Design of Natural Composite Beam for SAMPE 2019

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INTRODUCTION:

A composite material is a material resulting from two or more different materials with significantly different physical or chemical properties that, when combined, produce a material with characteristics superior to those of the original components in specific applications. [1] The properties of the composite allow the material to be used in applications where the individual components would have otherwise failed. As technology advances and industries such as aerospace, robotics, civil structures, prosthetics, marine and automotive develop, there becomes a need for better materials that can withstand stresses other materials cannot while maintaining a high strength to weight ratio. Due to this demand, advanced fiber-reinforced composites have developed to meet the needs of the industries. These applications require lightweight materials with high specific strengths, high specific stiffness, excellent fatigue resistance, and outstanding corrosion resistance compared with metals such as aluminum or steel. [2] Fiber-reinforced composites get their strength through the fibers that are laid within a polymer matrix. The fibers have a much higher strength and modulus than the matrix, allowing them to become the load bearing component. The matrix serves to hold the fibers together, bonding them, and distributing the forces through the matrix to the fibers. The primary advantage to these types of composites is their high specific strength and high specific modulus. The specific strength is the ratio of specific strength and density and the specific modulus is the ratio of modulus to density. These high properties are a result of the high performance, low density reinforcing fibers. [3]

The problem with commonly used composite materials such as carbon fiber or fiberglass is that they are energy intensive to produce the fibers and the resins that make up the matrix. Fiberglass consumes much less energy during production but is heavily dependent upon the process used to manufacture them. Large manufacturers can produce glass fibers much more efficiently but varies greatly based on the process. [4] Fiberglass is relatively inexpensive but has a higher density than other composites. Carbon fibers are much more energy intensive to produce and are derived from petroleum, are not easily recyclable, and do not decompose readily. The energy intense process causes carbon fibers to be the most expensive of the group. The need for use of sustainable, natural fiber-reinforced composites is clear. Sustainability refers to the materials environmental and public impact it causes throughout its life cycle from raw material to waste. It also considers how its usability now will affect its usability later and ensures it will remain an accessible and economical option. By using flax fibers pre-impregnated with a plant derived bio epoxy, the flax composite is more sustainable and does not face many of the environmental issues that traditional materials face. Table 1 shows how energy intense the fibers and polymers are for some commonly used composite materials. Flax fibers would also cost much less as the process to manufacture is relatively simple and cheap. The environmental issues extend to health hazards as well with some of the polymer uses. Epoxy resin and its curing agents have been found to be toxic to human health before being cured and is often used for fiber-reinforced composites. [5]

Table 1: Energy Content of Various Materials [4]

Material	**Energy intensity (MJ/kg)**
POLYMERS	
Polyester	63-78
Epoxy	76-80
LDPE	65-92
PP	72-112
PVC	53-80
PS	71-118
PC	80-115
FIBERS	
Glass fiber	13-32
Carbon fiber	183-286
China reed fiber	3.6

Flax fiber	6.5
METALS	
Aluminum	196-257
Steel	30-60
Stainless Steel	110-210
Copper	95-115
Zinc	67-73
Cast Iron	60-73

Flax fiber is a great alternative to glass fibers. Flax has a low cost, requires much less energy to produce, is readily available, renewable, and will easily biodegrade. Flax is a sustainable material taking only 100 days to grow, being very efficient in water usage and grows in long continuous fibers making the manufacturing less labor intensive. [6] It has been used for thousands of years to produce linen and recently in the composites world. The process to produce flax fibers is a CO2 negative process and can be thermally recycled as opposed to glass and synthetic fibers where there exist many problems when trying to thermally recycle. When compared to glass fibers, flax fibers have a much lower tensile strength at 344 MPa compared to 3400 MPa. The modulus of the two are comparable at 72 GPa for the glass and 27 GPa for the flax. When the specific properties are looked at though, the specific modulus (modulus/specific gravity) is higher for the flax at 50 compared with the glass fibers at 28. [7] This makes the flax a great alternative E-glass where lightweight is desired but high strength is still required. For these reasons, a movement could occur to replace traditional fiberglass used in many applications with flax fiber reinforced composites. Figure 1 below illustrates how flax fibers compare with wood and fiber glass.

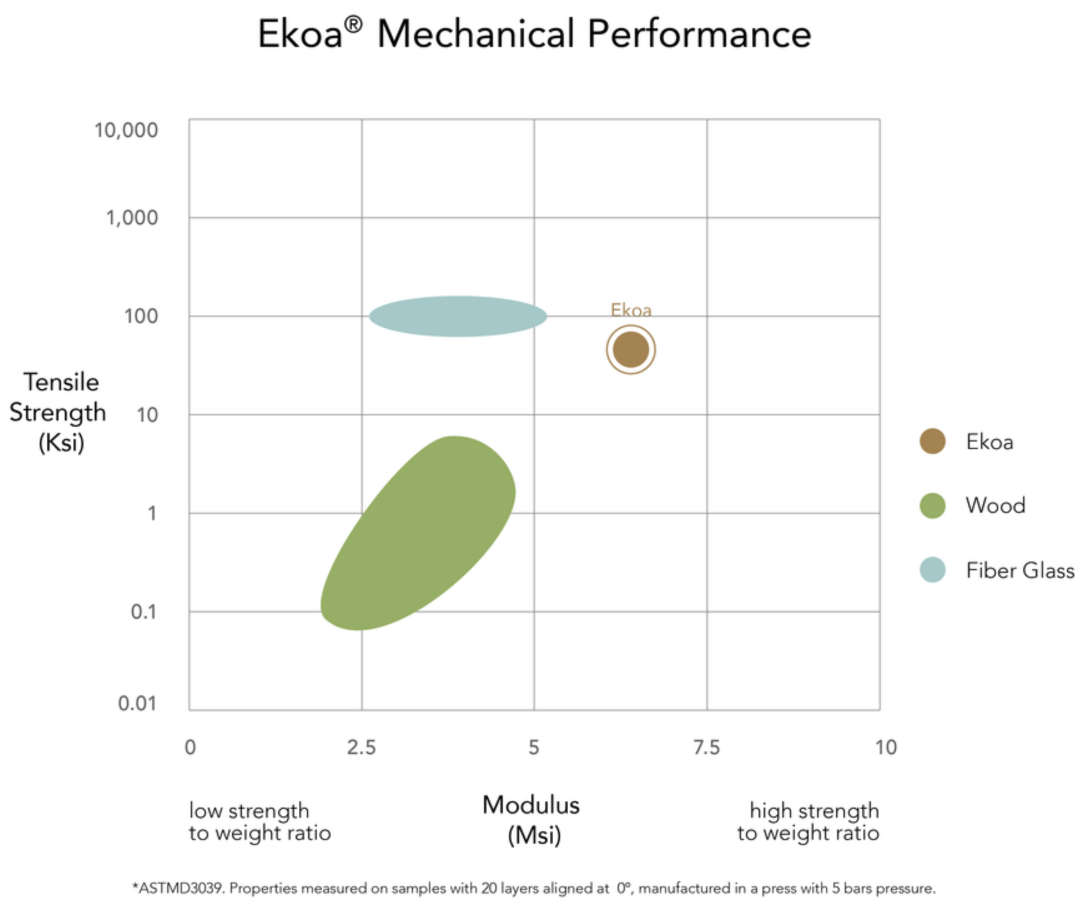

Figure 1: Ashby Diagram of Flax Compared with Fiber Glass and Wood [8]

Epoxies used in producing fiber reinforced composites are generally not environmentally friendly either. Most epoxy resins in the market are petroleum based. Overall, 90 billion pounds of petroleum-based polymers are used in various industries such as coatings, textiles, and automotive; and production of the mentioned number of polymers requires 300 million tons of the oil and natural gas world supply. [9] The need for a more environmentally friendly epoxy is clear. By producing a bio-based epoxy resin, Entropy Resins was able to reduce the greenhouse gas emissions from production of their resins by 33% over conventional petroleum-based resins. [10]

Current uses of theses natural fibers exist in the sports equipment industry, in musical instruments, and in the automotive industry. [11] Flax's secondary properties are as appealing as its mechanical properties due to its sound absorption and vibration dampening abilities. It has been experimentally proven that flax fiber reinforced composites have a 21.5% and 25% better sound absorption coefficient at higher frequency (2000 Hz) and lower frequency (100 Hz) than glass fiber reinforced composites and 51% higher vibration dampening. [11] These properties make flax a possible alternative to fiberglass for musical instruments and automotive interior door panels where sound dampening is desirable. Currently many European automotive manufacturers are utilizing flax fibers in production vehicles [10]

The Society for the Advancement of Material and Process Engineering (SAMPE) is an international professional organization providing educational opportunities and knowledge on new and developing manufacturing processes and materials through several sources. Since 1998 SAMPE has hosted a competition that allowed students to design, analyze, manufacture and test a section of a bridge at the annual spring SAMPE Convention. This competition consists of different categories varying through the years of either I-beams or square beams made from carbon, glass, or natural fibers. SAMPE provides an opportunity for students to learn about the design and manufacturing of composite materials.

To show that natural fibers can be applied to producing a lightweight load bearing product where carbon fiber or fiberglass may traditionally be used, an I-beam made of natural materials will be designed, constructed, and entered in to the 2019 SAMPE Bridge Competition in Charlotte, North Carolina. The competition requires that the beam be constructed from natural fibers and a natural core and must be able to withstand a load of 3,000 lbf under a three-point bending. The beam being entered must have a 4”x4” cross section and be at least 24” long while maintaining as low of a weight as possible.

The beam will first be designed, manufactured, and finally tested. The design will be done in such a way to utilize past years methodology and techniques and improve upon already optimized beam designs. The manufacturing of the beam will be completed in the Union College Materials Lab while facing challenges regarding the tooling and process necessary to complete the beam. Testing will then occur on a preliminary manufactured beam, which will serve as a learning tool, to further improve upon up to the final testing of the beam at the SAMPE competition.

BACKGROUND:

In order to effectively produce the I-beam for the 2019 SAMPE competition, the following will have to be taken into consideration. The material being used must be carefully chosen for the beam, then optimization must occur in the design to be a competitive contender in the competition. Finally, the tooling to complete the manufacturing will have to be considered to effectively produce the designed beam.

Beam Design

When loads need to be supported, I-beams are often used. I-beams are great at holding loads while maintaining their strength and geometry at lower weights than solid members. The I-beam consists of two parallel horizontal pieces called flanges connected by one vertical piece in the center called the web. A typical load will apply force on the beam in the center and be supported on the ends. As the load increases, the beam will begin to bend, putting the top flange in compression and the bottom in tension. There is an area along the center which does not experience compression or tension known as the neutral axis. The further away from the neutral axis toward the flanges, the higher compression or tension until the maximum at the very top or bottom. For this reason, the flanges of the beam carry most of the load in normal bending stress. Figure 2 illustrates the normal bending stresses on the loaded I-beam.

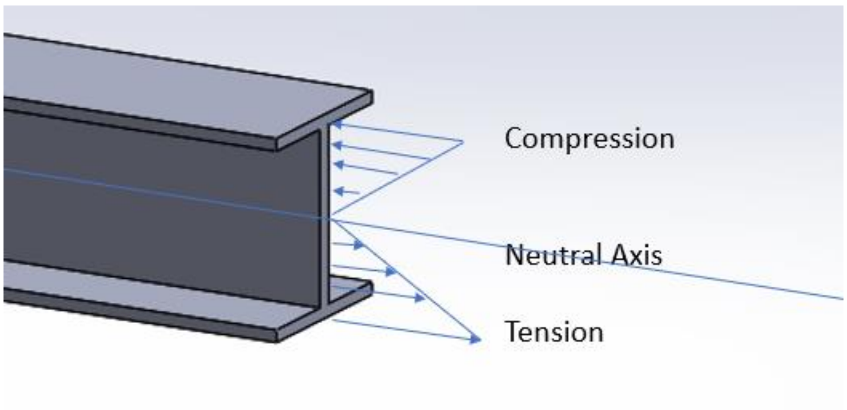

Figure 2: Normal Bending stresses on I-Beam

The web must be considered as well even though it does not see as much normal stress. As the beam begins to bend, the beam is subjected to shear stress becoming greatest at the neutral axis at an angle of 45°. These shear stresses are horizontal stresses along the web of the beam and differ in magnitude as the location up or down the beam change. For this reason, the web of the beam must be enough to support the shear stresses.

The beam being built for the SAMPE 2019 Bridge Contest natural fiber category will consist of a natural fiber laminate wrapped around a natural balsa core. Core materials are needed in composite manufacturing because the fiber laminate has highly anisotropic mechanical properties. In other words, the laminate can handle stresses very well, primarily tension, but only in a specific direction. Core materials are then needed to handle the remaining compressive and shear stresses.

Past Designs

Past designs of beams produced for this competition have failed in the web section of the beam due to shear stress. Due to this, in 2015 Ryan Granger optimized the core thickness. Using Solidworks modeling, Ryan was able to run simulations to determine both the web and flange thickness for the balsa core. He ran simulations using a thickness of 1/8” up to 3/8” in increments of 1/8”. He determined that shear stresses were minimized when a thicker web material was used and that the best choice for the web should be 3/8” balsa. 1/4” Balsa was determined to be used for the flanges. [12]

In 2017 Evan Armanetti optimized the beam design further using Ryan’s optimized core. Again, using Solidworks modeling, Evan was able to determine weight was able to be reduced from the beam by drilling holes near the neutral axis, since normal stress is minimized in that location. He also determined that material was able to be removed from the flanges near the ends of the beam where stress is also minimal. Figure 3 shows the optimized design with stresses shown using Solidworks finite element analysis.

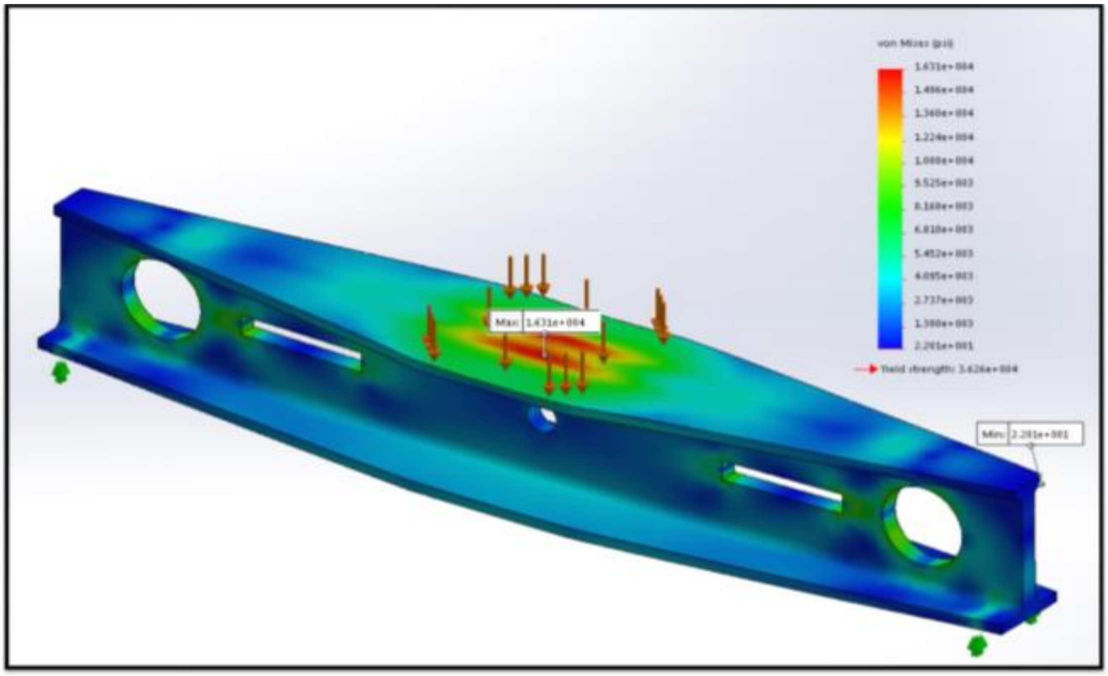

Figure 3: Evan Armanetti's optimized beam design [13]

Sustainable Material Options

When considering a natural, sustainable material to be chosen for the bio-composite that the I-beam for SAMPE will be built from, there are many options. These consist of flax, jute, hemp, rice straw, banana, sugar cane, cotton, silk, oil palm, and sisal to name a few. Of the ones listed, flax and hemp have the highest specific moduli, exceeding that of commonly used E-glass. Both options could serve as suitable replacements for glass fiber composites with the same performance at less weight. [14] Figure 4 below illustrates how flax fibers compare with many other natural materials. Both flax and heme are sustainable, economical options but flax fibers were chosen due to availability of manufactured prepregs.

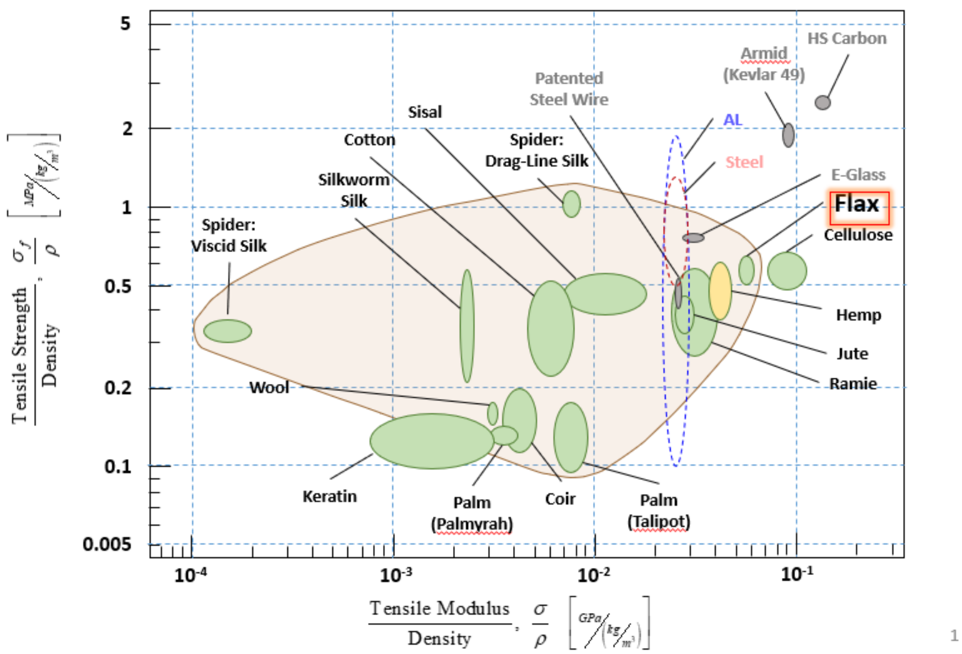

Figure 4: Ashby Diagram of Natural Fibers [15]

Flax fibers pre-impregnated with a plant derived bio-epoxy will be used for the beam. Lingrove is a composites company based out of California and will be producing the prepreg for the project. The company started out making guitars from the flax due to their great sound dampening properties but have more recently started selling their prepregs to consumers for other uses and teamed up with Entropy Resins for the bio-epoxy.

The process of pre-impregnating the fibers with the bio-epoxy has many advantages. Prepregs allow for the hand layup of composite parts without having to worry about an improper resin content, less waste, and more uniform parts. An improper resin to fiber content could lead to reduced mechanical properties or brittleness in the matrix.

Failure Methods

Since the laminate has anisotropic properties, it is important to lay the fibers in proper directions to mitigate the stresses formed in the beam under loading. Lingrove produces multiple flax prepregs available for this reason. A biaxial layup will be used for the web to prevent failure due to normal and shear stresses. A biaxial layup will have the fibers oriented 90° apart from each other and will allow for the stresses to be carried out by the fibers. Because compressive and tensile stresses are carried through 0° fibers, some layers will be oriented in that direction. Other layers will be oriented at a 45° angle to mitigate the shear stress that will build up in the web. The flanges of the beam will see minimal shear stress and therefore primarily unidirectional prepregs will be used.

During loading, failure could occur in the beam in several ways. Compression could occur on the spot being loaded, fibers could break in the matrix, micro cracks could develop in the matrix, or delamination could occur. The beam could fail in compression at the location being loaded. Proper core materials and dimensions are selected to prevent this from occurring. One problem with natural fibers is that not all fibers have the same properties. Because of this one fiber could break at much less than the tensile strength, the total stress would then be distributed through the matrix to the other fibers. Once too many fibers break, the unbroken fibers can no longer handle the load and the beam will fail. [16] Micro cracks begin to occur in the resin matrix where stresses are not aligned with the fibers. These cracks will also occur when the strain of the laminate exceeds what the resin can handle. Delamination can occur due to poor bonding between the layers of fibers or repeated cyclical stresses and strains. Wetting of the fibers is another problem that also leads to premature failure in composite parts. If the fibers are not sufficiently wetted by the resin being used, the stress will not be distributed through the matrix properly. Lingrove takes care of these problems by carefully selecting the resin used in their CPM resin system and problem. Their Super Sap CPM resin has excellent wetting properties and thixotropic characteristics to limit sag in high temperature curing. A high modulus combined with excellent elongation properties enable durable yet lightweight products.

Manufacturing and Tooling

The process for fiber reinforced composites starts with the core. Once the core is designed and built it can be covered with a thin shell of the fiber reinforced prepreg. The prepreg is laid on the core in the directions to handle the stresses from loading, then goes through a process called vacuum bagging. The process applies an evenly distributed pressure in the fiber matrix and ensures that adequate bonding will occur between the layers. The vacuum bagging process also removes any trapped air that may still exist in the piece and removes any moisture around the work piece. The process begins by applying a peel ply to the work piece. This will ensure an easy removal of the bagging and associated cloths once cured. On top of the peel ply goes a bleed cloth. This bleed cloth will absorb any excess resin that may come out the laminate once pressure is applied. This is also beneficial to the piece to ensure that excess resin will not cause premature failure. The bagging creating the pressure boundary is then wrapped around the piece and sealed up using tape. A valve is installed in the bagging to hook up to a vacuum pump. The piece is then depressurized and placed inside an autoclave or a large pressurized oven. The autoclave can provide the temperature necessary for a strong resin cure and pressurize the surrounding area. This can further remove trapped air and make for a stronger piece with less risk of delamination.

While in the autoclave, the beam requires tooling to hold the flanges apart and prevent them from becoming italicized. The tooling used for this is 2 pieces of 1/2” aluminum with screws threaded into a coupler. The tooling used in the past is cumbersome and difficult to use as the screws cannot be adjusted while the tool is installed into the beam. To fix this problem the adjustment screws need to be changed over to a left-hand to right-hand turnbuckle. This will make for easier adjustability and ultimately allow for a better finished product.

The design and optimization portion of this project is being completed using Solidworks finite element analysis. Using designs created in past years, the beam design will be further optimized fail just above the design load of 3000 lbf. Evan Armanetti’s project in 2017 held almost double the design load before failing. This project is also using a different manufacturer of the flax prepreg than past years to utilize their bio-epoxy. Using their prepregs, the capabilities of not only the sustainable flax fibers but also a plant derived epoxy will be proven.

DESIGN SPECIFICATIONS:

This section will break down the requirements and specifications of the 2019 SAMPE Bridge Competition set by the SAMPE governing committee. This includes specifications for bridge geometry, building materials, means of loading, and an explanation of the judging that will occur to determine a winner. This list of specifications and requirements must be met to participate in the competition. The reliability and ease of production will also be discussed in this section.

Specifications and Requirements

The first thing SAMPE requires before entry into the bridge contest is a proposal submitted to the Governing Committee for approval. This should consist of a title page with unique identifying information such as name, registration number, school, advisor name, and contest category. The proposal will also contain a one-page description of the analysis used to design the beam and the manufacturing process used to manufacture the beam. Lastly the proposal will contain a drawing of the bridge and the materials used to construct it. The proposal will then be approved by the Governing Committee or sent back for revision.

The bridge being built will be entered in to the natural fibers category. The fibers and core materials being used must be naturally occurring. The beam can be built in the form of either a square beam or an I beam and will be subjected to a design load of 3000 lbf. Any beam that will not hold up to 500 lbf will not be judged. The beam will be loaded up to 3000lbf using a modified 3-point bend on 23” centers and must be designed to be used in this fixture. The loading frame will consist of a 4x4 block applied on center of the produced beam supported by 2-1” round supports spaced at 23”. An example of this fixture can be seen in Figure 5.

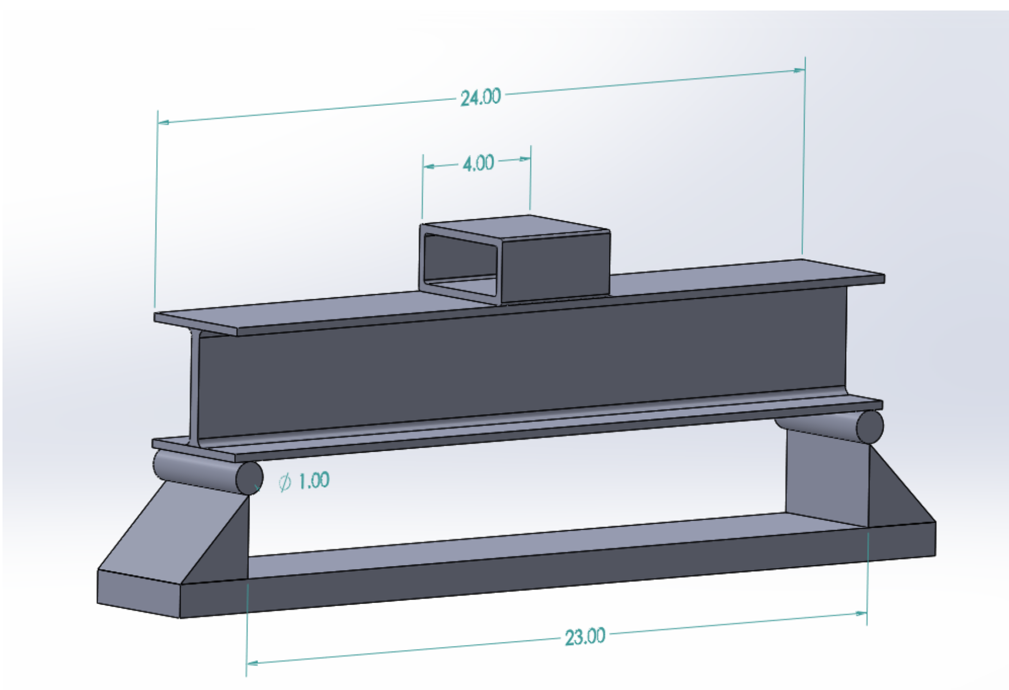

Figure 5: Beam Loading Fixture

The beam must be at least 24” in length and must be a structurally continuous length. The beam must be less than or equal to 4” height by 4” width and the I beam must have a single web less than or equal to 0.6” thickness. The caps may be different lengths, widths, or thicknesses, but the bottom cap must be 24” in length. Cross section may vary along the length of the beam and does not have to follow centerline if all required dimensions are maintained. The maximum radius of the web-to-cap fillet is 0.5”and caps may be no greater than 0.375” thick. Figure 6 illustrates the constraints for I-beam geometry.

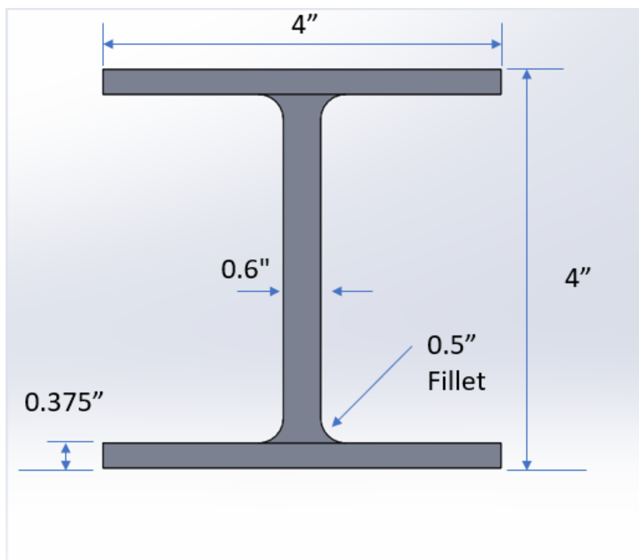

Figure 6: I beam geometry

The beam will be evaluated based on the maximum compressive load the beam will hold up to the design load of 3000 lbf. If there are multiple beams that withstand the design load, beam weight will be used as a tie breaker. This is not a ratio of maximum load to beam weight, but rather just minimum weight. Therefore, no benefit exists from designing a beam that will withstand greater than the design load.

SAMPE also requires that each student submits a poster presentation highlighting some material, process, or design aspect of their beam. The poster should also document the manufacturing process used in production of the beam. The poster must be 24”x36” landscape format and should be submitted at least one week prior to the SAMPE Conference. The poster will be judged on the depth of technical content, effective use of images, readability, presentation and layout, and the relevance to the beam entry.

The production of the items required by SAMPE are all very achievable. The I beam design was chosen to be entered in the competition due to ease of manufacturing and high functionality as discussed in the prior sections. Other beam geometries were considered in the initial phase of the project, such as a curved I-beam or square tube beam, but due to difficulty of manufacturing it was determined to use a traditional I-beam geometry. The ability to manufacture the beam is key to a successful project as all the modeling being done is based on no manufacturing errors and ability to effectively produce the model.

Reliability problems arise with an increasingly difficult beam geometry. The beam will need to be supported while in the autoclave and specialized tools would need to be produced to help it maintain its shape. If this was completed and the tooling was available to maintain the shape, difficulty of proper vacuum bagging, and flax prepreg layup could lead to premature failure due to delamination or matrix failure.

Use of a traditional I-beam allows for the flax prepregs to be easily laid up, and tooling exists to maintain beam geometry while in the autoclave. Vacuum bagging can easily be achieved and will result in a beam that will perform as expected without the fear of premature failure due to manufacturing errors.

FEASIBILITY:

This section will discuss the production of the I-beam and will determine its feasibility. The means of design, producibility, material procurement, and optimization will all be examined and determined to be a very feasible task.

The design can be pre-determined and simulated loadings can be applied using Solidworks. The balsa core can be easily produced as the core is held together with wood glue and can be simply clamped in the I-geometry while the glue dries.

All equipment needed to produce the beam is available in the Union College Composite Materials Lab. This includes the autoclave to apply heat and pressure to the beam while the resins cure, the vacuum pump to assist in applying equal pressure to the flax prepregs while curing, and all necessary consumables used in the production of the beam. The tooling used to maintain beam geometry also was already available but was difficult to use as discussed in the prior sections. This was modified to result in less manufacturing error and achieve a better resulting product.

Obtaining the flax prepreg material is also very feasible. The supplying and producing company are United States based, located in California, making the acquisition of the material much simpler than in past years when the material was obtained from a company in France. The flax fiber material comes already pre-impregnated with their bio-epoxy in optimal proportions. This avoids issues with wetting or overuse of epoxy which could also lead to premature failure.

Once the beam is cured with the flax fibers applied, weight can be removed with simple tools and ease as the flax and epoxy cut with similar characteristics to wood. There exists minimal hazard with dust or tool damage as does with other composites such as carbon fiber because of this. The environmental risk also makes this project feasible due to the advantages of flax composites and bio-epoxy as discussed in prior sections.

As the above states, the production of the I-beam for the 2019 SAMPE bridge competition is very feasible. The designs used and completion of the project will be discussed in the following sections.

PRELIMINARY DESIGN:

This section will discuss the design approach that went in to the production of the 4 beams that were produced during the project. The hand calculations used to determine sizing of the core materials will be explained followed by an overview of the production process including improvements made to the process and tooling. Performance estimates of the beams will be included to verify the results of the hand calculations and to show the opportunity for optimization. Finally, a cost analysis will be performed on the project materials and how the cost compares to other common fiber reinforced materials.

Hand Calculations

The first step to begin the design of the beam is to determine the stresses the beam will be subjected to and build the beam base on those calculations. The loading shown in the prior section, Figure 5 subjects the beam to a total load of 3000 lbf over a 4-inch distance. This loading of 750 lbf/in is represented in figure 7 below. The internal forces of the beam are found by performing an analysis of the shear stress and bending moments. First a free body diagram analysis is done to find the reaction forces at the supports located at 1” and 23”. Since the beam is in static equilibrium, the following equations can used stating that the sum of all forces in the Y direction will sum to zero, and all moments about the 1” mark will also sum to zero.

$$\sum F_x = 0 \qquad (1)$$

$$\sum M_{1"} = 0 \qquad (2)$$

These equations are used to determine the reaction force at both the 1” and 23” marks are equal to 1500 lbf. Next the shear and bending moments are found by using a method of sections, placing an imaginary cut at each section shown in Figure 7 below allows for the shear stress (V) and bending moments (M) to be calculated.

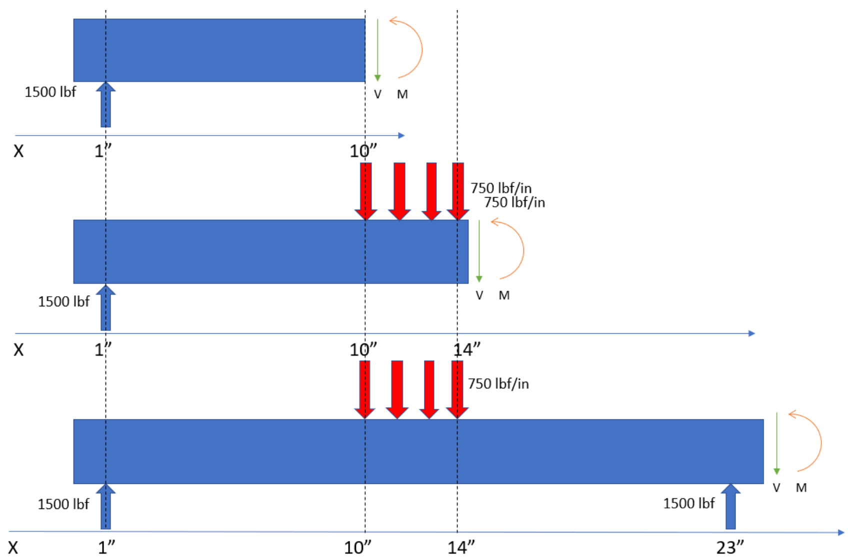

Figure 7: Free body diagram of the beam loading used to determine the shear and bending stresses throughout the beam.

Using equations 1 and 2, the shear forces and bending moments can be determined at each location throughout the beam. The resulting equations for shear and bending moments can be found in table 1 below.

Table 2: Resulting shear and bending moment at specific locations along the beam.

Segment	Location	Shear (V)	Bending Moment (M)
One	0” – 1”	V = 0	M = 0
Two	1” – 10”	V = 1500	M = 1500x

Three	10”-14”	V = 1500-750x	M = $-375x^2$ + 1500x + 13500
Four	14” – 23”	V= -1500	M = 13500 – 1500x
Five	23” – 24”	V = 0	M = 0

Figure 8 below shows a graphical display of the shear force throughout the beam and Figure 9 shows the bending moments.

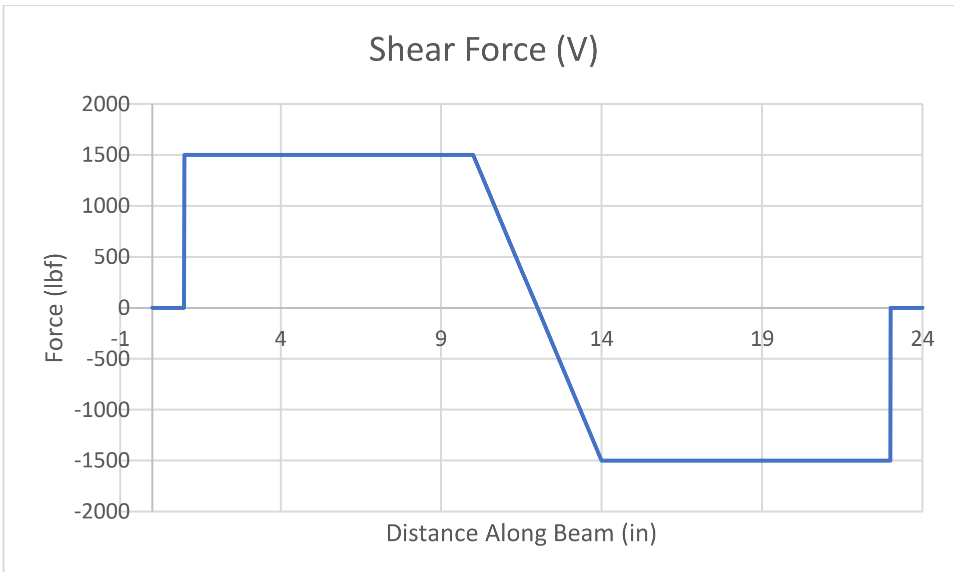

Figure 8: Shear force distribution throughout the beam

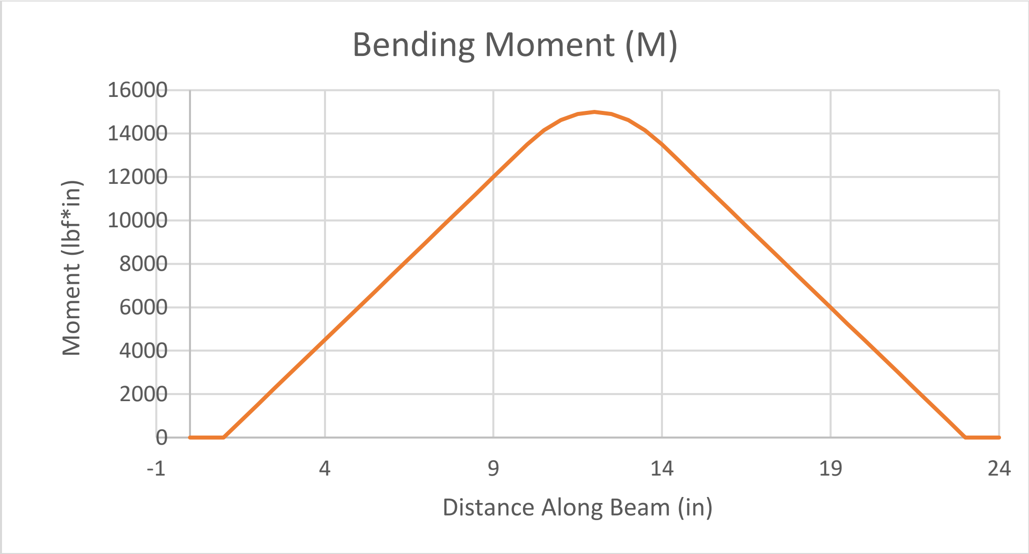

Figure 9: Bending moment distribution throughout the beam

As seen in the figures above the maximum bending moment occurs at x = 12” equaling 15,000 lbf*in. The normal stress can now be calculated for any location throughout the beam using the following equation.

$$\sigma = -\frac{My}{I} \qquad (3)$$

Where M is the bending moment, y is the distance from the neutral axis, and I is the second-area moment. From this equation the stress along the neutral plane at y = 0 will be zero. The maximum magnitude of normal stress will occur when y is at a maximum. The second-area moment for a symmetric I-beam can be calculated using equation 4 referencing figure 10 for the variables.

$$I = bh^3 + \frac{B}{12}(H^3 - h^3) \qquad (4)$$

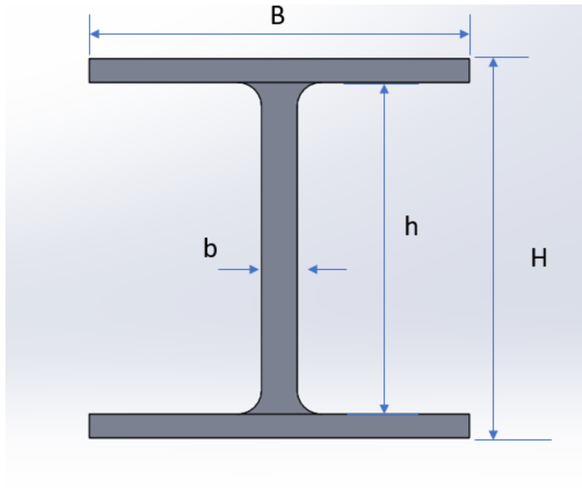

Figure 10: I beam geometry used for analysis.

To determine the web core thickness, the thickness was varied from 0.25” to 0.375” while maintaining a constant flange geometry of 4” wide and 0.25” thick. The second-area moment was calculated for each scenario. Using equation 4, the 0.25” web resulted in a second-area moment equal to 7.93 in^4 and the 0.375” web resulted in 8.38 in^4. The normal stress in the beam was then calculated where the maximum will occur in the flanges at the maximum distance from the neutral axis in the center of the beam using equation 3.

$$\sigma = -\frac{15000*2}{7.93} \quad (5)$$

$$\sigma = -\frac{15000*2}{8.38} \quad (6)$$

The results of normal stress from equations 5 and 6 can be seen Table 2 below.

Table 3: Normal stress calculation results

Web Thickness	Maximum Bending Moment	Maximum Distance from Neutral Axis	Second-Area Moment	Maximum Normal Stress	Ultimate Tensile Strength	Modulus of Rupture for Balsa
0.25”	15,000 lbf*in	2”	7.93 in^4	3,783 Psi	10,500 Psi	5,366.4 Psi [19]
0.375”			8.38 in^4	3,580 Psi		

The maximum normal stresses occurring for both the ¼” and 3/8” web scenarios above are well under the ultimate tensile strength of the balsa wood for the beam at which the wood fibers will begin to break. However, due to the physical properties of wood, the modulus of rupture used in analysis as well. This is because the compressive strength is so much lower than the tensile strength, loadings that result in beam bending lead to compressive forces greater in the top of the web greater than the compressive strength. During this, the neutral axis shifts toward the tensile side of the beam and eventually the stress exceeds the ultimate tensile strength and a brittle fracture will occur. Both scenarios above exceed the modulus of rupture and a load-carrying fiber will need to be applied to the beam to handle the applied load. [17] The calculation of the modulus of rupture is dependent upon the density of the balsa. This information is included in appendix A.

The maximum transverse shear stress occurs in the beam at the neutral axis from 1” to 10” and at the other end past the loading from 14” to 23” near the beam supports. This is calculated using equation 7

$$\tau_{max} = \frac{VQ}{It} \qquad (7)$$

Where V is the maximum shear stress, Q is the first-moment of area about the neutral axis, I is the second-area moment, and t is the thickness at the location being examined. In this case, the location being examined is the neutral axis. The results from equation 7 can be seen in table 3 below.

Table 4: Shear stress calculation results

Web Thickness	Maximum Shear Stress	Maximum Distance from Neutral Axis	First-Area Moment	Second-Area Moment	Maximum Transverse Shear Stress	Allowable Shear Stress (UTS/2)
0.25”	1,500 Psi	0”	2.258 in^3	7.93 in^4	1,708.3 Psi	5,250 Psi [18]
0.375”			2.449 in^3	8.38 in^4	1,169.0 Psi	

Both scenarios above result in a transverse shear much less than the allowable shear and the justification to use the 0.25” balsa in the web is met.

Production Process

This section will discuss how the beams were produced and what tooling was used in the process. Cost estimates will be included along with any additional resources that were included in the process of production.

All the beams were produced with balsa cores and came in 4” x 36” pieces. These pieces had to be cut down to 24” long and the web piece to 3.5” wide. They were then assembled by first gluing the pieces perpendicular to each other in the required geometry using Elmer’s Wood Glue Max. Once the I-beam was assembled, a ½” epoxy fillet was added to each interior edge by holding the beam at a 45° angle, damming up the ends using pieces of silicone, and pouring 35 mL of liquid epoxy into the beam. This can be seen in Figure 11 below.

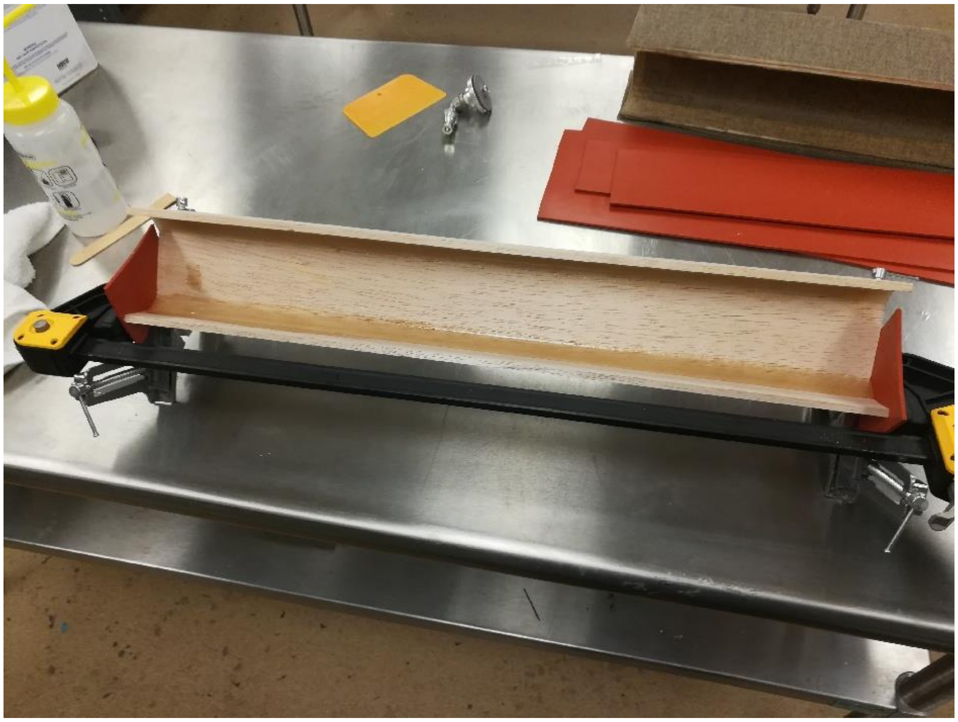

Figure 11: Making epoxy fillet at inner corner of I-beam

Once the four epoxied fillets are dried, the beam can then be covered in flax fiber prepreg as intended. The process for this involves cutting the material to size for each surface with the fibers oriented in the desired directions, allowing it to rest at room temperature for at least 12 hours because it is stored in sub-freezing temperatures. This rest time allows any condensation that is formed on the surface to evaporate and will not cause any adhesion issues when the material cures on the surface of the beam. Next the material is placed on the surfaces and wrapped in a peel ply release fabric, followed by cut to size pieces of ¼" silicone, then a bleed cloth, and finally the vacuum bagging to maintain the pressure boundary as explained in the Background section. The process can be seen in Figure 12.

Figure 12: Beam with associated consumables waiting for fiber composite to be applied.

Once the bagging is wrapped and sealed with tape, the flange tools can be inserted. These maintain I-beam geometry and prevent thermal stresses from italicizing the flanges while in the autoclave.

The new design for the tooling is shown on the right while the old is on the left of Figure 13. The old design required a pre-set height adjustment using an Allen wrench on the top bolt then locking down with the jam nut. The assembly could then be forced between the flanges, peel ply, silicone, bleed cloth, and bagging. The new design allows the user to insert the tool between the materials and then open the tool by spinning the turnbuckle. This part was produced from 9/16” steel hex stock cut down to 1.5” and drilled and tapped with 3/16” left- and right-hand threads. Left- and Right-hand studs were then installed into tapped holes on the aluminum bars and held in place with red high temperature Loctite. All drilling and tapping work were done by the Union College Engineering Machine Lab. A mechanical drawing of the turnbuckle is attached in Appendix B.

Figure 13: Old method to adjust flange tooling (left) and new method (right)

The curing of the prepreg is done in a 3-phase process. First, the autoclave is set to 185° F and 60 Psi. The beam can cure for 300 minutes and then temperature is increased to 250° F for another 90 minutes. The beam is then allowed to cool to room temperature in the autoclave and may be removed once cool.

Performance Estimates

This section will analyze the beam to determine if the design load will be met before failure. It will also look at how the beam can be optimized to weigh less while still maintaining its ability to carry the design load.

Using the beam geometry above, ¼" web and flanges, it is estimated from calculations above and Solidworks Stress Analysis that the beam will support the 3000 lbf loading with only flax fiber reinforcement on the upper and lower flange surfaces. The Solidworks Stress analysis of the beam can be seen in Figure 14 showing a loaded beam with only one layer of flax material on the top and bottom flanges. The simulation shows about 3000 psi Von Mises Stress in the web and figure 15 shows shear stress to be equal to what was calculated in the prior section.

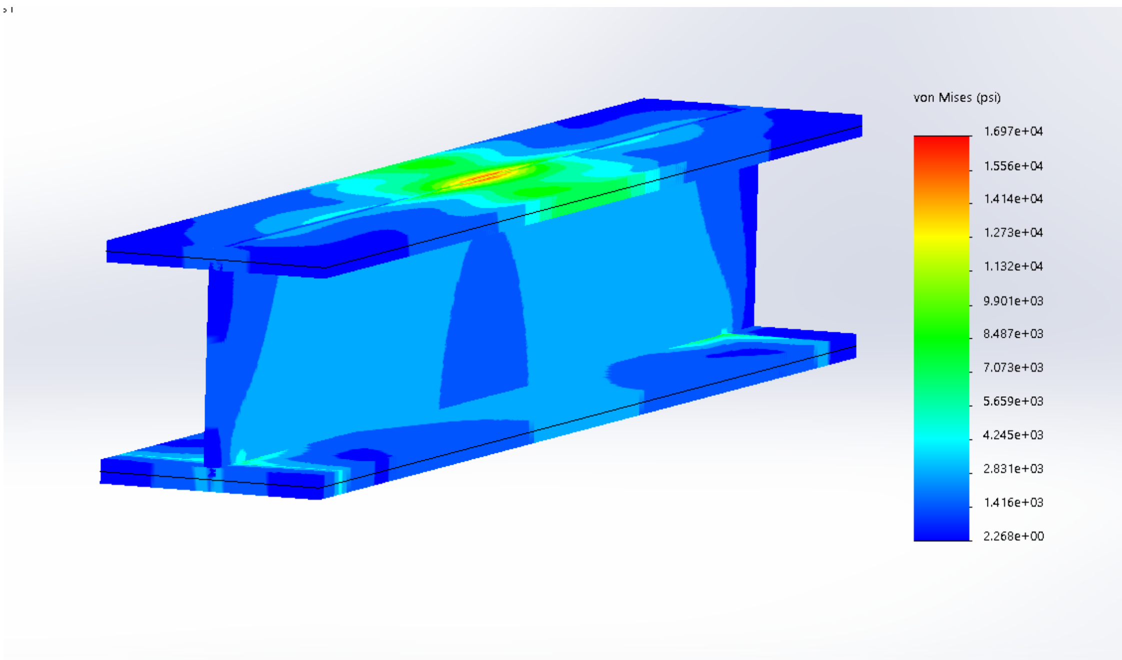

Figure 14: Von Mises stress shown on beam with one layer of unidirectional flax fiber on top and bottom flanges laid in 0 degree orientation.

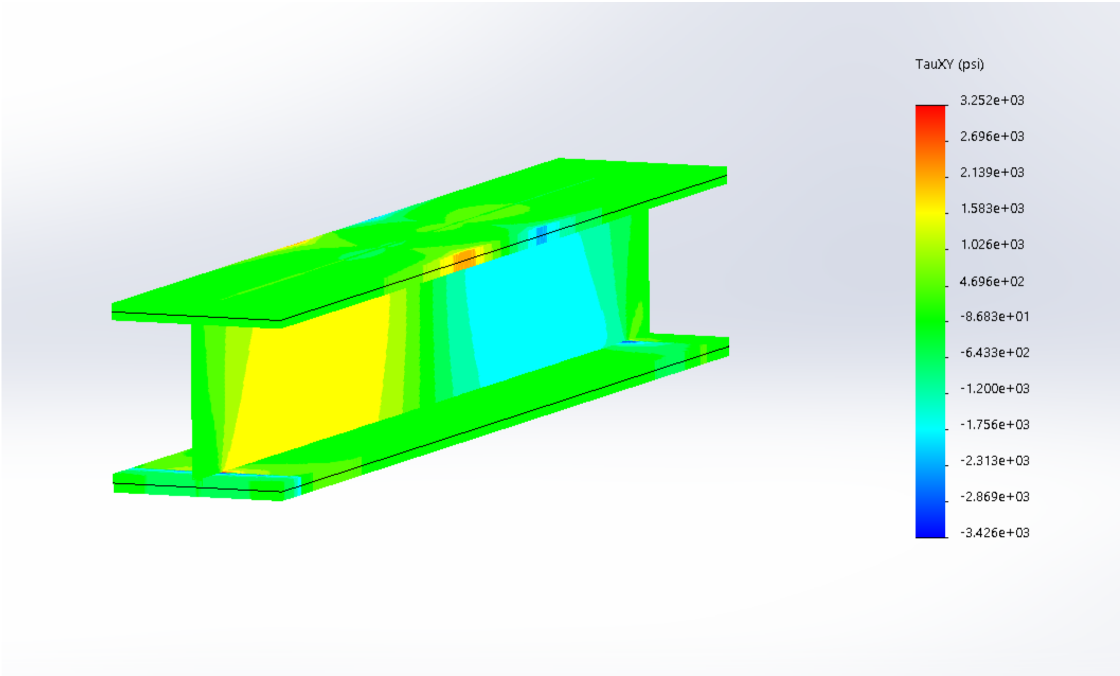

Figure 15: Shear stress being shown on beam with one layer of unidirectional flax fiber on top and bottom flanges laid in 0 degree orientation.

The figures above prove the usability of the 1/4" balsa in the web section of the beam. Since the Von Mises Stress is greater than the ultimate tensile stress of the balsa, the need for the load carrying flax fiber is justified. The stress is still much less than the ultimate tensile strength of 56,800 Psi for the flax fiber and optimization can be performed to remove weight from the beam. To verify this, two beams will be made of the ¼" balsa wood. The first will be made of just balsa and have the 1/2" epoxied fillets. The second will be the same as the first but will have a layer of the unidirectional flax prepreg composite on the outer most flange surfaces. Modeling in Solidworks indicates this scenario will handle the 3000 lbf loading with a maximum Von Mises Stress of 16,970 psi at the upper flange as shown in Figure 13 above. The balsa core will see a maximum Von Mises Stress of 4,000 psi and is less than the modulus of rupture. Therefore, the beam should handle the weight with only flax material on the flanges. The test of the two built beams will be completed by applying a 3000 lbf load to the beams via the load frame in the Engineering Mechanics Lab in Butterfield 101.

Since the beam discussed above is expected to handle the design load, optimization was done in Solidworks to lower the overall weight by removing material from the web and flanges. By starting one piece at a time, material was removed while maintaining symmetry throughout the beam. It was determined the best location to remove material from the top flange was at the ends of the beam while the bottom flange saw minimal stress increase while removing material from the middle section. The material removed from the web was done so my placing 13/16" holes at the neutral axis and spacing them every 2.5". The sizing was determined by maintaining Von Mises stresses less than the modulus of rupture of balsa. This design will be tested experimentally as well but it is expected to hold the design load as the max stress is occurring on the top flange which should be carried by the unidirectional flax fiber. The material removed was estimated to be equal to 2.6 ounces which will be a substantial weight reduction for the beam. The optimized beam geometry and results from the loading simulation can be seen in figures 16 and 17 below.

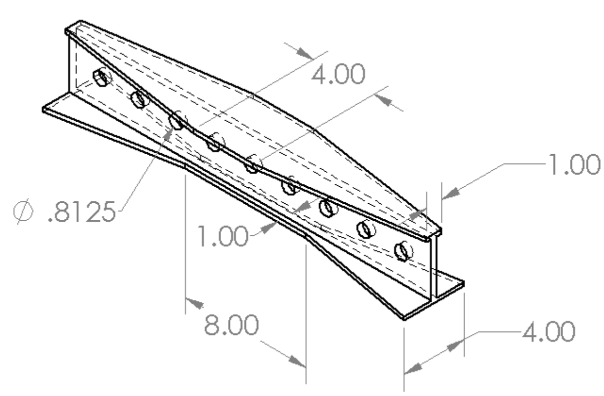

Figure 16: Optimized beam geometry.

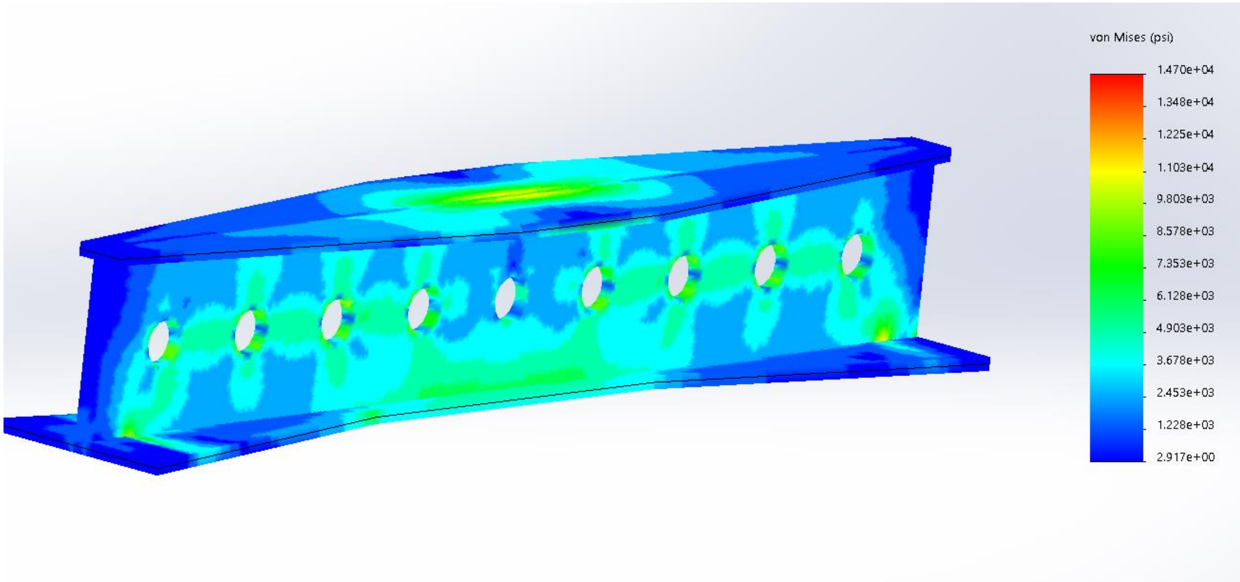

Figure 17: Optimized Beam loading simulation results

Cost Analysis

This section will perform a cost analysis of the project specifying the cost and labor associated with each part. The total cost to produce all beams produced is outlined in table 3 below even if the materials were supplied and obtained by other means than the project funding. The cost will then be compared between other materials commonly used when producing fiber reinforced materials.

Table 5: Cost Analysis

Material	**Supplier**	**Unit Price**	**Quantity used**	**Total Price**
1/4" x 4" x 36" Balsa Wood – 10 pack	Tower Hobbies	$37.37 - 10 pack	1	$37.37
3/8" x 4" x 36" Balsa Wood – 5 pack	Tower Hobbies	$25.70 - 5 pack	1	$25.70
Ekoa P-SX 10.3	Lingrove	$76.54 per yard	5	$382.70
Ekoa P-UD 3.2	Lingrove	$21.05 per yard	3	$63.15
Shipping Costs	Lingrove	$30.00	1	$30.00

Stretchlon 800 Bagging Film	Fiber Glast	$29.95 – 5-yard roll	.5	$14.98
Nylon Release Peel Ply	Fiber Glast	$59.95 – 5-yard roll	.3	$17.99
Breather and Bleeder Cloth (4 oz)	Fiber Glast	$24.95 – 5-yard roll	.3	$7.49
Gray Sealant Tape	Fiber Glast	$10.95 per roll	4	$43.80
2000 Epoxy Resin and Hardener	Fiber Glast	$149.95 per gallon	.1	$15.00
9/16" Steel Hex Stock	Supermarket of Metals	$7.29 per foot	1	$7.29
Machine Shop Labor	Union College	$55.00 per hour	1	$55.00
Total Project Cost	**$700.47**			

The cost of the flax biaxial prepreg was $382.70 for a 5-yard roll. E-glass is sold by Fiber Glast for $241.95 for the same sized roll. Carbon fiber is sold by Fiber Glast for $645.45 for the same sized roll. The cost of the fiberglass is lower than the flax, however carbon fiber is much higher. Although carbon fiber is highly demanded, the production process experiences many difficulties, causing the price to drive high. Fiberglass is a commonly used material in the industry and the price point is low due to years of use and improvements made to the processing of it. Flax fibers are still relatively new and once the demand rises for natural materials that are less dependent on petroleum, the cost will likely fall.

DISCUSSION/CONCLUSIONS:

This section will discuss the difficulties encountered up to the production of the final beam for the competition, the manufacturing of the final beam, the results from the competition, as well as lessons learned from this project. The beam failure is also examined to determine how its design could be improved upon and recommendations will be made.

Manufacturing Difficulties

The production process of the beam did not go as straight forward as intended. Unfortunately, problems occurred while making the intended beams for testing. Figure 18 shows an instance where while adding the epoxy fillet to the beam, some leaked past the silicone dam and on to the flange of the balsa. While attempting to remove it, the balsa had broken, rendering the beam unusable. More materials were also required due to errors such as this one and the lead time on the material was excessive due to a shortage. This led to no time to test these beams and the beam for the competition had to built instead due to time constraints. This however did not go without difficulties either.

Figure 18: Beam produced with broken balsa.

Once it was determined the beam would not be able to be tested prior to the competition, the design was finalized in Solidworks. To be conservative with the design, it was decided to eliminate the holes in the center of the beam directly under the loading and instead go with 3-

1.75” holes in the outer webbing of the beam. The flange geometry remained relatively constant, only changing by making the bottom flange an inch wider in the center. Figure 19 shows this new dimensioned geometry. Three layers of unidirectional fibers were laid in the 0° orientation on the top and bottom surfaces, while two layers of the biaxial ±45° were utilized on the webbing and inner surfaces of the flanges on the beam.

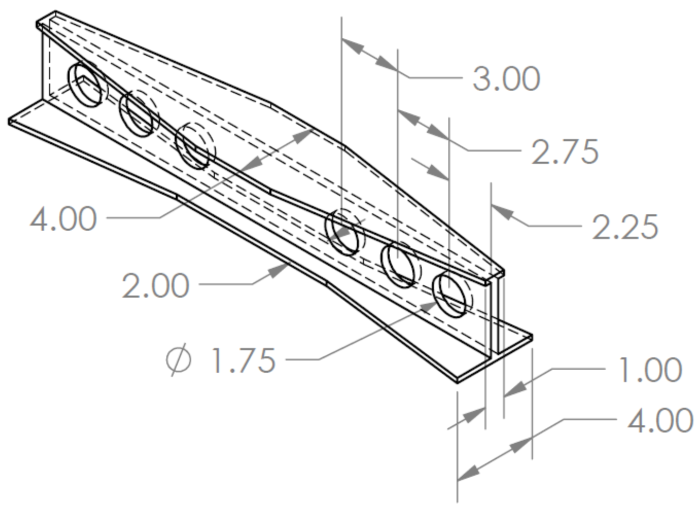

Figure 19: Dimensioned beam built for competition

Figure 20: Beam with crushed webbing and flanges

To produce this proposed beam, it had taken 4 attempts. The first 2 attempts resulted in beams with a crushed webbing and partially crushed flanges. This is shown in Figure 20. This was assumed to have occurred due to the pressure that the vacuum bagging had applied to the balsa and uncured flax during the curing process while in the autoclave. The balsa prior to curing is simply not strong enough to support the vacuum. This was not encountered in the beginning of the project because the balsa used at that time had a significantly different density than the balsa used at the end. The density of the original balsa was 240.7 $\frac{kg}{m^3}$ while the balsa ordered the second time had a density of 110.4 $\frac{kg}{m^3}$. This could be felt easily while handling the wood but was assumed it would not cause an issue. The lower density balsa could be crushed down easily be simply pinching it. This resulted in the beam coming out crushed where any excess pressure was applied. This was most seen on the top where the silicone did not fully cover the entire surface of the beam and would end up pushing into the wood, causing deformations.

The third attempt at producing the beam ended up losing vacuum shortly after placing the beam into the autoclave. This was likely due to the bag ripping open while placing it into the autoclave by catching a metal edge. Without the vacuum in place, evenly distributed pressure was not applied to the outside of the beam, and the flax fibers did not adhere fully to the beam. The unidirectional tape that was used on the flanges of the beam only had resin applied to one side of the fibers. Without the vacuum pressure, the excess resin was also not forced through the prepreg and the top surface of the fibers did not fully wet. A picture of this is shown in Figure 21. Finally, on the fourth attempt, a successful beam was produced using some of the balsa that was originally ordered for the project.

Figure 21: Beam that lost vacuum during production resulting in top fibers not wetting through the layer.

To prevent similar problems from occurring in the future, care should be taken to consider the density of the balsa before ordering. This will be difficult as many distributers do not list this detail. This project may have gotten lucky by receiving the higher density material from the first distributer, Midwest Products, or it may be a consistent quality from that distributor. The lower density, softer balsa was produced by a company named Bud Nossen Models.

Competition Results

The 2019 SAMPE Bridge Building Competition had 14 schools enter in the natural fiber category for the bridge competition. Most of the beams entered were of I-beam geometry and were made with flax fibers. There were a few beams that were square geometry but were on the heavier side when compared with the group. There were also a couple made from bamboo fibers at the competition. The beam that was entered for this project weighed 648 grams, and supported 1889 lbf. This did not support the design load of 3000 lbf and failed prematurely. Table 6 below shows a full list of the schools that attended and entered the natural fibers category, their weights, and the load the beam held. Note that the loading stopped at 3000 lbf and some may have held much more than this.

Table 6: Results from SAMPE 2019 Bridge Contest Natural Fibers Category.

School Name	Mass (g)	Load (lbf)
U. Maryland	423	983
WVU	546	2870
FEI	560	3000
U. Delaware	568	3000
U. Washington	580	3000
McGill U.	594	1621
Union College	648	1889
U. Washington	740	3000

UABC	784	2753
U. Washington	840	3000
Western Washington U.	1110	3000
UCLA	1192	3000
UABC	1304	3000
UABC	1552	3000

The beam that was produced for this competition failed in shear in the areas near the holes that were removed from the webbing. Figures 22 and 23 show the failure. The flax fiber also delaminated partially in this area. In the future, this can be prevented by not using such large holes in the material. The beam originally weighed 810 grams before material was removed and ended at 648 grams, or 20% of its weight was removed. Without the material removed in the webbing, I suspect it would have held the design load, however, would have still been too heavy to win the competition.

Figure 22: Picture of beam produced for competition. Failure at right hand holes.

Figure 23: Picture of beam produced for competition. Failure at left Holes.

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Appendix A: Modulus of Rupture Calculation

The modulus of rupture of balsa is heavily dependent upon the widely varying density of balsa and can be seen in Figure 12 below. To determine the MOR for the balsa being used in the project, the density was first calculated by taking a piece of balsa, measuring the weight and the volume. The piece weighed 142 grams and the volume was 36 in^3 or .000590 m^3. The density was calculated to 240.7 $\frac{kg}{m^3}$. Using Figure 18 below, the modulus of rupture was determined to be 37 MPa or 5366.4 Psi.

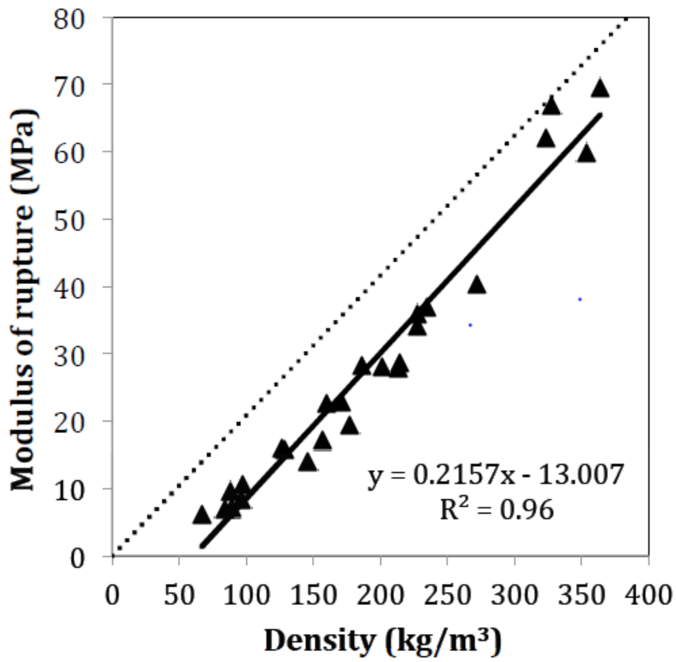
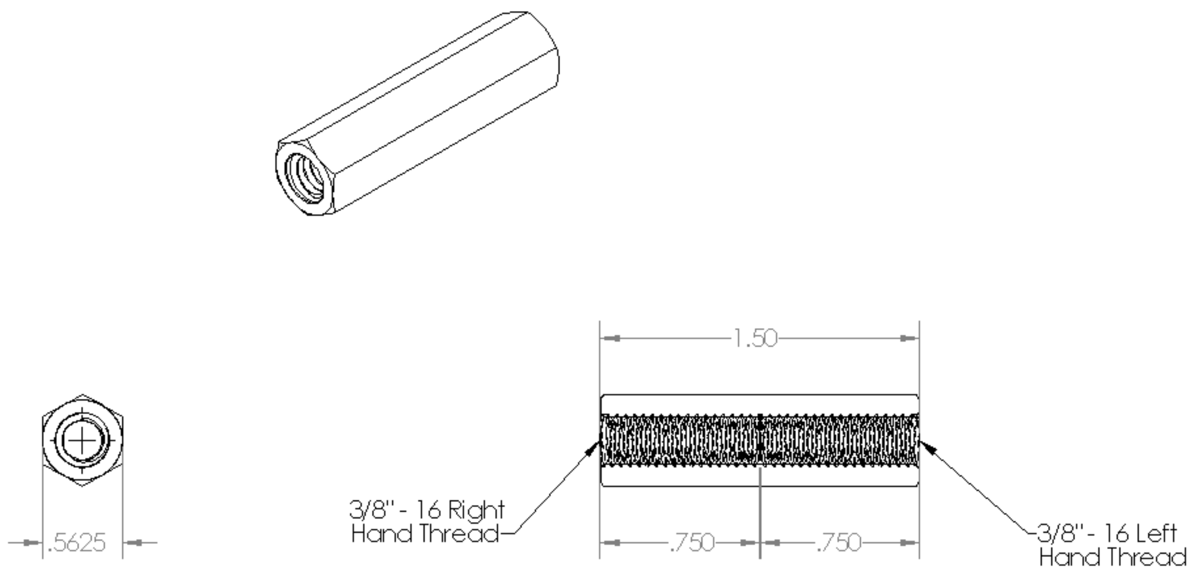


Figure 18: Modulus of Rupture of Balsa Vs Density [19]

Appendix B: Turnbuckle Drawing for Flange Tool Modification



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: Distance Between Threads in Center Allowable ± .125	DRAWN	BH	11/11/18	
	ADVISOR	Ronald Bucinell		TITLE: Turnbuckle for MER-497 Brian Harkness harknesb@union.edu
	ADVISOR APPROVAL			
Quantity Needed: 4				
Material Carbon Steel PROVIDED BY STUDENT	COMMENTS: Parts are already completed, need them modified to this size.			SIZE A DWG. NO. turnbuckle REV
DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 1 OF 1