MATERIALS CHARACTERIZATION OF BAMBOO AND ANALYSIS OF BONDING STRENGTH AND INTERNAL STRENGTH AS A STRUCTURAL MEMBER IN REINFORCED CONCRETE

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Abstract

This study evaluates the potential to utilize bamboo as reinforcement in concrete structural members. In this project, the mechanical properties of bamboo were tested, specifically force required to embed a 0.5" diameter ball 0.016" into the bamboo samples and its bonding strength with concrete.One type of bamboo, Bambusa Oldhamii, was cut into eight sections, approximately 2.54 cm wide, along the length of the culm. The compression test recorded the bamboo's strength at eight points along the length of the internode and at three points along the transverse direction of each specimen.Bambusa Oldhamii's specimen base 1 data for inner, middle, and outer points were 253.58 N, 531.54 N, and 1032.5 N respectively. The fiber density also increases towards the outer diameter which shows a direct correlation between the two. The values of bamboo vary over a range of 758.65 N unlike wood which varies minimally.For the bonding strength test procedure, fifteen bamboo samples were prepared by cutting the bamboo culm into strips of 0.609 m long by 1.9 cm wide and 1.27 cm thick. The strips were embedded into the concrete cylinder 15.24 cm deep. The concrete samples cured for a period of two weeks and the concrete's resulting strength was 4520.37 psi. Two coatings, asphalt emulsion and polydimethylsiloxane (PDMS), were applied to the bamboo sample ends and were tested along with the control samples, which contained no coatings. The test results indicated that the bonding strength between the bamboo and concrete with the asphalt emulsion coating was the greatest at339.27psi. The next strongest was the control sample at 319.07psi, then PDMS resulting in 154.20psi.

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1.0 Introduction

1.1 Broader Impacts

Bamboo is a valuable resource for many people. Its huge variety in species and ability to grow in multiple parts around the world provide easy accessibility. Bamboo is an aesthetically pleasing material and inexpensive to grow which makes it an affordable material. The bamboo grass plays a major role for living organisms. The bamboo forest is a habitat for many animals and for some is the only source of food. As for humans, one million people live in bamboo houses and for many it is the primary source of income. Since there are so many people utilizing bamboo as their housing structures, it creates a huge market in the construction industry. Due to bamboo being inexpensive, bamboo houses can be built for people in different parts of the world. With the successful construction of the many bamboo houses, companies and researchers can look into using bamboo in more sophisticated types of construction, for example using bamboo reinforced concrete. Furthermore, bamboo has the potential to inspire innovation of construction using new materials that can be less harmful for the environment.

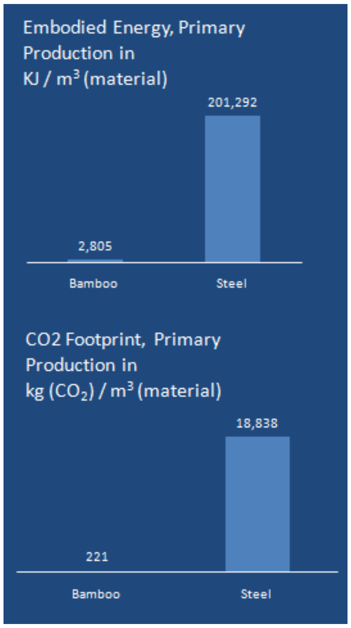

Figure 1: The top graph shows the values of embodied energy for bamboo and steel. The bottom graph shows the amount of CO_2 produced for both materials.

Bamboo is a great renewable resource and can grow very rapidly with minimal help. When substituting bamboo for steel, it could save a lot of money and energy that goes into manufacturing, shipping, installation, and the disposal of steel for construction. Figure 1 compares the amount of energy that is used during the primary production for the same unit volume of both bamboo and steel. In addition, steel has about 85 times more carbon impact of the environment than bamboo during its primary production. The bottom diagram in Figure 1Figure 1compares steel and bamboo's carbon footprint in kg of carbon dioxide per same unit volume of material. Another benefit that bamboo has is its ability to sequester up to 12 tons of CO_2per hectare. Just by growing bamboo without removalfrom the land, it helps fight the reduction of CO_2 in the atmosphere [1]. Also, compared to other equivalent areas where

trees are grown, it releases 35% more oxygen [1].

Unfortunately, bamboo is in danger because the increase in human civilization is the major cause for the reduction of the bamboo forests. Bamboo is a tough grass and with the increasing awareness of the many advantages, bamboo will continue to be an essential resource.

1.2 Background

This study focuses on the chemical and physical structure of bamboo, concrete, and different types of coatings. In addition to understand the properties of bamboo, growth factors were investigated to determine what influencesthe mechanical properties of bamboo.

Bamboo is a natural composite that is classified as an arborescent grass. In more specific terms, it is a group of woody perennial evergreen plants in the grass family of Poaceae, in the sub family *Bambusoideae* [2]. There are over 1200 documented species of bamboo. Bamboo can be found in many countries across the globe that is grown closer to the equator as shown in Figure 2.

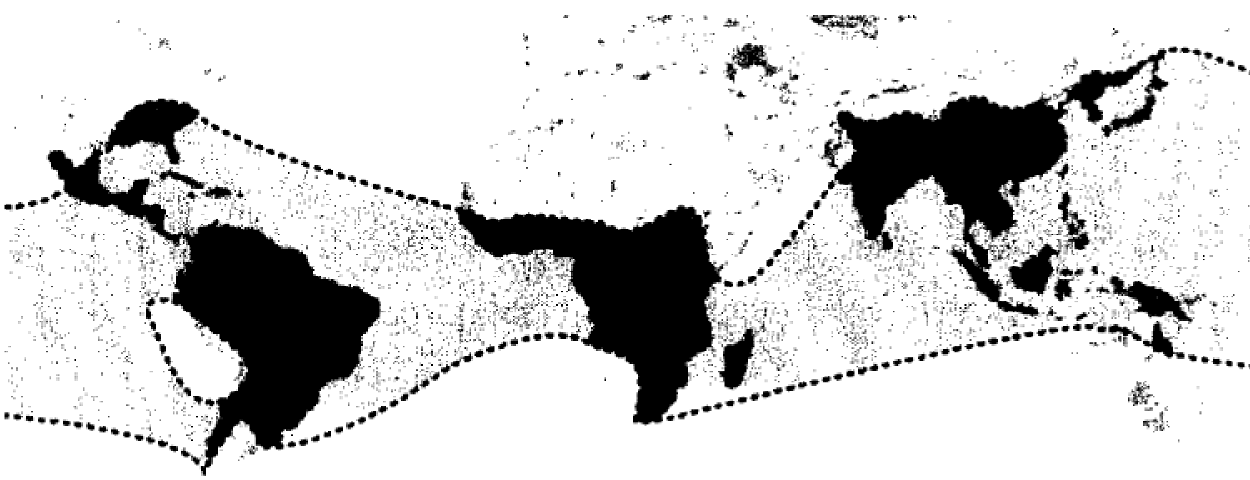

Figure 2: Bamboo tends to grow across the globe in between the 46N and 47S latitude lines.

1.2.1 Chemical Structure of Bamboo

The chemical structure of bamboo is the same as the chemical structure of wood. They are composed of cellulose, hemicellulose, lignin, and water. Cellulose, [($C_6H_{10}O_5$)n] is a polysaccharide that consists only of repeating glucose monosaccharides. The glucose units are linked together by strong hydrogen bonds, classified as β-1,4 [3], which establish cellulose as a strong crystalline structure. This organic compound is the structural component in the cell walls. Cellulose is resistant to hydrolysis, which is the breaking up of bonds by H_2O. Cellulose aggregates which form the microfibrils that makes up the reinforced fibers in the matrix.

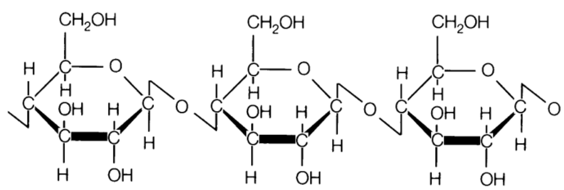

Figure 3: A molecular diagram of three glucose monosaccharides which make up cellulose.

The next component is hemicellulose which is similar to cellulose but contains a variety of different types of monosaccharides.Some of these monosaccharides include xylose, mannose, galactose, and rhamnose.Since the type of monosaccharide varies throughout the structure, the type of bonds between them varies also. Therefore, hemicellulose is a random amorphous structure with little strength. It forms hydrogen bonds with cellulose which helps bind cellulose into the microfibrils. Hemicellulose also is covalently bonded to the next component in the chemical structure, lignin.

Lignin is a complex natural polymer and is the agent that sequesters C out of the atmosphere. Lignin is hard to breakdown and therefore supplies strength and rigidity to the cell walls.This can be seen in Figure 4 Figure 4which is a schematic of the molecular structure of lignin. Due to the nature of lignin, it provides bamboo with its compressive strength.

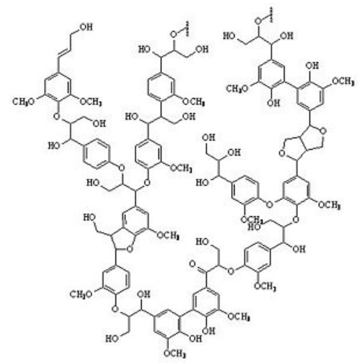

Figure 4: Molecular diagram of lignin which is a natural complex polymer.

The last component is water. Along with wood, bamboo also has a specific moisture content that is in equilibrium with its surrounding environment.

1.2.2 Physical Structure of Bamboo

Bamboo is commonly compared to wood products due to its similar chemical structure. The physical structure is the aspect that differentiates bamboo from wood. Wood has anisotropic properties and contains grains oriented in the same direction throughout the whole structure. However bamboo has fibers and grains oriented in multiple directions, decreasing its anisotropy throughout the whole culm.Figure 5 helps illustrate the difference in its morphology. On the exterior edge of each node, branches form creating different types of grass looking leaf structures. Bamboo contains parallel fibers that are reinforced along the axial direction of the culm. At the node sections however, fibers are reinforced along the transverse direction towards the inner diameter of culm. These transverse fibers are aligned parallel with each other to a certain degree in a circular shape similar to observing rings at the base of a tree, as demonstrated in Figure 6. Since these node sections contain material that connects the bamboo walls together, bamboo is not a completely hollow material. However, the internode sections of the bamboo are hollow in majority of the species. Another major point to identify is the fact that the length of the internode sections increase as the bamboo grows. Also, the thickness of the culm walls decrease towards the topside section of the bamboo.

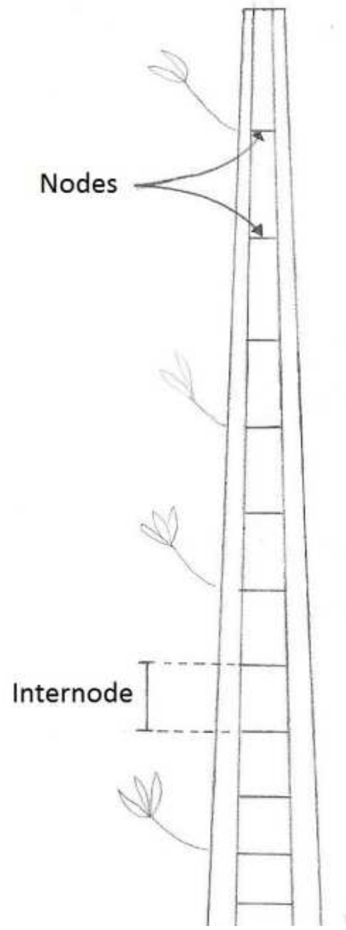

Figure 5: This diagram shows relationship of internodes along the length of the culm.

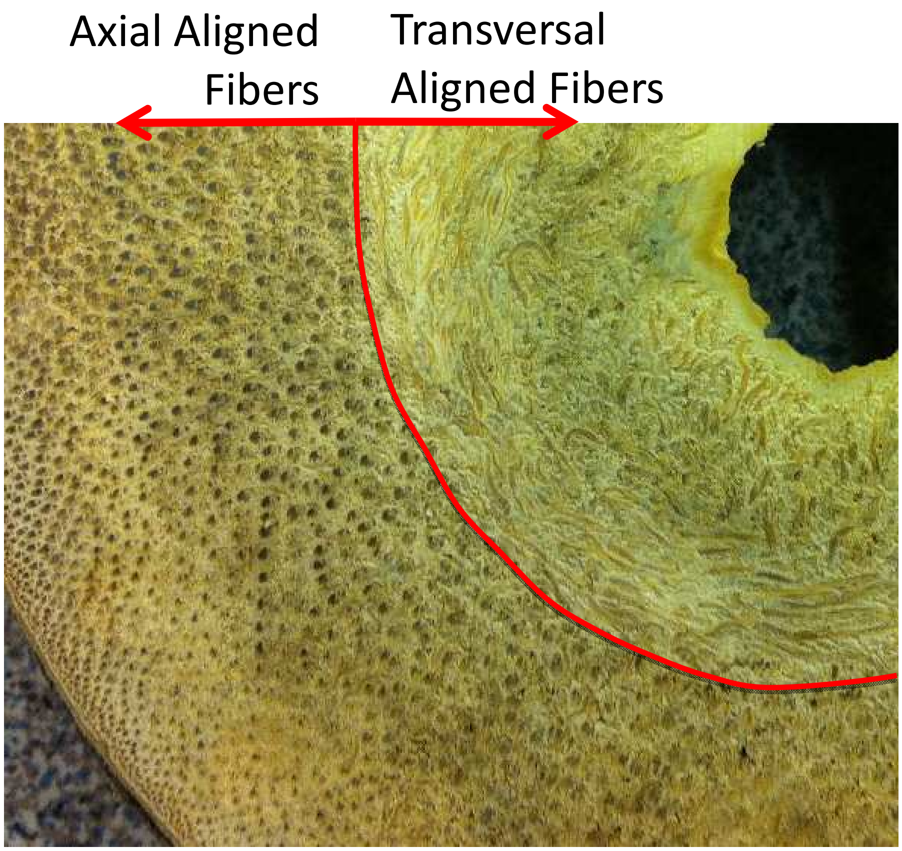

Figure 6: Cross section image of a node section test specimen displaying axial and transverse aligned fibers.

As seen in the picture, the axial aligned fiber density increases towards the outer edge of the diameter. This is universal throughout the whole bamboo culm. Therefore, the ratio of fiber density to its surrounding matrix will also increase. In literature, it is stated that the internal strength increases with increasing diameter. The conclusion to draw from this is that internal strength and fiber density are dependent of each other. The optimal strength related to these parameters would result from a compromise between having a thicker culm wall and having a relatively smaller overall diameter. The thicker the culms walls are, the greater amount of fibers will grow into the space. The smaller the overall diameter, the greater the ratio of fiber density to its surrounding matrix will be. In literature, it is noted that the mechanical properties of the bamboo towards the top section of the culm are superior to its properties near the base. The lengths of fibers vary significantly throughout bamboo. Generally, the longest fibers are located in the middle of the internode and the shortest fibers are located near the node sections [4].

One way to understand how the chemical and physical structures relate is to analyze the vascular bundle component in the bamboo.Figure 7 is a close up view of a vascular bundle which shows the arrangements of the fiber bundles and its adjacent features.

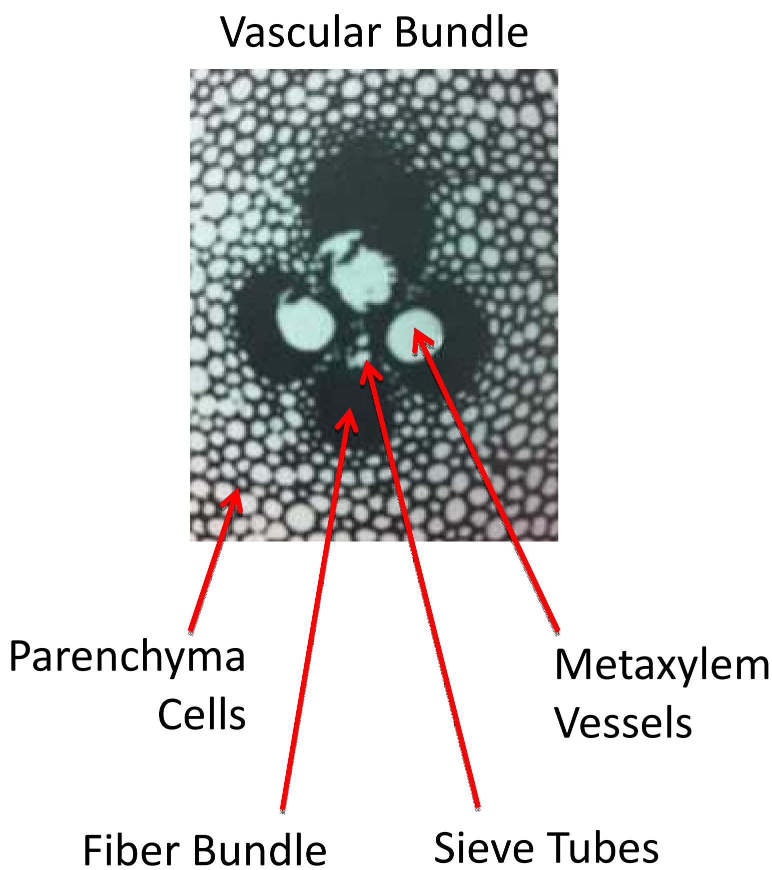

Figure 7: Close up image up a vascular bundle and all its essential components [4].

As mentioned in section 1.2.1, the cell walls structural support consists of cellulose and lignin. Each individual cell contributes to making cell tissues which are aligned to form microfibrils. These fibers are bound together and are represented as the black space in Figure 7.The Metaxylem vessels are elongated cells that transfer water and minerals throughout the bamboo culm and usually mature after the surrounding cells and tissues form. Sieve tubes are elements that transfer sugars and nutrients up and down the culm. The parenchyma cells that surround the vascular bundle are the agents that absorb and release water from and to the environment.

Parenchyma cells are simple tissues, composed of only one cell type, that are comprised of soft tissues (i.e. pith, cortex) [5].

1.2.3 Growth Factors that Influence Bamboo Properties

Since structure has a major impact on properties and performance, it is important to understand how the physical and chemical structures of bamboo can be influenced during its growth period. Multiple growth factors can affect, for example, whether species of bamboo will result in thicker culm walls, greater fiber density, amount of nutrients the cell tissues can receive to grow larger.

1.2.3.1 Climate Factor

Climate has a big impact on the development of bamboo with regards to moisture content. Bamboo, just as in any other plant, exchanges moisture with its surrounding environment until it reaches equilibrium. Absorbing and releasing moisture causes expansion and contraction of the parenchyma cells. This will theoretically affect the internal strength of the bamboo because it is a variable in the ratio of fiber density to parenchyma cells (the surrounding matrix). In literature, it is recorded that the moisture content generally increases towards the inner diameter along the transverse direction. Along the axial direction, the nodes have higher moisture content than the middle of the internode which theoretically has the least. It is also documented that the moisture content also increases towards the base of the whole bamboo culm.

1.2.3.2 Topography Factor

Different types of topographical contours can affect the mechanical properties of bamboo. The best way to demonstrate this effect is by comparing bamboo grown in different types of settings, one grown on level ground, and the other grown on a hillside.

1.2.3.3 Soil Factor

Bamboo is versatile and can grow in multiple types of soil. However, the amounts of Nitrogen (N), Potassium (K), and Phosphorous (P) affect the growth of bamboo on a minor scale.

1.2.3.4 Altitude Factor

When considering the altitude affects, the sequestering of CO_2 and the release of oxygen is the main concern. Generally, the more CO_2 absorbed from the environment, the greater the bamboo yield will be. Therefore, it is no surprise that bamboo can yield a larger volume at sea level than species being grown at a high altitude.

1.2.3.5 Culm Age Factor

Properties of bamboo are dependent upon the maturity level of the culm. As a general rule, the culm should have grown for a minimum of three years in order to achieve quality mechanical properties. If the bamboo has reached a mature stage, the cells and tissues in the culm have not fully developed and its mechanical properties will be inferior.

1.2.3.6 Post Harvest Treatment

Bamboo can be treated immediately after being harvested. Depending on the application of the bamboo, coatings can be applied; the septum (which helps make the bamboo swell and contract) can be removed to solidify its properties, the type of environment the bamboo will dry in, whether it is air dried or kiln dried, can all affect its properties.

1.3 Design Constraints

1.3.1 JankaHardness Test Standard

The compression test performed on the bamboo was modified after the JankaHardness Test Standard. This standard is commonly used to compare the hardness and durability of wood products used for variety of applications, mainly flooring panels. The standard compares the variety of materials be measuring the forced required to embed a 0.444 inch diameter steel ball indenter to a depth of half its diameter. Therefore, the only parameter that is varying in this test is the innate material property which differs between materials. The force is dependent only upon this variable. The Janka hardness values have units of pounds-force (lbf). The idea behind a large diameter indent into the material is to average out any inconsistencies that could occur on the surface.

The compression test performed in this project does not follow the Janka Hardness Test Standard exactly. Therefore, data values from the test could not be compared with values recorded under the standard.

1.3.1.1 Steel Ball Indenter Size

Due to the feasibility of this project, a ½ inch diameter steel ball indenter was obtained through the Materials Engineering department. Using a larger diameter indenter was favorable for the outcome of this project because it could average out more inconsistencies on the surface of the test samples due to its larger surface area.

1.3.1.2 Indenter Embedded Distance

The thickness of the culm walls from the bamboo test samples obtained were approximately the same size as the ½ inch steel ball diameter. This prevented the compression test to be performed at different radial distances for each specimen. The original goal of this project is to be able to test the internal strength across the transverse

direction of the bamboo culm. Therefore, the steel ball indenter had to be embedded to a smaller depth. This resulted in a smaller surface area indent which enabled to the modified compression test to be performed at multiple radial distances.

1.4 Pull Out Test Introduction

As you can see from the introduction sections, bamboo is a fascinating material. It has many unique properties that make it strong and suitable to be used as a construction material. In many countries around the world, concrete is used as a foundation for most buildings, in which the most common reinforcement material is steel [6, 7]. Steel requires great amount of energy to produce and is expensive. In many developing countries, due to their limited resources, steel is not affordable. Bamboo however, is less expensive and more viable to maintain.

In literature, it is known that bamboo swells up as it absorbs water (Figure 8) [5, 8]. In bamboo reinforced concrete, this swell up might cause voids and loss of adhesion between the surface of bamboo and the concrete as the bamboo shrinks and dries, which could lead to failure in the concrete structure. One way to counter this problem is to coat the bamboo with a water repellant coating.

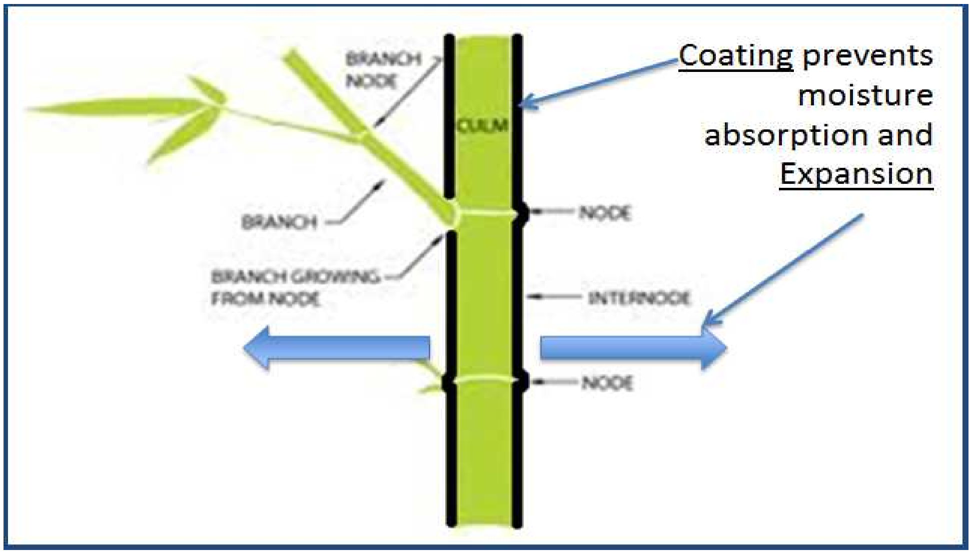

Figure 8: Bamboo swells up and expands once it absorbs water or moisture from the surrounding environment. A coating will provide a barrier against the water absorption and prevent the swelling.

In every concrete reinforcement project, which introduces a new material for rebar, requires knowledge of how strong the bonding strength and adhesiveness between the rebar and the concrete. In order for the correct calculations of forces required to withstand tension or compression that the concrete members might experience throughout its use may be determined and the stability of the building could be standardized. The pull out test is one of the standardized testing procedures for determining the bonding strength between concrete and the rebar [9, 10, 11]. Therefore, we make use of this test to determine the bonding strength of the bamboo rebar using different types of coating.

1.5 Design of Experiment for the Pull Out Test

Three experimental factors that might alter the pull out strength for the bamboo rebar were being considered: 1) Types of Bamboo, 2) Types of Coating, and 3) The bamboo with the node and without the node.

Factor 1: Type of bamboo - we selected two different bamboo species, Dendrocalamus Asper and Bambusa Oldhamii (Figure 9), which grew in a similar environment and were around 3 years of age.

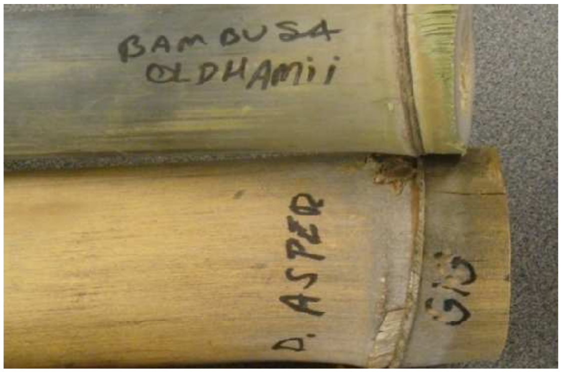

Figure 9: Two different bamboo species, Dendrocalamus Asper and Bambusa Oldhamii, were selected for the pull out test due to their availability.

Factor 2: Type of coating - we selected the traditional asphalt emulsion coating and the experimental polydimethylsiloxane (PDMS) polymer as the coatings for our experiment. As you can see from the structure of PDMS (Figure 10), there are the CH_3methyl groups surrounding its structure. These arehydrophobic which prevent polar molecules such as water from permeating to the surface of the bamboo therefore producing swelling. And more importantly, PDMS is more sustainable than the traditional asphalt emulsion coating. Control samples with no coating were also made for comparison (Figure 10).

Figure 10: Three levels were considered for the types of coating in the experiment; Control Samples (left), Asphalt Emulsion Coating (middle), Polydimethylsiloxane (right).

Factor 3: The bamboo with the node and the bamboo without the node were also considered for the pull out test (Figure 11). According to some literature, by using the bamboo rebar with the nodes, the nodes create friction and bearing stress against the concrete which increases the pull out strength.

Figure 11: The picture on the left is bamboo without the node and the picture on the right is bamboo with the node.

2.0 Experimental Procedure

2.1 Bamboo Sample Preparation for Compression Testing

Preparing bamboo samples was a two step process. First, the samples were cut using a Miter saw and then sanded down and polished to provide a flat surface. Each specimen was labeled with a sharpie marker to keep track of the type of bamboo and the order of specimens had to be along the axial direction.

2.1.1 Cutting Bamboo Samples

The bamboo samples we obtained varied in length from four internode sections to 10 internode sections. The size of the desired test samples were one internode length. Each sample was cut along the axial direction into eight specimens approximately one inch each in height. After each specimen was cut, they were labeled with numbers to keep track of their location along the length of the internode.

Figure 12: The bamboo culm was cut into sections along the internode forming the array of test specimens.

2.1.2 Fabricating Level Bamboo Samples

The cut bamboo specimens were sanded down using a sanding belt from an automatic machine. This was performed because the specimens that were cut from using the miter saw were not completely level. Sanding the specimens also allowed for a smoother testing surface which would average out rough inconsistencies across the face of the bamboo.

2.2 Compression Test Procedure

2.2.1 Compression Test Apparatus Set Up

The Instron machine was used for compression testing bamboo. The top and bottom tensile testing grips were removed and a flat steel plate, approximately 6” x 6” was set on the bottom support. For the top support, a 5” x 2” fabricated steel plate, containing four holes at the corners and a hole in the center for the steel ball indenter, was used to allow for a successful compression test. This set up is shown in Figure 13.

Figure 13: Sample modified compression test set up.

The top support had holes in its fixture to allow the upper tensile testing clamp to attach. Polypropylene string was tied throughout the holes in the upper support and the four holes on the corners of the fabricated steel plate. The steel ball indenter was inserted in the hole in the center of the fabricated steel plate and utilized duck tape to prevent from vertically falling out.

2.2.2 Running the Compression Test

Each bamboo specimen was placed on the 6” x 6” steel plate at the bottom support. The steel ball indenter was lowered to approximately 1/8 inch above the bamboo specimen. For each test run, the bamboo specimen was visually adjusted to the desired location and the start button on the software program was clicked. During the testing period, data was outputted on a graph displaying the load (N) on the y-axis and the compression displacement (mm) on the x-axis. The test was stopped once the graph displayed measured results that were greater than ½ mm from the first data point recorded. This test was run five times at two different radial distances, labeled outer point and middle point. Since two of the test specimens were not hollow and contained the node section, the test was run at a third radial distance, labeled the inner point. Figure 14 shows a test specimen after the compression test was performed.

Figure 12: A single test specimen that had the compression test performed at two radial distances, outer point and middle point.

2.3 Formatting Compression Test Results

The data generated by the compression test was recorded in a raw file. Therefore, this raw file was exported to Microsoft Excel to allow for formatting and achieving the desired data points. A column of data was created which tracked the total change in compression extension starting at a value of zero for the first data point. In this column, the desired change in compression extension, 0.4064 mm, was located and highlighted. The corresponding load value to this data point was recorded. If the extension number wasn't exactly 0.4064 mm, then the closest value adjacent to it was recorded because the difference was insignificant. This process was repeated for each of the five test repetitions at each radial distance. An average load was recorded from this data for each data point.

Two graphs were generated the recorded test results. The first graph shows the compression load (N) on the y-axis and the test specimen number on the x-axis for both the outer points and middle points. The second graph shows the compression load (N) on the y-axis and the non-dimensional radial distance on the x-axis for all the test specimen sections.

2.4 Compression Testing Wood Samples

Test samples of Red Oak, Douglas Fir, and Hemlock were obtained (Figure 15). These samples followed the same procedures as in section 2.1, 2.2, and 2.3 except for the output of the graphs. Only one graph was generated that displays the results for the wood data values. This graph shows the average compression load (N) on the y-axis and the type of tested species on the x-axis. Each type of wood contains one data value that has been averaged, but bamboo contains three different data values, outer, middle, and inner points. The data values corresponding to the outer, middle, and inner points were averaged across the length of the internode.

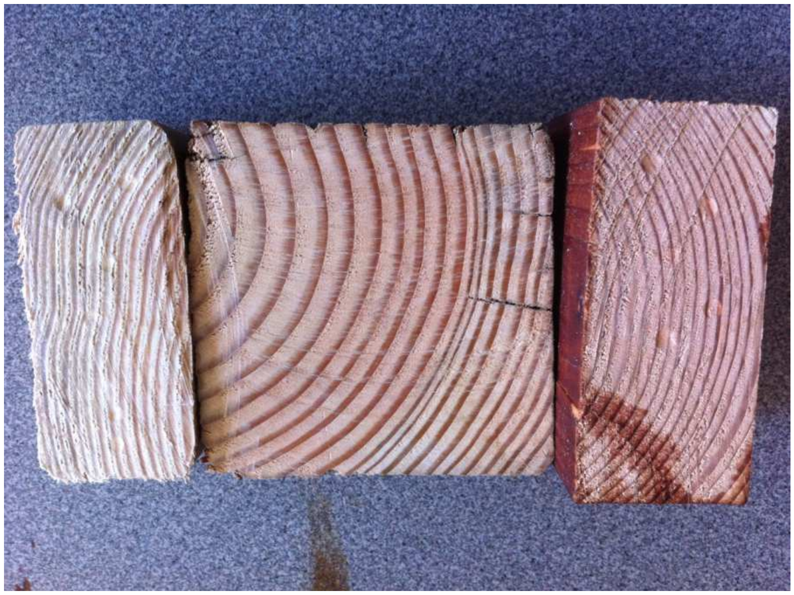

Figure 13: Three different types of wood test samples from left to right, Douglas Fir, Hemlock, and Red Oak.

2.5 SamplePreparation for Pull Out Test

2.5.1 Cutting Bamboo Samples

The bamboowe used was selected by specific age group and growth location to make sure that they are similar in strength and other properties. The bamboo were allowed to dryfor 3 months prior to any kinds of preparation in standing position, which would allow the bamboo to dry faster. After a period of 3 to 4 months, the bamboo culm was cut into strips of¾ inch wide by a ½ inch using table saw and band saw (Figure 16). The length of each strip was cut to 2 feet, which was the required length for the testing machine.

Figure 14: Bamboo culms were cut into strips using table saw and further modified to more precise dimensions by the band saw.

2.5.2 Applying Coatings

After all the bamboo strips were cut out, different types of coating wereapplied to the bamboo strip ends where it would be embedded into the concrete cylinder: traditional asphalt emulsion coating and the experimental Polydimethylsiloxanecoating were applied onto the surface usinga paint brush and allowed to dry for a period of 72 hours to make sure the coatings were completely dried and reached the maximum desired adhesiveness (Figure 17). No coating was applied to the control samples.

Figure 15: Coatings were applied to the ends of the bamboo strips where they would be embedded in the concrete cylinders. Coatings were left to dry for 72 hours before any further preparations.

2.6 Concrete and Cylindrical Formwork Preparation

The concrete we used for this test was commercial grade quikrete 5000 high strength concrete mix, which can be purchase at regular hardware store, which required only water for mixing. The concrete mixture for our experiment was 80 pounds of concrete per ¾ gallons of water. Once the concrete was thoroughly mixed with the right ratio, it was poured into the 12 inch by 4.5 inch diameter cylindrical formworks.A thin layer of WD-40 was applied to the inside of each formwork as a lubricant for the ease of removing the concrete samples out of the formwork once they are ready for testing.

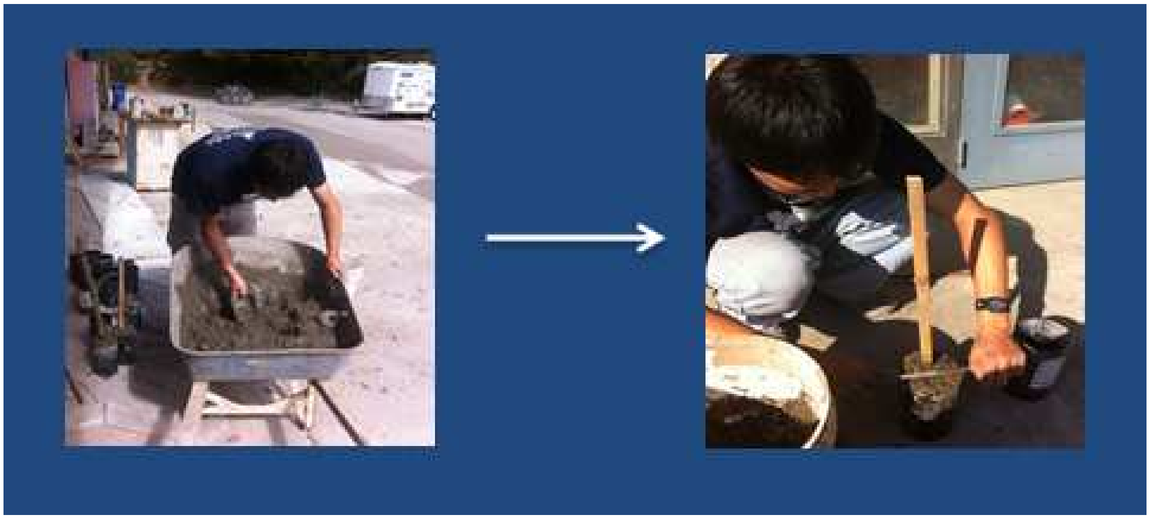

Figure 16: Mixing the concrete and pouring it in the cylindrical formworks before embedding the bamboo at the center.

The 15 concrete samples with bamboo embeddedat the depth of 6 inches and at the center of the cylindrical formwork were made, plus 3 samples without the embedment for strength test (Figure 18). All samples were allowed to cure in the wet room for a period of two weeks (Figure 19).

Figure 17: Samples were carried to the wet room and allowed to dry for a period of two weeks.

2.7.1 Concrete Compression Test

To determine the strength of concrete, three concrete samples without bamboo embedment were made for compression testusing the FX-400 Forney TPILOT tester (Figure 20). The purpose of this test was to determine the strength of the concrete samples to make sure that every sample was at an acceptable strength for testing. A 14-day test was followed due to the time constraint. However, a 28-day test would be ideal.

Figure 18: The Cylinder Tester measured the compressive strength of concrete using a 14 day test approximation. Its strength was close to 90% of maximum strength.

2.7 Pull Out Test Procedures

Once the concrete samples had been cured in the wet room for a period of two weeks and made sure that the strength was good by compression tests, they were loaded into the 120-HV SATEC hydraulic universal testerone by one (Figure 21). The top grip was tightenedby cranking the lever clockwise to hold the bamboo in place. The bottom grip was not necessary to tighten since this is a modified pull out test. Instead, thin aluminum plates were inserted at the bottom part of the machine to help secured the stability of concrete samples. Once the sample was secured, a

computer software program was used to activate the machine. After the machine was activated, a hydraulic pump pushed the top part of the machine upward, which at the same time pulled the bamboo out of the concrete (Figure 21). The computer software program collected the data and graphical images and recorded on an external drive for further analysis. The pull out samples were examined and analyzed.

Figure 19: Above is showing a quick schematic of the pull out test procedure. This same procedure was repeated fifteen times for all the samples.

3.0 Results

3.1 Compression Test Results

All of the data that was recorded are valid for the modified compression test. Figure 22 shows the magnitude of stress along the length of the internode.

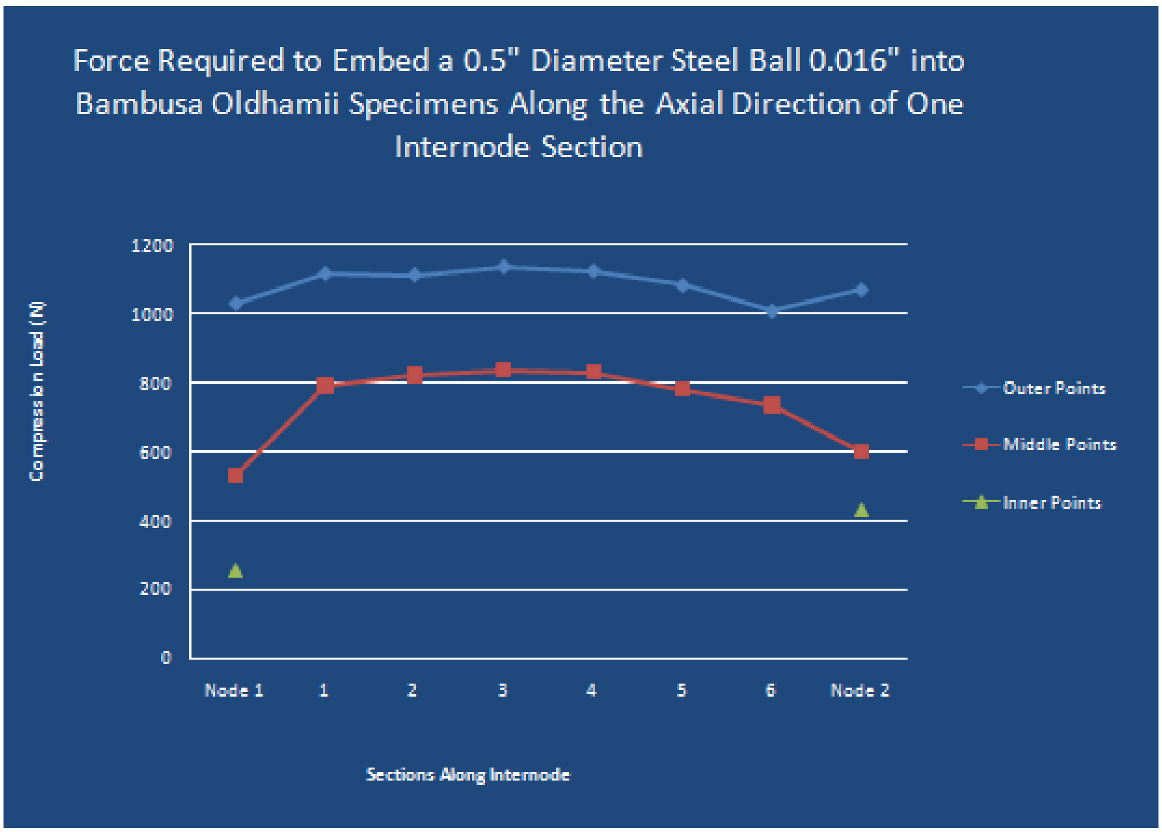

Figure 20: Quantitative load values of each test specimens for outer, middle, and inner points. There was no compression test performed for sections 1-6 at the inner point. This graph shows the trend in stress along the length of the internode.

The highest strength resulted in the middle of the internode at test specimen 3 for both the outer and middle points. The values for the highest outer and middle point were 1136.42 N and 835.7 N respectively. The lowest value for the outer points was 1011.48 N at specimen 6. However the lowest value for the middle points was 531.54 N for the Node 1 specimen. The strength of the average outer point is 1.47 times greater than the average middle point. Also, taking into

account the inner point data values from the two node specimens, the strength of the average middle point is 2.26 times greater than the average inner point. Table II provides the minimum, maximum, standard deviation (Std. Dev), and average (Mean) quantitative values for the outer, middle, and inner data points.

Table I: Statistically Significant Quantitative Values for the Compression Test

	Minimum (N)	**Maximum(N)**	**Std. Dev (N)**	**Mean (N)**
Outer Points	1011.48	1136.42	45.39	1086.31
Middle Points	531.54	835.7	113.88	740.4
Inner Points	253.58	401.74	104.76	327.66

The magnitude of strength across the transverse direction is displayed in Figure 23. These are the same values that are displayed in Figure 22 and Table II but are organized different to show the strength at different radial distances.

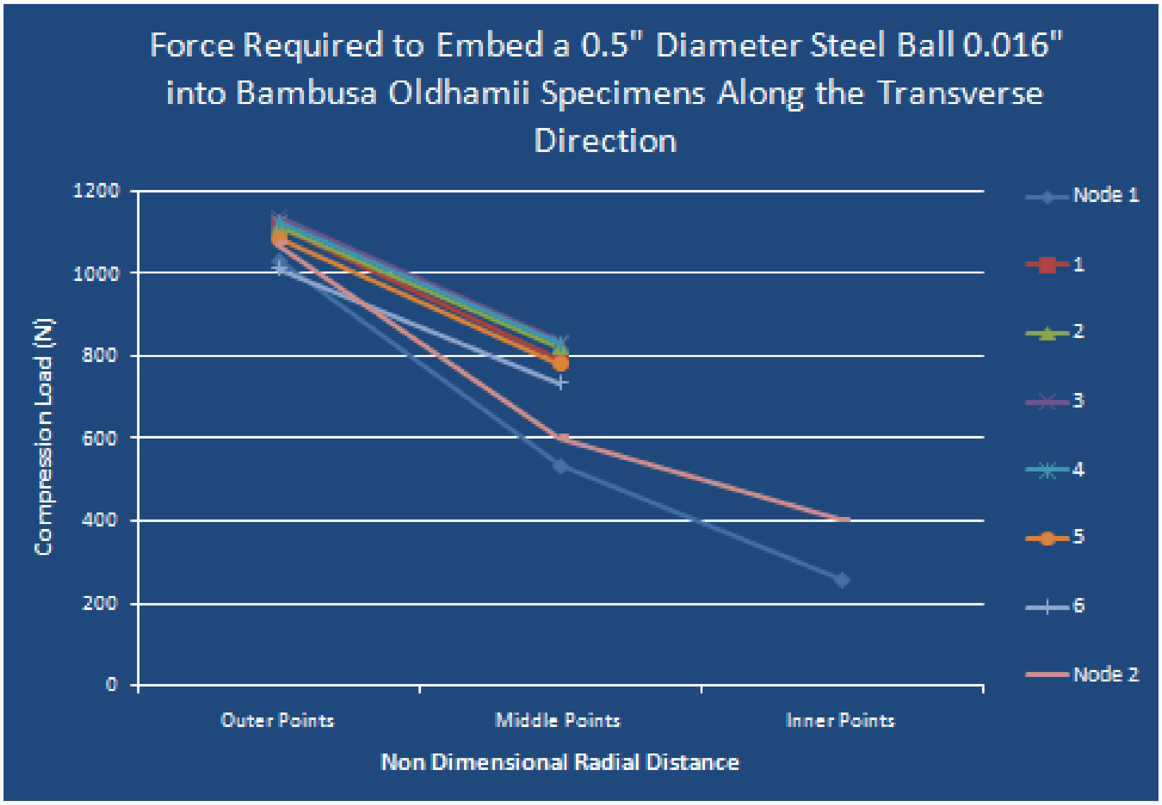

Figure 21: Quantitative load values of each test specimens for outer, middle, and inner points. There was no compression test performed for sections 1-6 at the inner point. This graph shows the trend in stress across the diameter of the culm.

As you can see, the outer points are the strongest compared to the middle points, and then followed by the inner points which are the weakest. None of the data points within their respective categories interact with others.The following diagram, Figure 24, compares the strength of outer, middle, and inner points for Bambusa Oldhamii to the average strength of Red Oak, Douglas Fir, and Hemlock.

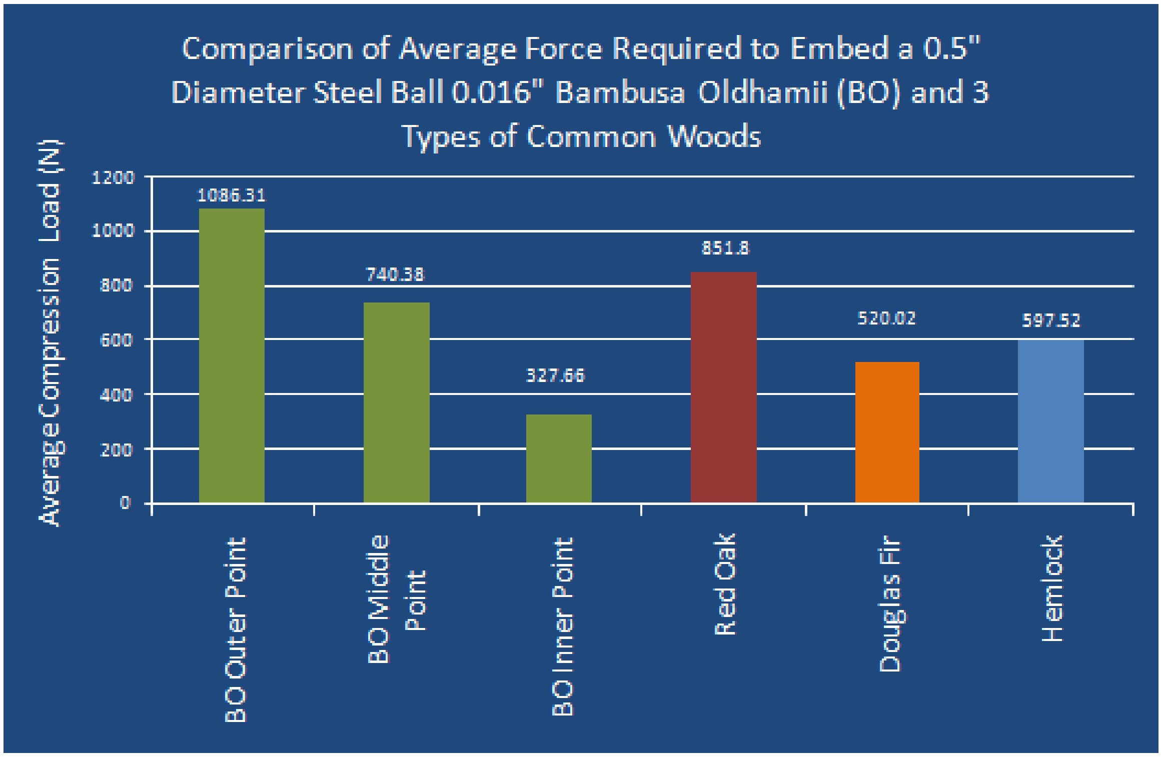

Figure 22: Comparison of quantitative load values for the average outer, middle, and inner points with average load values for Red Oak, Douglas Fir, and Hemlock.

The strength between the outer, middle, and inner points of Bambusa Oldhamii vary significantly. Its strength values range from 327.66 N to 1086.31 N. 851.8 N, 520. 02 N, and 597.52 N are the recorded values for Red Oak, Douglas Fir, and Hemlock respectively.

3.2 Pull Out Test Results

3.2.1 Factor 1: Types of bamboo- *Dendrocalamus Asper and Bambusa Oldhamii*

For the comparison between the types of bamboo and their bonding strength, a statistical analysiswas performedusing a 3 wayANOVA and linear regression model on Minitab. The results show significant of higher pull out strengthfor all the samples for Bambusa Oldhamii type.The main effect plot shows Bambusa Oldhamii has higher pull out strengths(5089 lbs, 2313 lbs, 4786 lbs) than the Dendrocalamus Asper (3709 lbs, 1883 lbs, 2289 lbs) for all types of coatings (Figure 25).

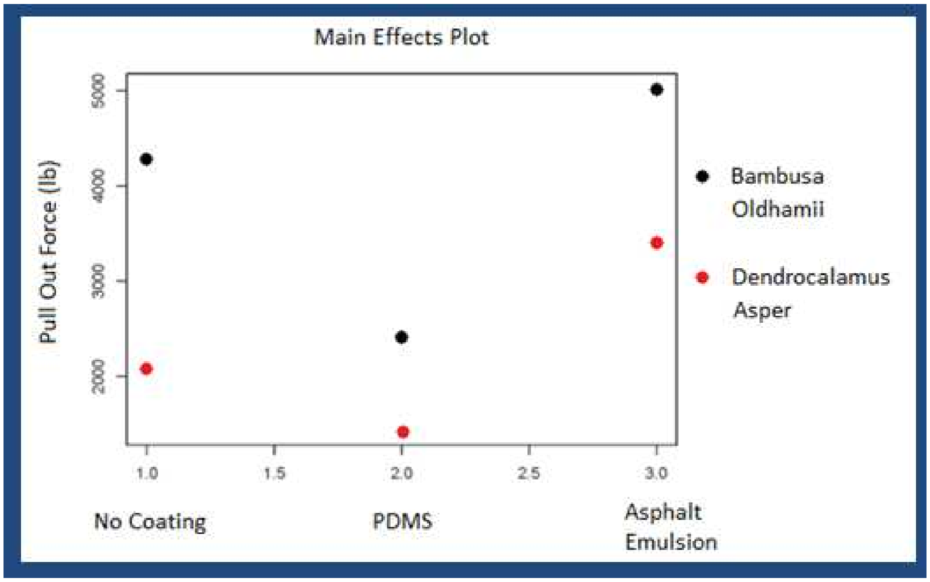

Figure 23: The main effect plot shows the comparison of the pull out strength between Bambusa Oldhamii and Dendrocalamus Asper.

The reason for the differences in the pull out strength between the two types of bamboo is still unknown at this point. See discussion 4.2.

3.2.2 <u>Factor 2</u>: Types of coating- *Asphalt emulsion, Polydimethylsiloxane, Control*

The results obtained from the pull out test using a hydraulic universal tester-120 HV series indicated that asphalt emulsion has the higher pull out strength (5089 lbs) as compared to the PMDS (2313 lbs) or the control samples (4786 lbs) (Figure 26). Unfortunately, the PDMS did not show a very high strength due to the surface chemistrybetween the bamboo and the coating interface. See discussion 4.3.

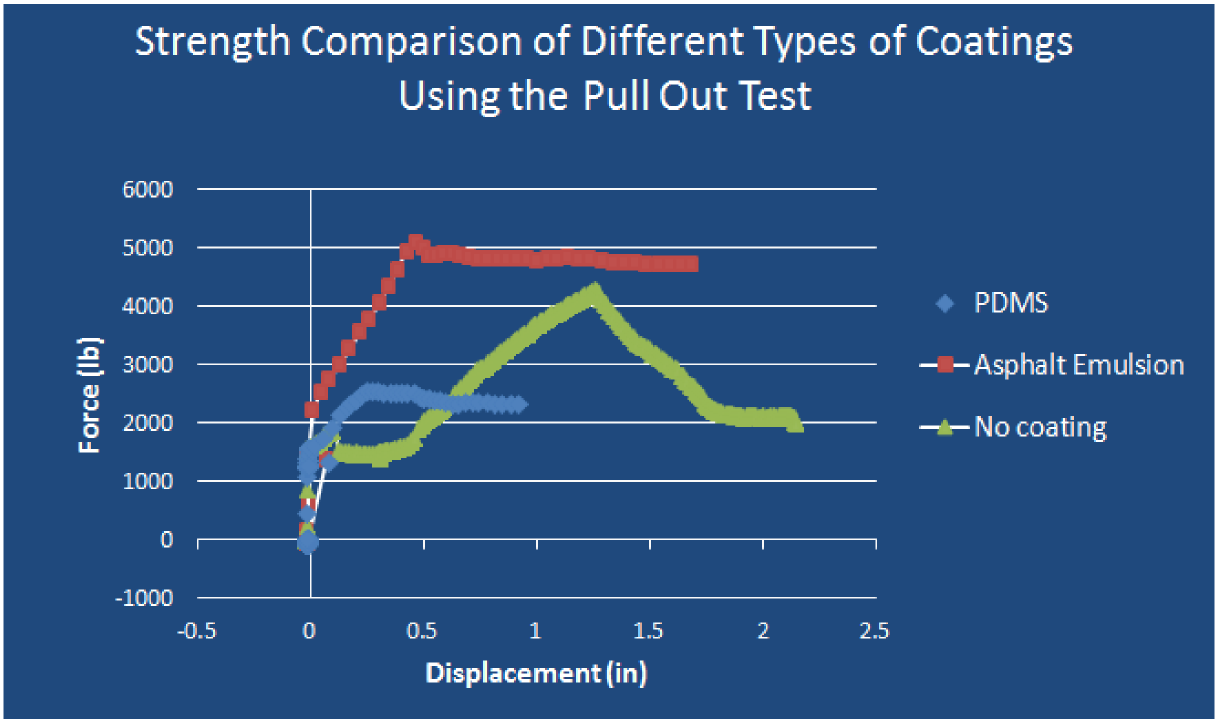

Figure 24: The graph is showing the pull out strength comparison of the results for the different types of coating.

The graph for no coating shows a steeper drop after it had reached its maximum strength. See discussion 4.5.

3.2.3 Factor 3: The bamboo with the node and without the node.

According to the data collected, the nodes pull out strength varied from high to low in which it makes sense looking at how the samples failed during the pull out test. Because of a large variation in the data, the test results were inclusive and excluded from the statistical analysis and calculations. There are two failure modes for the bamboo with the node and without the node during the pull out test (Figure 27).

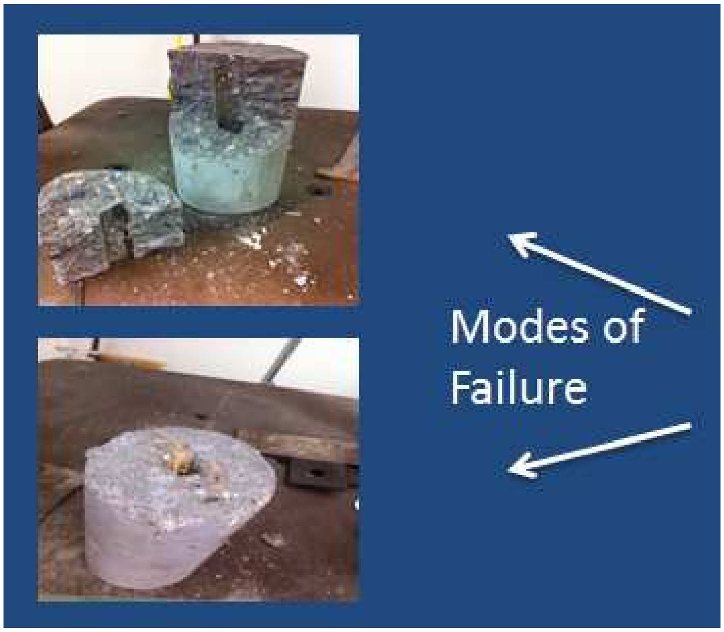

Figure 25: There are two modes of failure as the bamboos are pulled out of the concrete.

Failure mode 1: The bamboo samples without the node were being pulled out smoothly. Failure mode 2: The samples with the node cracked the concrete. This led to invalid results. See discussion 4.4.

3.2.4 Interaction Between Factors

To determine which, if any, combinations of factors would yield a higher pull out strength, a Minitab interaction plot used. The results show no correlation or significant interaction between the type of bamboo, the type of coating, or the bamboo with the node and without the node (Figure 28).

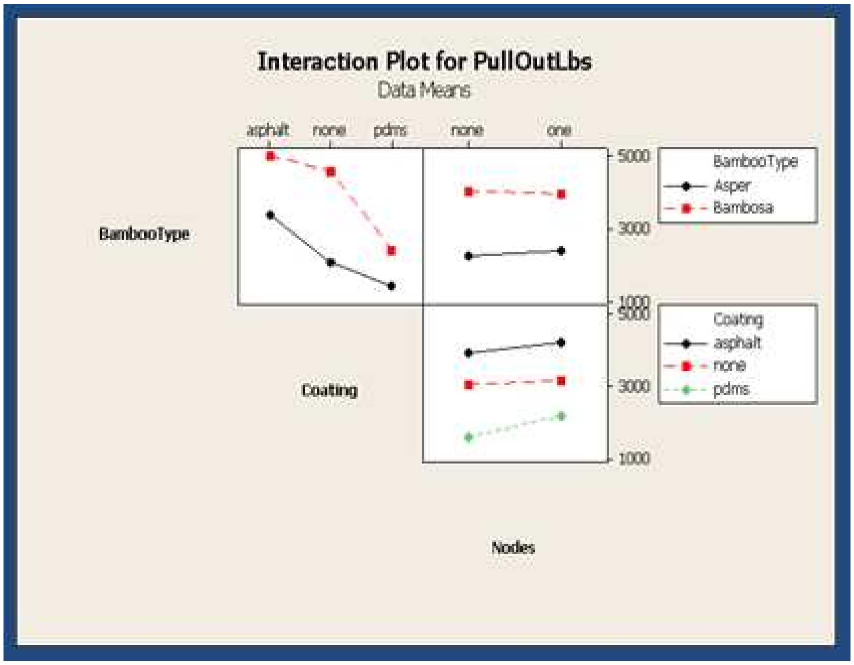

Figure 26: The interaction plot shows no interaction between the different factors.

However, this plot might show a different result if we had more test samples.

3.2.5 Concrete Compression Test Results

The maximum strength that could be achieved for this type of concrete was 5,000 psi at a 28 days curing process, as mentioned on the product package description. However, we ran a 14-day test and achieved the average concrete strength of 4520.37 psi, which is within 90% of the maximum strength. Therefore, we concluded that all of the concrete samples were within an acceptable range for testing.

Table III: 14 Day Concrete Compression Test Results

14-day test	Sample 1	Sample 2	Sample3	Average*
Strength (psi)	4533.81	4501.32	4525.98	4520.37

3.2.6 Results of Pull Out Test

The average bond stress at each load, P, was calculated using the followingequation:

$$\mu = \frac{P}{A} \tag{1}$$

$$A = 2(w \times l) + 2(t \times l) \tag{2}$$

Where μ is the average bond stress (psi); A is the cross section area of the bamboo where w (width) = ¾ in and t (thickness) = ½ in; and l (length) is the embedment length 6 in.

Table III: Load and Bonding Stress Results for Dendrocalamus Asper

Dendrocalamus Asper	**Load (lbs)**	**Bond stress (psi)**	**Bond stress (MPa)**
Asphalt emulsion	**3709**	**247.27**	**1.70**
Asphalt emulsion	**3490**	**232.67**	**1.60**
Asphalt emulsion with node*	**2951**	**196.73**	**1.36**
PDMS	**1811**	**120.73**	**0.83**
PDMS	**1883**	**125.53**	**0.87**
PDMS with node*	**580**	**38.67**	**0.27**
No coating	**2111**	**140.73**	**0.97**
No coating	**2289**	**152.60**	**1.05**
No coating with node*	**3504**	**233.60**	**1.61**

***Node data were excluded from statistical analysis**

Table IV:Load and Bonding Stress for Bambusa Oldhamii.

Bambusa Oldhamii	Load (lbs)	Bond stress (psi)	Bond stress (MPa)
Asphalt emulsion	5089	339.27	2.34
Asphalt emulsion with node*	4978	331.87	2.28
PDMS	2313	154.20	1.06
PDMS with node*	2552	170.13	1.17
No coating	4786	319.07	2.20
No coating with node*	4441	296.07	2.04

*Node data were excluded from statisticalanalysis

Table V: Strength Comparison Between Bamboo Type.

	Dendrocalamus Asper	Bambusa Oldhamii
Asphalt emulsion	3709 lbs	5089 lbs
PDMS	1883 lbs	2313 lbs
No coating	2289 lbs	4786 lbs

4.0 Discussion

4.1 Axial Fiber Dimensions

The goal of this project contains two overall parameters, decreasing environmental impact and determining how to achieve the highest strength of bamboo reinforced concrete. The values generated from CES EduPack 2010 [12] comparing the embodied energy and carbon footprint of steel for the same unit volume of bamboo supports the claim of saving money and energy by choosing bamboo as an alternative reinforcement. However, determining the internal strength throughout the bamboo and understanding its connection with its properties was not easy. Just as in literature, the axial aligned fiber density and strength increased towards the outer diameter. This result was expected, however understanding the distribution of strength along the length of the internode was a little more ambiguous. Finding explanations in Literature for this type of information was hard to come by. Recording the lengths and tracking the fibers throughout the bamboo culm is a difficult process. However, it does state in Literature that, generally, the longest fiber lengths are located at the middle of the internode and the shortest lengths are located near the nodes. If this statement is true, then fiber length and internal strength are dependent upon each other theoretically. Knowing that bamboo can be thought of as a natural composite material, composite mechanics can be used to examine this theory. A longer fiber surrounded by a matrix should resist more force than a shorter fiber surrounded by the same matrix. This is because the longer fiber has more surface area of interaction with the matrix than the shorter fiber. The greater the surface area, the greater the shear stress.

4.2 Comparing Radial Strength Variances

There were several deviations from the theoretical results. The minimum strength should occur at the node specimens for every test sample. However, the minimum value for the outer data point occurred at test specimen 6 which is slightly lower than the Node 1 and 2 specimens. Also, a few data points had a bigger variation than expected. For example, the two inner point values had a standard deviation of 104.76 N. This number should be closer to zero which is the

theoretical standard deviation. Another point of interest is the percent difference in strength between the outer and middle points for each of the eight test specimens (Table VI).

Table VI:Strength Difference Between Outer and Middle Data Points

	Node 1	1	2	3	4	5	6	Node 2
% Difference in strength	94.2%	41.5%	35.8%	36.0%	35.4%	38.7%	37.8%	78.3%

The greatest difference in strength occurs at the node specimens. The other specimens all fell within a range of 6%. Test specimens 1-6 all had approximately the same wall thickness. However, the two node specimens had a greater thickness in the area where the axial aligned fibers were located. With a larger distribution of fibers, there can be a greater discrepancy of strength across the transverse direction.

The compression test was performed five times for each data point to achieve more accurate results. However, the quantitative values could have been more accurate if thicker walled samples of bamboo were obtained to allow the steel ball indenter to embed itself at a greater depth. Moreinconsistencies would be averaged out and the quantitative values would be more precise. Therefore, the project could rely more on statistics to back up the data recorded from the compression test.

Due to time constraint, the compression test was only performed on one internode section of one species of bamboo. It would be ideal in the future to repeat the modified compression test procedure for multiple internodes of the same species and for multiple species. Performing these types of tests would evaluate if the top part of the bamboo culm has better mechanical properties which is stated in literature. From the physical structure of the fibers distributed through the culm wall, I believe this would be true. The internode lengths increase but the wall thickness decreases towards the top section of the bamboo culm. Since the internode length increases, the fiber lengths should also increase. This change in fiber length will aid in increasing the internal strength. Simultaneously, decreasing the culm wall thickness should increase the ratio of fiber

density to matrix. Since the volume of the matrix decreases, the contact surface area increases allowing the fibers to resist more shear strength.

When comparing the hardness of bamboo to other wood products using the Janka standard values, bamboo is listed as general bamboo species with a single value. Having a single value can easily mislead companies and customers to believing in bamboo's relative hardness. The relative hardness of woods is easy to determine because the properties varies minimally in the same direction. Bamboo could have a recorded Jankavalue that could be off by a factor of three depending on which parts of the bamboo culm are utilized in production. Therefore, the Janka value for a bamboo species should have a note describing which part of the bamboo was tested.

4.3 Differences in Strength Between Types of Bamboo

It's not clear at this point why Bambusa Oldhamii shows higher pull out strength than Dendrocalamus Asper under the same experimental set up. Since Bambusa Oldhamii were greener in color than Dendrocalamus Asper, our best assumption is that the greener bamboo, Bambusa Oldhamii, could still absorbsome moistures from the chemical mixture of coatings and caused the bamboo to swell up. This swell up pushed the bamboo against concrete and created more frictional force. The pull out strength, therefore, increases due to the added frictional force against the concrete. If this assumption were to be true, this could mean that Bambusa Oldhamii might not be a good candidate for use as a rebar due to the bamboo' nature, as they will shrink and lose the adhesiveness to the concrete when they lose moistures.Second assumption could be due to the fact that heat from the curing concrete could be transferred to the bamboo. The heat transfer caused expansion or contraction within the bamboo.

4.4 Bamboo and PDMS Interface

PDMS were used in this experiment due to its hydrophobic property and its more sustainable life cycle than the traditional petroleum based asphalt emulsion coating.Although the structures of PDMS provide good barriers against polar molecules such as water and moisture absorptions from the concrete from penetrating into the bamboo, but at another interface; the bamboo and the

coating interface, there is not enough charge interaction and molecular entanglement between that surfaces to provide mechanical interlocking of diffusions between the surface of the PDMS and the bamboo (Figure 29). This is one of the main reasonsPDMS does not have high pull out strength.

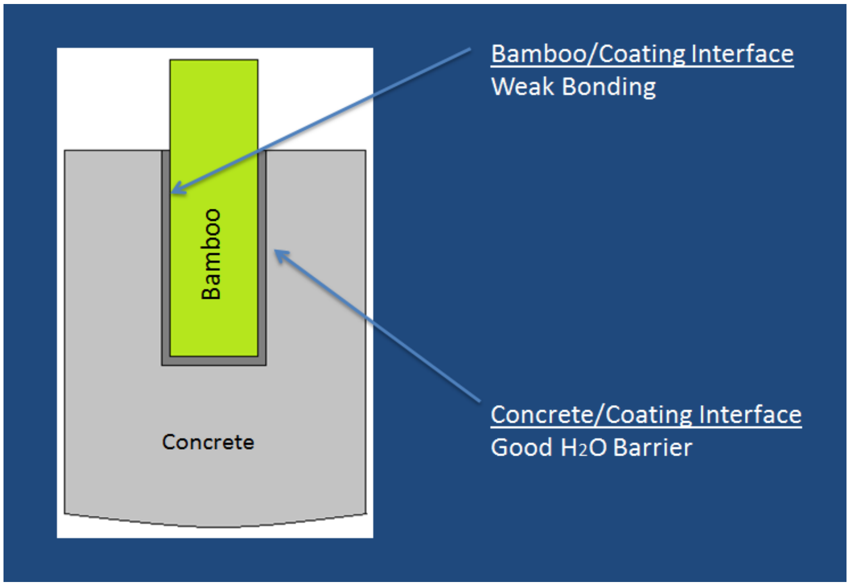

Figure 27: The bamboo and the coating interface lacks surface adhesion resulting in a weak bond.

4.5 Modes of Failure

All samples without the node were pulled out of the concrete smoothly. All samples with the node were believed to have shown significantly higher pull out results due to the added stress. However, the samples with the node cracked the concrete due to the added bearing stress that the node has on the concrete while the bambooswere being pulled out. The data did not show any pattern in the pull out strength for bamboo with the node. A different testing method might be necessary to determine whether the nodes would crack the concrete member when it is being used in a real application. A higher strength concrete mixture might also be considered for the test.

4.6 Pull Out Mechanism

The failure of the bamboo samples occurs at the interface between the reinforcing bamboo and the surrounding concrete. The failure between the bamboo and the concrete occurred due to the shear strength. During the first few seconds of the pull out test, the bamboo did not show much movement. Once the shear force overcame the bond stress, the bamboo moved more rapidly. According to the results from control samples, the bamboo slipped out without much resistance as can be seen by the steep drop in the graph (Figure 26). This could results from voids being created inside the concrete and the lack of coating to provide surface adhesion.

4.7 Comparison Between Bamboo and Steel Pull Out Strength

In literature, the pull out strength of steel rebar was reported to be approximately 8 MPa (1160 psi). Our experimental pull out strength of bamboo was as high as 2.34 MPa (339.27 psi), which is about 30% as high as steel. In some applications, bamboo may be used in place of steel rebar. The pull out strength of bamboo could still be improved by using more extremely adhesive types of coatings.A modification on the surface roughness of the bamboo, such as denting the surface or using coils or ropes to wrap around the surface of the bamboo, might help increase the bamboo pull out strength. An epoxy type of coating could also be considered.

5.0 Conclusion

- Fiber density and internal strength both increase towards the outer edge of the bamboo culm
- If bamboo was chosen as an alternative reinforcement in an application where the strength of bamboo is sufficient, a vast amount of energy will be saved and minimal amount of CO_2 will be emitted into the atmosphere
- The maximum stress locations throughout the bamboo culm are located in the middle of the internode and closest to the peripheral edge
- Compared to the variance in stress throughout the bamboo, the Red Oak, Hemlock, and Douglas Fir test samples varied minimally
- Bambusa Oldhamii has a higher pull out strength and bonding stress than the Dendrocalamus Asper
- Asphalt emulsion coating has the highest bonding strength compared to PDMS and the control sample
- The pull out strength of bamboo is approximately 30% of steel pull out strength.

6.0 Recommendations

A) The modified compression test should be performed on more samples at different sections along the length of the culm.

B) Different types of bamboo should be tested using the modified compression test

C) Test each factor listed in section 1.2.3

D) Perform bend test using bamboo samples that do and do not contain node sections.

E) One possibility is to perform a tensile test on the single bamboo fibers.

F) To understand a more in depth correlation between the properties of bamboo and its structure, determine a method for measuring the size and counting the number of fibers throughout culm.

G) Number of replication of the samples should increase for each of the three factors.

H) Experiment with other types of coating and compared the bonding strength with the traditional asphalt emulsion coatings.

I) Higher strength concrete maybe necessary for testing bamboo with the node.

J) New testing procedure may be necessary for testing the bamboo with the node.

K) Beam test using a three or four point bend test is recommended for the bamboo reinforced concrete.

L) Corrosion and deterioration of bamboo once used as a rebar in the concrete is highly recommend for future studies and testing.

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