Abstract

A bamboo fiber reinforced polymer (BFRP) was modeled and fabricated using a plain weave of bamboo fibers embedded in an epoxy matrix to present a new alternative to carbon fiber reinforced polymers (CFRP). A unit cell model of two sets of parallel fibers weaved perpendicularly in a matrix was used to represent the BFRP. The model was generated using TexGen and imported into ANSYS where a finite element (FE) analysis was performed in the form of a tensile test simulation. Periodic boundary conditions were applied to simplify results. Fabricated BFRP samples were tensile tested and compared to the simulations to verify results. Energy cost of production of BFRP was calculated to be 72 MJ/kg as compared to the energy cost of production of CFRP, being 380-420 MJ/kg. This value is substantially lower and is a main motivation for this project.

Motivation

Lightweight, high strength CFRP and glass-fiber reinforced polymer (GFRP) composites are increasingly used in high performance applications ranging from aerospace to hobby products and sporting goods; however, the production of carbon fibers relies on non-renewable petroleum feedstock and has high energy costs [1]. These ecological issues, combined with the increasing societal concern for designing renewable and eco-friendly products, has led to the consideration of organic bamboo fibers as an alternative to carbon and glass fibers in polymer-fiber composites. Good quality BFRP are a potential eco-friendly alternative for CFPRs or GFRPs and could replace these types of composites in some current applications. Our project aimed to develop a woven BFRP; with a weave we hope to achieve better properties than BFRPs with randomly oriented fibers, in imitation of woven CFRPs.

Materials Science & Engineering Aspects

Processing:

The processing of the bamboo fibers gives rise to many interesting materials science and engineering challenges. Bamboo is an organic material so processes necessary to produce fibers are different from the processes to produce fibers more traditionally used in composites, such as fiberglass or carbon fiber. Fiber separation is a processing step unique to natural fibers like bamboo. Unlike carbon or glass fiber, bamboo fibers do not need to be created but must be separated from the bulk bamboo, a natural composite with both fibers and a lignin matrix [2].

Soaking the bamboo in water or solutions of NaOH can break down lignin and separate pure bamboo fibers [3]. Another soaking step during fiber separation can be used so that dry, brittle splintered bamboo can be pulled apart into fibers without fracturing. These processes all help to later optimize the structure and properties of the materials and full device. Another processing factor must be taken into account because, unlike these fibers, bamboo has a tendency to biodegrade in the presence of water. Our design must bypass this obstacle by ensuring that the weave is properly encapsulated in the matrix to prevent water intrusion. In addition, any large scale fabrication would also need to consider humidity and other ways that water could be introduced into the bamboo during processing to prevent early degradation of the bamboo fibers. Optimizing all of these techniques requires knowledge of the chemical principles at work and their potential effects on the properties of the final product.

Structure:

A weaved structure can give additional displacement resistance to the composite not obtainable in a normal, unweaved fiber structure. However, the strength of the weave will still be dependent on the efficiency of the processing of the bamboo fibers, and if the fibers are high or low quality. Also, a weave structure may exhibit different adhesion properties between the bamboo and matrix than a flat structure. A conformal adhesion of epoxy to the bamboo is ideal, but not always achieved. Complicating the structure through a weave could affect the material properties either beneficially or detrimentally.

Properties:

Composite materials offer combinations of properties that cannot be obtained with a single materials. Typically composites have a matrix material and a reinforcement material. The matrix binds the entire composite together while the reinforcement gives it its strength. Typically, the reinforcement is a strong material that by its nature could not act alone. For example, in mortar, cement, the matrix, is mixed with sand, the reinforcement. Sand alone, though each grain is quite hard and strong, could not bear a load; however, when it is held in place by the cement matrix it can. Similarly fibers - bamboo, carbon, or glass - are simply not suitable to bear many types of loads, except perhaps a purely tensile load if they were formed into a rope. Yet, when bound together within a matrix, fiber composites can bear a variety of loads in many

diverse applications. Composites allow strong or brittle materials of challenging morphologies to be used in a wider range of shapes.

Composites can offer a midpoint in the spectrum of two dissimilar materials' properties. The elastic modulus(Ec) of a composite material can be simply represented by the following equation, a formula derived from the law of mixtures, which assumes uniform distribution of the hardening material in the matrix:

$$Ec = E_f * V_f + E_m * V_m \tag{1}$$

where E_f and E_m represent elastic moduli of the strengthening fiber and matrix respectively, and V_f and V_m represent their respective volume fractions. This gives rise to an important consequence that the stiffness of a composite is proportional to the volume fraction of the strengthening fiber. This equation can be affected by the structure of the weave and degree of undulation. The higher the undulation of the fibers, the higher the volume fraction of fibers. Also, again, the processing of the efficiency of the processing of the bamboo fibers will affect the strength of the fibers and can change the results of equation (1).

4. **Previous Work**

Fiber-based Composites

Composites are two or more materials with different physical or chemical properties – categorized as "matrix" or "reinforcement" – combined in a way that together they comprise a material, yet remain separate and distinct at some level because they don't fully merge or dissolve into one another [4]. One popular form of composites are fiber-reinforced polymer (FRP) composites which combine a polymer matrix with a fiber reinforcement such as glass, carbon or other reinforcing fiber material. The advantage of using a composite material lies in the fact that their constituent materials retain their identities/properties (don't dissolve or merge completely into each other) while acting together to provide a range of new benefits that wouldn't be possible as an individual material. These characteristics can include, but are not limited to having high strength, corrosion resistance, high strength-to-weight ratio and directional strength.

Bamboo Fiber Composites

Increasing prices of raw materials in engineering applications, along with a continuous threat to our environment from processing, has led to the use of natural renewable materials for development and fabrication of polymer composites [5]. There has been extensive research on making composites with synthetic fibers in the past, however utilizing natural fiber reinforcements as a substitution has garnered increasing attention in various applications [3]. Specifically, researchers have extracted fibers from both softwood and hardwood materials for reinforcement in composites [3]. Bamboo fiber composites have served as an area of research as a renewable alternative to petroleum-chemical based materials [6].

We have investigated several areas of research that were related to our design goal, including studies on the fabrication of various bamboo fiber composites and bamboo's mechanical properties. There is previous research involving bamboo treatment methods, bamboo fiber extraction techniques, and carbon fiber weaving patterns that simulate the models that we incorporated; however, no existing studies could be found that weaves the bamboo fibers or optimizes a weaving pattern.

Bamboo Treatment

Bamboo fibers are highly hydrophilic due to their chemical constituents such as lignin which can decrease adhesion with hydrophobic matrix materials [7]. Many researchers have taken chemical-treatment based approaches such as alkalization, graft copolymerization and coupling agents in order to delignify the bamboo [7,8]. However, other designs are based around finding a natural, eco-friendly solution. Kushwaha, Varadarjulu, and Kumar employed a method that modified the bamboo fiber surface through the use of distilled water [9]. This was a clean, environmental-friendly process because no chemicals were involved. The work done by this group involved setting bamboo in distilled water for varying time intervals including 1 month, 3 months, 6 months and boiling for 6 hours. The results found that the bamboo soaked for 3 months provided the best balance between mechanical and water resistance properties. However, even the 1 month water modified bamboo improved the tensile strength of their composite by 36% when compared to untreated surfaces [9]. Results from chemical and non-chemical based treatments provided a flexural strength of about 120-145 MPa [8,9]. Both treatments have the potential to successfully remove the lignin from fibers.

Subsequent to the soaking, the bamboo is put through a drying process in order to reduce the water absorption of the fibers. The interfacial adhesion between the polymer matrix and bamboo fibers can be heavily degraded if levels of water absorption are too high [10]. One group exposed the bamboo to 120°C of heat for three hours in a drying machine before processing the fibers [11].

Fiber Extraction Techniques

Previous research has shown that bamboo fibers have been extracted from culms by a number of innovative techniques. Some of these techniques include steam explosion, roller mill techniques, compression and a sifter machine. While all of these techniques can result in successful fiber extraction, the difference lies in the fiber diameter and length achieved. According to research done by Okubo et. al, voids around the fibers seen in SEM imaging result in a higher risk of surface fracture and poor adhesion between bamboo fibers and the epoxy matrix [11]. Additionally, they concluded that when bamboo fibers are stacked on top of each other, these spaces are more likely to occur. In order to reduce the number of voids in the composite, optimal designs will decrease the diameter of the fibers as much as possible.

The smallest diameter that was discovered involved using a steam explosion method. This is an extraction technique that uses a vessel to violently boil water into steam and thereby breaking up the wood into small pieces and fibers [11]. This method resulted in fibers ranging from 10-30 micrometer in diameter and lignin almost completely removed from the surface of the fibers [11]. While this method may produce desirable fibers, access to this type of equipment is not always readily available or found.

Other fiber extraction techniques involve using compression techniques. These techniques are outlined in the work done by Deshpande et. al. Their research employed both a rolling mill technique (RMT) and compression technique. The RMT resulted in an average fiber diameter of 90 micrometers, and the compression technique resulted in an average fiber diameter of 149 micrometers. The two parameters that need to be optimized in order to obtain quality fibers are compression time and the starting bed thickness. After a series of trials, Deshpande et. al determined that a constant load of 10 tons with a compression time of 10 seconds and bed thickness between 1.25-2 cm resulted in an optimal fiber generation [2].

In addition to the fibers and processing techniques, previous work has been done with other materials and simulations involving a fiber weaving technique. In Ahmed's paper, *AA Weaving*, he develops various algorithmic methods for weaving designs that can be done using simple dobby (4 shaft) looms [12]. These AA patterns and algorithms may provide useful information when running computer simulations of the woven bamboo fibers. Additionally, much research has been conducted on woven carbon fibers. Although the material properties are different, modelling and testing methods may be drawn from this research.

5. **Design goals**

Our goal is to reduce the energy consumption and pollution upon fabricating composite materials through the replacement of synthetic fibers with natural fibers while retaining the performance of CFRPs or GFRPs. Production of carbon fiber requires the burning of high energy fossil fuels that also create considerable amounts of pollution; the primary energy of production of carbon fibers is 380-420 MJ/kg and this production results in 23.9-26.4 kg/kg of CO_2 emissions [13]. With the use of bamboo fibers as a replacement, this high energy intake and pollution production can be circumvented all the while keeping the mechanical integrity of a woven composite. Bamboo has been found to be a strong natural material, having tensile and compressive strengths stronger than several types of wood and close to the strength of steel. Using this material keeps the high mechanical strength while using natural materials. This in turn helps lead the reduction of energy consumption and pollution creation when building woven composites [14].

6. **Technical approach**

In order to complete our design of a bamboo fiber reinforced composite BFRC, we developed a technical approach which consisted of modeling our composite, performing a finite element (FE) analysis and producing a prototype of the product. The model was used to perform a finite element analysis in which we simulated tensile loading conditions. By varying the parameters of the model (i.e. yarn width, yarn height and yarn spacing) and running numerous tensile tests we hoped to determine the contribution of each of the various

parameters on the tensile strength, and Young's modulus. A prototype was produced to be a proof of concept, validate our analysis and as a means for comparison between a carbon fiber composite and our bamboo fiber composite.

Modeling

A top down approach was taken to perform our FE analysis, meaning a general structure was generated and manually prepared for FE analysis afterwards. The geometric structure, was defined using a third party, python based application called TexGen. TexGen is a textile modeling software that allows the easy creation of woven fabrics, including a domain, through a simple graphical user interface (GUI). Afterwards, meshing is performed on the geometry which creates elements and nodes. These elements and nodes correspond to domains and intersections of domains within every component of the model. Although TexGen is very useful for creating the model, the files are not directly compatible with the FE software, ANSYS Mechanical APDL 15.0 (ANSYS). Within ANSYS, the proper interactions between the components of the model needed to be defined. Contact areas, surfaces and volume elements were among the components of the model that were manually defined. This process was done on individual components using the command prompt. The contacts had frictional forces applied to them to characterize the interaction between the fibers and the adhesion of the matrix to the yarns.

It is necessary to define the material properties of each of the model's components to accurately simulate a tensile test. Since we wanted to compare our model with tests done on our prototypes, we want to used experimentally determined mechanical properties of the individual composite components (bamboo and epoxy) as our inputs in order to avoid any deviations that could arise from a difference between the prototype's component properties model's component properties. A script in the command window was developed in ANSYS to define all applicable material properties. These properties included density, coefficient of friction, elastic modulus and shear modulus.

The model that was generated is our foundation of a representative volume element (RVE) that can be iterated in any direction using ANSYS. With this methodology, a BFRP of specified unit dimensions can easily be constructed. A script for ANSYS was developed within the command prompt that could be run to duplicate the RVE in any direction to create a model

of desired size. The script copied every element and node then reconstructed them a specified distance from their originating point . This specific distance was just the n lengths of the unit cell in a. The resulting structure was a model of (m x n x p) RVEs where m,n and p are integers.

After altering the geometric model within ANSYS and defining all material properties, boundary conditions needed to be defined in order to run simulations properly. For the geometric model, we applied rigid constant equations to each of the corner nodes, halfway nodes between the corners and central nodes positioned at the middle faces parallel to the fiber plane of the finite element model (FEM).

$$0 = u \; {}_x^{(1)} + (-1)u \; {}_x^{(5)} \tag{2}$$

$$0 = u \; {}_x^{(2)} + (-1)u \; {}_x^{(4)} \tag{3}$$

These equations specify that the displacements of these nodal points will be equal, so that the regions of the material connected to the same face or edge react equivalently. If these boundary conditions are applied to each corner and face node, the entire model will deform uniformly unless additional constraints are applied to the model. Note that these conditions assume an ideal structure without weak points or defects. In addition, periodic boundary conditions are also implicitly applied with these equations, as the nodal points in question lie on parts of boundaries of the RVE that reside on the faces of the model, and the end edge of one unit cell becomes the beginning edge of the next cell. With these boundary conditions applied at the corner and edge nodes, the geometric model will behave in a realistic manner assuming static conditions and linear uniform displacement.

The next step is to set up a tensile strength test. In a finite element model, the best way to simulate this type of behavior is to apply a constraint to fix one face of the material, and displace the opposite side by a small distance. With the fixed face, the force applied will be equally applied in the opposite direction due to Newton's Third Law, which states when an a force is applied, an equal and opposite force will result. This validates the simulation to be representative of a tensile test. The displacement distance must be small, or else we risk provoking a change to dynamic behavior, and thus achieving unrealistic results.

Prototyped

The first part of our prototype was to design a mold that could be used to shape our composite into a 1 inch wide by 4 inch long by ¼ in thick sample. This geometry was suitable for mechanical tests such as tensile testing. We designed the mold using autodesk then 3D printed multiple molds out of PLA in the EPSL library. Before using the molds a releasing agent was applied to prevent the epoxy from sticking to the mold.

In order to prototype our composite we needed to make a weave from bamboo fibers and incorporate them into epoxy. We started with bamboo which we harvested from a local garden. The dimensions were roughly 2 inches in diameter and 25 feet long. The 25 foot long sections were cut on either sides of the nodes then cut longitudinally splitting the bamboo culm into six sections. Once sectioned and separated, the bamboo was soaked in a 0.1 molar solution of sodium hydroxide to delignifying the bamboo. Our previous research [3] suggested that this is important in order to promote adhesion between the bamboo and epoxy. After the bamboo soaked for 72 hours, it was soaked in water for 3 hours and rinsed several times to remove any remaining sodium hydroxide. After being thoroughly rinsed the bamboo was placed in an oven at 120 C for 2 hours then allowed to air dry for five days. A roller mill was used next to break down the bamboo sections into splintered bamboo. The splinter bamboo facilitated the separation of the bamboo fibers. The splintered bamboo was then soaked in water again to increase the flexibility of the fibers during final separation. Without wetting the splintered bamboo, the fibers were difficult to extract without breaking them. Once the fibers were extracted, they were collected into bundles of eight fibers. The bundles were then mounted into a loom, from which a weave was constructed. A simple plain weave pattern was then used which consists of an alternating over-under pattern. The weave was then inserted into the mold.

After producing the weave the epoxy was mixed. The epoxy is a two part epoxy with a mixing ratio of 3:1. Three parts epoxy resin and 1 part hardener. After thoroughly mixing the epoxy it was placed into a vacuum chamber to extract trapped. After roughly 15 minutes the bubbles were completely removed and the epoxy was poured into the mold filling the cavity to the top. The epoxy was allowed to cure for 24 hours before it was extracted from the mold.

Measured

The tensile strength of our composites (bamboo and carbon fiber) were measured using a universal testing instrument (UTI) and compared with each other and our FE simulations. These tests were performed in order to determine whether the composite is a viable replacement or competitive alternative to current materials on the market. Additionally, we will be able to verify the accuracy of our models by comparing properties such as the elastic modulus to the results of the simulations that were performed.   If the prototype and model are in agreement, we can conclude that our simulations provide acceptable results.

7. **Prototype**

The first step taken towards prototyping the composite was harvesting bamboo culms. The bamboo was harvested from a local garden on the University of Maryland campus. After obtaining the culms they were processed into segments by cutting the culms before each node, and then into strips by hitting the segments with a rubber mallet and allowing the bamboo to fracture naturally. The strips were struck until the desired width of less than 1.5-2.5 cm was achieved in order to ensure the bamboo was semi flat and not curved. Having little to no curvature was necessary for the bamboo to successfully be run through a roller mill. After the strips were obtained, they were soaked for approximately 72 hrs in 0.1 M sodium hydroxide solutions. This solution was chosen based off of research by Desphande et. al who determined that a very strong NaOH solution and a long soaking time will lead to greater lignin dissolution [2]. These authors used a 0.1 M NaOH solution because this concentration achieved maximum delignification results while maintaining the mechanical properties of the bamboo. After soaking, the bamboo was rinsed with water to fully remove the sodium hydroxide, and heated at 120 C^o for two hours until they were dry.

The next step for the prototype involved extracting the fibers using a roller mill. We used Dr. Na's lab from UMD's Aerospace Engineering department to access a roller mill. The gap height between the rollers was set in such away that it was slightly smaller than the thickness of the bamboo. The bamboo segments were run through the roller twice at the same height but the bamboo was flipped for the second run through. The gap height was then made smaller and the strip was run through right side up and upside down for a second time. This was repeated until the gap height was very small and caused the strip to separate into splintered bamboo pieces. The fibers were obtained from these splintered bamboo fibers through peeling the fibers out by hand after they were soaked in water to reduce their brittleness. The fibers were separated by

size so that the smaller fibers would be used for the transverse weaves and the longer ones would be used for the longitudinal weaves. The diameter of the fibers ranged from 170 micrometers to 300 micrometers. The table below shows the average fiber diameter from a sample size of 100 fibers, along with their standard deviation.

Table 1: Dimensions of separated bamboo fibers

Minimum Diameter	170 micrometers
Maximum Diameters	300 micrometers
Average Diameter	213 micrometers
Standard Deviation	21.4 micrometers

The longer fibers were bundled in groups of 8 fibers and fixed to a loom at equally spaced points. The operating principle of this loom involved wrap threading that is moved up and down by a shaft. Each thread of the wrap goes through a heddle on a shaft. The heddles are raised as the shaft is, resulting in the wrap (bamboo) threads being threaded through the heddles. This loom will give us the option of equally distributing on the shafts, depending on our chosen design. The transverse fibers were also bundled in groups of 8 and were woven through the longitudinal fibers to create a plain weave pattern. All of these fibers were again soaked in water before weaving to reduce brittleness and ensure the fibers stayed intact. The dimensions of the final mat was 1in X 4in. A total of 3 bamboo weaves were created to be fabricated into a BFRP composite.

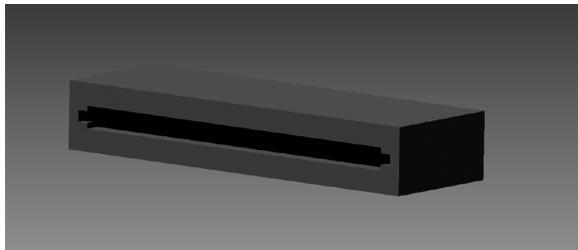*Processing of Mold and Prototype*

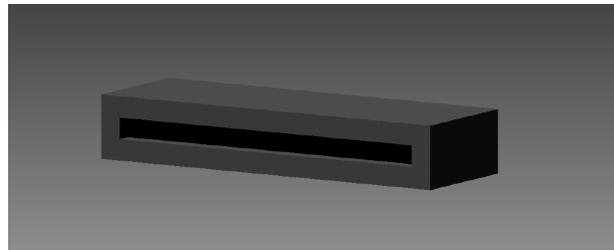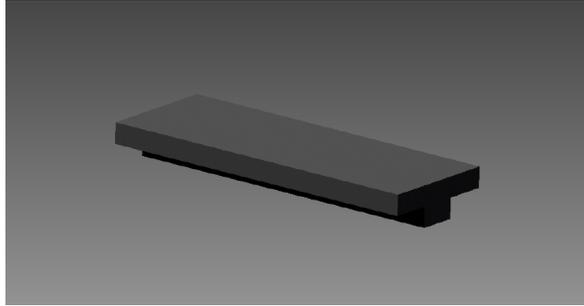Figure 1: Mold 2 Perspective 1(Top)   Figure 2: Mold 2 Perspective 2 (Bottom)

Figure 3: Mold 2 Insert

A CAD created casting mold consisting of two parts, the mold and an insert, was 3D printed. Two different perspective of the mold are shown above (Figures 1 and 2). One side has an extra slit that will be for sliding the sheet of weaved bamboo. The perspective in the top figure (Figure 1) is specifically the top of the mold where the slit can be accessed while the perspective in the bottom figure (Figure 2) has the slits absent. The insert of the mold (Figure 3) will fit into the top and bottom. The top will have the extra space at the bamboo weave slit for any extra air or space to escape from the mold enclosure when pressure is applied.

The mold was lightly covered in a releasing agent wax (TR-104 High Temp Mold Release Wax or PVA #10 Mold release) so that when the epoxy was added, our composite material would not get stuck in the mold. Our bamboo fiber mat was slid into the smaller slit of the mold and mixed a 3:1 ratio of epoxy and epoxy hardener. A syringe was used to insert the epoxy into the mold. Using the syringe allowed for the epoxy to be deposited smoothly and minimized the air bubbles that were caught in the epoxy, as well helped to measure the ratio of epoxy needed. The epoxy was then allowed to set for 24hrs before the composite material was removed from the mold. This same process was followed for three carbon fiber samples, using a purchased carbon fiber sheet. Additionally, we created three samples of just epoxy in order to have a testing comparison and verify the mechanical properties of the epoxy.

8. **Ethics and Environmental Impact**

Our product was designed to be better for the environment than similar products using existing fiber composite technologies, such as CFRPs and GFRPs. Since we are not creating a new product, but rather replacing the materials of an existing product, it is sufficient for us to improve upon the existing material's environmental impact to justify our project environmentally.

We must confirm that our product is indeed better for the environment in some respect and must also admit areas where it is not as green at it could be, such as our choice of epoxy, which makes recycling impossible, or our use of NaOH for fiber separation in the prototype. Although these choices are not ideal from an environmental standpoint, they do not make our product less green than competing fiber composites since these use similar matrix materials, are also not recyclable, and often require chemicals to process. If the production scale energy expenditures for the embodied energy of the matrix, weaving the fibers, producing a prepreg, and molding the composite are assumed to be equal between any fiber composites, then the main difference environmentally would be the embodied energy of the fibers themselves. Thus we conducted an energy assessment for our prototype fibers to determine how much better they are environmentally than competing fibers.

The results of this energy assessment are shown in Table 2. Each major energy contributing step in fiber processing was taken into account: the embodied energy of raw bamboo, the embodied energy of NaOH used in fiber separation, the energy supplied to the oven used for drying soaked bamboo, the energy of driving the roller mill used for fiber separation, and the energy burned by human laborers manually completing the separation. When all steps besides the manual labor are summed, the energy required to produce fibers is only 32 MJ/kg, significantly less than that of either carbon or glass fiber which have embodied energies of 380 - 420 MJ/kg and 68.7 - 75.9 MJ/kg respectively [13]. When the human energy is included, the embodied energy becomes 72 MJ/kg which is comparable with glass fibers, but is still far less than carbon fibers; however, our fibers are still environmentally preferable to glass fibers since the human energy is renewable, fueled by the human's food. Thus, in terms of energy, our prototype fibers are environmentally preferable to carbon or glass fibers since the energy is much less than that of CFRPs and comes from more renewable sources than that of GFRPs.

Table 2: Energy Assessment of production of BFRP

Process	Energy	Amount in Prototype	Calculations	Data Sources
Embodied Energy Bamboo	6 MJ/kg	150 g	From source	CES EDU Pack 2014 Level 3, Bamboo
NaOH	4 MJ/kg	1.5 L	(20.5MJ/kg)*	NaOH embodied

Production Energy		0.5 M solution	(1.5L*.5M)*(40g/mol)= 20.5MJ/kg * 30g = 0.61MJ 0.61MJ/150g	energy= 20.5MJ/kg http://cpmdatabase.cpm.chalmers.se/Scripts/sheet.asp?ActId=ABBCR000115702
Drying Oven	13 MJ/kg	2 hr at 120°C ~0.25 L water to be evaporated (overestimate)	194 W * 2 hr = 1.4MJ Energy to boil 0.25L water = 0.6 MJ 2MJ/150g	Power at 150°C = 194W Model OGS60 http://www.thermoscientific.com/content/dam/tfs/LPG/LED/LED%20Documents/Catalogs%20&%20Brochures/Heating%20Equipment/Heating%20and%20Drying%20Ovens/D21468~.pdf
Roller Mill	9 MJ/kg	~25 bamboo pieces ~ 2.5 min per piece 45% speed	P = IV = 80V * (10 A * .45) = 360W (25*2.5 min) * 360W = 1.35MJ 1.35MJ/150g	V and I Listed on Device Emerson Electric Co. DC Motor International Rolling Mills RI 02860
Manual Human Separation	40 MJ/kg	10 hr labor 150 lb human	.95 Cal/(lb*hr) * 10hr * 150 lb = 6 MJ 6MJ/150g	Energy Expenditure rate = .95 Cal/(lb*hr) (standing) https://www.wolframalpha.com/input/?i=standing
Total	72 MJ/kg			

The energy assessment of the prototype bodes well for the environmental friendliness of a production scale design; we have opted to remove NaOH from our final process, thus eliminating one energy contributor, and plan to automate the bamboo separation process, thus eliminating the energy intensive human labor. An optimized process will likely be able to create bamboo fibers at nearly half the energy cost of glass fibers.

While building our prototype, we had to ensure that we used equipment responsibly in order to maintain ethical standards. We used an International Rolling Mills RI 02860 rolling mill in Dr. Alison Flatau's lab within the Manufacturing building to help separate the bamboo fibers. Before using this device we contacted Dr. Suok-Min Na, who operates the lab, explained our proposed process, received training from him on how to use the device and its safety features, and demonstrated our proposed process on a sample under his supervision. He then approved our plan to use the device to separate the remainder of our fibers. We confirmed that the device was available each time before using it to avoid hindering the work of the lab in any way and cleaned any fiber residue and fragments from the device after each use. Thus we ensured that our use of the device was entirely ethical by taking precautions that ensured the device would not be damaged and by ensuring that we did not cause any hindrance to the work of the lab that generously allowed us to use the device.

If we were to bring this project to a production scale, we would need to contact manufacturers of roller mill or other devices that we would use and determine with them using their device for our purposes would create any safety hazards. We would also need to determine the amount of wear on the devices and an average time to failure so that we could factor the embodied energy of the fiber separation equipment into our energy assessment. In a production scale, we would also need to determine whether our devices result in small fibers becoming airborne and, if so, whether this would pose any chronic or acute health risks to our workers. If we determine that such airborne particles exist, to ensure maximum ethical standards we would require our workers to wear dust masks.

Our proposed application for our material is in snowboards, so a failure could potentially result in injury or even death. Thus, we must to ensure that our product does not pose any greater safety risk to customers than current products before we market it. Low temperature mechanical testing would be necessary to ensure that our selected epoxy does not become brittle at the typical operating temperatures of snowboards. We would also need to test whether the material weakens while wet. One possible failure mode could be that water is absorbed into the fibers, undergoes cyclical freezing and thawing, expands and contracts cyclically, cracks, and then fails catastrophically. To test this mode we would need to soak our material in water, cycle it above and below freezing temperature many times, and then observe it under a microscope to look for cracks. A rigorous mechanical testing regime including these tests, followed by professional tests in use, should ensure the safety of our device for the consumer.

9. **Intellectual Merit**

A great deal of research was necessary for this design to be realized, including investigation of bamboo treatment, fiber processing, optimal weaving patterns and techniques, polymer matrices, additives and post treatment, as well as modeling and simulations of mechanical testing. Many different areas of work were touched upon, expanding our knowledge, especially because a lot of this work was introduced to the group for the first time. Much knowledge was gained throughout the extent of the project, making us better students.

This project helps give not only us, but the scientific community, a better idea of what methods can be used to obtain a bamboo fiber size of one's choice, as well as an idea of what bamboo fiber size will end up exhibiting the best mechanical properties. Many techniques can be used to create a large range of bamboo fiber sizes, but no single bamboo fiber size has been definitively determined as the best for use in structural applications. Bamboo fiber processing was a topic that required further studying, specifically, to obtain optimal fiber diameters. Fiber weaving patterns is another area that required further insight. Although weaving has been performed to make products for millennia, the exact effects of the weaving pattern on the mechanical strength of the weave have been unclear. This parameter allowed for our group to look at a variability in the design that is not completely intrinsic with the material properties, and can open our minds to other types of engineering that can couple with materials science and engineering to make the best possible product. Finally, work with modeling and simulations of weave patterns are scarce. This project is heavily influenced by these computational analysis methods and broadens the range of the small amount of information there is on the subject.

The several necessary pre-steps before fabrication give our group the chance to learn more about pre-processing treatment techniques. Bamboo treatment is necessary in order to achieve proper mechanical strength and adhesion. Additionally, the hydrophilic properties of the bamboo must be treated properly, as this can lead to quick degradation. Various polymers and additives may play an effect of the mechanical strength and durability of the composite. The broad range of possible matrices used creates the need for research of matrix properties and the interaction between matrix and polymer, giving our group another unique topic to learn about.

10. **Broader Impact**

A woven BFRP composite could replace CFRP composites in some applications and thereby could consume part of the market where non eco-friendly products dominate. Since bamboo fiber is less expensive than carbon fiber, BFRPs could offer high strength, high performance composites at a lower cost for expensive products like snowboards and hobbyist activity kits. To environmentally conscious consumers these products may be even more enticing. Furthermore, bamboo is a natural resource in many underdeveloped countries and could be used to supply these types of demographic populations with stronger building materials.

One main inspiration to this project is the use of eco-friendly, easily reproducible materials so that people can use efficient supplies and leave a minimal environmental footprint. Ultimately, our goal is to create a composite or minimally, further an area of research, to provide a commercial use for bamboo based composites and be able to incorporate more eco-friendly materials in applications resulting with better or comparable properties. We hope to not just see this design used in popular markets, but around the world, having people from rich hobbyists to meager village workers being able to use this eco-friendly and cheap material.

11. **Results and discussion**

Simulation Results

A script was developed that would simulate a tensile test on a specific predefined geometry. The boundary conditions explained above in the Technical Approach: Modelling section are employed before the model is subjected to the tensile test. A displacement of ten substeps from 0.25E-04 inches to 0.25E-03 inches with ten substeps of time from 0-1 seconds is applied. Once the tensile test has been run, results can be reviewed over time. Figures 4 and 5 below show the initial and final time of the tensile test. It is evident that a high amount of stress is induced within the bamboo fibers of the BFRP, showing that they do indeed reinforce the epoxy matrix.
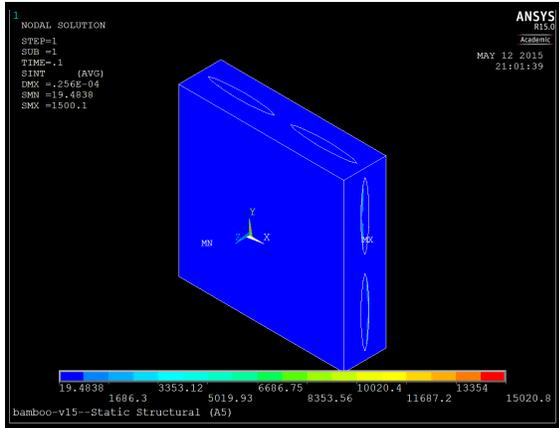
Figure 4: A snapshot of the stress intensity during a tensile test. This picture shows the beginning point of the tensile test
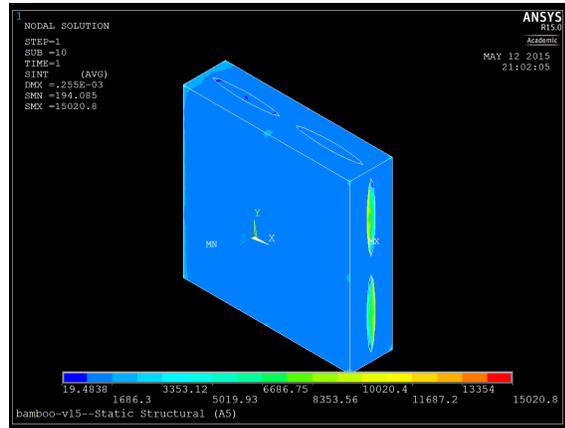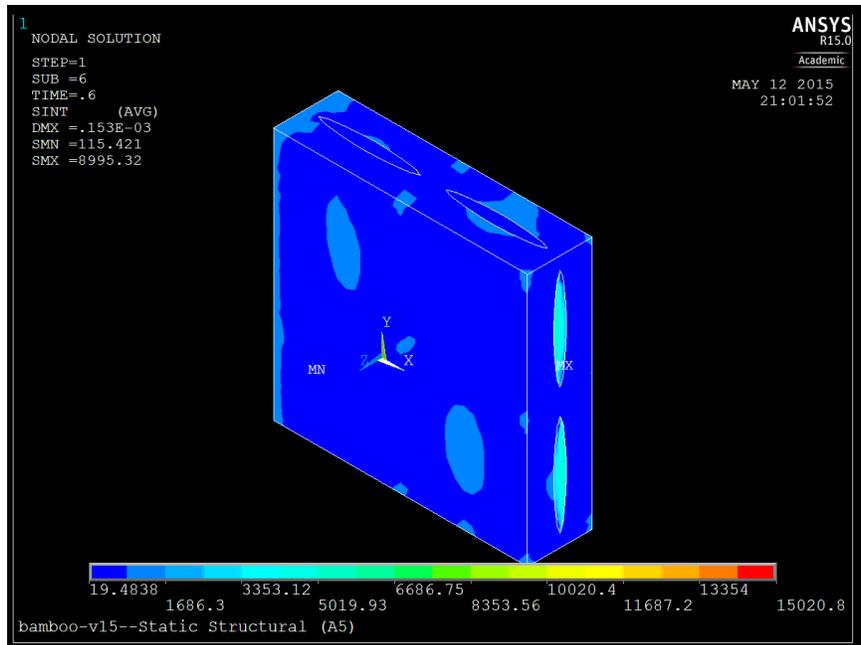

Figure 5: A snapshot of the stress intensity during a tensile test. This picture shows the final point of the tensile test

A middle substep is shown in Figure 6 which shows the unequal distribution of stress. The circles on the face pointing in the 'y' directions are indicative of the transverse fiber running over the longitudinal fibers where stress is localized. It is also important to note how the stress is distributed. The unequal distribution gives evidence that the model is describing the components differently. However, there is some symmetry between the two longitudinal fibers and the matrix on both sides, showing that the fibers are defined as one material and the epoxy as another.

Figure 6: A snapshot of the stress intensity during a tensile test. This picture shows a point in time in the middle of the tensile test

Tensile Test Results

After successfully creating three prototypes of BFRP, CFRP, and plain epoxy, we performed a tensile test. We aimed to determine parameters such as ultimate tensile strength (UTS) and Young's modulus (E) that would be comparable, if not better, to previous research and confirm the results of our finite element analysis simulations. Using the results from the tensile tests, the properties of each material could be input into ANSYS for simulations. Inputting the experimental mechanical properties allows us to directly compare the experimental results with our simulations. However, our data was not valid because of the unsuccessful fabrication of our samples. It was determined that our volume fraction was too low and the fiber was not contained in the epoxy properly.

Ultimately, Snowboards experience only a small amount of force in tension and majority of force in bending [15]. A three-point bend test would reveal the flexural properties of the material. This is essential in order to determine if our composite can withstand the bending forces that snowboards are subjected to. In addition, this would give us a more complete understanding of our materials mechanical behaviors. Although a three-point bend test is an essential part in understanding the mechanical properties of our material, we chose to omit the

three-point bend test from our testing because the volume fraction of our epoxy was too high. Since the stress transitions from compression (on the top face) to tension (on the bottom face) and the weave is centered in the middle, the weave would essentially be in the plane with zero force applied to it. Our composite was 0.25 inches thick with a 0.1 inch thick bamboo fiber weave in the center. The resulting data would be more representative of an epoxy and not a composite. Increasing the volume fraction of the bamboo in our BFRP would need to be completed for the results to be meaningful. The calculation of our fiber volume and the fiber volume fraction of the composite is shown below.

$$V_{fiber} = [(\pi * r^2 * l) * n * y] \tag{4}$$

$$V_{fraction} = V_{fraction} / (L * W * H) \tag{5}$$

where r is the radius of the fiber, l is the length of each fiber i, n is the number of fibers in a yarn, y is the number of yarns and V is the volume. L, W and H are the length, width and height of the composite respectively.

Volume fraction of a typical fiber-based composite is usually around 50-60% [16], while ours was only 4.13%. One assumption we made when calculating the volume fraction was that each fiber was cylindrical and equally sized. The fiber diameter we used was 213 micrometers which was the average of the sample of 100 fibers from Table 1. The low volume fraction of our fibers ultimately diminished the quality of our final samples as seen from the tension test data. When creating future prototypes, we would opt to use a vacuum bag molding technique, which is a refinement of a hand lay-up process. This technique uses a vacuum to eliminate entrapped air and excess resin. The method provides higher reinforcement concentrations, better adhesion between layers, and more control over resin/fiber ratios [1].

The tensile test experiment was performed at the Army Research Laboratory, located in Aberdeen Proving Grounds, MD. A unique technology known as Digital Image Correlation (DIC) was used to perform the tensile test. DIC tracks the position of the same physical points shown in a reference image and a deformed image [17]. The images are then processed using a program that applies an image correlation algorithm. These points were applied to each of our samples by first applying a white primer to the sample, followed by a speckle of black spray paint. The prime and specked samples are shown below in Figure 7.
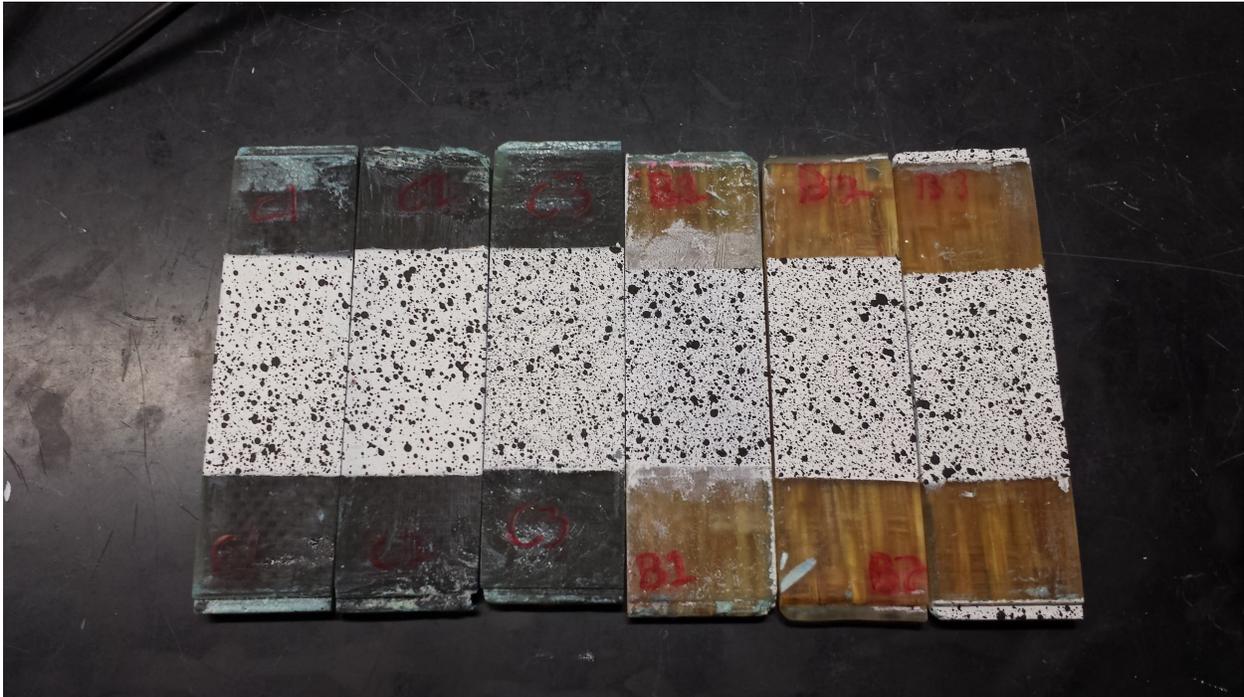
Figure 7: Samples with primer and black speckles prior to tensile test

The tensile test was performed on an Instron - Model 1123 machine and the digital images were captured using a Point Grey GS3U3-23S6M-C camera that captures images at a framerate of 1 million frames per second. A load cell of 25 kN and pull rate of 2 mm/min were applied for all samples. The experimental set up of the tensile test is shown in Figure 8 below.
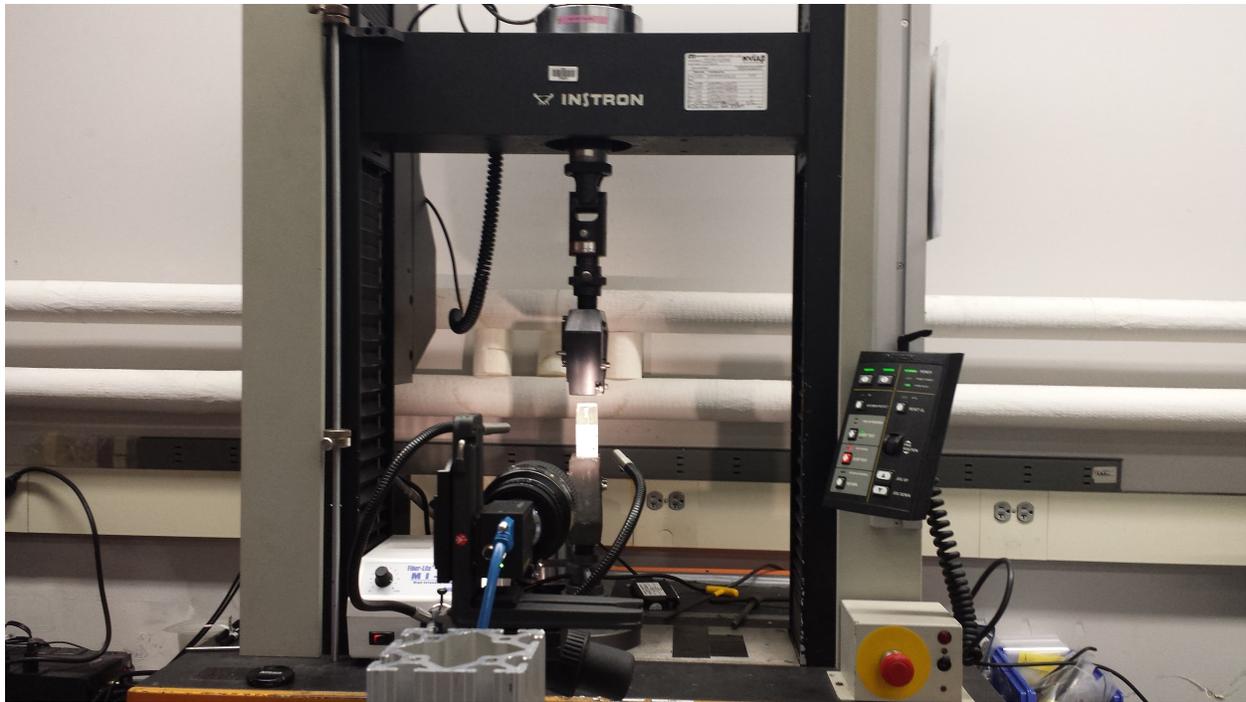
Figure 8: Experimental setup of the tensile test with camera in place

Results from the tensile test indicate that our sample production was unsuccessful. Of the 9 samples, we only achieved proper results for one of each type: bamboo fiber, carbon fiber and epoxy. The other samples experienced a variety of issues that were the result of poor fabrication methods (fiber-epoxy ratio). All but one of each of the carbon fiber and epoxy samples broke at the grip, which is indicative of voids and air bubbles within the sample. This tells us that our vacuum and mold technique was not successful. The bamboo fiber reinforced composite did not perform as expected, either. One sample broke at the grips of the Instron machine, and another fractured along the side of the sample as shown below in Figure 9. The fracture along the samples side is most likely a result of poor adhesion between the bamboo fibers and epoxy. As mentioned previously, future fabrication would apply a vacuum-bagging, layer-up approach to increase this adhesion along with the ratio of fibers to epoxy.
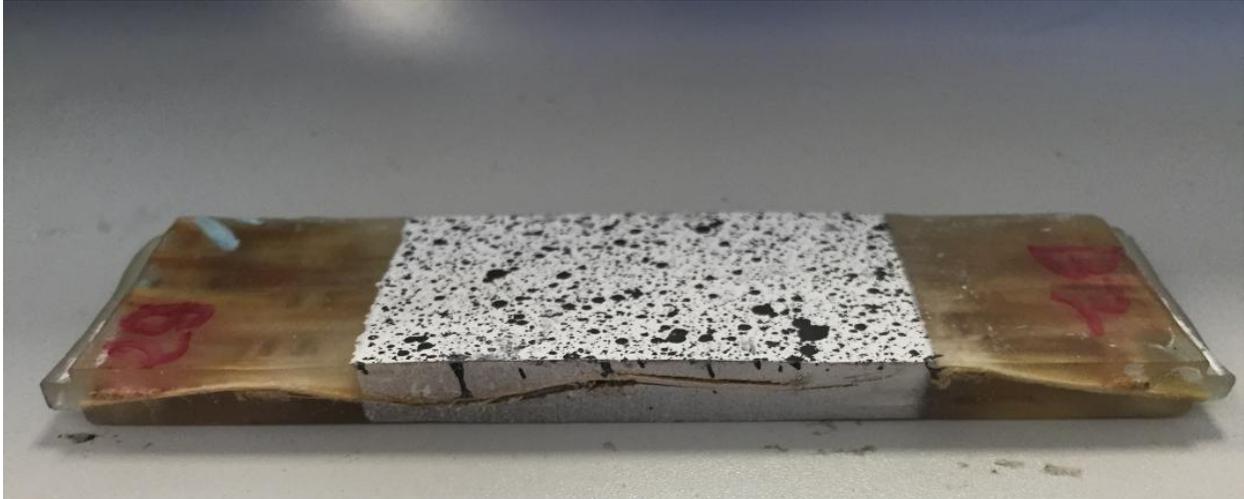
Figure 9: BFRP sample that fractured along its side due to poor fiber/epoxy adhesion

Although most of our samples failed, we were able to perform a proper tensile test from one of each sample. Stress-strain curves were generated from these samples and are shown below in Figure 10.
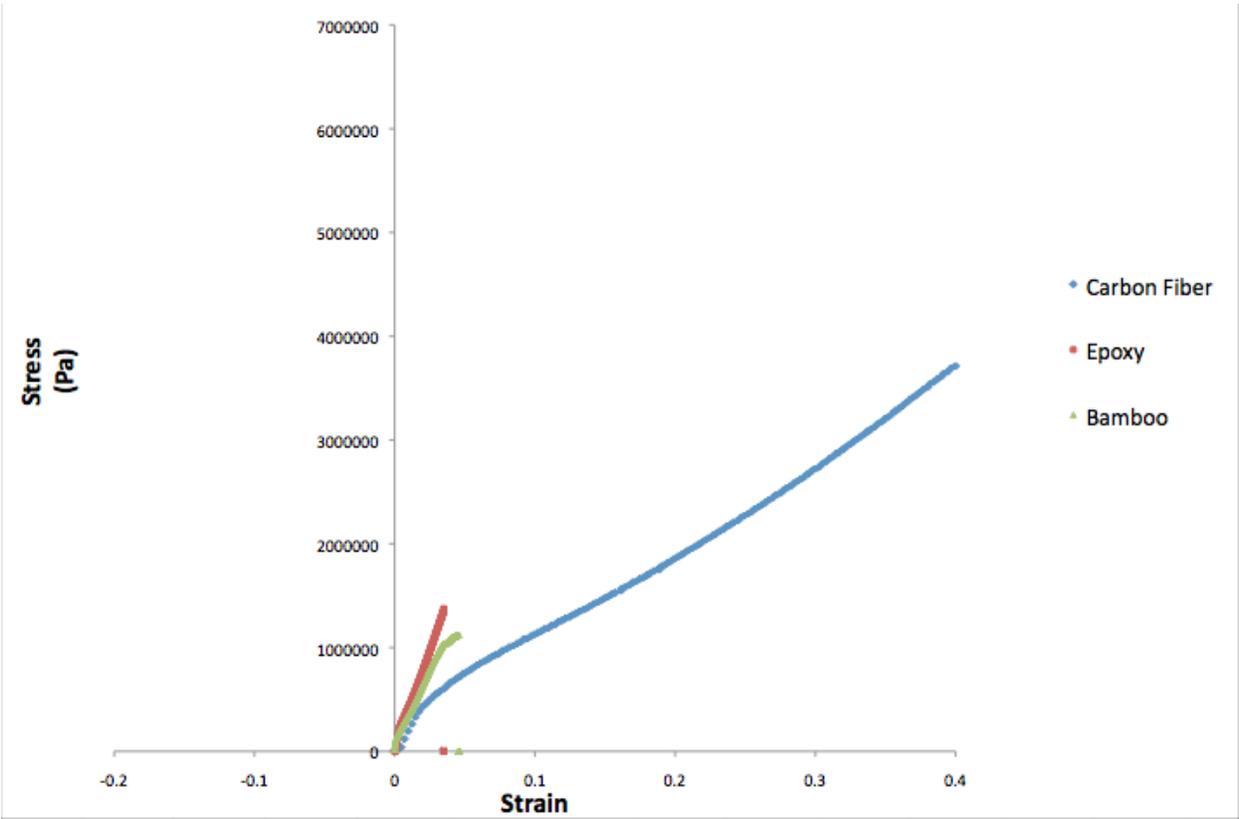

Figure 10: Stress-Strain curves for the 3 non-failing samples

The CFRP composite clearly demonstrated the highest tensile strength. The bamboo-fiber reinforced polymer composite did not perform as expected. It's ultimate tensile strength (1.123 MPa) was lower than that of the plain epoxy sample itself. Although the maximum stress of the bamboo composite was less than that of the epoxy, the stress that was induced within the BFRP was less than the stress induced within the epoxy when the same strain was applied. This gives evidence of the shared properties of each material in the composite, and that BFRP has the potential to be a cheaper, more eco-friendly alternative to CFRP.

12. **Conclusions**

In conclusion, our project fell short of our initial goals to optimize the weave parameters to produce the strongest possible BFRP. We were able to create a model of a RVE, mesh it with user defined elements and define the interactions between components of our material. We were also able to iterate our RVE in all directions to make a full representation of a composite. In addition, we were able to apply a tensile load to the model and determine the maximum and minimum stresses in the material. If we had more time we would define a failure criteria to the model and run multiple tests that vary parameters of the model to determine the contribution of each parameter to the material properties. Furthermore we would perform the same analysis but for a three-point configuration.

In terms of prototyping, we were able to successfully produce, treat and weave the bamboo fibers. However, our technique for creating the composite materials (bamboo and carbon fiber) was flawed because we did not properly account for the volume fraction of fibers to epoxy. This was a contributing factor to the failure when performing a tensile test. Additionally, we were not able to do a three-point bend test because the volume of epoxy was much too high. In the future, we would use a vacuum bag approach that incorporates a "bottom-up" method. This would ensure that the adhesion between the fibers and epoxy was strong, in addition to having a more accurate volume fraction of fibers. Most of the samples failed due to the aforementioned flaws in the prototyping process. The carbon fiber and bamboo fiber composites that failed showed tensile strengths much less than previous literature results. Again, this is attributed to our fabrication methods. If we had more time for the prototyping, we would have made the BFRP with the bottom-up approach and also done a three-point bend test to more accurately test our bamboo snowboard application.

The environmental results met the expectations of our goals. Energy cost of production of BFRP was calculated to be 72 MJ/kg as compared to the energy cost of production of CFRP,

being 380-420 MJ/kg. This value is substantially lower and was a main motivation for this project.

13. **Acknowledgements**

14. **References**

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