The Study of Natural Composite I-Beam in a Three Point Bending Test

Abe Shabbar
California Polytechnic State University, San Luis Obispo, California, 93405

The objective of this experiment is to conduct a series of unidirectional tensile test on several samples of natural occurring plant fibers. Among the materials tested, hemp has proven to be the most promising candidate as the base material in creating an all-natural composite I-Beam. This I-Beam will be entered into the annual SAMPE 2012 competition to compete against other schools and universities nationwide. These I-Beams will undergo a three point bending test, and must withstand the greatest load whilst remaining in the parameters set by SAMPE. This I-Beam will go on to take third place internationally. In addition, the properties of hemp composites will be further investigated by creating the same I-Beam, but introducing a small fracture to the underside in order to observe how the composite interacts in the presence of fracture.

Nomenclature

Θ = Angle
a = Area
b = Base
M = Bending Moment
K = Column effective factor
Gi = Grack driving Force
A = Cross Sectional Area
ρ = Density
af = Final crack length
P = Force
γ = Shear Strain
h = Height
ai = Initial Crack Length
Nf = Life in cycles
I = Moment of Inertia
□ = Poisons Ratio
τ = Shear
G = Shear Modulus
Q = Statical Moment of Area
□ = Strain
σ = Stress
t = Thickness
E = Young's Modulus

I. Introduction

A competition is held annually by SAMPE to encourage students in participating schools to push the envelope in the world of materials. In this competition, a category is held to design an I-beam using only materials that occur naturally. The submitted I-beam must undergo a three point bending test in accordance with SAMPE testing standards. The winning school is the one that can produce the I-beam with the best weight to load ratio.

SAMPE specifies the design criteria for I-beams. These I-beams may weigh no more than 600 grams and hold a minimum of 1000 pounds to be eligible for an award. The I-beam may only have a single web exceeding no more than .6" in thickness. The maximum cross sectional area allowed for the I-beam is set to 4"x4". An I-beam is considered to be compromised when it undergoes 1" of deflection.

Traditionally, schools who compete in the natural I-beam category construct their I-beams from solid bamboo akin to ply wood. Last year the winning school, McGill, produced an I-beam that held 1769lbs before reaching failure. This year, Cal Poly is to enter the nature I-beam category using an I-beam made purely from composites, consisting only of materials that occur naturally.

Before construction of an I-beam can begin, the material must first be selected. The test subjects included hemp, cotton, linen, jute bamboo, silk, and a bamboo/cotton blended material. Each of these materials will be made into long composite strips in order to conduct tensile tests on each specimen to produce the elastic modulus E for each material. Once the final material is selected using the elastic modulus as the primary deciding factor, among other properties such as mass, thickness, and texture of the material, the actual process of constructing and I-beam can begin.

In accordance with SAMPE guidelines, the I-beams were constructed and tested using the optimal materials, it should be noted that additional designs went into the final product such as the addition of bamboo in order to allow the beam to become more rigid and resistance to deflection.

Once the I-beam design has been finalized, additional material testing using basic I-beams made only of the selected material are tested with a small fracture on the underside of the beam in order to better study and understand the material properties of natural composites.

II. Procedure and Apparatus

A. Apparatus

To conduct this experiment, the most important piece of equipment is the vacuum. A vacuum such as the one shown in figure 1 below is the primary component in creating any composite.

Figure 1 Three of the vacuums used to create natural composites.

In addition to the vacuum, the resin used is also incredibly important. As the vast majority of all resins are petroleum based, and the guidelines specify that only natural products may be used in the construction of an I-beam, the resin had to be carefully chosen. In the end, it was deemed that a soy bean based resin produced by EcoPoxy was the best to use as a matrix in the composite. EcoPoxy uses only all natural ingredients and is comparable to

Figure 2 Two part resin EcoPoxy as used in the experiment.

petroleum based resins. It should be noted that the EcoPoxy is incredibly easy to work with compared to standard petroleum based products such as AeroPoxy. The all natural resin is relatively safe for skin contact and exudes very little vapor, none of which is toxic to human health.

High quality industrial vacuum bag was used to ensure that no air escapes the molding process while the composite is allowed to cure. Pores release fabric is also used to aid in the removal of the composite once it has been allowed to cure. This release fabric will also affect the final finish of the composite.

Other materials used consist of cotton to protect the vacuum port and prevent excess resin from flowing into the pump and ruining the equipment. Special vacuum tape referred to as gum tape was used to seal the vacuum and any holes within the bag should any manifest.

All testing was done using the Cal Poly San Luis Obispo composites lab Instron machine. This machine, capable of a multitude of material testing was used to conduct unidirectional tensile test on the sample strips for all the different materials in order to select a final material that could be used to construct an I-beam. The Instron machine was configured for the tensile test by carefully attaching large, 80lb clamps to the top and bottom fixtures of the machine such as in figure 3.

Figure 3 Instron machine configured for tensile testing.

It should be noted that safety is a major concern when handling the tensile testing clamps as it is very difficult to attach them to the fixtures of the Instron Machine. Serious injury can occur if improper mishandling of the equipment occurs.

To configure the machine to conduct the three point bend test used to conduct the optimal design for the competition and to examine the material under fracture, the Instron Machine needs to be configured properly by swapping out the tensile testing clamps and replacing them with the three point fixture. As with the tensile clamps, extreme safety should be observed when handling the Instron equipment. With the Instron configured properly for three point bending, such as in figure 4, testing of I-beams can begin.

Figure 4 Instron Machine configured for three point bending test.

Along with the physical tests used to find material properties of the material, a burn test was conducted in order to calculate the fiber to matrix ratio within the composite. This test was done by taking a small sample of the material composite and placing it within a small oven within the lab that would bake the composite until all resin was burned away, leaving only the fiber.

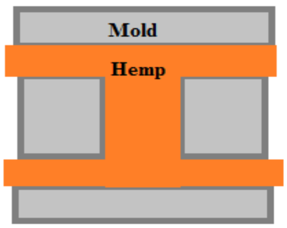

Figure 5 Setup of molds for I-beam

To construct the I-beam itself, four molds were used to give it the distinctive shape. These molds consisted of two 2"x2" aluminum beams approximately 26" long, and two long flat aluminum plates approximately 30" long. Figure 5 shows how the molds are used to create an I-beam. The square beams go on either side, and the flat plates are fixed to the top and bottom to ensure the proper shape and a clean finish. Notice that the hemp actually protrudes slightly from the mold. This is okay as the end product when removed from the mold is cut to size in order to make the maximum allowable mass of 600grams

Figure 6 Example of tabs used for tensile test

In accordance with ASTM standards, aluminum tabs measuring 1"x1" are used for the tensile testing phase[1]. These tabs help protect the sample from the Instron Machines extreme clamping pressures and ensure the sample stays in the grips, figure 6 shows an example of the tabs used. These tabs are fixed to the specimens by high adhesive industrial glue. It should be noted that according to the ASTM standard, both sides of the tabs should be scratched in order to help the tabs properly bond to the specimen[1].

A simple tile saw is used to cut each samples. This saw uses a water cooled blade and the water level should be monitored during operation to ensure safety and minimal wear on the blade.

B. Procedure

1) Tensile testing.

Each candidate material was cut into long sheets measuring approximately 6"x54". Next, the EcoPoxy was prepared by pouring four parts resin, one part hardener. A large area of the lab is cleared of debris and a large plastic garbage bag is placed on the table to protect it from the resin and to assist in cleanup.

Before the resin is mixed, the vacuum bag should be prepared as the resin has a work time of approximately 30 minutes, so time management is crucial. To prepare the curing area, a small piece of vacuum bag is laid on a large open area. Release fabric is then placed over that measures 6"x12". Another piece of release fabric of the same dimensions is placed to the side for when the composite is ready to be sealed. Using gum tape, a parameter is laid out that is much larger than the first vacuum bag. A second vacuum bag that is to be just larger than the dimensions of the parameter laid out by the gum tape is cut and placed over the entire apparatus; however, only ¾ of the gum tape should be allowed to seal so as to allow enough room for the wet composite to easily be placed within the bag.

At this point, make sure the garbage bag protecting the table is secured to the table in order to ensure minimal play of the bag whilst applying the resin to the fiber. Now the resin can be mixed. Once this happens, you have 30 minutes to work with the resin before it starts to harden.

Each fiber is laid on the bag and resin in small controlled doses is poured on the material and carefully spread thin. It is very important to squeeze out as much excess resin as possible as this will reduce the weight of the final product. After an area measuring 6"x12" has sufficient amount of resin introduced to the resin matrix, another

6”x12” section is folded over that, and the process of spreading the resin is repeated, carefully monitoring how much resin is introduced to the fiber, but allowing sufficient spreading of the resin in order to prevent dry spots.

This process is continued until the specimen has been folded over five times. The finished specimen should measure 6”x12’. At this point it can then be placed within the vacuum bag on top of the release fabric. The extra piece of release fabric is placed on top of the resin, in effect sandwiching it between the pores release fabric. The vacuum bag is then sealed except for a small area approximately two inches long in order to allow a tube connected to the vacuum pump to be inserted. If excess vacuum bag is present, a pleat can be used to compensate for this. A pleat is extra gum tape used to seal any excess vacuum bag.

Before inserting the tube, the end of the tube should be covered in cotton fabric in order to ensure no resin enters the tube and finds its way to the pump, which would destroy the precious lab equipment. Once cotton has been added to the end of the tube, insert the tube so that the cotton rests on the edge of the composite. This is to ensure that the pump pulls any excessive resin out of the material, in turn reducing the weight of the final product, but also removing any air bubbles from the composite, which will help strengthen it. The entire process should look like figure 7 at this point.

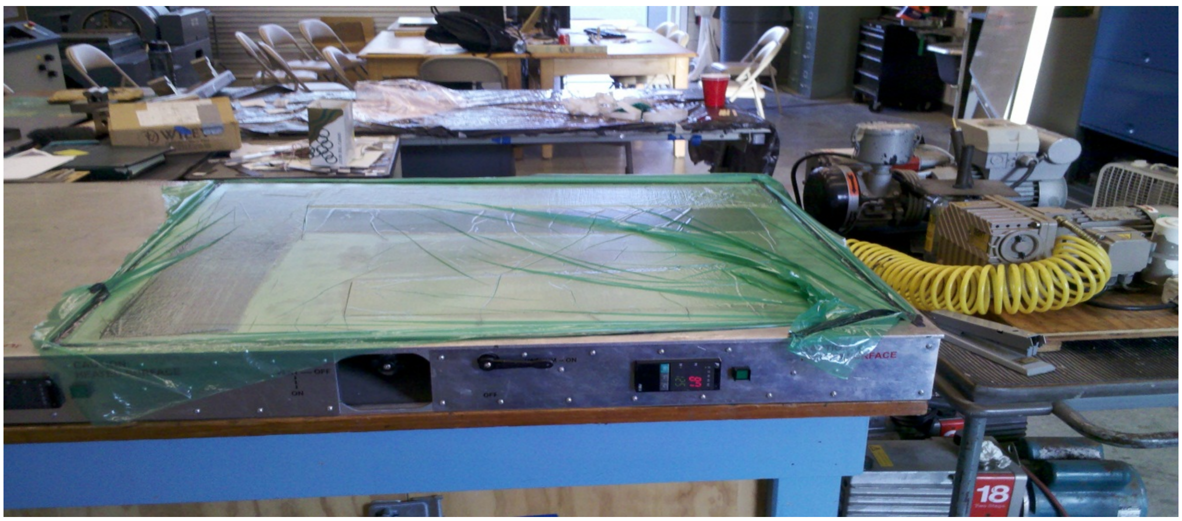

Figure 7 Composite specimen sealed in vacuum bag, waiting suction pump to be activated.

Once the vacuum bag has been sealed, the vacuum can then be turned on. It is important to make sure that there is absolutely no leaks in the vacuum bag as this can completely defeat the purpose of the vacuum by not allowing it to properly remove excess resin and air pockets within the resin.

After activating the vacuum and checking for leaks, place a long flat plate over the entire specimen. Care should be taken so as not to disturb the specimen or puncture the bag. With the plate over the specimen, place approximately 80kg on top of the plate dispersed evenly in order to allow additional pressure to help flatten out the specimen.

The composite should be allowed to cure for 24 hours before shutting off the vacuum, and then allowed to dry cure for a further five days before the samples can be cut into shape.

Once fully cured, the samples are carefully removed from the vacuum bag. Each sample is carefully inspected for flaws, if there are any present, they are recorded and logged for future reference.

After each sample has been removed, they are cut into five strips measuring 1”x10” in accordance with ASTM standards[1] using the tile saw. Glue was added to the ends and tabs were fixed to the ends of each sample strip and placed between two sheets of release fabric. A flat plate is placed over the strips with weight on top of that and allowed to sit for approximately 24 hours to harden.

At this point, the sample strips are ready to be tested. The Instron Machine is configured for tensile testing, making sure the hydraulic pump is activated, and the computer is prepared to accept data from the Instron Machine. Each sample strip is first fed into the top fixture and clamped down while being position perfectly vertical. The bottom fixture is moved into position to reach the bottom tab of the sample and then allowed to clamp down. Using the fine tune setting on the fixtures, the sample is pulled apart just enough to be taut. Make sure there is no twist to the sample strips as this can greatly affect the modulus of elasticity.

Once the sample is in place, the Instron Machine is calibrated and balanced and the test can begin. The samples are pulled apart and data is taken and recorded into Microsoft Excel where the Modulus of Elasticity can be calculated using equation 1.

$$E = \sigma/\epsilon \tag{1}$$

The modulus of elasticity for each sample is taken and recorded. It is this value, along with the mass and elasticity of each material that will be used to determine the final material to be used in an I-beam.

The first I-beam was constructed completely of hemp material. Table 1 and figure 8 detail how the strips were cut and placed on the molds to create the first I-beam.

Position	Number of strips	Height	Length
A	8	3.5	26
B	8	3.75	26
C	4	5.5	26
D	4	2	26

Table 1

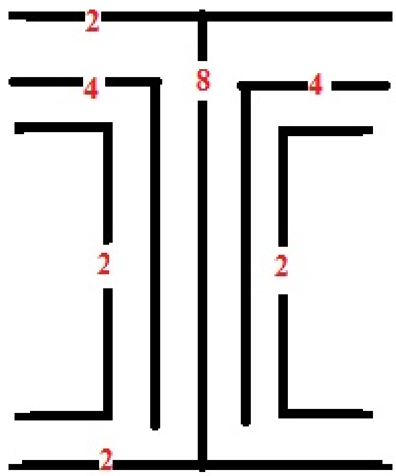

Figure 8 shows how each I-beam is made and how many layers go into each section of the beam

As you can see from figure 8, the top flange is considerably thicker than the bottom one. This is done because composites are typically much weaker in compression then in tension. The web has also been maximized to be the thickest possible in order to withstand high levels of buckling that can be experienced during loading.

Once all of the strips have been cut, the vacuum bag is prepared much like before. The molds are wrapped in vacuum bag, and release fabric. A very large vacuum bag is cut measuring approximately 24”x36”. The large vacuum bag has gum tape placed on half of it such as in figure 9 to prepare it for when the I-beam is placed within.

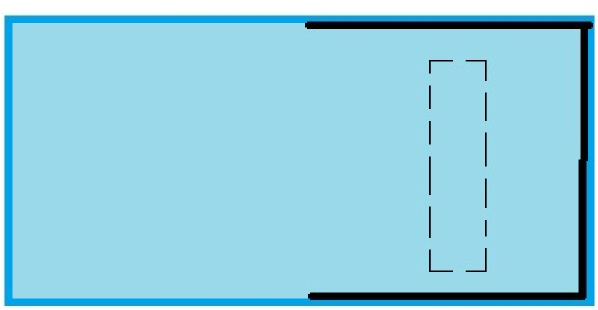

Figure 9 The black signifies the gum tape and the dotted lines show where the I-beam is placed

Before work with resin can begin, a large black garbage bag is placed on a table to ensure no reason damages any lab equipment. Next, approximately 1000 grams of EcoPoxy resin and 200 grams of hardener are mixed in small batches to prolong the work life of the product. Each strip of hemp is placed over the work area and has resin poured over the material. Starting with the D strips (Refer to table 1 for the dimensions of each section); the matrix is spread evenly on the strips. Using a basic tab any excess resin is scrapped off in order to ensure the minimal amount of resin to fiber ratio. The D sections are then placed over the square beams. The B sections are then introduced to the resin next and placed over the D section. Afterwards, the A sections are wetted and all eight strips are placed on one of the square molds. The C sections are also wetted and placed on the flat sections.

At this point it is best to proceed with two people, however with care; this step can be done with one person. Taking both square molds with the wet composites still on them, carefully put them together, next, place one of the flat molds with the C strips over that, carefully ensuring that the excess material folds to the sides evenly. Once this is accomplished, the other flat mold with the wet composite can be placed within the vacuum bag and the three molds that were put together can carefully be placed over that.

Take great care to ensure that the molds do not fall apart at this point until it is sealed within the vacuum. It is also important that the mold is properly lined up before sealing it in the vacuum to ensure approximately even geometry of the final I-beam.

With the I-beam in place, the vacuum bag can then be sealed. Take care in ensuring the molds are not knocked over in this step. Leave a small hole at one end of the vacuum bag so that a hose can be inserted into the bag. The hose should be protected by a cloth to deter resin from reaching the vacuum pump. The hose is then placed far enough so that it rests on the wet composite to absorb excess resin and remove any air bubbles within the composite. Once the hose is in place, the vacuum bag can then be completely sealed. The hose is then fitted to a vacuum pump which is then turned on. Once this stage has been reached, any leaks within the vacuum bag should be accounted for and sealed.

A combination of clamps and weights are then placed on the mold to ensure a tight fit and to physically squeeze out any excess resin from the composite. Figure 10 shows how the process should look like at this point.

Figure 10 an example of an I-beam beginning it's curing cycle.

It is important to check for any leaks or punctures caused by the weights or clamps at this stage before allowing the composite to cure.

The composite is then allowed to sit in the bag for 24 hours with constant suction, and then a further five days to allow it to cure properly. After the six days from layup, the I-beam can be cut in order to reach the 600 gram mass limit. The beams are cut so that the flanges are approximately and 1” wide and the entire beam are trimmed from both ends so that it is 24” long.

The beam is then allowed to dry over night from becoming wet due to the water from the tile saw. Once dry, the weight of each I-beam is recorded in grams and is tested using the Instron machine.

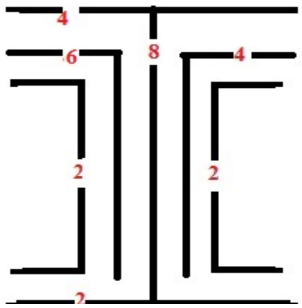

Figure 11 The fiber arrangement of the second beam

The second I-beam was made in the same exact way the first one was made, however the amount of fabric in the top flange and the web was increased by two extra strips on the top flange and four total on the web. Figure 11 shows how the fabric of the second beam was arranged. This beam was cut and fabricated exactly the same way as the first; however, the flanges were cut just under an inch in order to keep the weight at approximately 600 grams to compensate for the extra weight.

The subsequent I-beams took a different direction in terms of design. During testing of the first two beams, it was discovered that the I-beams were failing due to 1” deflection at the center, for this reason a method to make the I-beams more rigid was developed.

The idea is to take strips of bamboo and insert them in the web of the web to make the overall beam much more rigid. It should be noted that the proper orientation of the fibers of the bamboo is crucial as it is more resistant to bending in a one direction compared to the other.

For the third beam, approximately four strips of bamboo measuring approximately .5”x.3”x26” and laid one over the other in the web. In the third beam, the B section of material is completely excluded. Only three strips of material are put on the square beam, and an addition three strips are placed over that. The bamboo is carefully covered in resin and placed on one of the molds and the other identical square mold is placed over that and the bamboo is squished between that like in the first two beams. The top and bottom molds are then fixed with three strips of material on each and it is placed in the vacuum bag for curing exactly like with the first two beams. Figure 12 shows how the third beam is configured.

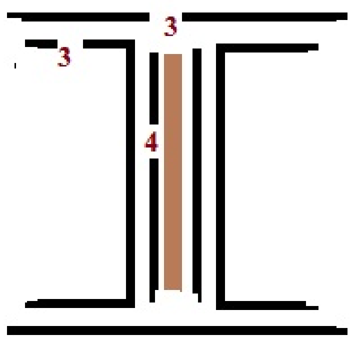

Figure 12 The configuration of the third I-beam. The brown segment denotes bamboo core.

The bamboo segments were fabricated by taking a stock of bamboo and cracking them into long strips. Each strip is then sanded down to ensure an even and flat finish for each part using a belt sander. Once each bamboo segment has been sanded, they are washed to ensure no interference between the resin and bamboo dust counter act the bonding properties of the resin. The fifth beam was an exact replica of the third I-beam.

The fourth I-beam was laid up just like the third and fifth I-beam, however the largest difference is instead of bamboo strips within the web of the beam, and a special truss was constructed as illustrated by figure 13. This truss is made so as to take the compression loading from the top of the beam and convert them to tension in the bottom of the beam where the composite is the strongest. To compensate for this transfer in loading, the bottom flange of the I-beam was increased in thickness.

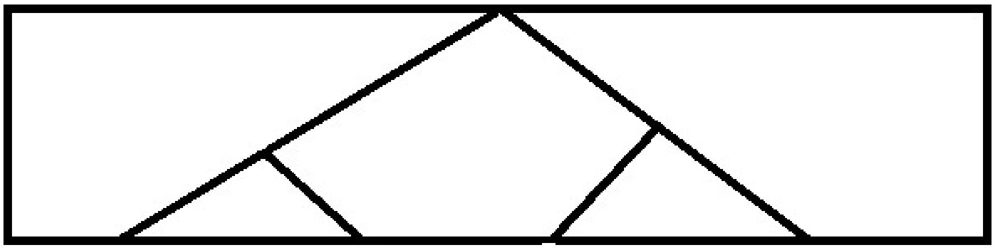

Figure 13 An example of the truss used in the fourth I-beam

The truss was created by wetting two 2.5”x26” pieces of hemp fabric and carefully laying down the bamboo design on one of the wet fabrics after the bamboo has been covered in resin. The second piece of wet fabric is placed over that, which is then placed in a vacuum. The suction from the top and bottom ensure equal compression on both side of the truss. A flat plate is then laid down over that, with weight on top to help flatten out the bamboo and apply additional pressure on the truss.

Once this has been allowed to properly cure, the truss section is cut to fit and wetted again with resin and placed in the web of the fourth I-beam during fabrication.

The fibers were laid up as shown in figure 14.

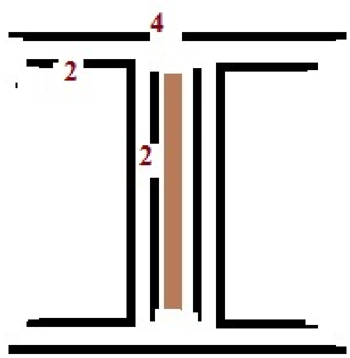

Figure 14 The layup of the forth I-beam. The brown segment denotes the bamboo truss

The final I-beam submitted for the competition was an exact replica of the fourth I-beam, as that was the found to be the most efficient of all the I-beam design tested. In order to make the weight limit of 600 grams, the corners of the flanges were sanded off.

To test the fracture mechanics of the composites used to create the I-beam, two separate I-beams were manufactured in the exact same method as the first I-beam, however, these beams measured only 10” long in compliance with ASTM standards[3] which specifies that the length must be of the sample must be four times larger than the height of the sample. One of the two beams, beam seven, was taken and had a narrow notch such as the one in figure 15 below cut into it using a tile saw. This notch measured approximately 1.125”, or 45% of the total height of the sample as specified by the standards. This notch is located in the middle of the beam.

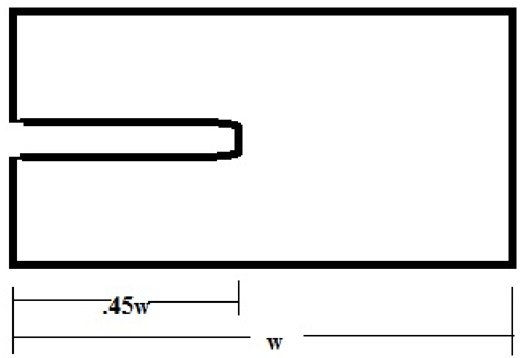

Figure 15 Notch cut into beam 7 to test fracture mechanics of composite

The second beam, labeled beam eight, was left as normal to act as the control. Both beams were tested using a four point bend using the Instron Machine just as the other beams were tested.

III. Analysis

Tensile testing done using the Instron machine recorded values of the force applied to each specimen, along with the strain. Using these values, the modulus of elasticity could be calculated by using equation 1 from above.

After these values have been calculated, a material from the samples can then be selected and used to create an I-beam. The I-beam undergoes several different stresses while subjugated to a three or four point bend. Such stresses include tension, and compression which are shown by equation 2.

(2)

Other stresses that the I-beam is subjected to include buckling (Note: The column is considered to be fixed, thus k=.5), bending, and shear. These stresses are represented by equations 3, 4 and 5 respectively.

(3)

(4)

(5)

Where the moment of inertia, I and the static moment of area, Q are equations 6 and 7 respectively.

(6)

(7)

It is important to note that to properly calculate the moment of inertia, I, one must use the parallel axis theorem which can be found below.

$$I_z = I_x + Ar^2, \tag{8}$$

To analyze the fracture mechanics of the hemp composites, the shear modulus of the fiber must first be calculated by using the max shear strength and strain.

$$G = \frac{\tau}{\gamma} \quad (9)$$

The stress intensity factor K can be calculated below

$$K = \sigma * \mathrm{sqrt}(\mathrm{pi} * \mathrm{a}) \quad (10)$$

Where σ is the bending stress calculated by using equation 4. Finally, the force which drives the crack to propogate, Gi, is calculated by the relationship of the stress intensity and Young's modulus.

$$Gi = K^2/E \quad (11)$$

Next, the life of the composite structure is to be calculate to see how many cycles the structure will go before failure after it has been subject to fracture. To derive an equation to come up with Nf, we begin with the relationship in equation 12.

$$\frac{da}{dN} = A(\Delta K)^3 \quad (12)$$

Where

$$K = \Delta\sigma * \mathrm{sqrt}(\mathrm{pi} * \mathrm{a}) \quad (13)$$

Thus, equation 12 becomes equation 14 after making the proper substitution.

$$\frac{da}{dN} = A(\Delta\sigma * \mathrm{sqrt}(\mathrm{pi} * \mathrm{a})\ )^3 \quad (14)$$

If we rearrange the variables, we can take the integrals of both side in terms of the life of the structure and the crack length, respectively.

$$\int_{Ni=0}^{Nf} dN = \int_{ai}^{af} \frac{da}{A(\Delta\sigma * \mathrm{sqrt}(\mathrm{pi} * \mathrm{a})\ )^3} \quad (15)$$

After integration we end up with equation 16, where A is the constant 1.5e-6 ($\frac{in}{cycle*sqrt(in)}$), and ai and af are the initial and final crack lengths.

$$Nf = \frac{2}{A * \Delta\sigma^3 * \mathrm{pi}^{1.5}} * \left(\frac{1}{\mathrm{sqrt(ai)}} - \frac{1}{\mathrm{sqrt(af)}}\right) \quad (16)$$

The only thing left to do is calculate the final crack length, which is done taking equation 17 and rearranging it into equation 18.

$$K = \sigma * \mathrm{sqrt}(\mathrm{pi} * \mathrm{af}) \quad (17)$$

$$af = \frac{1}{pi} * \left(\frac{k}{\sigma}\right)^2 \quad (18)$$

IV. Results and Discussion

In this experiment, seven different natural materials were chosen as candidates to choose from to create an I-beam to compete in the 2012 SAMPE bridge competition. These materials where linen, cotton, silk, jute, hemp, bamboo, and a cotton bamboo blend. The mass to area ratio of each fiber is shown in table 2 below.

Material	(g/in^2)
100% Linen	.234
100% Cotton	.220
100% Chinese Silk	.0598
100% Jute	.510
60% Cotton, 40% Bamboo Blend	.201
100% Hemp	.406
100% Bamboo	.279

Table 2.

As you can see from the data above, silk is the lightest of all the material selected. It should be noted however that silk is also the thinnest of all the material. This means that many more layers of material are required to produce the same I-beam that the other materials would. This in turn drives up the cost of silk material already which excludes it from the final selection process, however, the silk was still tested using a tensile test in order to compare it with the other material.

Each of the samples that were tested in accordance with SAMPE standards were cut into long strips approximately 1"x10" called coupons. Under ideal conditions, these coupons should snap in the middle when placed under tensile testing. Many of the coupons however broke near the end right on the tabs which would invalidate the results of those samples.

Figure 16 shows the bamboo/cotton blend coupons after testing. All with the exceptions of specimen four snapped at the middle. It is important to note however that during the layup process, several defects were apparent after the curing cycle had completed. Wrinkles in the coupons had formed due to a lack of proper pressure on the samples which caused massive stress concentrations within the specimens. It is at these stress concentrations the samples experienced failure.

Figure 16 Bamboo/Cotton blend coupons

Figure 17 is the linen coupons. These specimens had no wrinkling in them, however all but one sample yielded invalid results due to failure within an inch of the tab.

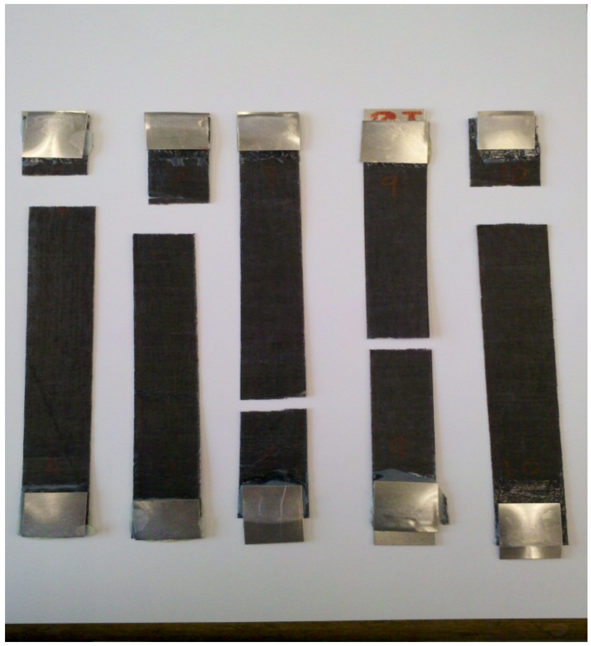

Figure 17 Linen coupons

The silk samples suffered from massive amounts of wrinkling. It should be noted that due to the frail nature and thinness of the material, it was extremely difficult to properly layup the silk samples. These wrinkles appeared mostly due to operator error during the layup process.

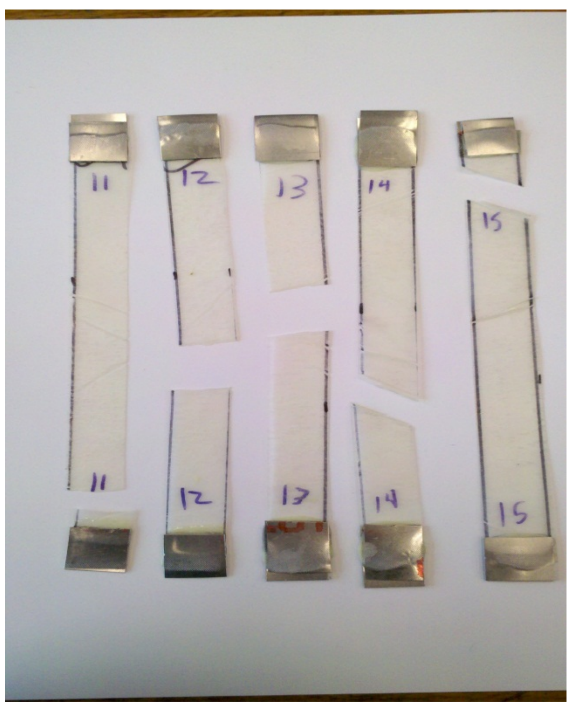

Figure 18 Silk

As with the linen samples, the cotton samples displayed no wrinkling like the silk and bamboo/cotton blend, however the majority of the coupons managed to break within an inch of the tab, only specimen 20 yielded usable results.

Figure 19 Cotton

` The jute samples had no wrinkles, and yielded two usable samples.

Figure 20 Jute

The pure bamboo samples only yielded a single usable sample.

Figure 21 Bamboo

The hemp samples only provided two usable samples from which data could be extracted from.

Figure 22 Hemp

Using the usable samples from the coupons, the Young's modulus was calculated using equation 2 above, and equation 19 below.

$$E = \frac{\sigma}{\epsilon} \tag{19}$$

The data is compiled below in table 3.

	Cotton/Bamboo	Cotton	Bamboo	Hemp	Jute	Linen	Silk
Young's Modulus (psi)	3.297e5	3.472e5	3.803e5	3.9579e5	5.336e5	3.741e5	3.674e5

Table 3

From Table 3, it is apparent that Jute has the highest value for Young's modulus, however, it is also the heaviest of all the fibers tested, thus Hemp was chosen not only for having one of the highest value of Young's modulus, but because it is not too heavy, and more importantly it is the cheapest at $11/yard^2.

The stress-strain curve for hemp as appears below in figure 23. To see the stress-strain curve for the other materials, please refer to the appendix.

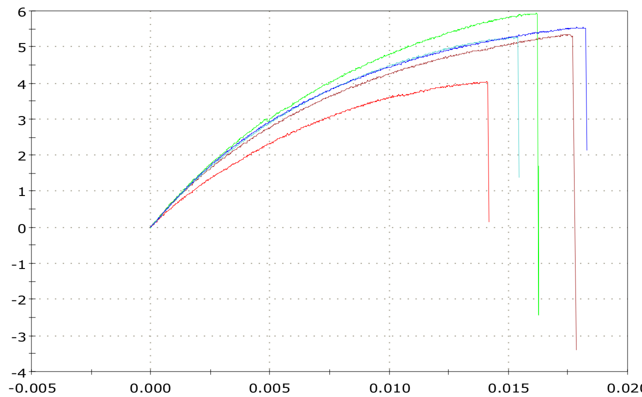

Figure 23 Stress-Strain curve for hemp

After the material has been selected, the I-beams were created. The first I-beam had a very rough finish due to it being the first trial run in creating an I-beam. There were many defects within the beam, including air pockets and dry spots on the sides of the web. The dry spots are likely due to a lack of sufficient resin during the layup process and the air pockets are due to improper layup technique. Figure 24 shows an example of one of the air pockets found in the first I-beam.

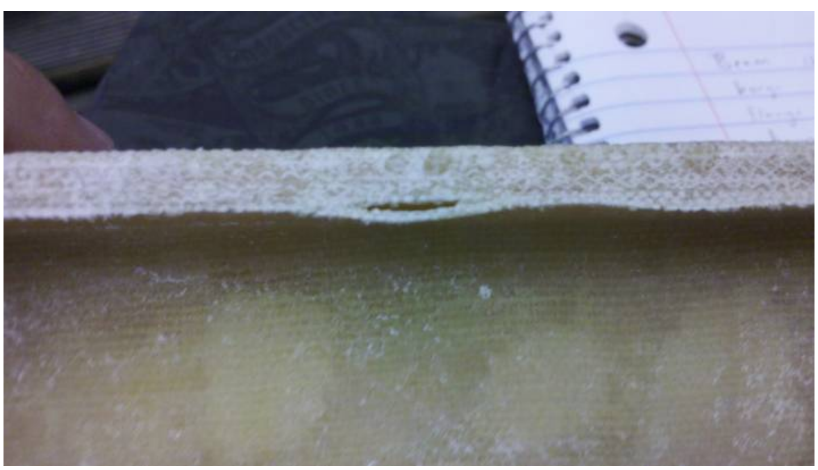

Figure 24 Air pocket found in I-beam 1.

The first I-beam weighed 699 grams and only held up 1260lbs before reaching failure due to 1" deflection. The second I-beam displayed none of the defects of the first I-beam since the manufacturing process was perfected at this point. This I-beam was made as an exact replica of the first. It weighed 630 grams and held up 1492 lbs. Just like the previous I-beam, it failed due to 1" deflection. It is apparent at this point that something had to be done in order to make the I-beams stiffer in order to prevent failure from deflection.

The third I-beam was created with a bamboo core in the center of the web using four strips of bamboo fashioned from a bamboo stock. This beam however was not allowed to properly cure due to time constrains. It weighed 679 grams; however it failed at 1400lbs due to deflection. The fifth I-beam was constructed in the same manner as the fourth beam, however this time it was allowed to cure properly. This time the I-beam using a bamboo core held 1490lbs and failed due to fracture at the center of the beam.

The breakthrough in design came when the bamboo core was instead substituted with a truss system made from bamboo. This bamboo truss takes the compression forces at the top half of the beam and transfers them to tensile forces at the bottom. The fourth beam utilized this design and as a result held 2177 lbs. before failing due to fracture while only weighing in at 629 grams.

The sixth I-beam that was submitted to the SAMPE competition was a clone of the fourth I-beam, however this I-beam only held 1600lbs while weighing in at exactly 600 grams. One possible reason the sixth I-beam was loaded differently at the SAMPE competition. Whereas all testing done here at Cal Poly was done with the Instron machine configured for either three or four point bending tests, the SAMPE competition was done using a square fixture which distributes the forces more evenly when compared to the three and four point bending tests.

To test the fracture mechanics of the hemp composites, a three point bend was conducted on an I-beam in order to see how the composite behaves once a fracture is introduced to it.

The beam with the fracture was tested first, it held only 500lbs before completely failing. The one without the fracture held approximately ten times that much. Figure 25 and 26 show the cracked and control specimens respectively.

Figure 25 Fracture at the center

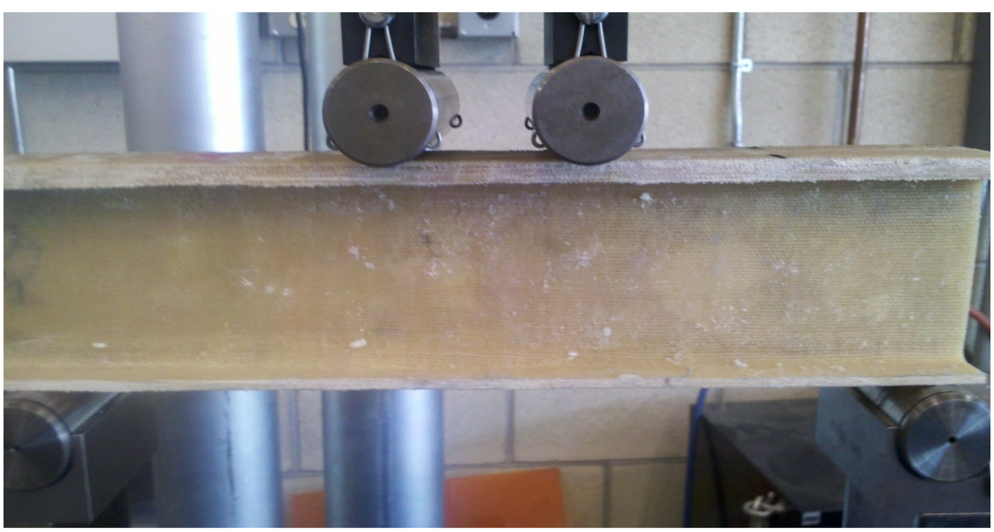

Figure 26 Control specimen

Notice in figure 25 that the crack further propagated at 500lbs. It was calculated the force propagation to further extend the initial crack of 1.2" was only 3842 lbs/in. This is a very low value, however, being that the initial crack is so large, it is not unusual.

The life cycle of the product with such a large is extremely low, the Nf value calculated was 2.66x-7. This value also appears low, however keep in mind that the crack is so large, under the loadings the I-beam underwent, it could not take a second loading. For this reason the life cycle is approximately zero.

V. Conclusion

Many naturally occurring fibers were tested and it was discovered that hemp proved to be the strongest under tensile loading. Based on this knowledge, construction of an I-beam was done in order to compete in the international SAMPE bridge contest. This year Cal Poly placed third in the natural I-beam category overall, holding only 1600lbs before failure. The two bridges that beat it were constructed of many very thin layers of wood using natural glue.

It can be concluded that while hemp composites does achieve its goal of becoming a strong and durable all natural product able to withstand large amounts of tensile forces, however, the product fails in many areas. It is extremely elastic, and in this scenario, many I-beams failed due to a one inch deflection under load. To counteract this, bamboo was introduced to the structure, however this further complicates the manufacturing process and increases cost. The wooden I-beams of the competition are much more practical and cheaper to produce and have the added benefit of being much stronger when made into an I-beam.

When the composite underwent fracture testing, it acted much like a fabric in that once a crack was introduced to the structure, it propagated by ripping through the materials rapidly, this is mostly due to the natural elasticity of the composite itself which does very little to resist pure bending.

It can be said that hemp composites are second to none when they are only loaded under tensile stress. Tensile tests done in the laboratory show that the hemp composites displayed the greatest Young's Modulus of all the material tested, while still retaining a respectable mass that was not overtly heavy when compared to other material. In addition, it is relatively cheap to produce when compared to traditional composites such as carbon fiber or fiber glass.

The greatest attribute to the hemp composites developed here at Cal Poly is they are safe to manufacture and safe to hand for the entire lifetime of the product and are environmentally friendly.

Appendix

A. Raw Data

Sample set of cotton specimens.

	Specimen label	Maximum Load (lbf)	Maximum Tensile stress (ksi)	Extension at Maximum Load (in)
1	Specimen 16	149.54552	6.56333	0.15592
2	Specimen 17	179.40531	5.56192	0.13928
3	Specimen 18	162.66110	6.99603	0.30062
4	Specimen 19	139.69677	4.18755	0.14058
5	Specimen 20	166.40229	6.93343	0.16288
Mean		159.54220	6.04845	0.17986
Standard Deviation		15.37129	1.18805	0.06825
Coefficient of Variation		9.63462	19.64219	37.94852
Mean + 1 SD		174.91349	7.23650	0.24811
Mean - 1 SD		144.17091	4.86040	0.11160

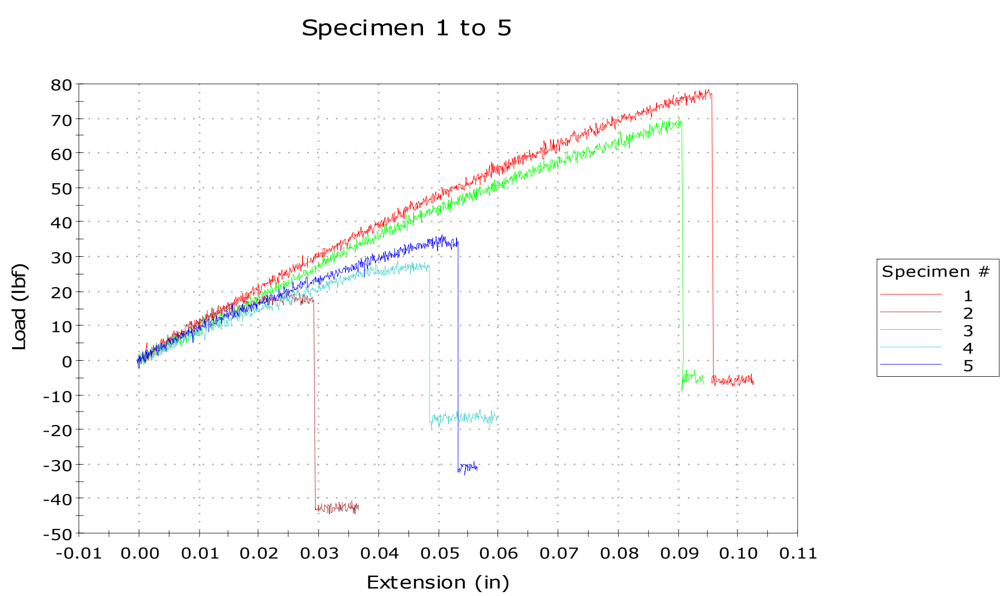

Figure 27 Bamboo/cotton stress-strain curve.

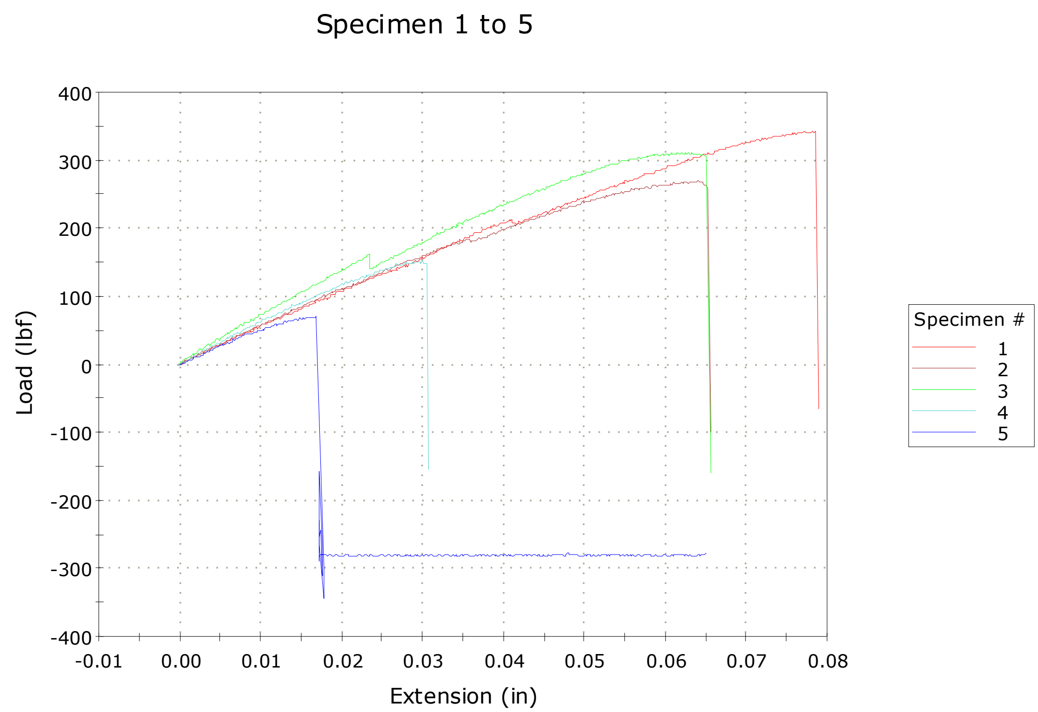

Figure 28 Bamboo stress-strain curve

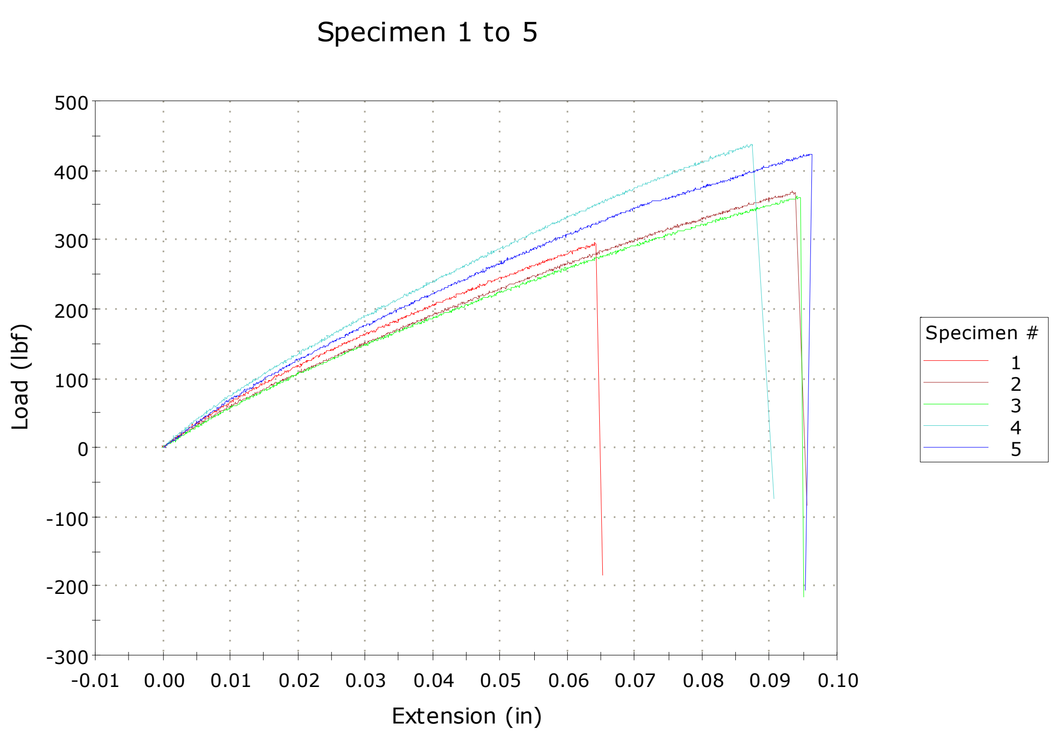

Figure 29 Jute stress-strain curve

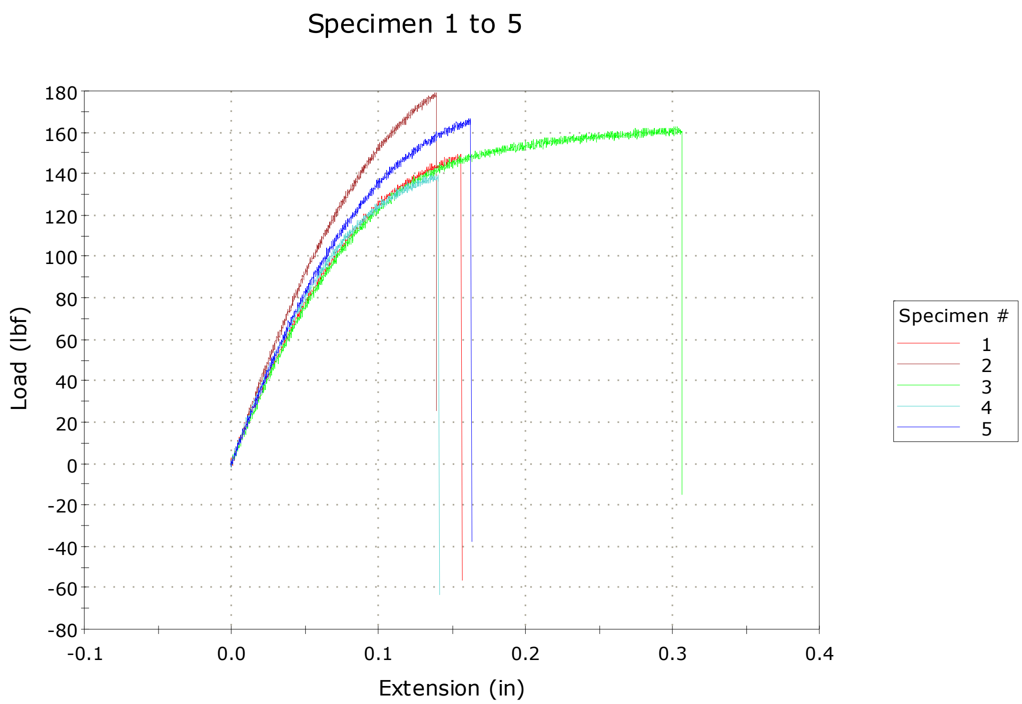

Figure 30 Cotton stress-strain curve

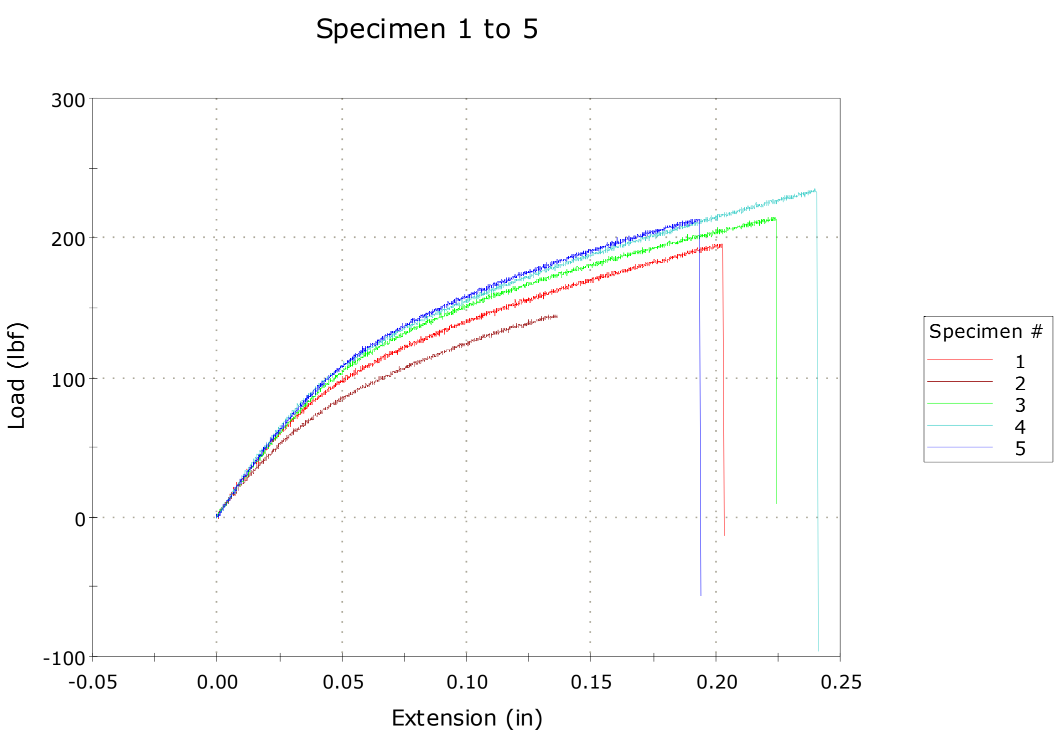

Figure 31 Linen stress-strain curve

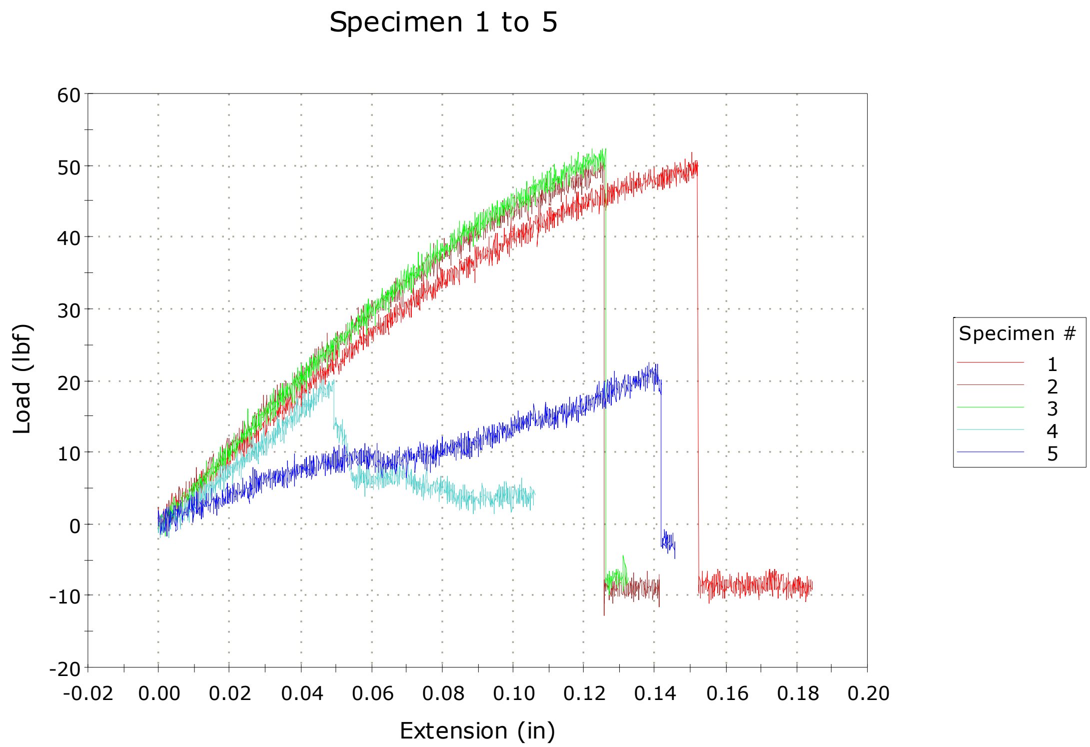

Figure 32 Silk stress-strain curve

B. Sample Calculations
See Attachment

References

[1] ASTM E8 / E8M - 11 Standard Test Methods for Tension Testing of Metallic Materials

[2] ASTM D790 - 10 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

[3] Standard Test Method for Crack-Tip opening displacement (CTOD) Fracture toughness Measurement

[4] Properties of hemp fiber polymer coposites.