methods. The data extracted from Ms. Muy's senior projects was the bi-directional hemp fabric cured under vacuum. Again, like the bamboo, the material properties of the hemp fabric were modeled using the engineering constants that Ms. Muy discovered. For the wall application, the bamboo parts were modeled identically to the bamboo modeled in the buckling case. However, for the wall application, only half shells are defined for the bamboo, instead of whole shells. For reference of the material properties used for the bamboo specimens, please refer to Section 7.1.1.

To build the model, a total of eight parts were manufactured and then integrated through the Abaqus software. To build the frame of the wall, four different U-channels were manufactured before integration. The interior of the wall consisted of the two bamboo composite sandwiches along with the two bamboo half internodes placed at the end of the wall for structural support of the frame. Figure 7.5 and Figure 7.6 shows the integration of the different parts in the Abaqus software. Figure 7.7 shows an exploded view of the wall application.

Figure 7.5 Interior view of wall application

Figure 7.6 Finished model of wall application

Figure 7.7 Exploded view of wall application

7.2.2 Load and Boundary Conditions of Wall Application

Once the material properties were inputted into the Abaqus software and all parts were correctly integrated, the load and boundary conditions were established. Like the buckling specimens, the first thing that was accomplished was the boundary conditions. Also, like the buckling specimen, the translation in the z-direction is fixed on the bottom of the wall application. The top end of the wall application did not have any applied boundary conditions. Instead the top end of the bamboo contained the applied load. The load applied to the wall application was a distributed load along the length of the wall application to model the square beam that was used in the experimental tests to distribute the load along the length of the wall. The distributed load used for the wall application to verify the results was 10,000lb_f.

Figure 7.8 load and boundary conditions of wall application

7.2.3 Mesh of wall Application

The meshing of the wall application was again generated with the help of the Abaqus software.

For the wall, different meshes were constructed for each part of the wall application. However, for each part, an 8-node linear brick element with reduced integration was chosen. Once the meshing of the parts was created, the mechanical properties of the hemp and bamboo were applied to the appropriate elements. Figure 7.9 shows the meshing of the wall application.

Figure 7.9 Mesh of wall application

7.2.4 Results

For the wall application, like the buckling case, the post processing analysis of the wall application is conducted statically under the specified load of blank 10,000 lb_f. The direct integration provided by Abaqus is the Hilber-Hughes Taylor operator, which is an extension of the trapezoidal rule. After the analysis of the submitted job was complete, the Abaqus software outputted contour plots of both stress and displacement. The numerical value of the deflection of the wall was approximately 0.2593 inches in the middle of the wall application, which is highlighted in green. The deflection value obtained experimentally at 10,000lb_f was 0.206 inches. The numerical value differed from the experimental values by approximately 25.87%. The reason for this large difference may be because all of the bamboo inside of the wall

application was modeled uniformly with a constant thickness of 0.12 inches, which was found to be the average. However, as it has been mentioned throughout this research, because bamboo's natural characteristics, the thickness of the bamboo varies throughout the culm. So with some of the bamboo having a thickness slightly greater than the 0.12 inches specified in the model, this could have greatly affected the numerical results from being similar to the experimental results.

Figure 7.10 Displacement contour plot of wall application

Figure 7.11 Interior displacement contour plot of wall application

Chapter 8. Conclusion

This study consisted of four primary objectives. The first two primary objectives of this research included obtaining the mechanical properties of the yellow groove bamboo species, as well as optimizing its mechanical properties through different curing treatments. The third primary objective was to determine if bamboo has the potential to replace current non-renewable materials used on higher strength applications in the aerospace, automotive, and construction industries. The last objective of this study was to develop design guidelines for bamboo as a building material.

The mechanical properties, specifically, the compressive and tensile properties of the bamboo were determined in accordance with ISO 22157. Through experimental tests, it was found that the mechanical properties of untreated bamboo would be insufficient to replace any synthetic materials in structural applications. However, it was found that when cured, the mechanical properties of the bamboo are significantly increased and do show potential.

In this study, a total of four different types of curing methods were analyzed to optimize the mechanical properties of bamboo. Each curing method included heat treating of the bamboo material. The curing treatments consisted of four heat treatments at different temperatures, three salt treatments, a lime treatment, and an oil treatment. The heat treatments consisted of heating the bamboo to 150°F, 180°F, 200°F, and 220°F and the salt solutions consisted of a 3%, 6%, and 9% salt solution.

It was determined through experimental results that curing the bamboo results in significant mechanical advantages for the bamboo. It was also found through experimental results that the bamboo obtains better mechanical properties with increased temperature cure cycles above 180°F. The mechanical properties of the bamboo when heat treated above 180°F were

increased by over 100% when compared to the bamboo's natural "green" form. It was found that the mechanical properties of the bamboo are directly related to the moisture content of the bamboo, and the amount of bound water ejected. A higher moisture content produced better mechanical properties of the bamboo. For this study, because the autoclave was unable to perform at temperatures higher than 220°F, the 220°F heat treatment was found to yield the highest mechanical properties. However, because the autoclave could not go above 220°F, it is believed that 220°F curing treatment may not be optimal, and more work is needed, which is described in the section Chapter 9.

Also, through experimental tests, it was concluded that introducing additives to fill the micro voids inside the bamboo before heat treating yields significant advantages for the bamboo. Bamboo internodes were soaked in each solution for a total of five days and then heat treated at the optimal 220°F curing treatment. Through a trade study between all of the curing treatments, it was found that the 3% salt solution was the optimal curing treatment in this study. One of the most significant reasons that the 3% salt solution was found to be optimal is because of the associated moisture content. The average moisture content for this curing method was 37.15%, approximately a 10% increase from the 220°F heat treatment. The reasoning behind this large increase in moisture content is due to the fact that salt water has a lower heat capacity than pure water, allowing the bamboo to feel higher temperatures than the other curing methods. It was also found that increasing the salt concentrations produced a negative effect on the bamboo, causing the bamboo to become more brittle.

With the third primary objective being to determine if bamboo has the potential to replace today's current non-renewable materials, the optimally treated bamboo was compared to the other materials using the specific strength property. It was found through this study that

bamboo shows great potential to become a substitute for non-renewable materials, as it has a greater specific strength for many aerospace structural grade materials, which include Aluminum 2024-T3 and 7075-T6. Although, the specific strength is not the only thing a designer should look at when designing, it merely shows bamboo's potential to become more widely used and assist in protecting the environment.

Not only is it important to provide design data with the mechanical properties of the bamboo, but it is also necessary to develop design rules against various modes of failure. With current and future bamboo applications pertaining to bamboo being used as columns, a buckling analysis was performed. The buckling analysis consisted of seven different testing group heights, ranging from 1.5" to 10". Through theoretical and experimental tests, it is suggested that the slender ratio of bamboo should be kept below approximately 34.7 to avoid depleting the strength of bamboo and global buckling. Also, to avoid any form of buckling, a slender ratio below 14.4 is suggested.

Overall through experimental tests, it is concluded that bamboo has great potential. However, the research on bamboo needs to be taken to the next step, which is described in section Chapter 9.

Chapter 9. Future Work

The research completed in this thesis shows that bamboo has great potential to be applied to future structural applications, yet requires more research to be substantiated. The first thing that one may want to consider is the analysis of the nodes on bamboo. Although, ISO standard 22157 states that the nodes have a negligible effect on the bamboo, this must be investigated because no structural application would ever employ just the internodes. The reason for this is because the internodes are inadequate to provide enough length to a structural application.

Other research that must be done to legitimize the feasibility of using bamboo in structural applications is that higher temperatures must be explored for curing treatments. With the autoclave being incapable of running at a temperature higher than 220°F, it was not possible to fully optimize the bamboo through this research. Ideally, one would want to slowly increase the temperatures until one reaches thermal degradation. The reason for this is because the strength of the bamboo should increase until the thermal degradation point is reached, where the strength would then significantly decrease. Along with higher temperatures, other natural additives should also be investigated as well as different curing cycles for optimization of the bamboo material.

Along with investigating different curing treatments, other bamboo species should also be investigated. Although it is known that all of the bamboo species have approximately the same chemical composition, it would be good to verify that all of the bamboo species have the same reaction to the curing treatments.

When utilizing bamboo as a building material, more often than not the structure will require joints. Today, there are many current bamboo applications that utilize joints. These structures consist of housing structures, scaffolds, or any truss structure. However, bamboo joints have

yet to be investigated or standardized to determine the optimum joint system. Not only is it extremely important to optimize the material properties of a material, but it is also important to have the optimum joint system, because if the joint system is defective, it could lead to failure of the design.

This research only investigates compression, tension, bending, and buckling. Another test method that is specifically suggested is dynamic testing through vibration. Although, it is known that bamboo has tremendous damping characteristics, it is important to know how the curing treatments have an effect on the damping characteristics of the bamboo material.

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