Mechanical Strength of Bamboo Fiber Biocomposites Within a Biorefinery Concept

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Abstract

A new approach to fiber pretreatment for a bamboo fiber-reinforced composite (BFRC) was utilized and its resultant biocomposites' strengths were analyzed via tensile and flexural mechanical testing. Co-solvent enhanced lignocellulosic fractionation (CELF) is a biomass pretreatment process that separates cellulose from lignin and hemicellulose in a way that preserves the lignin and hemicellulose rather than destroying them. This allows for further valorization of these components and proves to be a more sustainable pretreatment process for BFRC fabrication. In an effort to make a more sustainable biocomposite, the team found that there was no statistically significant data to prove that incorporation of CELF-treated fibers was more effective than raw bamboo fibers, concluding that CELF-treated fibers performed no worse than the bamboo fiber and epoxy counterparts. Tensile and flexural results were converted to specific strengths and compared to a common building material, 304 stainless steel. The CELF fiber composites' maximum tensile strength performed at 43.8% of 304 steel, and the maximum flexural strength was found to be 261.1% of 304 steel. It was found that limitations to the strengths of the biocomposite samples arose from random, discontinuous fiber alignment and incomplete degasification of the epoxy resin. Incorporation of a bio-based epoxy in an effort to promote greater sustainability of a biocomposite is suggested for future improvement upon the bamboo fiber reinforced composites fabricated in this study.

Table of Contents

Table of Figures

Table of Tables

Chapter 1. Introduction

Society heavily relies on certain building materials to accomplish the ever-increasing amount of construction and practical installations that growing populations demand. Common building materials used for many applications include steel and concrete, which are limited and continuously being depleted with increasing population and consumption. These nonrenewable materials are emitting carbon into the atmosphere with their fabrication and installment, negatively contributing to the global climate crisis. More sustainable alternatives to building materials like steel and concrete are becoming increasingly sought after due to their potential for providing an alternate use for plant matter as opposed to incineration for energy.

Biocomposites, especially fiber-reinforced composites, are a promising replacement for nonrenewable building materials. Fiber-reinforced composites consist of a matrix—typically a resin—that is reinforced by natural plant fibers to create a mechanically sturdy material. A biocomposite material's main benefits are its ability to remove carbon dioxide from the atmosphere during the plant feedstock's life cycle, and that the plant feedstock is a renewable resource that can continuously be produced. As a fast-growing plant feedstock, bamboo is a particularly promising option.

To make biocomposites, biomass must be converted into a usable form—i.e. consisting primarily of cellulose as opposed to its natural form of a complex network of cellulose, hemicellulose, and lignin—prior to reinforcing a resin matrix. Despite the inherent sustainability of using a renewable biomass feedstock, the process of removing hemicellulose and lignin is often done unsustainably; hemicellulose and lignin tend to be wasted by use of harsh chemicals during the pretreatment process. Thus, engineering a bamboo fiber-reinforced composite using a fiber pretreatment option that allows for hemicellulose and lignin to be valorized rather than wasted would create a novel, even more sustainable biocomposite.

Co-solvent enhanced lignocellulosic fractionation (CELF) is a biomass pretreatment option that does just that. With use of a water-tetrahydrofuran (THF) co-solvent, biomass can be fractionated into a solid cellulose residue, which could potentially be used for a biocomposite, and soluble hemicellulose and lignin, which can be separately extracted. This pretreatment technology has not been used in the scope of biocomposites, however the literature around CELF pretreatment portrays the cellulose residue as a promising option as a fiber for use in a biocomposite. The goal of this work is to fabricate a bamboo fiber-reinforced composite (BFRC) using CELF-pretreated bamboo and test its mechanical properties to analyze whether this pretreatment option is suitable for making a biocomposite that can eventually serve as a prevalent building material in the ways that steel and concrete are used. A reader of this study that is interested in biocomposites may take away valuable information regarding the mechanical performance of CELF fiber biocomposites and the potential for integrating CELF fibers into biocomposite fabrication processes to further enhance the overall sustainability.

Chapter 2. Background

2.1 Emission Concerns Related to Common Buildings

Due to worsening climate change, environmental waste, and pollution, there must be an increase in the creation of alternatives in industry for more sustainable, carbon neutral practices. Commercial industry currently contributes to 36% of all greenhouse gas emissions (*1*), making it one of the highest polluters of greenhouse gas and waste. Sustainable, bio-based alternatives have been sought after to replace existing commercial industry practices with something that works just as well or potentially better while being carbon neutral or negative in order to reduce emissions.

About 1500 million tonnes of steel per year are made for residential and industrial construction, infrastructure, and transportation industries, making it a plentiful material in the global economy (*2*). However, many problems arise when considering the sustainability of the steelmaking industry. For instance, steelmaking makes up 25% of all greenhouse gas emissions related to industry, and cement contributes an additional 19%. This means that the steelmaking and cement industry make up 17% of total greenhouse gas emissions worldwide, a significant portion for the construction industry (*1*). As of 2022, making 1.41 tons of steel creates 1 ton of carbon emissions, which is slightly better than the historical peak in 2015 of 1.54 tons of steel per ton of carbon emissions; however, the International Energy Agency labels the steelmaking industry as “not on track” with the goal of net zero emissions by 2050 (*3*). Figure 1 below contains the necessary reduction of carbon emissions within the steel industry in order to reach net zero by 2050:

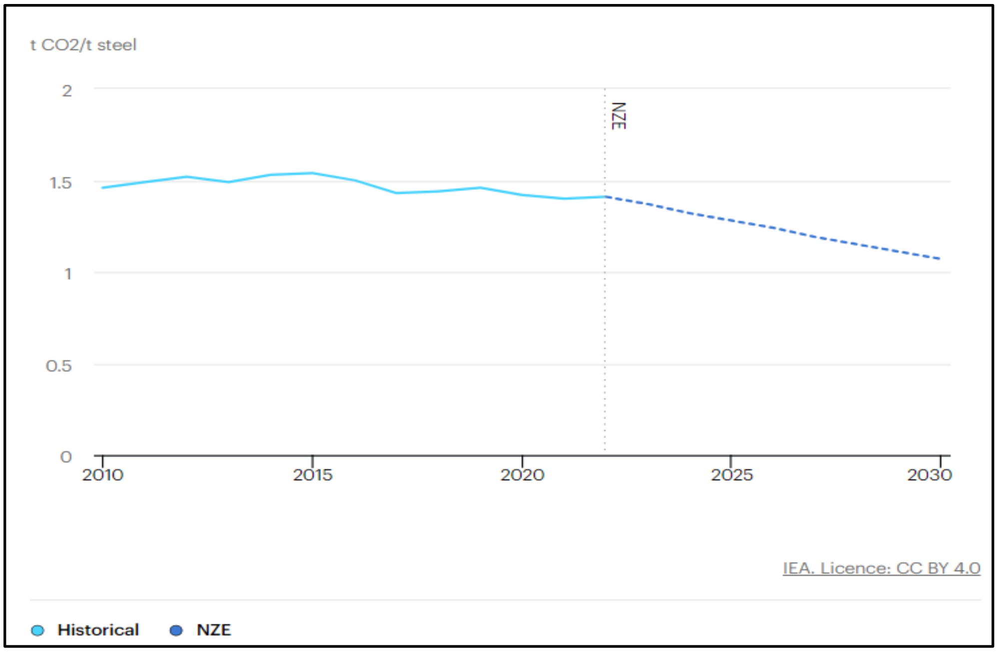

Figure 1. Historical carbon emissions from steelmaking and future carbon emissions needed for the net zero scenario (*3*)

2.2 Fiber Reinforced Composites

Due to concerns with emissions, new methods have been researched to find a more sustainable alternative to steel. One category of materials that has recently come to the spotlight of steel alternatives, referred to as fiber reinforced composites, produced notably good material properties relative to steel and other common materials used in industry today (*4*). Fiber reinforced composites can be classified into four different groups: metal matrix composites, ceramic matrix composites, carbon/carbon composites, and polymer matrix composites. These matrices act as a binding agent that holds the reinforcement together and enhances the material properties of that reinforcement (*4*). Polymer matrix composites also have subsets of classifications, being thermoset, thermoplastic, and elastomeric composites (*4*). All of these fiber reinforced composite types combine fibers with one of these other four categories to create a stronger material than the two parts separately. When seeking a rigid, strong material that could potentially replace steel, thermoset polymers are the most ideal competition as they establish crosslinked polymer chains during initial curing, which leads to a set, rigid product that does not deform easily but cannot be reshaped (*4*). Thermoset materials can also be compared to steel with thermal properties, as they can reach very high temperatures without compromising any structural integrity (*4*). The main issue with these composites is that they do not biodegrade quickly or easily, and can thus be subjected to more environmental waste and pollution (*5*).

2.3 Bamboo Fiber Reinforced Composites (BFRCs)

Fiber reinforced composites, specifically thermoset plastic matrix composites, are a main focus when studying sustainable building material alternatives due to their steel-like properties. In order to consider a suitable replacement for steel, this thermoset composite must be at a minimum carbon neutral- but ideally carbon negative. This material must also have the potential to either break down quickly in the environment or be incinerated for a net carbon neutral life cycle. In order to accomplish this, both the thermoset polymer and the fibers used must be harvested from sustainable practices, such as a combination of a bio-based epoxy and plant fiber. One such material that has begun to emerge as a viable replacement is a combination of bamboo fibers combined with epoxy resin, referred to as a bamboo fiber reinforced composite (BFRC). Bamboo is one of the more favorable sustainable natural fibers to use due to its properties, such as low density, high stiffness, high strength, as well as its common availability and extremely fast growth rate (*6*).

Although bamboo is typically a strong material on its own, the presence of lignin and other organic material prevent bamboo from reaching its maximum strength potential in a composite as they do not allow for proper infiltration of the matrix into the species. To fix this issue, it is common practice in bamboo fiber reinforced composites to pre-treat the bamboo to allow for easier infiltration of the matrix. One study used a combination of bamboo and epoxy with two different methods, with the first using pure bamboo fiber and epoxy resin, and the second using an alkali treated bamboo fiber and epoxy resin. Tensile tests were performed on the pure bamboo as well as the alkali treated bamboo, showing that the pure bamboo tensile strength was 717.53 MPa with a Young’s Modulus of 43.34 GPa, while the alkali treated bamboo performed significantly worse with a tensile strength of 473.05 MPa with a Young’s Modulus of 33.31 GPa (*5*). Using a microscope, both the pure bamboo and the alkali treated bamboo can be analyzed to see the following images:

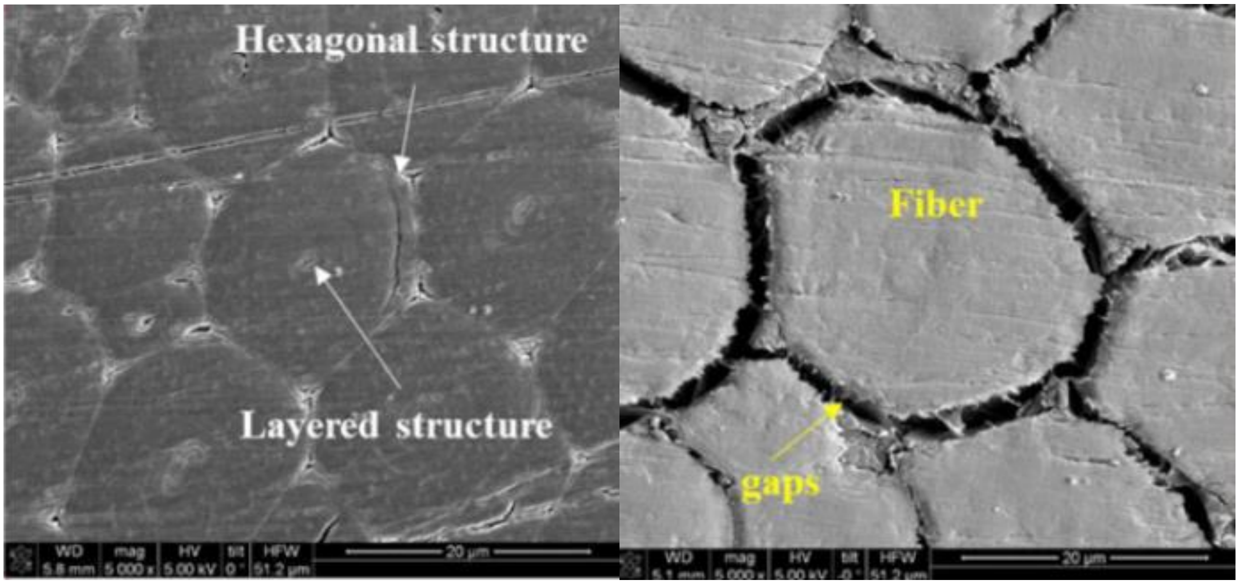

Figure 2. A microscopic photograph of the pure bamboo (left) compared to the alkali treated bamboo (right) (*5*)

As seen in Figure 2, the alkali treated bamboo is missing the lignin between the bamboo fibers due to the alkali treatment, resulting in it having lower strength properties than the pure bamboo. However, when a matrix is added to create a BFRC, the alkali-treated bamboo composite shows a significant increase in strength when compared to the pure bamboo composite as seen in Figures 3 and 4:

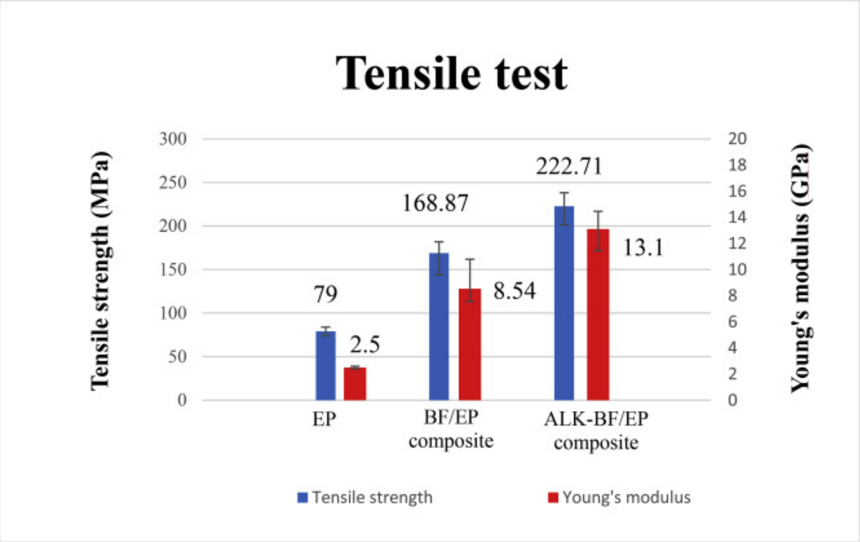

Figure 3. Tensile strength and Young's modulus of the epoxy resin matrix, the pure bamboo composite, and the alkali treated bamboo composite (*5*)

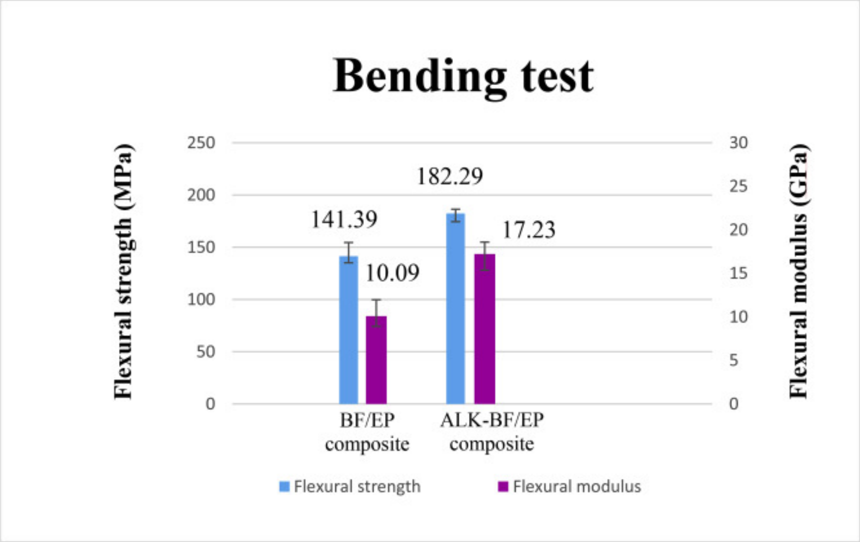

Figure 4. Flexural strength and flexural modulus of the pure bamboo composite and the alkali treated bamboo composite (*5*)

Thus when creating bamboo fiber reinforced composites, it is important to remove the lignin using alkali treatment or other methods to enhance the bonding between the fibers and the matrix, which is epoxy resin in this particular study.

2.4 Biomass Composition and Chemical Structure

The chemical building blocks of plant life are what catches the attention of the bioenergy and renewable energy industries as all plant life consists mainly of carbohydrates. Examples of these carbohydrates include starch, pectin, cellulose, and hemicellulose (*7*). Starch, the edible organic component of plants, is a key molecule for bioethanol production (*8*). This molecule is composed of the glucose polymers amylose and amylopectin (*7*), which can be broken down further into basic glucose monomers allowing for the production of ethanol through fermentation. Common feedstocks for bioethanol production include corn stover, sugarcane, and sugar beet (*9*).

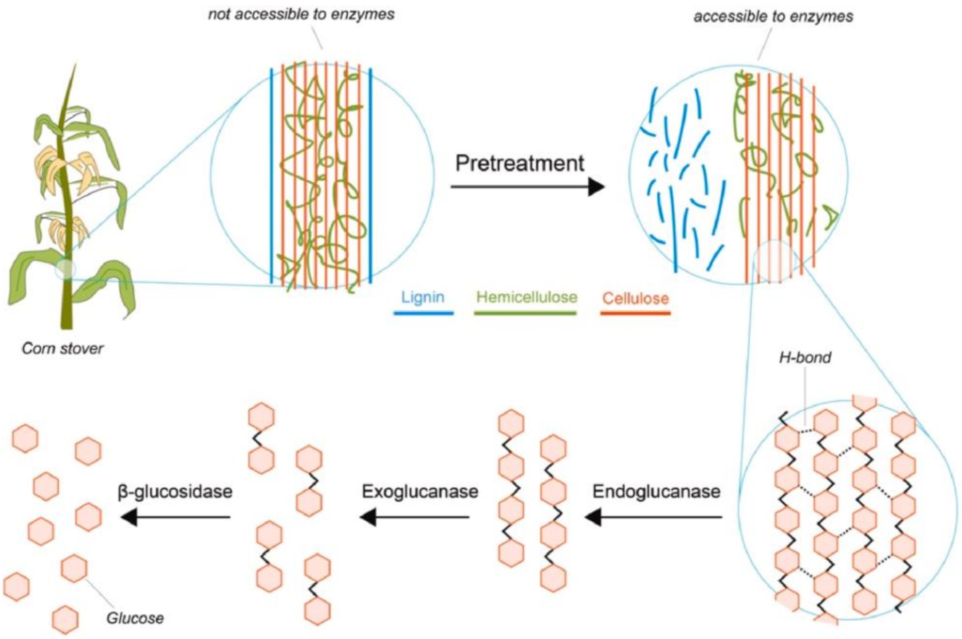

Figure 5. Composition of biomass feedstock (*10*)

For the purposes of this paper, the term 'biomass' will be used to describe the inedible portion of plant life. Lignocellulosic biomass consists of three main components: cellulose, hemicellulose and lignin (*7*). Each of these components has a distinct function within plants based on their chemical makeup and structure (*7*). Applicability in the sustainable building material industry is also dependent on these components' chemical compositions. Cellulose is the majority component in biomass, with hemicellulose and lignin accounting for the rest of the plant's biomass composition (*11*). The structure of cellulose is dependent on the 1,4-β-glycosidic bonds which hold together the D-glucose monomers comprising cellulose. The resulting geometry allows for cellulose units to hydrogen bond, forming large chains. This cellulose is naturally occurring in two crystal forms: Iα and Iβ. Cellulose Iβ is the most common lignocellulosic biomass present in plant cell walls (*12*). Due to the relative strength and structural integrity of its intermolecular chains, cellulose is considered a promising fiber source for biocomposites (*13*).

Hemicellulose is another main component of biomass, which acts as a natural binding medium for plants' cellulose fibers. Similar to how cement binds together iron rebars in skyscrapers, hemicellulose provides interfiber support for the stronger cellulose chains within plant walls. Xylan is the most common type of hemicellulose and is composed of 5-carbon xylose sugars bonded by β-(1,4)-D-xylopyranose backbone (*14*). Unlike cellulose which forms many uniformed chains based on its bonding structure, hemicellulose has many different structural subunits due to diversity in its bonding and composition. Other prevalent saccharides in hemicellulose are mannans and glucans, but relative presence within a given plant specimen varies based on species, developmental stage, and tissue type that a sample is taken from (*14*). As a result of the high composition variability and non-uniform structure, hemicellulose is not an important ingredient in biocomposite formulation.

Lignin is the third main component of biomass and is distinctly different from cellulose and hemicellulose. Lignin is a complex organic polymer found in the cell walls of plants, particularly in wood and bark. Lignin's chemical composition is composed of phenylpropanoid units; these being aromatic rings mainly composed of p-hydroxyphenyl (H), guaiacyl (G), and syringyl (S) units (*15*). These units covalently bonded to hemicelluloses, forming a complex three-dimensional network (Figure 6). Lignin's structure is highly heterogeneous, making it resistant to degradation by most enzymes and microbes (*15*). This resistance contributes to the durability of wood and other lignocellulosic materials.

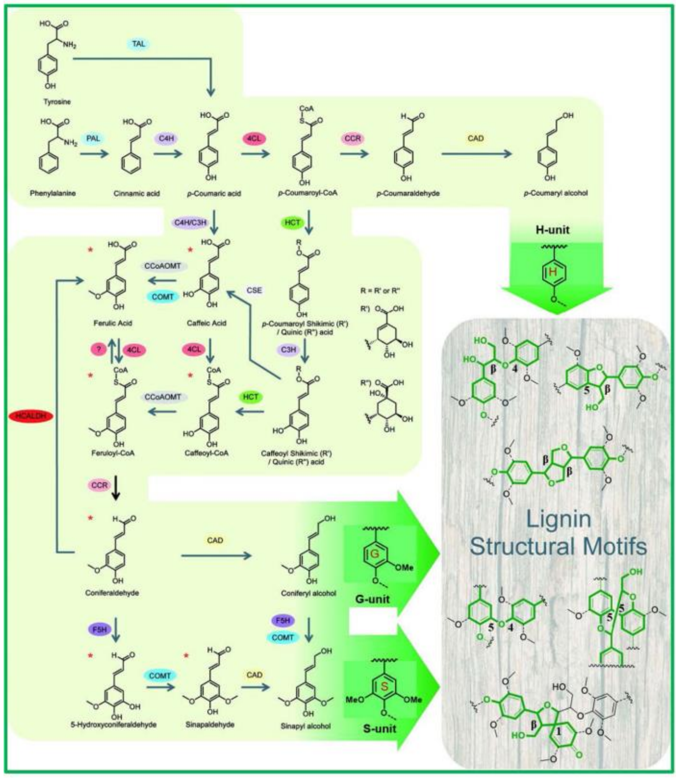

Figure 6. Lignin structure flowchart from (*15*)

However, due to lignin's hydrophobic and rigid characteristics, its presence in biocomposites can interfere with the adhesion between the plant fibers or particles and the matrix material in the composite. Poor adhesion can weaken the overall mechanical properties of biocomposite samples, such as tensile strength and flexibility. By removing lignin through biorefinery, the separated cellulose plant fibers can have improved compatibility with the matrix material, leading to better bonding and overall enhanced properties of biocomposite samples.

2.4.1 Biorefinery

Biorefinery is a broad term that is used when describing a future with completely sustainable building materials. The act of biorefining is described as the act of converting biomass into "a spectrum of marketable products and energy" by the International Energy Agency (*16*). Biomass such as agricultural residues, algae, and organic waste is processed to produce a multitude of valuable products including biofuels, biochemicals, and biomaterials. By harnessing renewable resources listed above, biorefinery has the potential to significantly reduce greenhouse gas emissions and dependency on finite fossil fuels, thus mitigating climate change and contributing to energy security.

Furthermore, biorefinery plays a pivotal role in the circular economy framework by promoting resource efficiency and waste valorization (*17*). Through integrated processes, biorefinery facilities promote the extraction of high-value compounds from biomass. Pretreatment of lignocellulosic biomass is an important process that the group identified when considering formulation of BFRCs. Pretreatment is a crucial first step in lignocellulosic biomass refinery as it facilitates the delignification of samples, increasing the accessibility to cellulose (*18*). Examples of bamboo pretreatment include alkaline solution treatment (*5*, *19*) and co-solvent enhanced lignocellulosic fractionation (*20*) As lignin is the most prevalent non-carbohydrate component of lignocellulosic biomass (*18*), removal along with preservation from bulk biomass is needed to optimize potential benefits of lignocellulosic biorefinery. Through preservation during pretreatment, all components of lignocellulosic have the potential to be valorized into profitable products, creating new sources of revenue and furthering the economic viability of biorefinery processes.

2.5 In Search of a Sustainable Pretreatment Technique

Given the need for biomass treatment to produce highly-pure cellulose fibers for application in a biocomposite, it is important to consider a pretreatment technique that is both effective and sustainable. The severe reaction conditions inherently present in alkaline hydrolysis (*5*), for example, is not sustainable due to a lack of use of "green" solvents (*21*). Utilizing a more sustainable pretreatment technique is important for promoting the overall sustainability of the composite material itself, which is the ultimate end goal of pursuing a biocomposite. This research will make use of a pretreatment technique discovered by researchers at University of California at Riverside in the last decade that has shown to have promising benefits in both effective fiber delignification and high potential for hemicellulose and lignin valorization.

2.5.1 Co-solvent Enhanced Lignocellulosic Fractionation

The treatment method being considered for this composite is co-solvent enhanced lignocellulosic fractionation (CELF), a co-solvent of water and tetrahydrofuran (THF) (*20*). The co-solvent is generally used in a range of 1:1 to 3:1 volume ratio of THF:water with a 1 wt% H_2SO_4 catalyst as it has experimentally shown high sugar yields while maintaining less energy usage and recovery costs (*20*). Before adopting the official name of "CELF," this organosolv pretreatment was analyzed for its ability to extract hemicellulose for furfural production (*20*, *22*), and was coupled with various metal halides to examine the effects on furfural yields (*23*). Research on CELF continued in the direction of sugar yields—now incorporating cellulose—in the context of ethanol yields upon fermentation of these sugars (*24*, *25*). Alongside research in sugar yields, research in the unique dynamics of lignin in this THF-water co-solvent was done (*26*, *27*, *28*, *29*), showing great potential for lignin valorization that is not observed with other pretreatment techniques. Along with keeping lignin more intact compared to other pretreatment options, CELF maintained cellulose-rich solids with higher crystallinity and degree of polymerization when directly compared to other organosolv pretreatments (*28*). CELF cellulose maintains much of its structural integrity due in part to less removal of structural lignin; as opposed to "blindly" removing all lignin—as displayed by other pretreatment techniques—CELF delignification appears to remove lignin and hemicellulose that do not provide structural integrity to the cellulose fibers (*28*). The highly-pure CELF cellulose fibers are optimal for use in this biocomposite, and the novel properties observed in CELF lignin can allow for its valorization.

The unique properties of CELF lignin as opposed to depolymerized lignin from other pretreatment options is that THF in the CELF co-solvent does not participate in a reaction with lignin; rather, the co-solvent separates lignin from cellulose by promoting disaggregation of lignin from globules into coils (*26*, *27*). This solvent interaction with lignin is described as a “theta” solvent, meaning that lignin:lignin interactions are of equal strength to CELF:lignin interactions (*26*, *27*). The solvation of lignin is primarily due to THF (*26*), as lignin contains hydrophobic faces that would agglomerate in the presence of water (*27*). Lignin linkages are thus exposed to the CELF co-solvent, where ether linkages—particularly ß-O-4 and ß-ß linkages—between lignin subunits are hydrolyzed by water, resulting in further depolymerization (*27*). This dissolution chemistry results in CELF lignin having a relatively low molecular weight and a higher content of phenolic and carboxylic acid hydroxyl groups, both of which contribute to enhanced bioconversion (*29*) and could see applications in lignin-based bio-epoxies (*30*). The particular use of lignin is outside the scope of this project; however, the idea that CELF lignin can be valorized, rather than simply burned for energy, is a major driving force of the sustainability of this biocomposite.

2.5.2 Applications of CELF Cellulose

The benefits of CELF cellulose are its purity and high crystallinity and degree of polymerization (*28*). Seeing that cellulose is a primary component responsible for the strength/structure of plant cell walls (*31*), maximizing its purity and structural integrity upon isolation of cellulose fibers could result in maximizing the strength of the composite being reinforced.

In the context of biocomposites, CELF cellulose is particularly beneficial compared to other organosolv pretreatments because it maintains the structural integrity of the fibers rather than increasing the accessibility of cellulose (*28*); while increased cellulose accessibility is desired for enzymatic breakdown (*24*, *25*), it would likely result in a weaker reinforcement for a biocomposite. Being able to use an organosolv pretreatment method to prepare high-quality cellulose fibers for a biocomposite is very beneficial because of the high-quality lignin that can be produced alongside it (*32*). The goal of this research, compared to other research in bamboo fiber-reinforced composites, is to explore the viability of using CELF pretreated cellulose fibers.

Chapter 3. Methodology

This study examined the impact of different variables on the strength performance of BFRC samples made using bamboo fibers and epoxy. To achieve this goal, several steps were taken to ensure the properties of the materials used were satisfactory. Samples of BFRCs were formulated following a procedure developed from a published study (*6*), varying the weight percent for each fiber type used. The BFRC samples were finally tested for both tensile and flexural strength at each weight percent for the two fiber types.

3.1 Materials Used for BFRC Construction

Two different types of bamboo fiber were used in this study. The first was a form of chemically treated and shredded bamboo fibers, provided by the Bamboo MQP working in the Timko lab. Bamboo stocks of the species *Phyllostachys nuda* from The National Zoo in Washington D.C. were imported and ground into fibers varying from 0.1–0.5 in. in length by use of a hand saw and coffee grinder. The fibers were subsequently dried in an oven for 6 hours. Finally, soxhlet extraction (*33*) was performed with toluene and ethanol to remove residual waxes and oils from the bamboo fibers. The other fiber type used in the study was CELF cellulose fibers derived from bamboo, sent to the Timko lab by UC Riverside with a composition of 89% glucan, 3% xylan, and 8% lignin with very little ash. The CELF cellulose fibers were ball milled using an Across International VQ-N High Energy Ball Mill (*34*) for 15 minutes to induce a slightly powderized consistency.

To create samples of BFRCs that would yield strength results comparable to existing literature values and remain workable, the epoxy type used in this study had to meet certain criteria. Epoxy characteristics considered for procurement included viscosity, hardening time, cure time, and rated strength. Various epoxies were trialed using (*35*) cellulose powder to create biocomposite samples and analyze epoxy performance without wasting the limited amount of CELF cellulose fibers available. One such test composite using an epoxy that was deemed too viscous can be found below in Figure 7. After testing multiple epoxies, the two most desirable characteristics for this study were deemed to be low viscosity and long hardening time with a quick total cure time. The epoxy that best fit this set of criteria, as well as being easy to work with physically, was the Loctite M-121HP (*36*) structural adhesive. Loctite M-121HP has a hardening time of 2 hours, a cure time of 24 hours, a viscosity of 11,000 cP, and a rated sheer peel strength of 4,800 psi. It is important to note that this is a petroleum-based epoxy used for the purpose of comparing the strength results between weight percent and fiber type, due to the unavailability of bio-based epoxies.

Figure 7. Trial composite using a high-viscosity epoxy that proved difficult to work with

3.2 Forming the BFRC Samples

The procedure developed for creating the BFRC samples in this study was adapted from published work by (*6*) researchers that investigated the properties of BFRCs involving longer bamboo splints with different thermosetting matrix types. An Excel spreadsheet was used to calculate the weights required per layer of epoxy and fiber for every weight percent examined in the study (Appendix B). Samples involved alternating layers of epoxy and fiber, with three total epoxy layers and two layers of fiber in between. Silicone molds 4 inches in diameter were used to form the BFRCs into thin disks. Molds were placed in a tray atop a scale, and the weight was measured and the scale subsequently tared. The M-121HP epoxy was then dispensed into the mold in accordance with the calculated weight required to satisfy one layer. The epoxy was then spread into a thin, uniform layer using a plastic epoxy spreader tool (*37*). Both the treated bamboo fibers and CELF fibers were measured in advance in accordance with required layer weights. The fibers were sifted onto the epoxy layer to form a uniform, randomly oriented layer; spreading the fibers with an epoxy spreader tool was occasionally necessary to ensure uniformity

(Figure 8). All steps involved in creating layers of epoxy and fibers were repeated until a complete sample was present in the mold. The molds with the BFRC samples were then immediately placed in a vacuum oven at room temperature (20°C) for 30 minutes at a pressure of 12 in. Hg to remove air bubbles. After time in the vacuum, the samples cured for the remainder of the 24-hour curing period at room temperature. One sample disk of 4 in. diameter was produced per fiber type and weight percent—1–4 wt. % of each fiber including one pure epoxy sample—making 9 total samples.

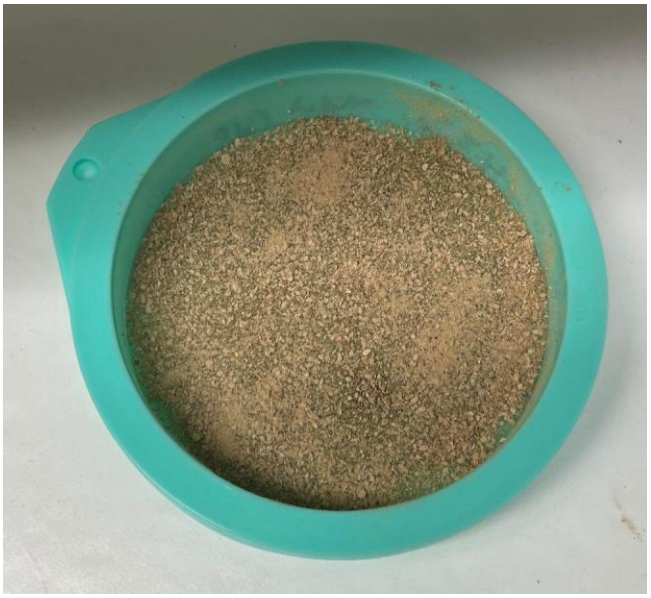

Figure 8. Ball-milled CELF layer atop epoxy layer of 2 wt. % composite sample

3.3 Material Strength Testing

In preparation for material strength testing, the BFRC samples were cut into coupons in rough accordance with ASTMs D790-17 & D3039 (*38*, *39*) for tensile and flexural testing, respectively. Due to constraints with the fashion in which the BFRC samples were created using the layering technique in a 4 in. mold, it was difficult to obtain scaled-down thicknesses when machining coupons as the test specimens. As these coupons were used purely for internal comparison between fiber types and weight percentages, the thicknesses were made uniform—within error—across all samples. Widths and lengths of the coupons were machined in accordance with specifications from ASTM D3039 for random-discontinuous orientation of the fibers, with a scaled-down length-to-width ratio of 10:1. This dimension ratio also fell in accordance with the maximum specified ratio in ASTM D790-17 of 16:1 for length-to-thickness given the uniform thickness of all specimens used for testing (see Table 1 for dimension ratios). The mean length among all coupons was 2.834 inches with a standard deviation of 0.014 inches. The mean width was 0.285 inches with a standard deviation of 0.002 inches, and the mean thickness was 0.176 inches with a standard deviation of 0.002 inches.

Table 1. Tensile & flexural specimen dimensions

Measurement Type	Length [in]	Width [in]	Thickness [in]
Mean	2.834	0.285	0.176
St. Dev.	0.014	0.002	0.002
Ratio Length:X	1	10	16

One sample disk was able to produce 7 coupons for testing, of which 6 were used; triplicates for both tensile and flexural tests were run to obtain an average of 3 for each of the respective strengths. The triplicate approach allowed for comparison within weight percent categories to observe the effects of potential defects, such as any remaining air bubbles or chips from machining. The majority of test specimens possessed defects to some degree, as evidenced by Figures 9 and 10 below, and were all tested using the same method and apparatus for both the tensile and flexural analyses.

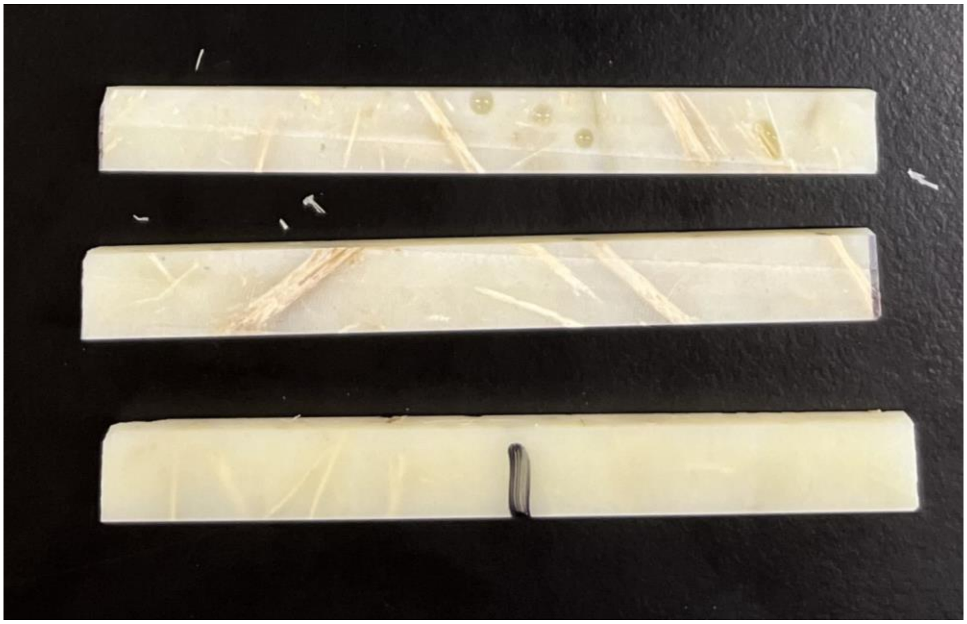

Figure 9. Three coupons of 1% wt. bamboo BFRC

Figure 10. Three coupons of 2% wt. CELF BFRC

The machine used for both material strength tests—tensile and flexural—was the Instron 5567A Universal Testing Machine. Tensile testing was performed using claw grips and a load rate of 0.025 in/min; flexural testing was performed using the Instron three-point fixture and a load rate of 0.1 in/min (see Figures 11 and 12 below). The measured tensile and flexural strengths in pounds per square foot were then analyzed for statistical significance using a T test for p-values.

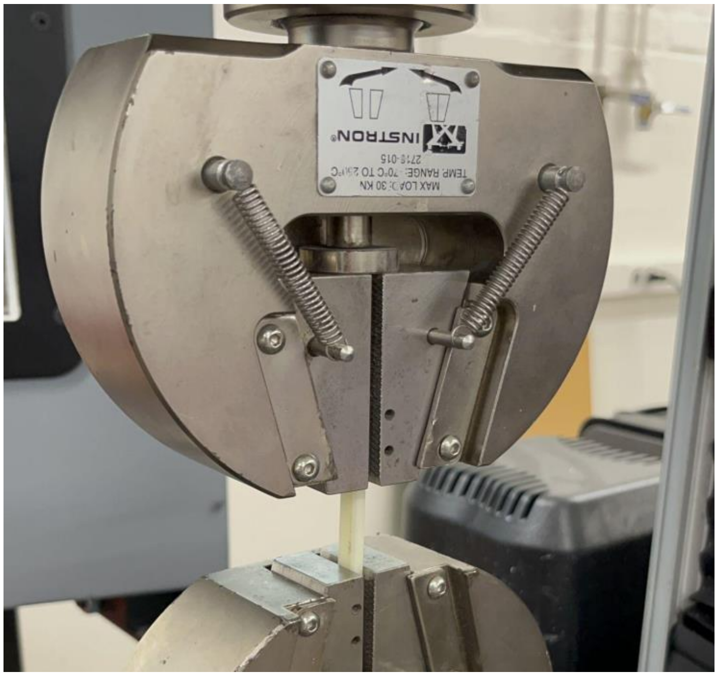

Figure 11. Instron 5567A tensile testing apparatus using claw grips

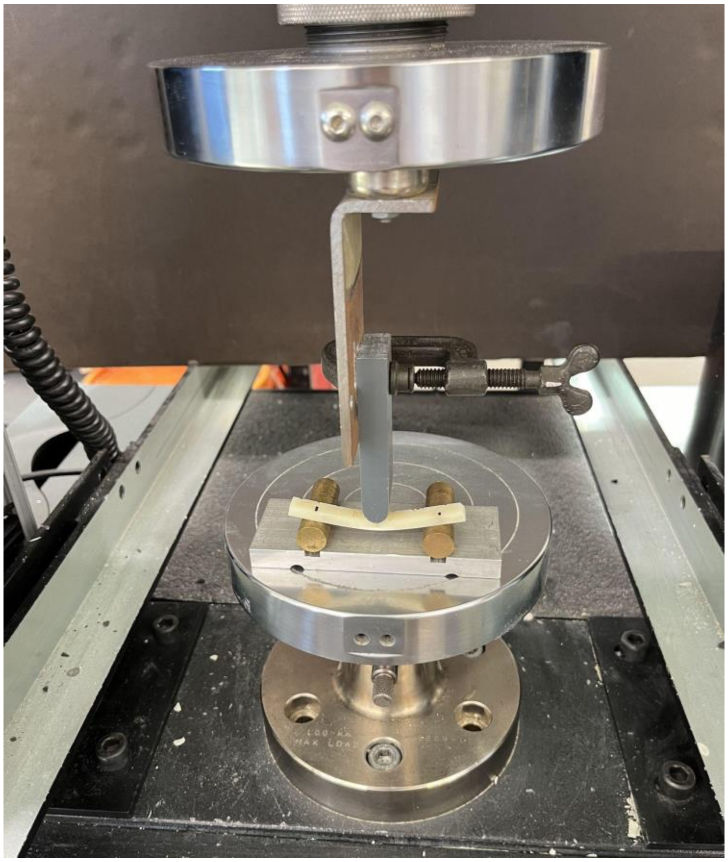

Figure 12. Instron 5567A flexural testing apparatus using a 3-point fixture

Density measurements of the various BFRC samples were conducted to aid in determining their specific strengths. The Archimedes method was used for determining density, utilizing mass divided by the volume of water displacement (Equation 1). Specific strengths were calculated using Equation 2, and allowed for comparison of the BFRC samples to 304 grade stainless steel—a common building material.

The fractures of the BFRC coupons resulting from tensile and flexural testing were qualitatively analyzed to aid in the understanding of factors contributing to the composites' failure under load. Cross-sections of coupons selected for apparent significant defects were chosen to be captured photographically by a Panasonic Lumix G7 camera with an Olympus 30mm macro lens.

$$\rho = \frac{M}{V} \tag{1}$$

$$SS = \frac{S}{\rho} \tag{2}$$

Chapter 4. Results and Discussion

4.1 Tensile Test Results

The tensile testing yielded tensile strength and modulus results for each coupon tested, evaluated as an average of each weight percent for both fiber types. Figure 13 below shows the performance of the triplicate samples for tensile testing. Pure epoxy (0 wt. %) had an average tensile strength of 4158.1 psi, and the bamboo and CELF fiber reinforced composites performed similarly for 2, 3, and 4 wt. %, with CELF composites slightly outperforming bamboo composites for all three weight percentages. However, for 1 wt. %, the bamboo and CELF fibers performed slightly better at 4530.7 psi and 4751.5 psi, respectively. The full breakdown of average tensile strength and modulus performances for all of the test specimens can be found in Table 2.

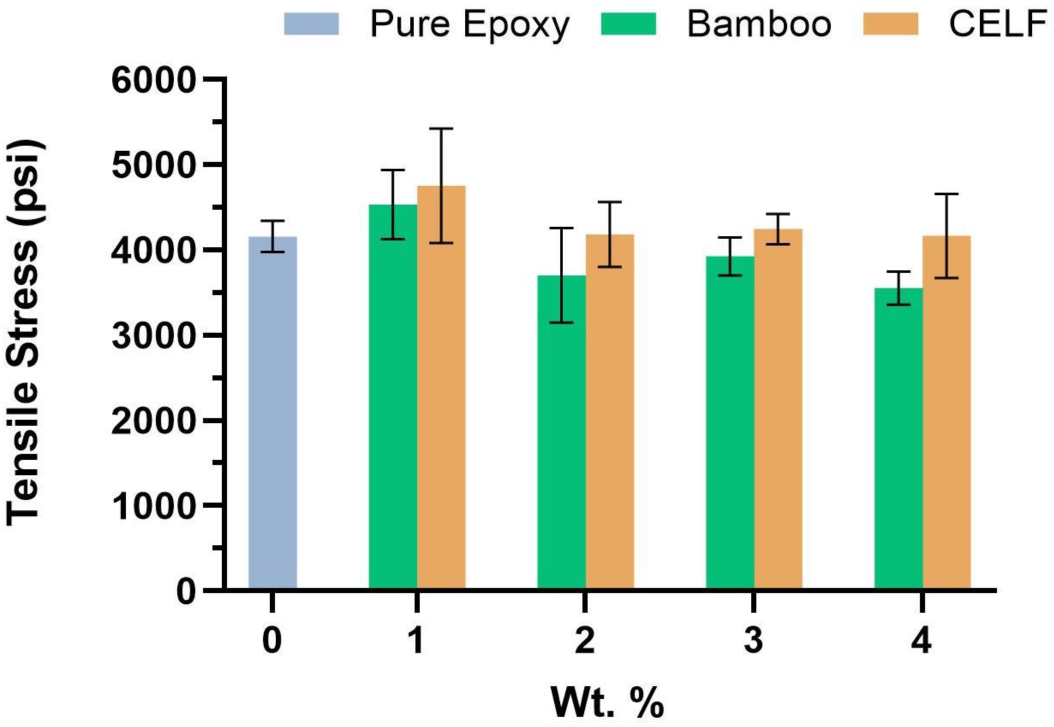

Figure 13. Tensile stress (psi) performance by wt. % for bamboo and CELF fiber composites

Table 2. Summary of tensile test results of CELF and bamboo-reinforced composites

Reinforcement	Weight %	Average Tensile Stress [psi]	Average Young's Modulus [psi]
None	0	4158.1 ± 182.0	315730.1 ± 10744.4
CELF	1	4751.5 ± 669.7	269669.0 ± 43297.1
Bamboo	1	4530.7 ± 405.2	353546.8 ± 70757.1
CELF	2	4184.2 ± 379.5	286835.7 ± 31976.4
Bamboo	2	3702.8 ± 554.7	404746.0 ± 42248.1
CELF	3	4245.6 ± 176.0	244800.2 ± 23811.6
Bamboo	3	3926.4 ± 223.4	334145.2 ± 34323.7
CELF	4	4166.4 ± 493.5	271526.4 ± 37501.2
Bamboo	4	3552.5 ± 193.6	357335.6 ± 24035.4

Upon performing statistical analysis on the recorded average tensile strengths, it was revealed that there is no statistically significant difference between the CELF and bamboo fibers (Table 2). It was also found that there is no statistically significant difference between the 1 wt. % coupons—which were the best performing samples—and pure epoxy for both fiber types.

4.2 Flexural Test Results

The flexural testing yielded flexural stress and modulus results for each coupon tested using the three-point method described in section 3.3. Like tensile testing, stress results were evaluated as an average of each weight percent for both fiber types. Figure 14 below shows the performance of the triplicate samples for flexural testing. Pure epoxy (0 wt. %) had an average flexural strength of 8804.9 psi. Both fiber types at 1 wt. % performed better than pure epoxy at 10389.4 psi and 10409.0 psi respectively. BFRC performance slightly decreased from 1 to 3 wt. %, and then increased marginally at 4 wt. %. The full breakdown of average flexural stress and modulus performances for all of the test specimens can be found in Table 3.

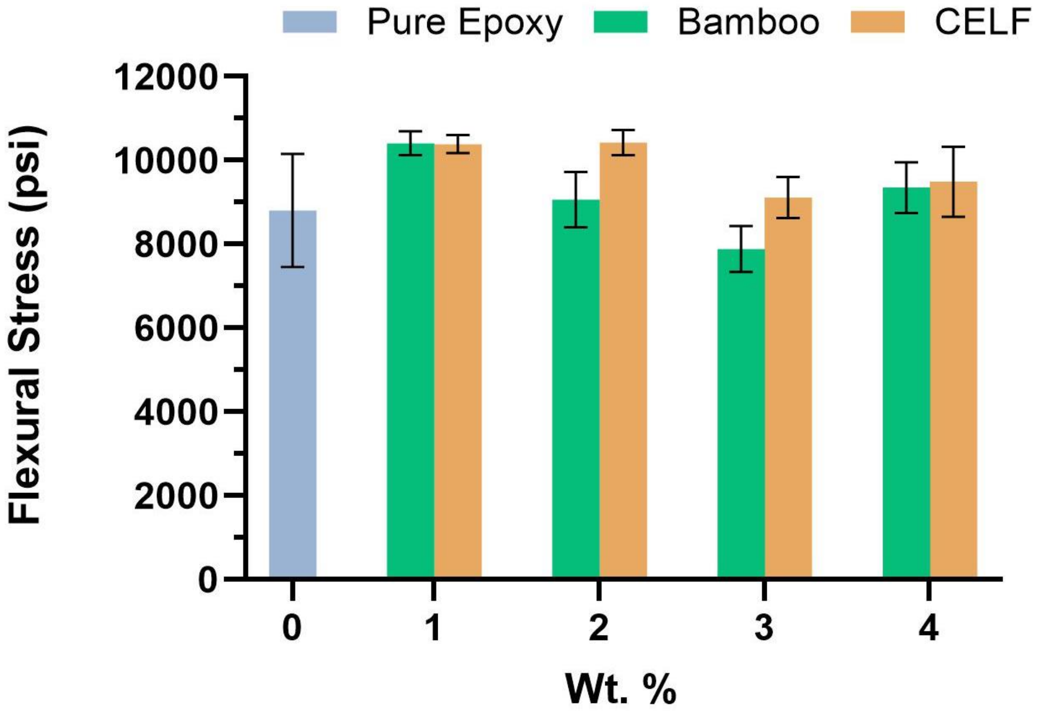

Figure 14. Flexural stress (psi) performance by wt. % for bamboo and CELF fiber composites

Table 3. Summary of flexural test results of CELF and bamboo-reinforced composites

Reinforcement	Weight %	Average Flexural Stress [psi]	Average Flexural Modulus [psi]
None	0	8804.9 ± 1350.8	296382.8 ± 1840.9
CELF	1	10389.4 ± 217.8	316258.6 ± 1467.4
Bamboo	1	10409.0 ± 286.9	314472.3 ± 16293.6
CELF	2	10427.7 ± 302.6	325313.6 ± 7022.5
Bamboo	2	9065.9 ± 656.1	303059.4 ± 20400.0
CELF	3	9115.6 ± 491.3	320939.9 ± 2972.0
Bamboo	3	7885.9 ± 548.5	269520.2 ± 44356.3
CELF	4	9494.7 ± 835.4	322323.7 ± 11147.6
Bamboo	4	9350.4 ± 601.6	316191.2 ± 15873.3

A statistical analysis on the recorded average flexural stresses, like the tensile results, showed that there is no statistically significant difference between the CELF and bamboo fibers (Table 3). It was also found that there is no statistically significant difference between the 1 wt. % coupons—which were the best performing samples—and pure epoxy for both fiber types.

One of the possible causes for this lack of significant difference for both tensile and flexural results could be the relatively small sample size of only three coupons per weight percent for every mechanical test performed. This result, however, shows promise for the use of CELF fibers in future biocomposites as they performed no worse than their bamboo and pure epoxy counterparts.

4.3 Specific Strength Determination

Using the values determined above regarding both the tensile and flexural strength of the composites, specific strength values, or the strength of the material with respect to its density, were calculated and compared to literature values of 304 stainless steel, a common alloy used in the building industry (*40*). 304 stainless steel was chosen as a comparison to the CELF and bamboo-reinforced composites due to its favorable tensile and flexural properties, being used for structural applications and industry such as beams, frames, and supports, as well as having excellent workability with welding and fabrication which allows it to be versatile in many types of industry (*41*). Densities were determined by weighing each coupon prior to testing and using the water displacement method to find the volume of each coupon, taking an average to calculate the average density of each weight percentage of both CELF and bamboo composites. These densities are located in Table 4:

Table 4. Average density results of CELF and bamboo-reinforced composites

Reinforcement	Weight %	Average Density (g/cm^3)
None	0	1.11
CELF	1	1.08
Bamboo	1	1.08
CELF	2	1.06
Bamboo	2	1.06
CELF	3	1.04
Bamboo	3	1.04
CELF	4	1.03
Bamboo	4	1.03

4.3.1 Specific Tensile Strength

The specific tensile strength of all composites was calculated using tensile strength values determined from testing and dividing them by their respective average density values, as seen in Table 5. These values were also taken as a percentage of strength compared to 304 stainless steel alloy, found to be 71.9 $\frac{kN*m}{kg}$ based on literature values for the density and stress, calculated using Equation 2. based on literature values for the density and strength, calculated using Equation 2. (*40*, *42*, Appendix XYZ).

Table 5. Average specific tensile strengths of CELF and bamboo-reinforced composites

Reinforcement	Weight %	Average Tensile Specific Strength [$\frac{kN*m}{kg}$]	% of 304 Stainless Steel Alloy
None	0	25.8	35.8
CELF	1	31.5	43.8
Bamboo	1	28.8	40.1
CELF	2	27.3	38.0
Bamboo	2	24.0	33.3
CELF	3	27.3	38.0
Bamboo	3	26.1	36.2
CELF	4	27.3	38.0
Bamboo	4	23.8	33.1

4.3.2 Specific Flexural Strength

The specific flexural strength of all composites was calculated using flexural strength values determined from testing and dividing them by their respective average density values, as seen in Table 6. These values were also taken as a percentage of strength compared to 304 stainless steel alloy, found to be 25.9 $\frac{kN*m}{kg}$ based on literature values for the density and stress, calculated using Equation 2. (*40*, *42*, Appendix XYZ).

Table 6. Average specific flexural strengths of CELF and bamboo-reinforced composites

Reinforcement	Weight %	Average Flexural Specific Strength [$\frac{kN*m}{kg}$]	% of 304 Stainless Steel Alloy
None	0	54.6	211.3
CELF	1	66.0	255.4
Bamboo	1	66.1	255.9
CELF	2	67.5	261.1
Bamboo	2	58.7	227.0
CELF	3	60.5	234.1
Bamboo	3	52.4	202.5
CELF	4	63.5	245.7
Bamboo	4	62.6	242.0

According to literature, the mildly treated bamboo fibers used in this experiment would be expected to be significantly weaker than that of steel (*19*), as the bamboo fibers used did not undergo any lignin removal treatment therefore preventing infiltration of epoxy into the bamboo (*5*). The bamboo fibers were also scattered in random orientation and not aligned with the load axis, suggesting that the product may have been weaker than if the fibers were aligned with the direction of the load (*6*). When considering CELF, although it is treated to remove lignin and hemicellulose, it has never been used to make a fiber reinforced composite before this study. Therefore, there is no evidence that epoxy deeply infiltrates CELF fibers similar to lignin removed bamboo. The team is only able to infer that CELF behaves similar to infiltration of epoxy into lignin removed bamboo based on previous literature. This would be an essential step in proving the viability of CELF for any future research, as this study did not investigate microscopic interactions between CELF epoxy resin due to lack of resources and time. CELF used in this study was provided in a powdered form, with no ability to directionally align fibers.

4.4 Fracture Analysis on Tensile Breaks

Qualitative fracture analysis was performed on all of the coupons broken in the tensile testing method to determine common breaking points between all coupons. Flexural fracture analysis proved to be difficult, as the three-point bending test significantly deformed the material, discoloring the epoxy matrix and making it difficult to analyze the fracture points. Many common fracture points had noticeable defects leading to a compromise of strength within the material, most notably air bubbles. On the bamboo-reinforced composites specifically, stray fibers that ran perpendicular to the load axis were notably present. Figure 15 shows a tensile break of a 4% bamboo-reinforced composite with a noticeable perpendicular fiber and air bubble along the broken face. This lack of alignment in the direction of the tensile load is another factor that serves as a major contributor to the compromised biocomposite coupon strength because aligned fibers would promote uniform load distribution that would provide much greater reinforcement to the epoxy matrix (*6*). The random, discontinuous fiber alignment arose from practical limitations as the fibers were very small and aligning on top of an epoxy layer would take too much time compared to the quick hardening time of the epoxy used for these biocomposite samples.

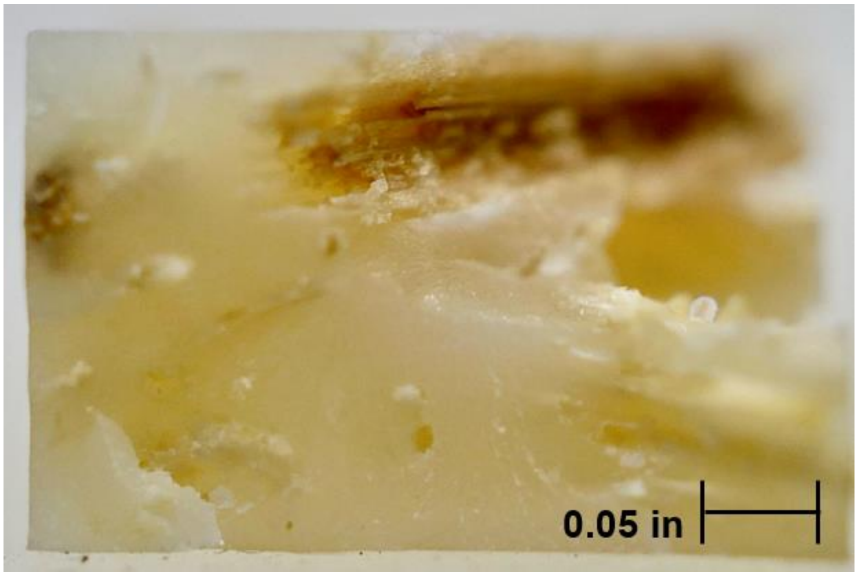

Figure 15. Tensile break on 4% bamboo-reinforced composite coupon

The CELF reinforced composites exhibited similar patterns along the broken face, with air bubbles being common among breaking points. However, since the CELF fibers were ball milled into a more uniform powder, they lacked the dimensional aspect seen within the bamboo-reinforced composites. What was noticeable, however, were larger pieces of CELF that partially protruded from the broken face of the composite as seen in Figure 16. This finding aligns with the decline in strength observed as weight percentages increased from 1 wt. % to 4 wt. % because air bubbles are a large contributor to decreases in tensile strength in epoxy resins (*43*).

This increase in air bubble concentration at higher weight percentages likely arises from the fact that layering epoxy upon greater amounts of fibers will inevitably lead to air bubble formation. While the team degassed each sample for half an hour in a vacuum oven, the curing conditions did not successfully remove all air bubbles.

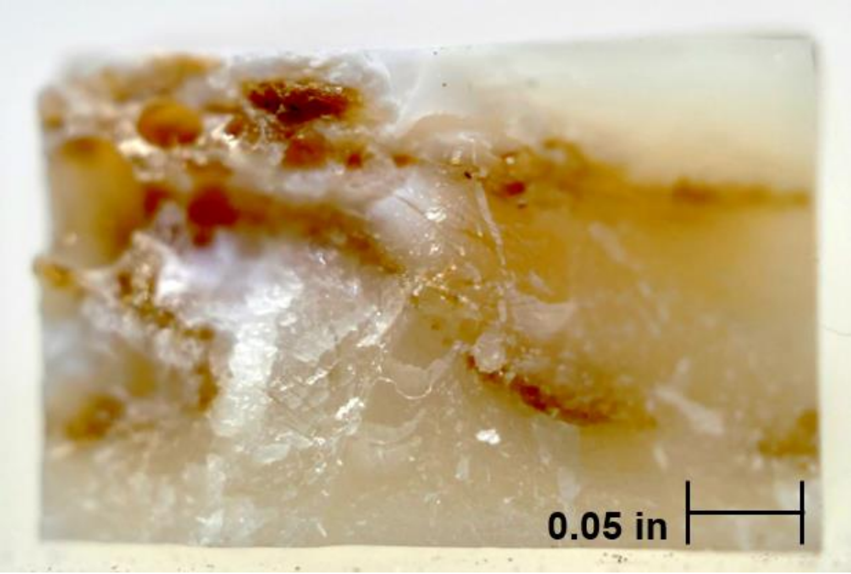

Figure 16. Tensile break on 4 wt. % CELF reinforced composite coupons

4.5 Recommendations for Future Work

The project team's recommendations for future work focuses on the following three areas of the methodology: bamboo fiber alignment, biocomposite sample curing conditions, and use of a bio-based epoxy in replacement of petroleum-based. In addressing these three areas, the team believes that the new bamboo biocomposite samples should have the potential to exhibit improved mechanical strength properties, based upon supporting evidence from literature, and improved sustainability as a result of implementing a more sustainable epoxy.

The first area the team recommends future groups address is correction of bamboo fiber alignment with the biocomposite samples. As mentioned previously, the biocomposites samples were machined with random, discontinuous fiber alignment leading to the occurrence of fracture points on bamboo fibers misaligned with the axis on which the load was being applied. Future work developing the bamboo fiber biocomposite samples should aim to achieve unidirectional fiber alignment to achieve a uniform load distribution when subjecting biocomposite coupons to mechanical tests (*44*). Through addressing the issue of random, non-uniform fiber alignment, future biocomposite samples have the potential to exhibit improved tensile and flexural strengths.

The second area of the methodology identified for improvement involves the curing conditions that biocomposite samples are subjected to. The 30-minute degassing period in the vacuum oven did not yield the desired outcome of eliminating air bubbles. The team recommends varying both curing time and vacuum pressure that biocomposite samples experience during the degassing process. Epoxy manufacturing practice specifies that epoxy be kept at a specified temperature based on the kind of epoxy to see uniform cure time and lack of air bubbles (*45*). Although the team achieved this by keeping the composite at room temperature once made, the presence of air bubbles persisted which could be due to insufficient time or vacuum. Investigating an applied vacuum over more extended periods of time could prove to be more beneficial for removing air bubbles throughout the composite (*46*). The team's main focus for this study was to develop a novel method for biocomposite construction and determining preliminary mechanical properties; integrating the manipulation of curing condition variables for future samples increases the ability to identify potential relationships relating to air bubble formation.

To improve upon the overall sustainability of future bamboo fiber biocomposites, implementation of a bio-epoxy should be considered. A more sustainable construction cycle of biocomposite sample manufacturing can be achieved through bio-epoxy use, replacing petroleum-based alternatives. Research into the specific applications of bio-epoxies is still ongoing, as their mechanical properties and strengths vary depending on bio-based composition (*47*). Additionally, studies on bio-epoxy synthesis utilizing biomass lignin (*48*, *49*, *50*) suggest the potential for utilization of lignin derived from the CELF pretreatment process. Further implications of developing bio-epoxies with lignin suggest biocomposite samples can be fabricated with nearly complete utilization biomass, as highlighted in (*49*). The implementation of bio-epoxies shows promise for enhancing the sustainability of future bamboo biocomposite samples, presenting the potential for a sustainable alternative to petroleum-based epoxies. However, continued research is necessary to produce more data and develop a better understanding on the mechanical properties of bio-epoxies.

Chapter 5. Conclusions

Although an essential part of the building and commercial industry, steelmaking's contribution to carbon emissions and other unsustainable practices calls for a more sustainable alternative building material in future applications. Currently, bamboo fiber-reinforced composites have emerged as a promising replacement for steel and other building materials. However, traditional BFRCs are not fully sustainable, due to harsh chemicals rendering parts of the plant unusable. The workaround to this issue is using co-solvent enhanced lignocellulosic fractionation, or CELF, a fiber pretreatment option developed by a team at UC Riverside which preserves all parts of the bamboo while also being usable to create BFRCs. Using CELF-treated fibers and Soxhlet-treated bamboo fibers that removed excess oils and waxes, the team created BFRCs of varying weight percentages that were tested using flexural three-point bending tests and tensile tests.

The study produced no statistically significant difference between the CELF and bamboo fibers (Tables 2 & 3) in regard to tensile and flexural strength; however, this result shows promise for the use of CELF fibers in future biocomposites as they performed no worse than their bamboo and pure epoxy counterparts. Additionally, the specific strength was calculated for tensile and flexural testing (Tables 5 & 6), where results were compared to 304 stainless steel, a common industry material. Both BFRCs underperformed compared to steel in tensile strength and overperformed in flexural strength. The novel biocomposite samples show initial promise towards developing more sustainable materials that exhibit mechanical properties comparable to steel or concrete.

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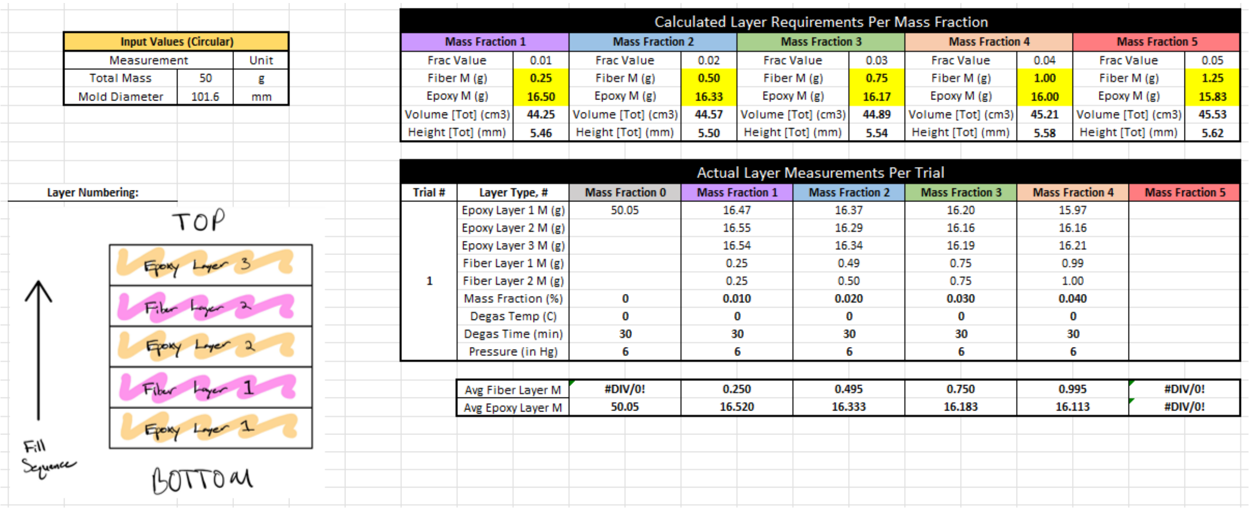
Appendices

Appendix A. BFRC Layer Calculations – Mass Fraction

A.1 Bamboo Fiber Composite Sample Layer Data



Input Values (Circular)		
Measurement		Unit
Total Mass	50	g
Mold Diameter	101.6	mm

Calculated Layer Requirements Per Mass Fraction									
Mass Fraction 1		Mass Fraction 2		Mass Fraction 3		Mass Fraction 4		Mass Fraction 5	
Frac Value	0.01	Frac Value	0.02	Frac Value	0.03	Frac Value	0.04	Frac Value	0.05
Fiber M (g)	0.25	Fiber M (g)	0.50	Fiber M (g)	0.75	Fiber M (g)	1.00	Fiber M (g)	1.25
Epoxy M (g)	16.50	Epoxy M (g)	16.33	Epoxy M (g)	16.17	Epoxy M (g)	16.00	Epoxy M (g)	15.83
Volume [Tot] (cm3)	44.25	Volume [Tot] (cm3)	44.57	Volume [Tot] (cm3)	44.89	Volume [Tot] (cm3)	45.21	Volume [Tot] (cm3)	45.53
Height [Tot] (mm)	5.46	Height [Tot] (mm)	5.50	Height [Tot] (mm)	5.54	Height [Tot] (mm)	5.58	Height [Tot] (mm)	5.62

Layer Numbering:

TOP

Epoxy Layer 3

Fiber Layer 2

Epoxy Layer 2

Fiber Layer 1

Epoxy Layer 1

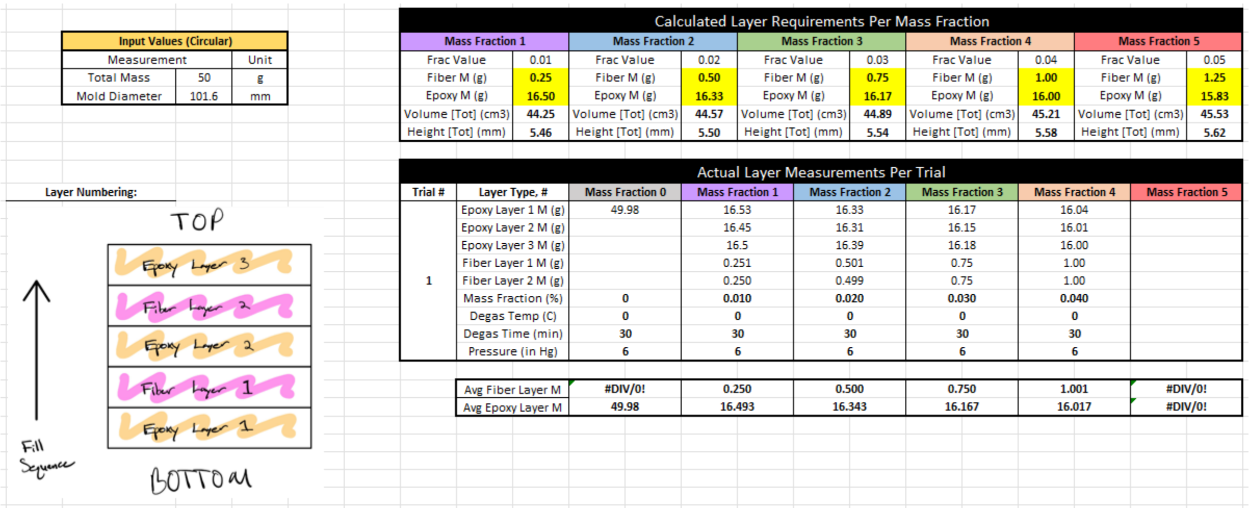
Fill Sequence

BOTTOM

Actual Layer Measurements Per Trial							
Trial #	Layer Type, #	Mass Fraction 0	Mass Fraction 1	Mass Fraction 2	Mass Fraction 3	Mass Fraction 4	Mass Fraction 5
1	Epoxy Layer 1 M (g)	50.05	16.47	16.37	16.20	15.97	
	Epoxy Layer 2 M (g)		16.55	16.29	16.16	16.16	
	Epoxy Layer 3 M (g)		16.54	16.34	16.19	16.21	
	Fiber Layer 1 M (g)		0.25	0.49	0.75	0.99	
	Fiber Layer 2 M (g)		0.25	0.50	0.75	1.00	
	Mass Fraction (%)	0	0.010	0.020	0.030	0.040	
	Degas Temp (C)	0	0	0	0	0	
	Degas Time (min)	30	30	30	30	30	
	Pressure (in Hg)	6	6	6	6	6	

Avg Fiber Layer M	#DIV/0!	0.250	0.495	0.750	0.995	#DIV/0!
Avg Epoxy Layer M	50.05	16.520	16.333	16.183	16.113	#DIV/0!

A.2 CELF Fiber Composite Sample Layer Data



Input Values (Circular)		
Measurement		Unit
Total Mass	50	g
Mold Diameter	101.6	mm

Calculated Layer Requirements Per Mass Fraction									
Mass Fraction 1		Mass Fraction 2		Mass Fraction 3		Mass Fraction 4		Mass Fraction 5	
Frac Value	0.01	Frac Value	0.02	Frac Value	0.03	Frac Value	0.04	Frac Value	0.05
Fiber M (g)	0.25	Fiber M (g)	0.50	Fiber M (g)	0.75	Fiber M (g)	1.00	Fiber M (g)	1.25
Epoxy M (g)	16.50	Epoxy M (g)	16.33	Epoxy M (g)	16.17	Epoxy M (g)	16.00	Epoxy M (g)	15.83
Volume [Tot] (cm3)	44.25	Volume [Tot] (cm3)	44.57	Volume [Tot] (cm3)	44.89	Volume [Tot] (cm3)	45.21	Volume [Tot] (cm3)	45.53
Height [Tot] (mm)	5.46	Height [Tot] (mm)	5.50	Height [Tot] (mm)	5.54	Height [Tot] (mm)	5.58	Height [Tot] (mm)	5.62

Layer Numbering:

TOP

Epoxy Layer 3

Fiber Layer 2

Epoxy Layer 2

Fiber Layer 1

Epoxy Layer 1

Fill Sequence

BOTTOM

Actual Layer Measurements Per Trial							
Trial #	Layer Type, #	Mass Fraction 0	Mass Fraction 1	Mass Fraction 2	Mass Fraction 3	Mass Fraction 4	Mass Fraction 5
1	Epoxy Layer 1 M (g)	49.98	16.53	16.33	16.17	16.04	
	Epoxy Layer 2 M (g)		16.45	16.31	16.15	16.01	
	Epoxy Layer 3 M (g)		16.5	16.39	16.18	16.00	
	Fiber Layer 1 M (g)		0.251	0.501	0.75	1.00	
	Fiber Layer 2 M (g)		0.250	0.499	0.75	1.00	
	Mass Fraction (%)	0	0.010	0.020	0.030	0.040	
	Degas Temp (C)	0	0	0	0	0	
	Degas Time (min)	30	30	30	30	30	
	Pressure (in Hg)	6	6	6	6	6	

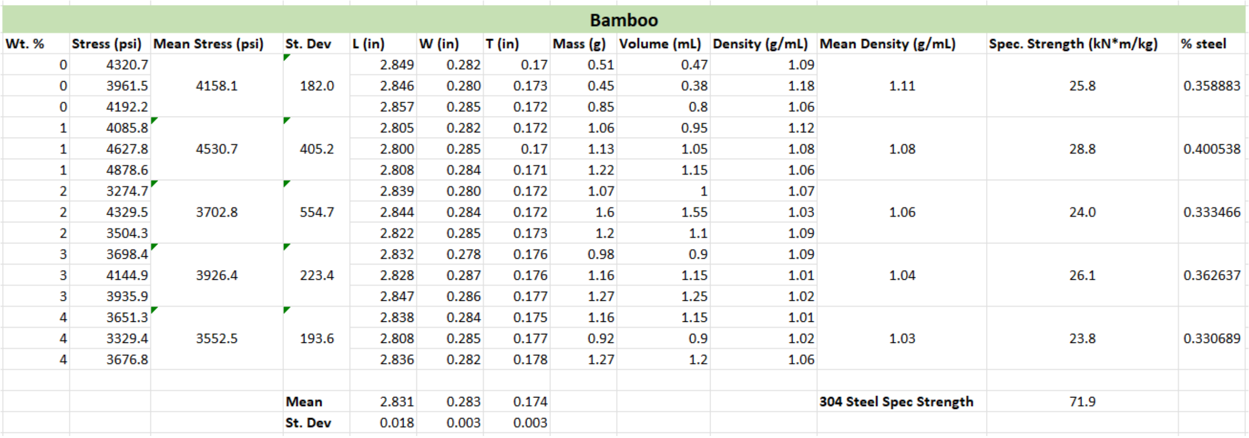
Avg Fiber Layer M	#DIV/0!	0.250	0.500	0.750	1.001	#DIV/0!
Avg Epoxy Layer M	49.98	16.493	16.343	16.167	16.017	#DIV/0!

A.3 Composite Layering Workbook Link

BFRC Mass Fractions

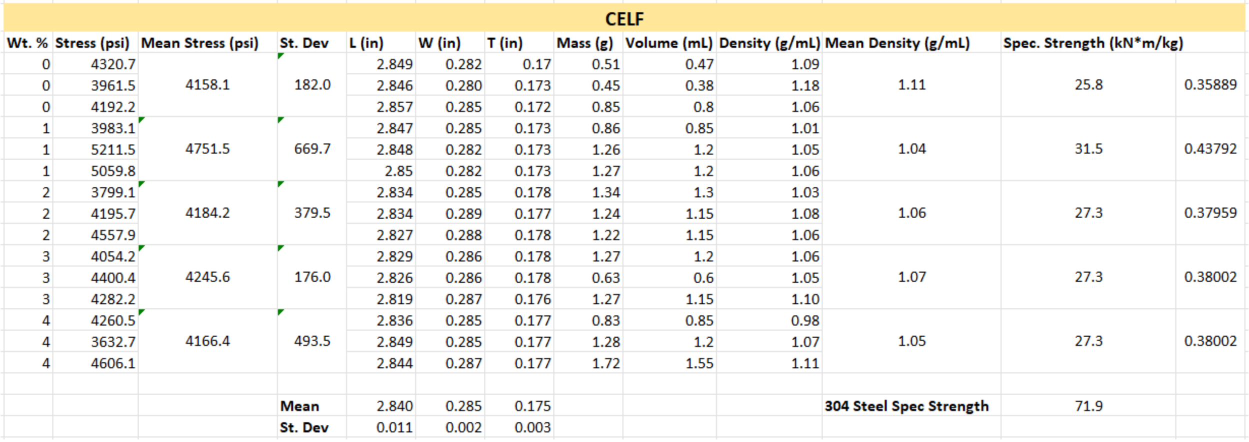
Appendix B. BFRC Tensile and Flexural Test Results & Analysis

B.1 Bamboo Fiber Composite Tensile Data



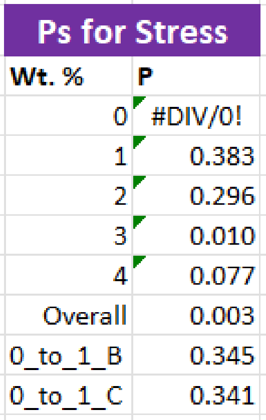
Bamboo												
Wt. %	**Stress (psi)**	**Mean Stress (psi)**	**St. Dev**	**L (in)**	**W (in)**	**T (in)**	**Mass (g)**	**Volume (mL)**	**Density (g/mL)**	**Mean Density (g/mL)**	**Spec. Strength (kN*m/kg)**	**% steel**
0	4320.7	4158.1	182.0	2.849	0.282	0.17	0.51	0.47	1.09	1.11	25.8	0.358883
0	3961.5			2.846	0.280	0.173	0.45	0.38	1.18			
0	4192.2			2.857	0.285	0.172	0.85	0.8	1.06			
1	4085.8	4530.7	405.2	2.805	0.282	0.172	1.06	0.95	1.12	1.08	28.8	0.400538
1	4627.8			2.800	0.285	0.17	1.13	1.05	1.08			
1	4878.6			2.808	0.284	0.171	1.22	1.15	1.06			
2	3274.7	3702.8	554.7	2.839	0.280	0.172	1.07	1	1.07	1.06	24.0	0.333466
2	4329.5			2.844	0.284	0.172	1.6	1.55	1.03			
2	3504.3			2.822	0.285	0.173	1.2	1.1	1.09			
3	3698.4	3926.4	223.4	2.832	0.278	0.176	0.98	0.9	1.09	1.04	26.1	0.362637
3	4144.9			2.828	0.287	0.176	1.16	1.15	1.01			
3	3935.9			2.847	0.286	0.177	1.27	1.25	1.02			
4	3651.3	3552.5	193.6	2.838	0.284	0.175	1.16	1.15	1.01	1.03	23.8	0.330689
4	3329.4			2.808	0.285	0.177	0.92	0.9	1.02			
4	3676.8			2.836	0.282	0.178	1.27	1.2	1.06			
			Mean	2.831	0.283	0.174				**304 Steel Spec Strength**	71.9	
			St. Dev	0.018	0.003	0.003						

B.2 CELF Fiber Composite Tensile Data



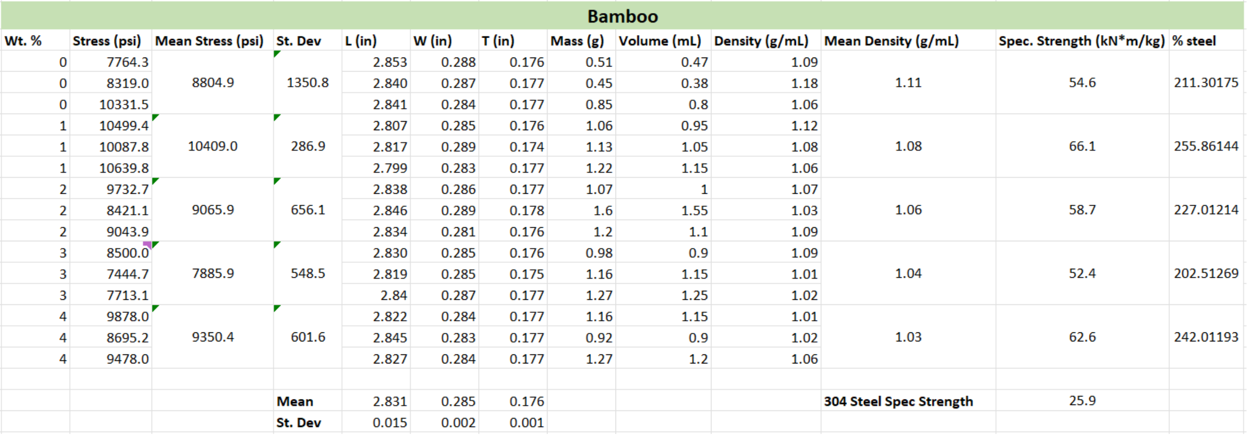
CELF												
Wt. %	**Stress (psi)**	**Mean Stress (psi)**	**St. Dev**	**L (in)**	**W (in)**	**T (in)**	**Mass (g)**	**Volume (mL)**	**Density (g/mL)**	**Mean Density (g/mL)**	**Spec. Strength (kN*m/kg)**	
0	4320.7	4158.1	182.0	2.849	0.282	0.17	0.51	0.47	1.09	1.11	25.8	0.35889
0	3961.5			2.846	0.280	0.173	0.45	0.38	1.18			
0	4192.2			2.857	0.285	0.172	0.85	0.8	1.06			
1	3983.1	4751.5	669.7	2.847	0.285	0.173	0.86	0.85	1.01	1.04	31.5	0.43792
1	5211.5			2.848	0.282	0.173	1.26	1.2	1.05			
1	5059.8			2.85	0.282	0.173	1.27	1.2	1.06			
2	3799.1	4184.2	379.5	2.834	0.285	0.178	1.34	1.3	1.03	1.06	27.3	0.37959
2	4195.7			2.834	0.289	0.177	1.24	1.15	1.08			
2	4557.9			2.827	0.288	0.178	1.22	1.15	1.06			
3	4054.2	4245.6	176.0	2.829	0.286	0.178	1.27	1.2	1.06	1.07	27.3	0.38002
3	4400.4			2.826	0.286	0.178	0.63	0.6	1.05			
3	4282.2			2.819	0.287	0.176	1.27	1.15	1.10			
4	4260.5	4166.4	493.5	2.836	0.285	0.177	0.83	0.85	0.98	1.05	27.3	0.38002
4	3632.7			2.849	0.285	0.177	1.28	1.2	1.07			
4	4606.1			2.844	0.287	0.177	1.72	1.55	1.11			
			Mean	2.840	0.285	0.175				**304 Steel Spec Strength**	71.9	
			St. Dev	0.011	0.002	0.003						

B.3 Statistical P-values for Tensile Testing



Ps for Stress	
Wt. %	**P**
0	#DIV/0!
1	0.383
2	0.296
3	0.010
4	0.077
Overall	0.003
0_to_1_B	0.345
0_to_1_C	0.341

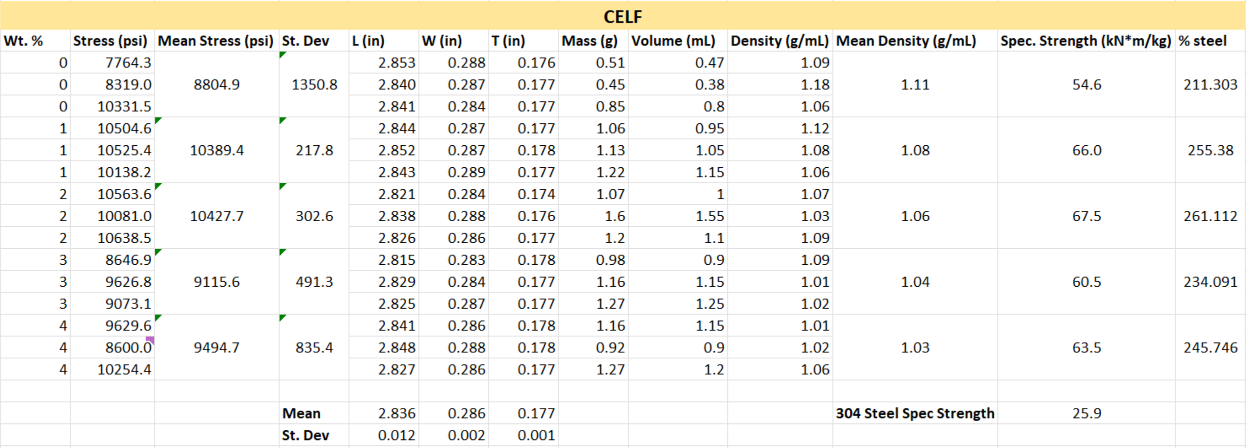
B.4 Bamboo Fiber Composite Tensile Data



Bamboo

Wt. %	Stress (psi)	Mean Stress (psi)	St. Dev	L (in)	W (in)	T (in)	Mass (g)	Volume (mL)	Density (g/mL)	Mean Density (g/mL)	Spec. Strength (kN*m/kg)	% steel
0	7764.3	8804.9	1350.8	2.853	0.288	0.176	0.51	0.47	1.09	1.11	54.6	211.30175
0	8319.0			2.840	0.287	0.177	0.45	0.38	1.18			
0	10331.5			2.841	0.284	0.177	0.85	0.8	1.06			
1	10499.4	10409.0	286.9	2.807	0.285	0.176	1.06	0.95	1.12	1.08	66.1	255.86144
1	10087.8			2.817	0.289	0.174	1.13	1.05	1.08			
1	10639.8			2.799	0.283	0.177	1.22	1.15	1.06			
2	9732.7	9065.9	656.1	2.838	0.286	0.177	1.07	1	1.07	1.06	58.7	227.01214
2	8421.1			2.846	0.289	0.178	1.6	1.55	1.03			
2	9043.9			2.834	0.281	0.176	1.2	1.1	1.09			
3	8500.0	7885.9	548.5	2.830	0.285	0.176	0.98	0.9	1.09	1.04	52.4	202.51269
3	7444.7			2.819	0.285	0.175	1.16	1.15	1.01			
3	7713.1			2.84	0.287	0.177	1.27	1.25	1.02			
4	9878.0	9350.4	601.6	2.822	0.284	0.177	1.16	1.15	1.01	1.03	62.6	242.01193
4	8695.2			2.845	0.283	0.177	0.92	0.9	1.02			
4	9478.0			2.827	0.284	0.177	1.27	1.2	1.06			
			Mean	2.831	0.285	0.176				**304 Steel Spec Strength**	25.9	
			St. Dev	0.015	0.002	0.001						

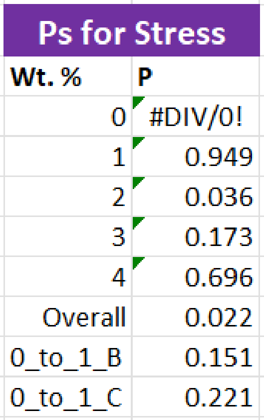
B.5 CELF Fiber Composite Tensile Data



CELF

Wt. %	Stress (psi)	Mean Stress (psi)	St. Dev	L (in)	W (in)	T (in)	Mass (g)	Volume (mL)	Density (g/mL)	Mean Density (g/mL)	Spec. Strength (kN*m/kg)	% steel
0	7764.3	8804.9	1350.8	2.853	0.288	0.176	0.51	0.47	1.09	1.11	54.6	211.303
0	8319.0			2.840	0.287	0.177	0.45	0.38	1.18			
0	10331.5			2.841	0.284	0.177	0.85	0.8	1.06			
1	10504.6	10389.4	217.8	2.844	0.287	0.177	1.06	0.95	1.12	1.08	66.0	255.38
1	10525.4			2.852	0.287	0.178	1.13	1.05	1.08			
1	10138.2			2.843	0.289	0.177	1.22	1.15	1.06			
2	10563.6	10427.7	302.6	2.821	0.284	0.174	1.07	1	1.07	1.06	67.5	261.112
2	10081.0			2.838	0.288	0.176	1.6	1.55	1.03			
2	10638.5			2.826	0.286	0.177	1.2	1.1	1.09			
3	8646.9	9115.6	491.3	2.815	0.283	0.178	0.98	0.9	1.09	1.04	60.5	234.091
3	9626.8			2.829	0.284	0.177	1.16	1.15	1.01			
3	9073.1			2.825	0.287	0.177	1.27	1.25	1.02			
4	9629.6	9494.7	835.4	2.841	0.286	0.178	1.16	1.15	1.01	1.03	63.5	245.746
4	8600.0			2.848	0.288	0.178	0.92	0.9	1.02			
4	10254.4			2.827	0.286	0.177	1.27	1.2	1.06			
			Mean	2.836	0.286	0.177				**304 Steel Spec Strength**	25.9	
			St. Dev	0.012	0.002	0.001						

B.6 Statistical P-values for Flexural Testing



Ps for Stress

Wt. %	P
0	#DIV/0!
1	0.949
2	0.036
3	0.173
4	0.696
Overall	0.022
0_to_1_B	0.151
0_to_1_C	0.221

B.7 Mechanical Test Workbook Link

Tensile_Flex_Tests_BFRC

Appendix C. Pictures of BFRC Samples and Their Creation

C.1 Additional Pictures of The BFRC-Making Process

Figure C1. Materials used for creating a CELF fiber composite

C.2 Tensile Cross-Sections of Fractures for All Bamboo Weight Percentages

Figure C2. Placing CELF fiber clumps into the mold during the sample-making process

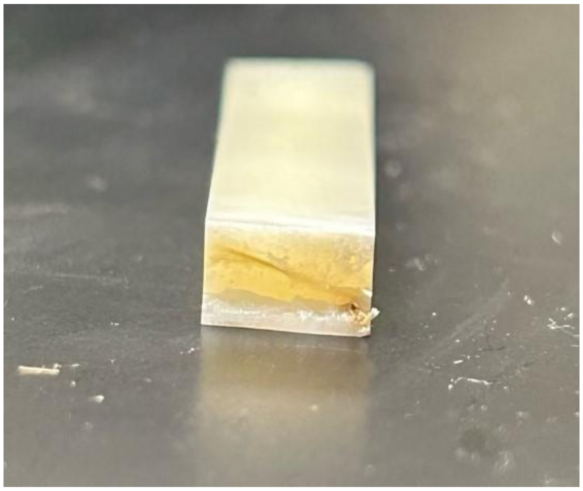


Figure C3. Bamboo fiber 1 wt. % tensile fracture cross-section

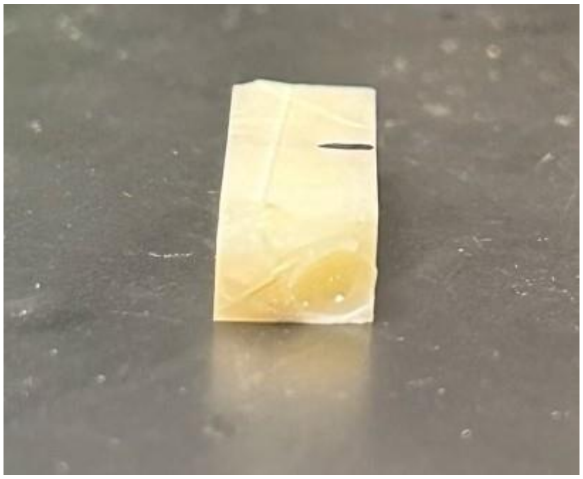


Figure C4. Bamboo fiber 2 wt. % tensile fracture cross-section

Figure C5. Bamboo fiber 3 wt. % tensile fracture side view

Figure C6. Bamboo fiber 4 wt. % tensile fracture cross-section

C.3 Tensile Cross-Sections of Fractures for All CELF Weight Percentages

Figure C7. CELF fiber 1 wt. % tensile fracture cross-section

Figure C8. CELF fiber 2 wt. % tensile fracture cross-section

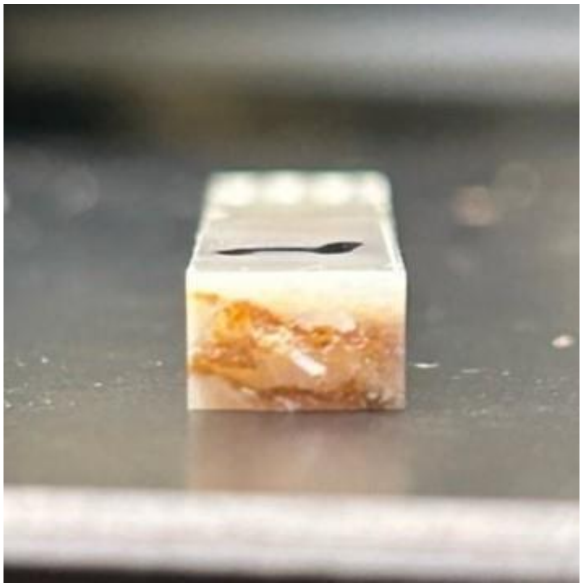


Figure C9. CELF fiber 3 wt. % tensile fracture cross-section

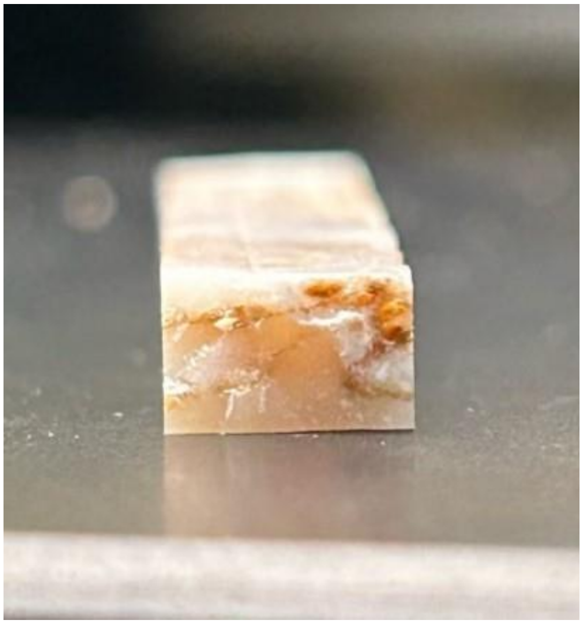
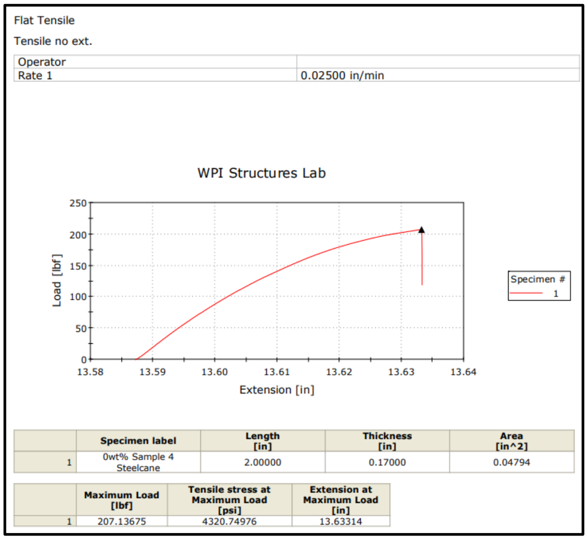


Figure C10. CELF fiber 4 wt. % tensile fracture cross-section

Appendix D. Full Mechanical Test Result Files Generated by Instron Software

D.1 Tensile Result Files



Flat Tensile

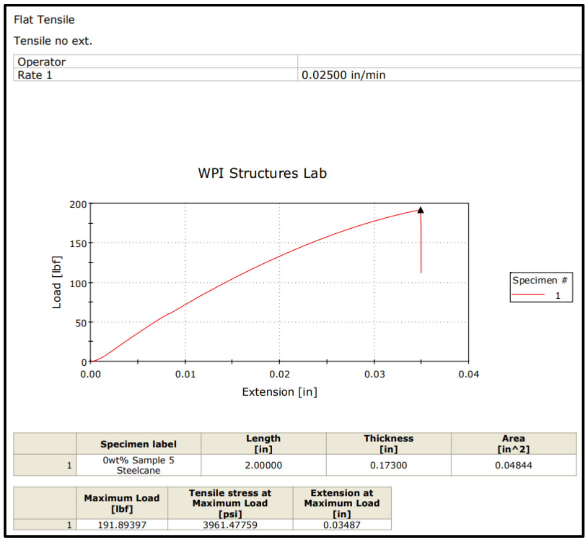
Tensile no ext.

Operator	
Rate 1	0.02500 in/min

WPI Structures Lab

	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	0wt% Sample 4 Steelcane	2.00000	0.17000	0.04794

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	207.13675	4320.74976	13.63314



Flat Tensile

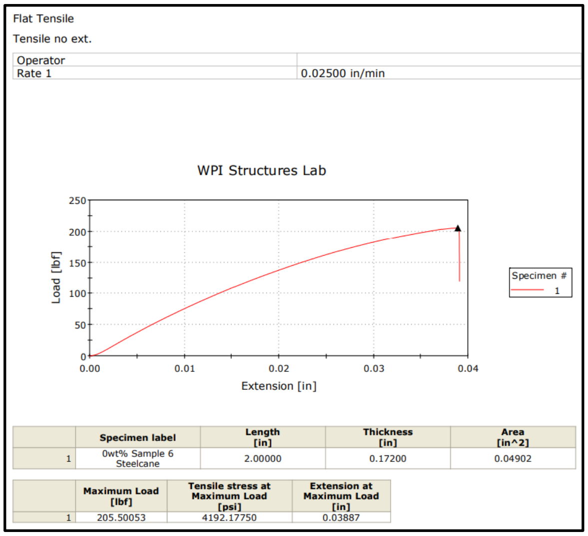
Tensile no ext.

Operator	
Rate 1	0.02500 in/min

WPI Structures Lab

	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	0wt% Sample 5 Steelcane	2.00000	0.17300	0.04844

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	191.89397	3961.47759	0.03487



Flat Tensile

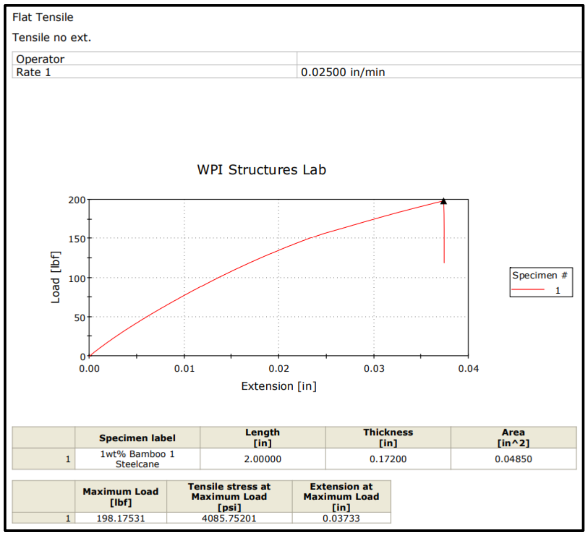
Tensile no ext.

Operator	
Rate 1	0.02500 in/min

WPI Structures Lab

	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	0wt% Sample 6 Steelcane	2.00000	0.17200	0.04902

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	205.50053	4192.17750	0.03887



Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

WPI Structures Lab

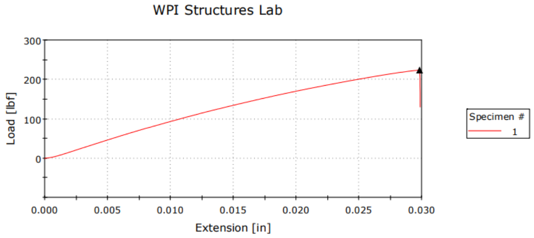
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	1wt% Bamboo 1 Steelcane	2.00000	0.17200	0.04850

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	198.17531	4085.75201	0.03733

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min


WPI Structures Lab

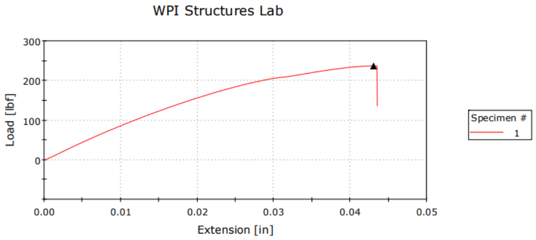
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	1wt% Bamboo 2 Steelcane	2.00000	0.17000	0.04845

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	224.21537	4627.76816	0.02979

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min


WPI Structures Lab

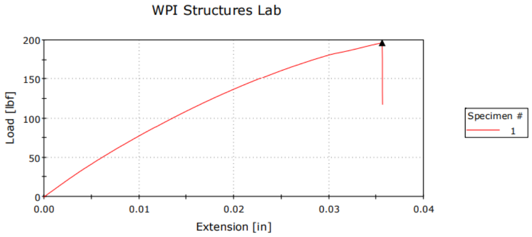
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	1wt% Bamboo 3 Tensile Steelcane	2.00000	0.17100	0.04856

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	236.92536	4878.62139	0.04299

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min


WPI Structures Lab

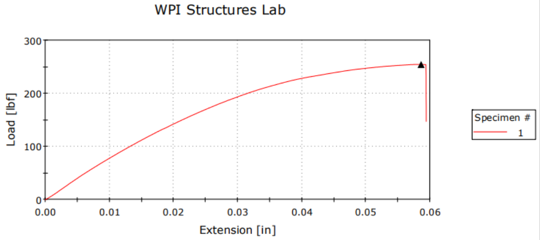
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	1wt% CELF 1 Tensile Steelcane	2.00000	0.17300	0.04930

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	196.38473	3983.05919	0.03558

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min


WPI Structures Lab

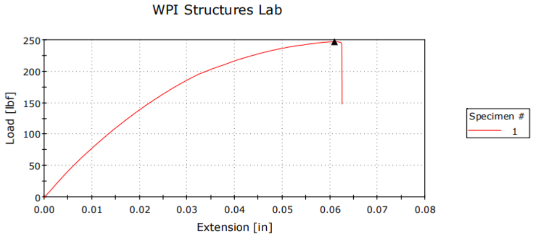
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	1wt% CELF 2 Tensile Steelcane	2.00000	0.17300	0.04879

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	254.24731	5211.48104	0.05854

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min


WPI Structures Lab

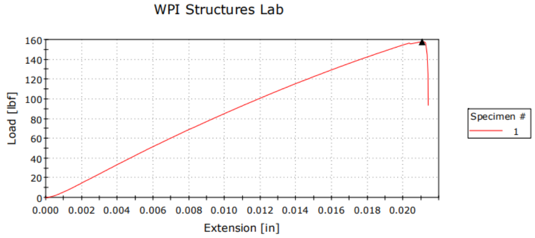
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	1wt% CELF 3 Tensile Steelcane	2.00000	0.17300	0.04879

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	246.84667	5059.78520	0.06091

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min


WPI Structures Lab

	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	2wt% Bamboo 1 Tensile Steelcane	2.00000	0.17200	0.04816

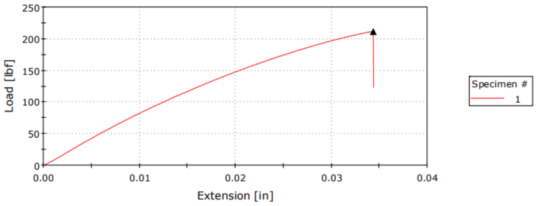
	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	157.70819	3274.67159	0.02104

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

WPI Structures Lab



	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	2wt% Bamboo 2 Tensile Steelcane	2.00000	0.17200	0.04885

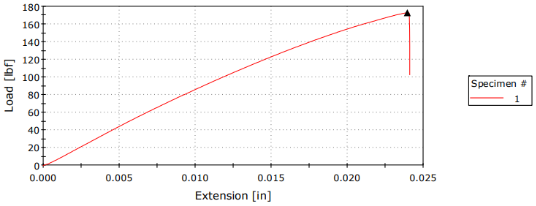
	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	211.48919	4329.53633	0.03432

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

WPI Structures Lab



	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	2wt% Bamboo 3 Tensile Steelcane	2.00000	0.17300	0.04930

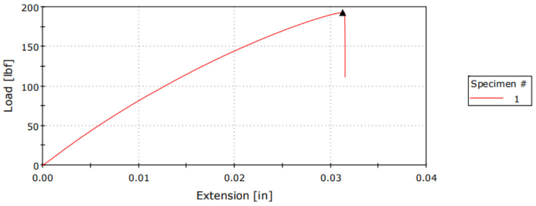
	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	172.77872	3504.28404	0.02391

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

WPI Structures Lab



	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	2wt% CELF 1 Tensile Steelcane	2.00000	0.17800	0.05073

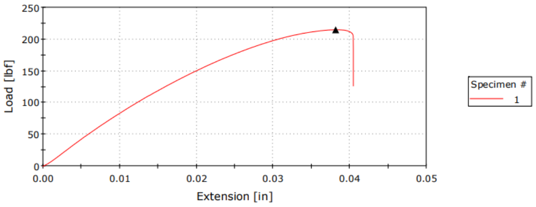
	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	192.72725	3799.07837	0.03125

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

WPI Structures Lab



	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	2wt% CELF 2 Tensile Steelcane	2.00000	0.17700	0.05115

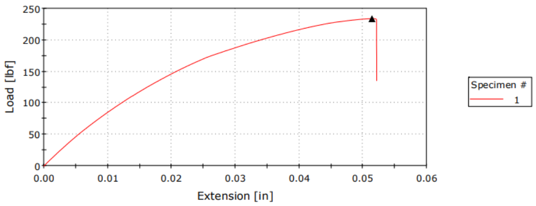
	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	214.62493	4195.74474	0.03812

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

WPI Structures Lab



	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	2wt% CELF 3 Tensile Steelcane	2.00000	0.17800	0.05126

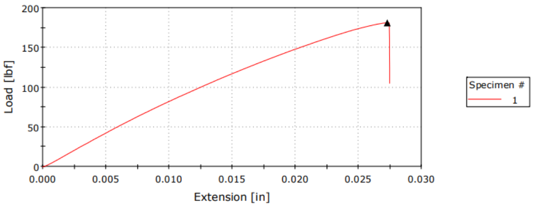
	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	233.65479	4557.87292	0.05137

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

WPI Structures Lab



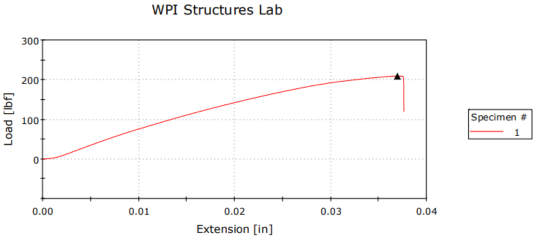
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	3% Bamboo 1 Tensile Steelcane	2.00000	0.17600	0.04893

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	180.95775	3698.44982	0.02725

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min



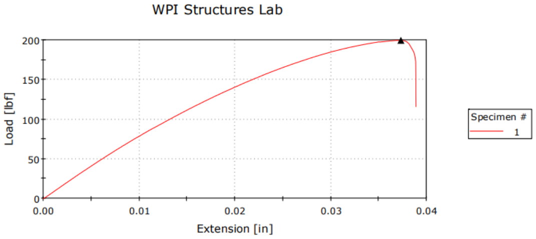
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	3% Bamboo 2 Tensile Steelcane	2.00000	0.17600	0.05051

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	209.36519	4144.86032	0.03691

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min



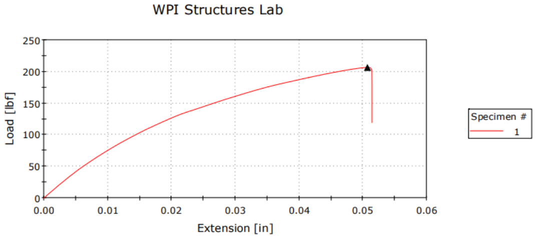
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	3% Bamboo 3 Tensile Steelcane	2.00000	0.17700	0.05062

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	199.24216	3935.88088	0.03729

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min



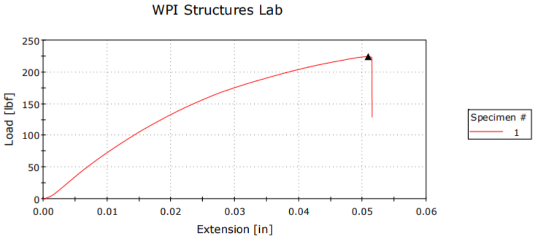
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	3% CELF 1 Tensile Steelcane	2.00000	0.17800	0.05091

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	206.38886	4054.15392	0.05067

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min



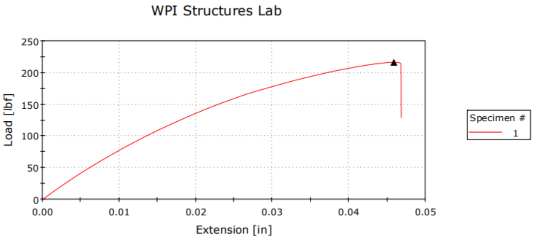
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	3% CELF 2 Tensile Steelcane	2.00000	0.17800	0.05091

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	224.01400	4400.36936	0.05083

Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min



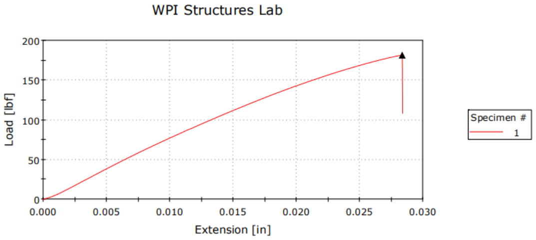
	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	3% CELF 3 Tensile Steelcane	2.00000	0.17600	0.05051

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	216.30198	4282.19009	0.04583

Flat Tensile

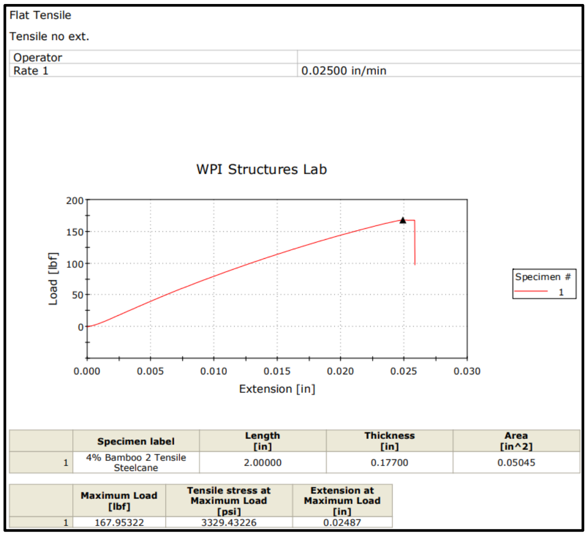
Tensile no ext.

Operator	
Rate 1	0.02500 in/min



	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	4% Bamboo 1 Tensile Steelcane	2.00000	0.17500	0.04970

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	181.46754	3651.25823	0.02832



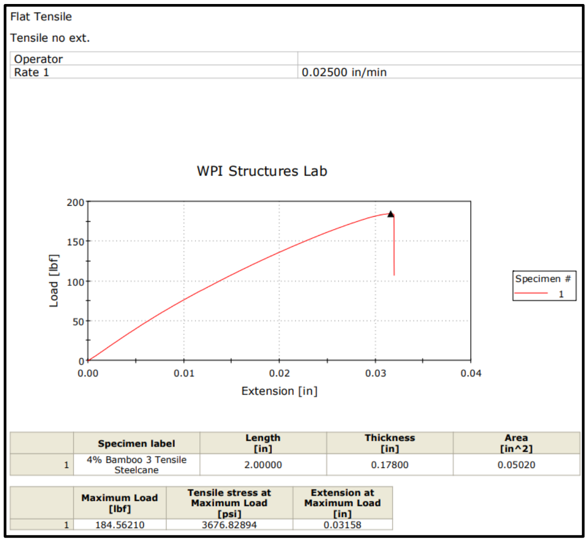
Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	4% Bamboo 2 Tensile Steelcane	2.00000	0.17700	0.05045

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	167.95322	3329.43226	0.02487



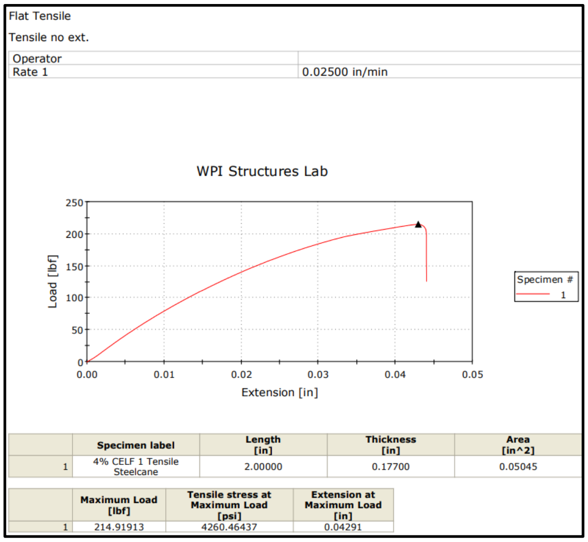
Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	4% Bamboo 3 Tensile Steelcane	2.00000	0.17800	0.05020

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	184.56210	3676.82894	0.03158



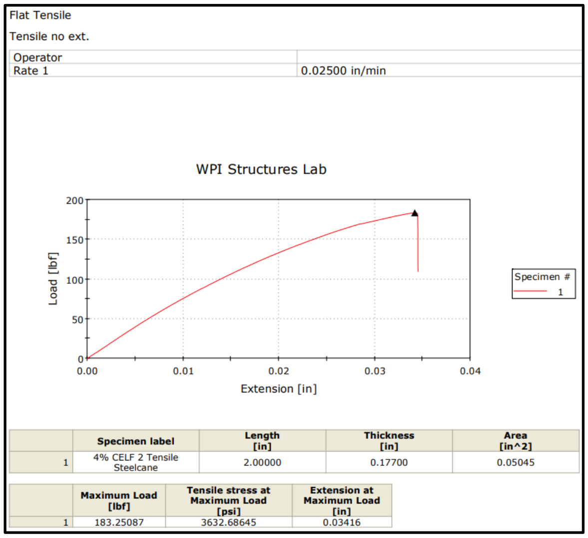
Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	4% CELF 1 Tensile Steelcane	2.00000	0.17700	0.05045

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	214.91913	4260.46437	0.04291



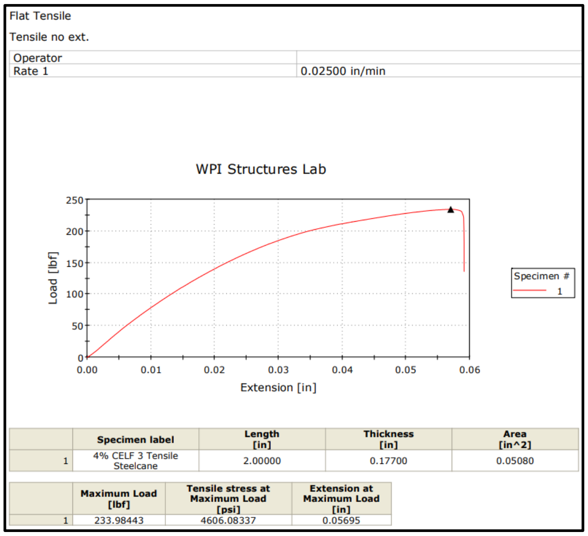
Flat Tensile

Tensile no ext.

Operator	
Rate 1	0.02500 in/min

	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	4% CELF 2 Tensile Steelcane	2.00000	0.17700	0.05045

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	183.25087	3632.68645	0.03416



Flat Tensile

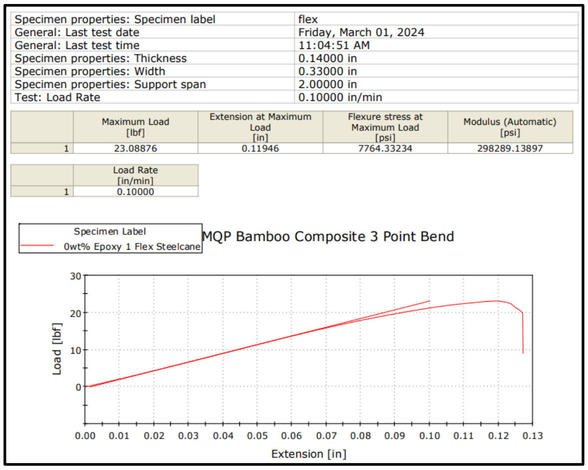
Tensile no ext.

Operator	
Rate 1	0.02500 in/min

	Specimen label	Length [in]	Thickness [in]	Area [in^2]
1	4% CELF 3 Tensile Steelcane	2.00000	0.17700	0.05080

	Maximum Load [lbf]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	233.98443	4606.08337	0.05695

D.2 Flexural Result Files



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:04:51 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

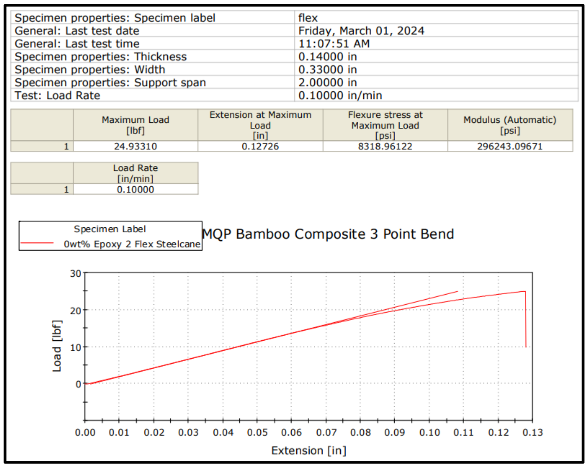
	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	23.08876	0.11946	7764.33234	298289.13897

	Load Rate [in/min]
1	0.10000

Specimen Label

0wt% Epoxy 1 Flex Steelcane

MQP Bamboo Composite 3 Point Bend



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:07:51 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

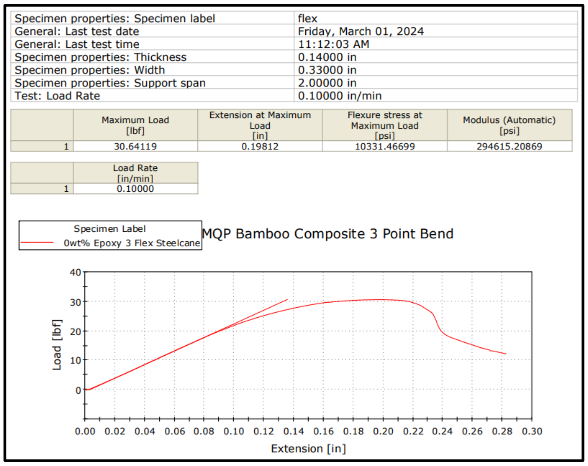
	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	24.93310	0.12726	8318.96122	296243.09671

	Load Rate [in/min]
1	0.10000

Specimen Label

0wt% Epoxy 2 Flex Steelcane

MQP Bamboo Composite 3 Point Bend



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:12:03 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

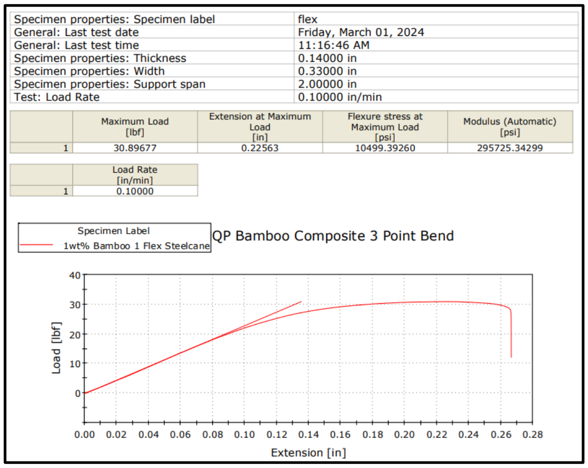
	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	30.64119	0.19812	10331.46699	294615.20869

	Load Rate [in/min]
1	0.10000

Specimen Label

0wt% Epoxy 3 Flex Steelcane

MQP Bamboo Composite 3 Point Bend



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:16:46 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

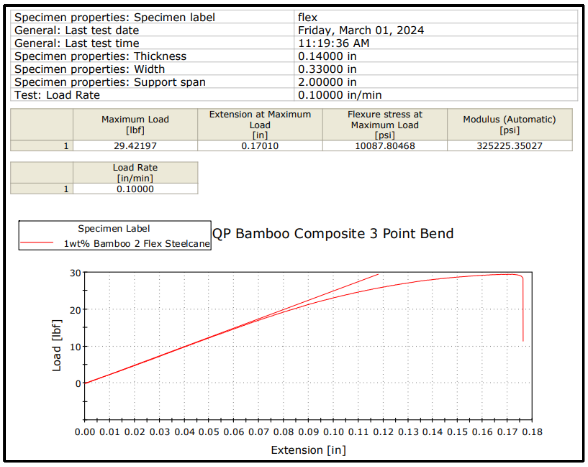
	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	30.89677	0.22563	10499.39260	295725.34299

	Load Rate [in/min]
1	0.10000

Specimen Label

1wt% Bamboo 1 Flex Steelcane

QP Bamboo Composite 3 Point Bend



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:19:36 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

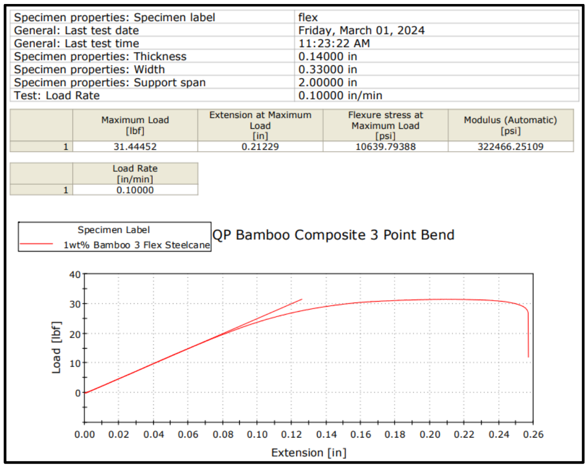
	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	29.42197	0.17010	10087.80468	325225.35027

	Load Rate [in/min]
1	0.10000

Specimen Label

1wt% Bamboo 2 Flex Steelcane

QP Bamboo Composite 3 Point Bend



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:23:22 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

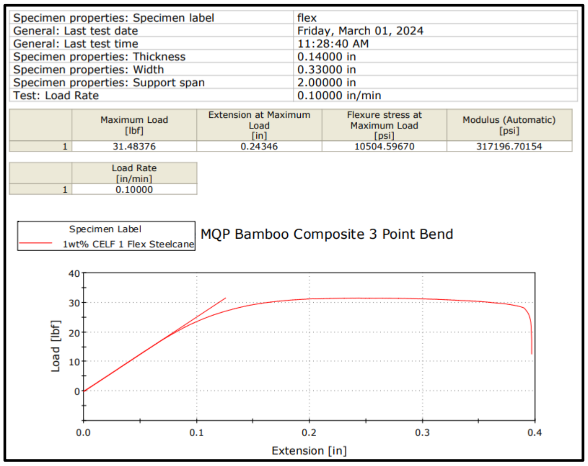
	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	31.44452	0.21229	10639.79388	322466.25109

	Load Rate [in/min]
1	0.10000

Specimen Label

1wt% Bamboo 3 Flex Steelcane

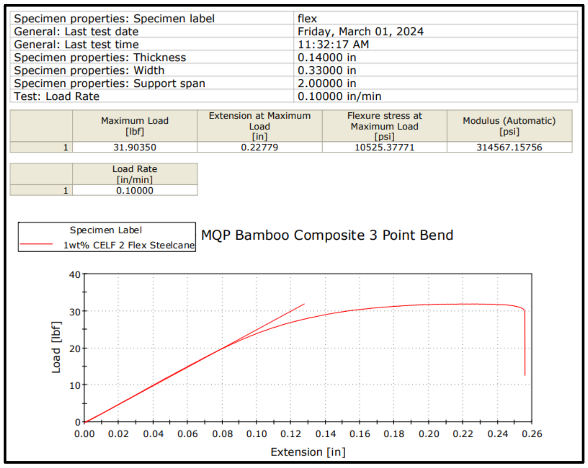
QP Bamboo Composite 3 Point Bend



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:28:40 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	31.48376	0.24346	10504.59670	317196.70154

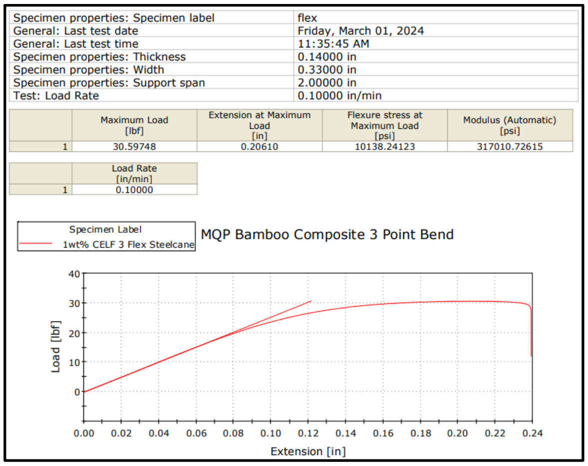
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:32:17 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	31.90350	0.22779	10525.37771	314567.15756

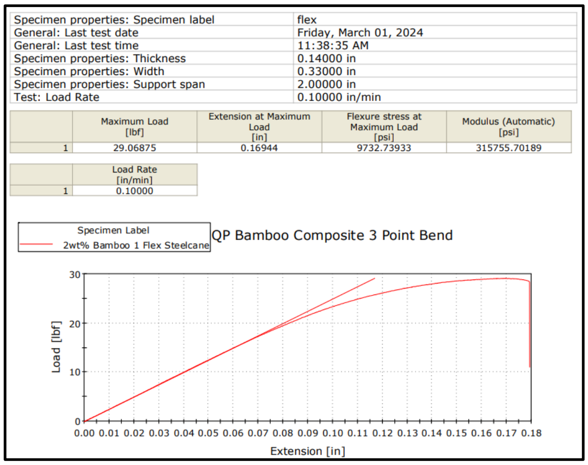
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:35:45 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	30.59748	0.20610	10138.24123	317010.72615

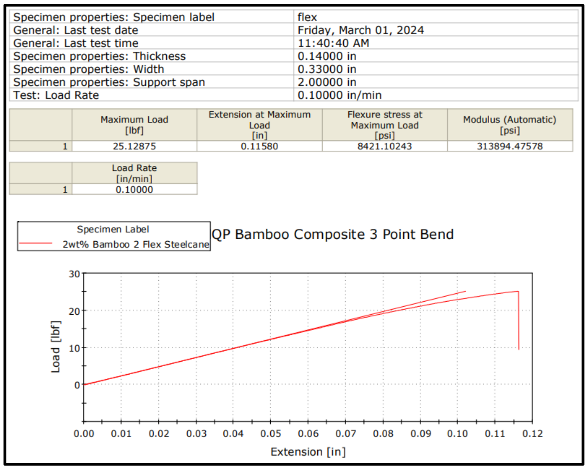
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:38:35 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	29.06875	0.16944	9732.73933	315755.70189

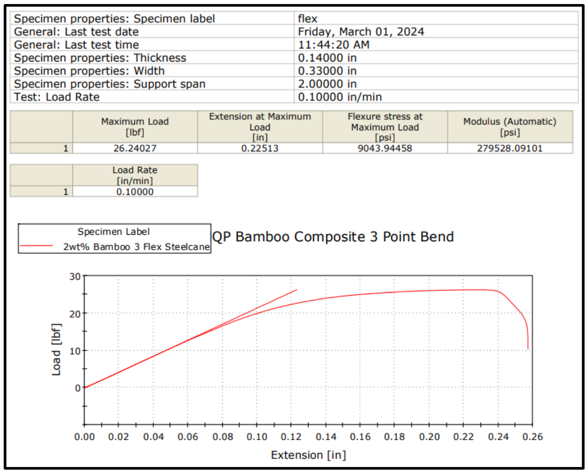
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:40:40 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	25.12875	0.11580	8421.10243	313894.47578

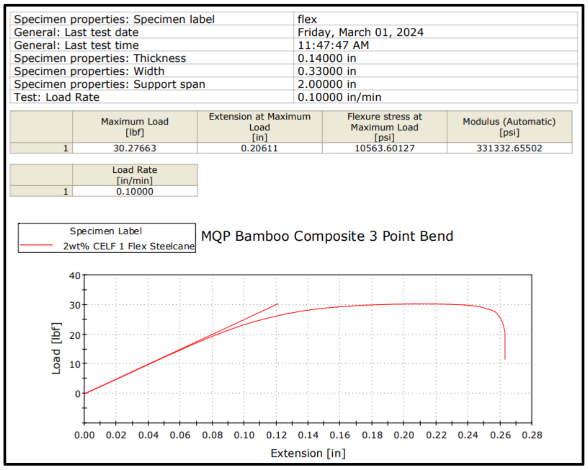
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:44:20 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	26.24027	0.22513	9043.94458	279528.09101

	Load Rate [in/min]
1	0.10000



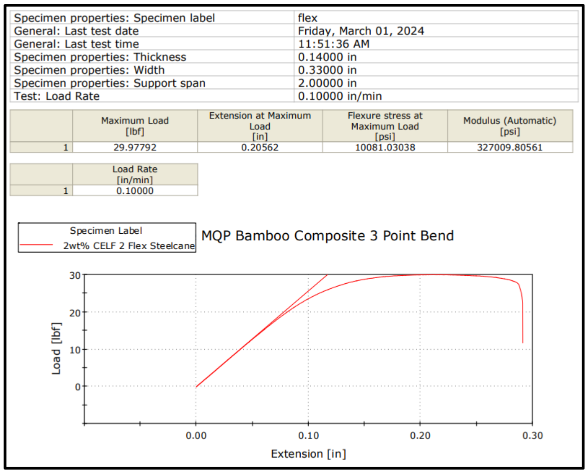
Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:47:47 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	30.27663	0.20611	10563.60127	331332.65502

	Load Rate [in/min]
1	0.10000

MQP Bamboo Composite 3 Point Bend

Specimen Label
2wt% CELF 1 Flex Steelcane



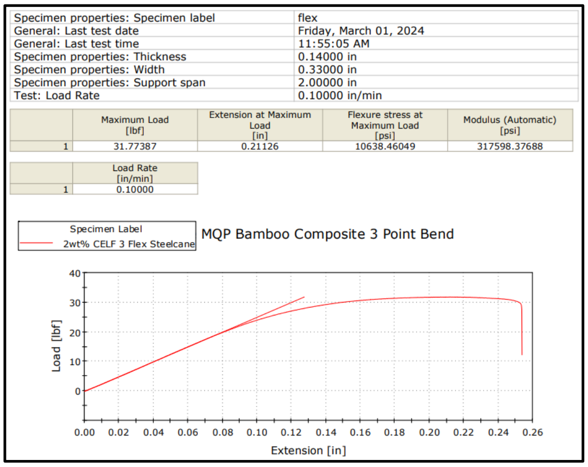
Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:51:36 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	29.97792	0.20562	10081.03038	327009.80561

	Load Rate [in/min]
1	0.10000

MQP Bamboo Composite 3 Point Bend

Specimen Label
2wt% CELF 2 Flex Steelcane



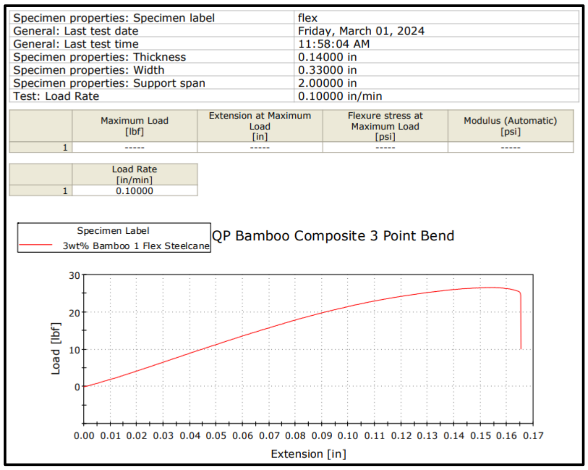
Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:55:05 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	31.77387	0.21126	10638.46049	317598.37688

	Load Rate [in/min]
1	0.10000

MQP Bamboo Composite 3 Point Bend

Specimen Label
2wt% CELF 3 Flex Steelcane



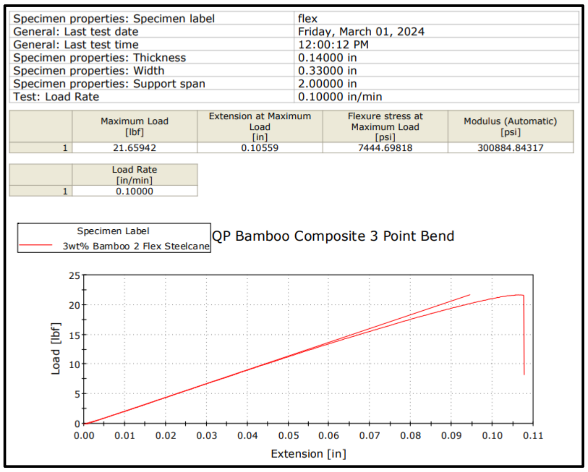
Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	11:58:04 AM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	-----	-----	-----	-----

	Load Rate [in/min]
1	0.10000

QP Bamboo Composite 3 Point Bend

Specimen Label
3wt% Bamboo 1 Flex Steelcane



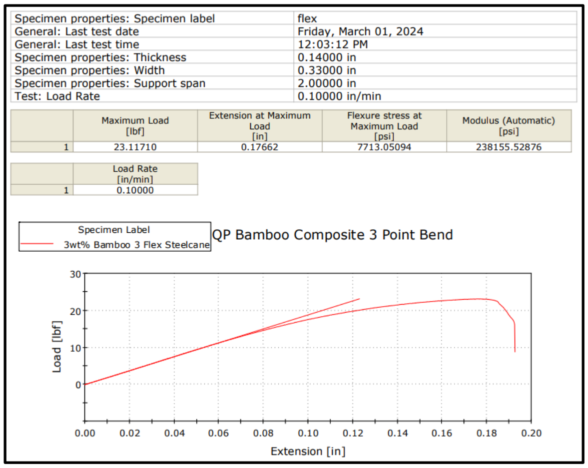
Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:00:12 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	21.65942	0.10559	7444.69818	300884.84317

	Load Rate [in/min]
1	0.10000

QP Bamboo Composite 3 Point Bend

Specimen Label
3wt% Bamboo 2 Flex Steelcane



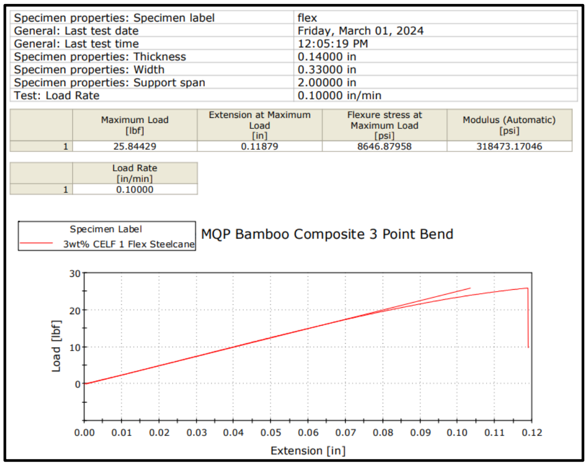
Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:03:12 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	23.11710	0.17662	7713.05094	238155.52876

	Load Rate [in/min]
1	0.10000

QP Bamboo Composite 3 Point Bend

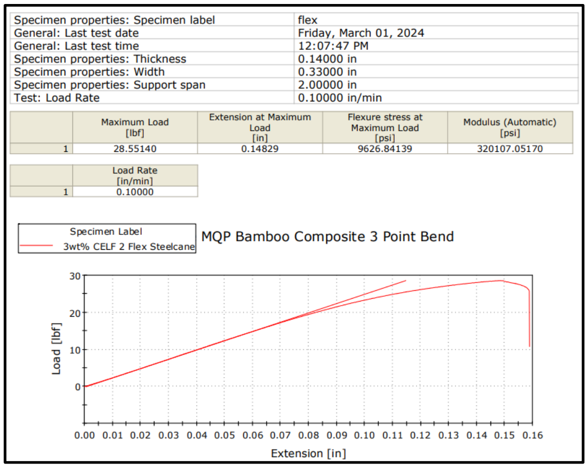
Specimen Label
3wt% Bamboo 3 Flex Steelcane



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:05:19 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	25.84429	0.11879	8646.87958	318473.17046

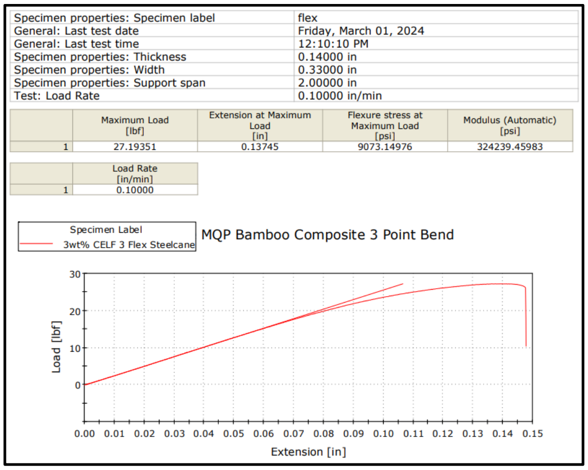
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:07:47 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	28.55140	0.14829	9626.84139	320107.05170

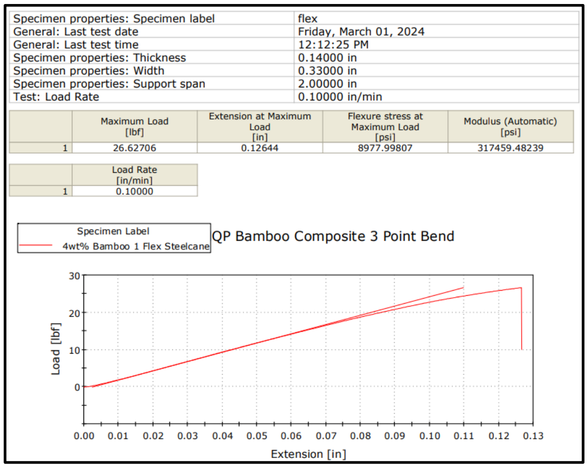
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:10:10 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	27.19351	0.13745	9073.14976	324239.45983

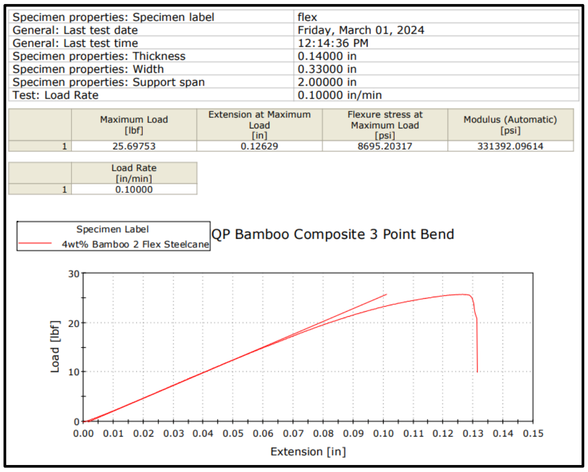
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:12:25 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	26.62706	0.12644	8977.99807	317459.48239

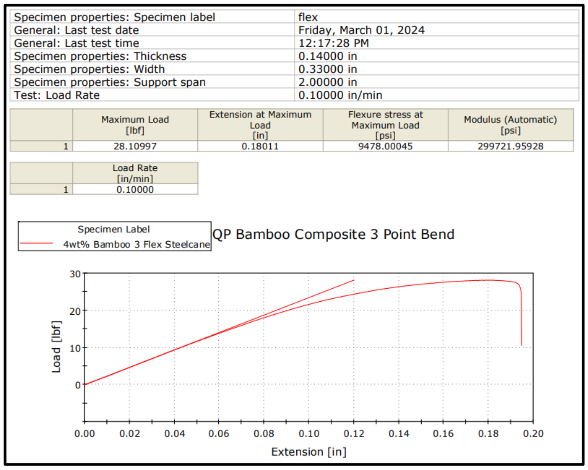
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:14:36 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	25.69753	0.12629	8695.20317	331392.09614

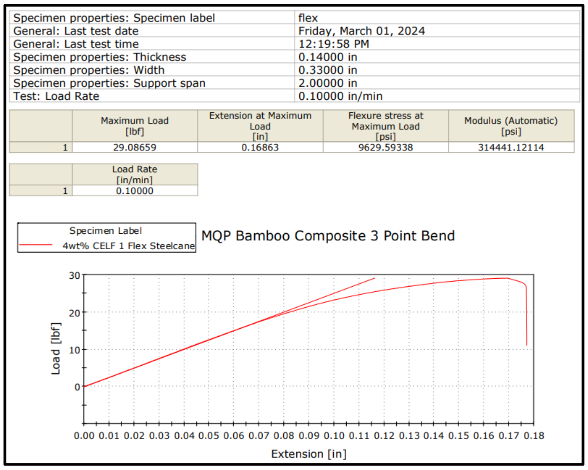
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:17:28 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	28.10997	0.18011	9478.00045	299721.95928

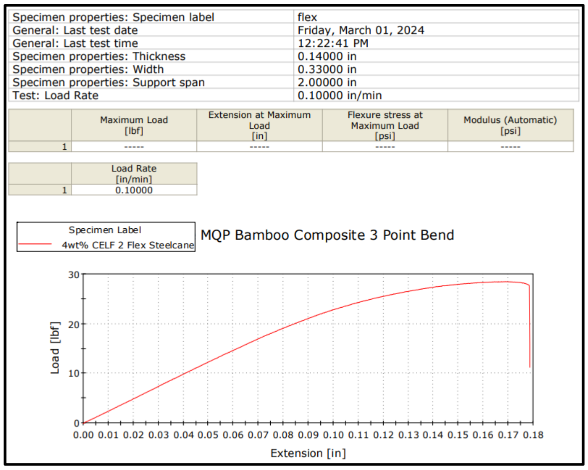
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:19:58 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	29.08659	0.16863	9629.59338	314441.12114

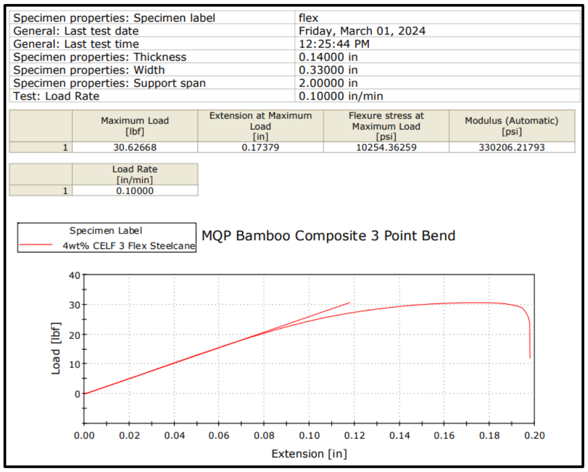
	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:22:41 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	-----	-----	-----	-----

	Load Rate [in/min]
1	0.10000



Specimen properties: Specimen label	flex
General: Last test date	Friday, March 01, 2024
General: Last test time	12:25:44 PM
Specimen properties: Thickness	0.14000 in
Specimen properties: Width	0.33000 in
Specimen properties: Support span	2.00000 in
Test: Load Rate	0.10000 in/min

	Maximum Load [lbf]	Extension at Maximum Load [in]	Flexure stress at Maximum Load [psi]	Modulus (Automatic) [psi]
1	30.62668	0.17379	10254.36259	330206.21793

	Load Rate [in/min]
1	0.10000