Study of Natural Composite Materials Square Beam Under Three Point Bending Test

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Abstract

The purpose of this report is to summarize the findings on three point bending tests to try to find the optimum geometrical shape and layup configuration of a square beam composed of natural composites. The final project was entered into the SAMPE 2013 bridge building competition to compete internationally against other universities in the natural square beam category. The main focus of the bridge project is to compose it entirely of natural occurring fibers and other natural materials to create a “green” beam. The beams in the competition are tested under 3 point bending tests and will be scored based on the beams’ ability to reach the design load while also minimizing weight. This report will detail the procedures used to create the natural beams and explain the results.
I. Introduction

Composites are materials that are formed when 2 different materials are combined together in order to create one stronger material. Composites consist of two main components, fibers and a matrix. The earliest example of man-made composites traces back to simply using straw and mud to create a reinforced material. The benefits of composites are that they are much stronger than their individual counterparts yet still weigh less than most metals for the same strength. The composites can be molded so that the direction of the fibers will determine the direction(s) which hold the most strength of the material. The orientation of fibers or having multi-directional fibers often depends on the type of weave the composites are made of.

Composites are applied all around the world today. Though relatively new to the aerospace industry, composites are making a large impact in that their high strength-low weight ratio can help to create much more fuel efficient vehicles than the previous metallic aircrafts. The large trade-off with this is that the composite material is expensive and when damaged become much more difficult to repair than metallic. The composite materials in the newer Airbus and Boeing aircrafts are all over, the nacelles, fuselage, wings and more. Particularly in the 787 and Airbus A350. The new usage of composites on the long distance aircraft saves a large amount of weight throughout the aircraft. Though composites are making a large impact in the aerospace industry, composites are also used in much less commercial aspects such as on bikes and surfboards, as well as on wind turbine blades. The use of composites on wind turbine blades allows for a much lighter material to use for the blades. In the space industry, composites are finding their way into satellites and fuel tanks designed for rockets. The composite material allowing for a lighter fuel tank can increase the payload of a rocket. Composites also already played a role on the space shuttle where the nose and leading edge of the wings were made of carbon fiber composites and are also emerging more and more in the space industry.

Green material composites are a relatively new field of study. Natural occurring fibers such as wood, bamboo and hemp, offer a cheaper, environmentally friendlier alternative to the current composite materials. In previous years in the SAMPE competition, Cal Poly teams have built natural I-beams made out of bamboo and hemp. However, the previous winners in the natural category used wood. The high strength to weight ratio of wood makes it an ideal choice for the beams acceptable. The study of green material composites is largely still unknown and so desirable to be completed to see if the material would be strong enough to replace existing composite parts on aircrafts.

The annual SAMPE competition involves a category of green material square beams. The design requirements and rules are as follows. The bridge will be tested under 3 point bending on 24 inch centers. The bridges must be 24 inches in length. For the square beam it must have 2 or 3 independent webs and must not have a solid cross section. An independent web is defined as having a minimum gap of 1/2” and 3/4” between webs and must be held true along the entire length of the bridge. This year a new change with the rules is that the beams no longer will have a weight requirement. Instead weight is taken into account once the bridges reach the design load. Any additional weight held after the bridge reaches the design load will not be taken into account as it will simply be the lightest bridge to reach the design load. For the natural square beam category the design load is set to 3000 lbf. The rules also state that if a bridge does not fail after it deflects for 1 inch the load at 1” deflection will be taken as its maximum load.

A. Main objective of project

The objective of this project is to design a square beam made entirely out of natural composite materials and be able to compete in the SAMPE 2013 competition.

II. Experimental Test

A. Experimental Set-up, Apparatus, and Procedures

Following the design requirements in the introduction above, the square beam must maintain a gap of .75” between the webs as well as .5” between the caps. The beam must also be 24” in length and not have a solid cross section at any point. Below is the initial design for the dimensions of the square beam. The initial design for a beam was created simply following the design requirements and modeled to have roughly the same size as previous beams made at Cal Poly while also adjusting the sizes to available metal square piping to be used for molds.

The design for beam 1 is shown below in Fig. 1. And in Table 1. With these initial dimensions set the materials chosen for the beam needed to be prepared before the layup. The hemp cloth used was cut into strips with 1” extra
in width and 26” long in order to leave room for errors in the layup. After the strips were cut the thickness of the cloth was taken in order to be able to approximate how many layers would be needed in order to satisfy the thicknesses desired from the initial designs. A 0.08” thickness was used for the first beam as an estimate to how much thickness would be added to the beam from the epoxy. Using that thickness and subtracting off what the desired width was, it could be calculated the amount of strips desired for beam A in Fig 1.

![Figure 1 Beam Configuration](image)

**Table 1 Beam Dimensions**

<table>
<thead>
<tr>
<th></th>
<th>Height (in)</th>
<th>Width (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.40</td>
<td>2.2</td>
</tr>
<tr>
<td>B</td>
<td>1.95</td>
<td>0.5</td>
</tr>
<tr>
<td>D</td>
<td>0.15</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Fig. 1 above shows the rough layout of the beam. The beam will be symmetric so the 0.1” gap is applied to the other side of the beam and both the top and bottom caps. Table 1 above has the actual dimensions of the beams. The brown bars in the webs and top cap represent the layers of bamboo. The thickness of the bamboo is not constant however is desired to be as thin as possible and so the design goal of the strips will be 0.1”. The reason for the top cap having a bamboo layer rather than the bottom cap is due to the fact that composites generally are very strong in tension however, much weaker in compression. The bamboo core in the top layer is used to reinforce the top layer from the compressive forces the bridge will undergo during the bending test. The other requirement for the beam is
that it must be 4’’x4’’ maximum. This initial design is based largely on conservation of materials. This first designed beam will be used simply to test the materials and as a basis to judge how the next beams should be designed. The beam will be tested using the Instron machine at Cal Poly with the same test set-up as the SAMPE competition and then using finite element analysis the beam geometry of subsequent beams will be changed to the results from the finite element analysis.

The design for the second beam was given the same dimensions as the first beam. Largely in part to errors made during the fabrication of the first beam. The purpose of the same dimension beam was to be able to test the difference in fabrication process. For the second beam the C-sections of the webs would be created first using the vacuum table. Finally the top and bottom layers would be added on after the webs were already dried.

B. Apparatus

The first apparatus used were the table and band saws in the hangar and Bonderson shops as well as the belt sanders. Also used to cut were the table saws available in the lab such as the one shown in Fig. 2. These tools were used in order to prepare the natural materials before the actual layup. For the process to actually lay up the beams, vacuum tables were vital in order to apply pressure to the beams while being constructed. The vacuum table used is pictured below in Fig. 3 along with the pumps used. The epoxy used for the final bridge was donated from SAMPE. However, due to the amount donated the initial test beams were constructed with epoxy already available in the lab. The other key piece to the actual lay up of the beams would be the molds. Initially metal square tubing pieces were used as the molds to wrap the hemp and bamboo pieces around however, due to the lack of availability of the correct sizes of these pieces for the later beams wooden planks were purchased and cut to size and used as molds. However, using wooden molds, would often become warped and have a slight curvature to them. Large C-clamps were also required in order to generate pressure onto the beams. With the vacuum table the additional pressure provided from the clamps was not needed for the C-section webs of the beams however, when the top and bottom layers were added on for the final molding of the bridge C-clamps were used on all the
surfaces in order to maintain the shape as well as add pressure to ensure that there were no gaps in between the layers of hemp and bamboo and that the epoxy was well distributed with any excess epoxy being squeezed out of the bridges. In order to test the materials the Instron machine pictured in Fig. 4 below was needed to be used in order to perform the three point bending test. The test was set-up per the SAMPE rules and guidelines outlined how the test would be performed at the conference. Note the figure below shows the Instron machine calibrated for tensile tests and not 3 point bending tests.

![Instron Machine](image)

**Figure 4 Instron Machine**

**C. Experimental Procedure**

To begin the bamboo poles ordered in 8’ poles had to be cut down into thin strips. The poles were cut into 26’’ sections and then split into eighths in order to reduce the amount of curvature from the bamboo sticks. The individual strips were then sanded using the belt sander to take off as much weight as possible. The strength of bamboo comes from the outer, and oldest layers so the outside of the bamboo was only sanded slightly in order to remove the slippery coat so the epoxy would stick on better, meanwhile the inside layers of the strips were sanded as much as possible while the sides were sanded just to achieve as straight of a strip as possible so that when the strips are pressed together there is a minimal amount of space inbetween them. Fig. 5 to the right shows strips of bamboo after being cut into eighths prior to being sanded down into thinner strips. The strip

![Unfinished Bamboo strips and Hemp Cloth](image)

**Figure 5 Unfinished Bamboo strips and Hemp Cloth**
on the far right side of the figure is the only strip that has been sanded in the picture.

The hemp cloth used was cut into strips with 1” extra in width and 26” long in order to leave room for errors in the layup. After the strips were cut the thickness of the cloth was taken in order to be able to approximate how many layers would be needed in order to satisfy the thicknesses desired from the initial designs. A 0.08” thickness was used for the first beam as an estimate to how much thickness would be added to the beam from the epoxy. Using that thickness and subtracting off what the desired width was, it could be calculated the amount of strips needed for the thicknesses of the caps.

When the two materials were prepped and ready for layups as depicted in Fig. 6, the molds were then covered using tape or a vacuum bag, additionally mold release was also applied to the molds in order to easier remove them without risking damaging the bridge. Next hardener and resin was poured and measured into two separate cups to be mixed. Once all the materials were laid out in the order they would be applied onto the beam on the table the epoxy was mixed together for approximately 2 minutes. The epoxy was then poured onto the hemp cloth and bamboo and using a squeegee the epoxy was pressed into the hemp cloth ensuring that all of the cloth was coated with epoxy. The same procedure was done to the bamboo strips as well, once one section of the final square beam was coated with epoxy the layers of hemp and bamboo were transferred one by one and placed onto the molds. The procedure was repeated until all the pieces were placed onto the mold in the correct shape. From there, the extra molds or flat plates were used as a surface in order to press onto the bridges. For the pieces that were warped, flat metal sheets were placed on top and once clamp pressure was applied the curvature in the wood was taken out. The clamps were then placed onto the plates covering the beams and torqued as tight as possible. This step was critical in that the clamp pressure needed to ensure that the hemp and bamboo pieces didn’t slip as pressure was applied, and that the force was as evenly applied as possible to the beam in order to avoid stress concentrations. With all the clamps placed on the beam was left to dry for 24 hours with the clamps placed on, after 24 hours the clamps were removed and the bridge was left outside in order to continue to cure before and testing could be done.

For the second bridge constructed, the dimensions were the same as the first, however, the vacuum table was to be used as part of the layup instead. The hemp and bamboo, were laid out for the webs. Next the vacuum table needed to be prepared, vacuum bags were cut with gum tape laid on the bottom surface all around the vacuum bag to ensure no leaks could escape from the bag, next a sheet of cotton was placed on top of the bag. The purpose of the
cotton sheet was to absorb the epoxy being sucked out of the beam and to stop the epoxy from entering the vacuum pumps. For this process, in order to create both C-section webs at once a 60’’ metal bar was used and both sides would be created at once. The hemp cloth was cut at approximately 52’’ in length however the bamboo sheets were left at 26’’ and once the beam dried it would be cut in half in order to obtain two symmetric C-sections. The metal bar was then covered with tape and mold release. The mold described is pictured in Fig. 8 on the left. Once the epoxy was applied to the hemp cloth and bamboo sheets to be used for the C-sections and placed onto the molds, a sheet of porous material was placed on top of the beam. Finally an additional piece of vacuum bag was placed onto the beam and lined with gum tape to seal the vacuum. The vacuum hoses were also inserted into the bag in this step and were taped around with gum tape pressed as tightly as possible in order to avoid any leaks. Once the vacuum bags were turned on, the apparatus was checked for leaks and then left overnight to apply pressure. With the C-sections now complete the 52’’ long piece was then cut in half to create the 2 webs. The sides were sanded to create flat surfaces if any epoxy leftover dried into droplets which would prevent the top and bottom surfaces from being applied on flat. From here the same process as the first beam was done in order to finish the layup with simply applying epoxy on the top and bottom surfaces first, and then using clamps to finalize the beam.

For the third and final beam the same process was used as the second bridge. The hemp cloth was cut to the new dimensions of the final bridge with an additional 2’’ width to ensure the sides could be pressed tightly. The only new procedures added to this bridge was that the bamboo sheets were taped together and then glued together using epoxy prior to the construction of any part of the beam as well as the center mold being cut to size once the webs were already dried. Previously the bamboo sheets were taped together however, at the points where the tape was the tape didn’t maintain the epoxy as well. Occasionally the taped pieces would also slip and fall out of alignment due to the pressure being applied. The epoxy first guaranteed the bamboo would remain in its positions as the hemp cloth placed over it was applied. Once the webs were completed from the vacuum table the webs were also used as a guide to cut the center wooden mold to the exact same height as the webs.

The final process once the clamps are removed off all the beams was to trim down the edges lengthwise and the side flanges to as small and even as possible. The flanges were cut down to ¼’’ wide on each side and the length was cut to 24’’. Any sanding required after cutting was also done using the belt sanders.

### III. FEM Analysis

In order to determine the geometry of the 3rd beam, finite element modeling analysis was used. The finite element study was performed using ABAQUS CAE. Because no material data was available for bamboo and hemp, beams made of hardened steel with properties listed in Table 2 were used instead. The actual performance of the steel beam in terms of the modulus and strength to weight ratio were not of concern for us but rather only the geometrical performance compared to other beams made of the same material but with different beam configurations. Instead what was tested was variations of the web heights and thicknesses, and top and bottom layer thicknesses. Figs. 9 and 10 show the results of the study with figure 9 as the initial beam and figure 10 as the end result beam used.
Table 2: Model Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Youngs Modulus, $E$</td>
<td>$29 \times 10^6$ psi</td>
</tr>
<tr>
<td>Poisson Ration, $v$</td>
<td>0.303</td>
</tr>
</tbody>
</table>

A three point bending test was set up with supports at the bottom unconstrained so the beam could still slide as it would in a real test. The top load was distributed in a square box with dimensions of 4x4” as shown in the SAMPE contest rules.
Beam 1 was loaded to an arbitrary load and the results were compared between the design of beam 1 and beam 3. For the same applied load it was noticeable that beam 3 showed much more resistance with a lower max principal stress. The deflection of the beams was also tested to ensure that neither beam would reach 1 inch. Beam 3 showed a lower deflection magnitude as well so it was concluded that beam 3 performed better in both tensile and compressive strength as well as deflection resistance. The 6 figures below are captures of the finite element test results.

Figure 12 Max Principal Stress Results [Beam Design 1]

Figure 13 Max Principal Stress Location [Beam Design 1]
Figure 14  Displacement Magnitude [Beam Design 1]

Figure 15  Max Principal Stress [Beam 3]
Figure 16  Max Principal Stress Location [Beam 3]

Figure 17  Displacement Magnitude [Beam 3]
IV. Experimental Results/Comparison

The result of the first layup was not as anticipated, the first beam had visible gaps. The gaps most likely occurred from insufficient amount of pressure from the clamps, and non-uniform bamboo sheets for the core of the beam. Additionally the bamboo core was not cut to the exact height of the molds which would also lead to a stress concentration where the webs would be thinner at the ends than in the middle. Because of these visible flaws on the beam, the first beam was not trimmed precisely down, meaning the size could still have been changed. The other issue with the beam was that the bamboo core sheets were too thick, because they were not thinned down into thin enough strips due to time constraints on just laying up the first bridge, the asymmetric sheets caused the beam to have those gaps visibly shown. On the top layer, where another bamboo sheet was placed, in order to help withstand the compressive forces, there were small dents where the bamboo sheet was asymmetric similar to the webs. These dents also may have been due to the width of the hemp cloth not being wide enough. The dents are pictured below in Fig. 23. A 1” extra margin was cut for the hemp cloth however, when wrapped around the metal molds there was not enough cloth on the sides to be effectively stretched and held down. These dents may lead to stress concentrations and lower the performance of the bridge. The first beam weighed 945.2lbs. However, as mentioned before the sides were not trimmed down precisely in order to save time.

For the second beam, during the layup a few issues were encountered. The first error that was encountered was that the sides could not be pressed down onto by the vacuum pressure. This issue could have been fixed had clamps been applied to sides. However, it was found after the beam was left overnight that a small leak in the vacuum bag also existed causing even less pressure to be applied to the sides. This led to the webs being already dried with uneven surfaces on the top and bottom leading to difficulties when the top and bottom layers needed to be placed. Despite being sanded already the amount of hardened epoxy on the top and bottom were difficult to remove without first making a cut. Eventually the surfaces were tinkered with until virtually flat, however during the layup another problem occurred with the center mold piece. Because the pieces being added were no longer dry. They had an added thickness would could not be pressed down onto. This meant that our center mold previously used no longer matched the height of the webs and so the top and bottom layers would fall into the gap between the webs. With no other alternative and the epoxy already applied onto the hemp cloth the pieces were placed onto the beam being stretched as tightly as possible in an attempt to keep the top and bottom pieces from sagging. The second beam layup once completed however, showed less gaps and had a much thinner bamboo core. However, no mold release was applied to the wooden mold in between the 2 webs and the epoxy seemed to have gotten through the vacuum bag which must have ripped at some point. Because of this the wooden mold was unable to be removed. It was decided to just proceed onto the next bridge after seeing that the layup did create smoother webs and so for the third beam the vacuum table procedure would be used.

For the final bridge, the first most obvious difference was the change in hemp cloth. We decided to use a thicker hemp cloth and fewer layers to try to obtain a better strength to weight ratio. In order to determine the amount of layers to reach the desired thicknesses, we simply calculated the thickness added by the old hemp cloth with X amount of layers and then interpolated the amount needed by the new ones with the proportion of the new thickness. The target thicknesses were nearly met however, it was found that the new hemp cloth when coated with epoxy did not harden as thick. The bridge after completion was always slightly under the target dimensions. Again we attributed this error to the new hemp cloth not maintaining the same thickness once hardened or possibly not having as much epoxy in the layup.

After the bridge was trimmed down to size the top layer showed signs of delamination. This likely occurred from an insufficient amount of pressure from the clamps. The other possible error that may have occurred was that the
molds were all very tightly fit so one of the molds may have been clamped down in place without actually being pressed as hard as possible against the beam but pressed on its sides. Visually from the outside it was very difficult to be able to tell if that had occurred by simply glancing in between the molds. The three bridges are pictured below with their cross sections showing in Fig. 24. The visible gaps of bridge 1 can be easily spotted as well as the wooden mold still inside of bridge 2. The figure displays them from left to right order.

![Cross Sectional Areas of the 3 Beams](image)

The first and second beam were tested together, the first beam despite its gaps managed to hold 3412 lbs. The failure occurred on the bottom of the beam showing that the bamboo core on the top layer was able to withstand the compressive force. As the bridge failed in tension. It also could be noted that since most of the gaps occurred at the ends of the beam where the bamboo sheet was less uniform, the loads on the ends of the beam are much smaller than the force it experiences in the middle from the deflection. Because of this the ends of the bamboo sheets could be made thinner if needed as well as the width of the flanges. The data from the first test showed that the bridge withstood 3412lbs. At a weight of 945.2 grams., Fig. 25 shows the Load vs Extension Plot from the test of the first beam and Fig. 26 below is a picture of beam 1 being tested inside the Instron machine.

![Load vs Extension Plot of First Beam](image)
The second beam was tested with the wooden mold still inside the middle. This bridge withstood nearly 3600 lbs and then the Instron machine stopped the test with no visible fractures occurring. It was assumed that the wooden mold inside of the bridge fractured which stopped the test and so no real assumptions could be made from the test. The decision to use the vacuum bag layup was made based off what could be seen or touched on the outside of the bridge, appearing to show a stronger layup.

The third and final beam was tested at the SAMPE convention. After observing some of the beams torque during the tests, it was shown that the alignment of the beam was a critical piece in the testing. Although no tools were given in order to ensure that the bridge was placed straight so each team needed to simply eyeball whether or not they thought the bridge was placed correctly. The rate at which the machine applied force was also based on the deflection per minute. The test at SAMPE was set to .5” per minute which was much faster than the test on the first two bridges at Cal Poly. The fast loading may have allowed the bridges to hold more weight as it quickly applied weight until the deflection slowed and the rate the load increases would also decrease. Also different from the tests performed at Cal Poly, the machine at SAMPE had a square fixture attached to the top of the Instron machine. This square would allow more even distribution of the force to the beam. This feature should increase the amount of weight the beam could hold as well as the increased rate. Because of the increased weight of this bridge, the third bridge held 8126lbs at .475” deflection at a weight of 1846 grams. With the design load only being 3000 lbs however, the beam clearly was overdesigned due to our misinterpretation of the rules. The Load vs Extension plot is shown in Fig. 27 taken from SAMPE.
Table 3 below shows the results of the layups as well as tests of the 3 beams. The Load vs Extension plot is shown in Fig. 27 taken from SAMPE.

### Table 3 Test Results of the 3 Beams

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Load</th>
<th>Extension</th>
<th>P/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 1</td>
<td>945.2g</td>
<td>3412 lbf</td>
<td>.570</td>
<td>3.61 lbf/g</td>
</tr>
<tr>
<td>Beam 2</td>
<td>987.6g</td>
<td>~3600 lbf</td>
<td>.472</td>
<td>3.65 lbf/g</td>
</tr>
<tr>
<td>Beam 3</td>
<td>1846.59g</td>
<td>8126 lbf</td>
<td>.521</td>
<td>4.40 lbf/g</td>
</tr>
</tbody>
</table>

As can be seen from Table 3, beam 3 displayed the highest strength to weight ratio. Despite the errors during the manufacturing process, the geometry of the beam appears to be consistent with our finite element modeling test results in that with a higher web height the beam is able to withstand more forces. Both beam 1 and beam 3 failed in tension on the bottom layer, where there is no bamboo reinforcements, proving that the bamboo core on the top layer can take on most of the compressive force that the top layer undergoes. The failure of beam 3 is shown below in Fig. 23. The beam fractured very close to the middle of the beam as well suggesting that the small delaminated layers on the top layer towards the ends of the beams did not affect the beams ability to withstand the weight. Likely due to the small amount of force felt on the ends of the beam compared to the middle as was also visible in the FEM analysis. In future years, for this competition the ends of beams should be sheared down smaller as a test to see whether or not the beam would still be able to withstand the high weight, while also reducing down a great amount of the weight.
V. Conclusion

Improving on the design of naturally occurring fiber square beams from last year, the bridge built this year was able to withstand a much higher load, though at the cost of a higher weight. However, the strength-to-weight ratio was much increased this year. While fabrication of natural fiber composites continues to develop, it was shown at SAMPE that the simplest beam made of wood, and simple wood glue built into a truss, still greatly outperformed any of the natural composite beams. While hemp and bamboo are still very strong as a cheap alternative composite, the complexity of the fabrication process shows that it fails in comparison to the equally as cheap wooden bridges. These bridges also are much simpler to create and with less steps in the fabrication there are fewer areas where mistakes and errors could occur leading to a flawed bridge.

What was shown well from the natural composite beams was that the bamboo core within layers of hemp greatly increased the strength of the beams. All of the beams tested failed in tension due to the bamboo core being on the top layer in order to combat the compressive forces. Adding a layer of bamboo in the bottom cap would be an interesting test however, the drawback would be the increased weight.

Some suggestions to further increase the performance of natural composite bridges would be to use a premade bamboo core, such as bamboo flooring if it could be purchased or cut into thin enough pieces. With flooring already removing any gaps that could occur between the strips of bamboo the chance for error there greatly reduces. In addition, access to metal molds that could be cut to the exact desired size would create a much higher chance that the bridge is fabricated near perfectly. With wooden molds the curvature due to wood warping was always a factor that had to be taken into account and the few metal molds used were in preset sizes which the bridges had to be designed to.

Despite its flaws, natural composite materials, specifically hemp and bamboo remain a material that is environmentally friendly to manufacture and show a relatively high strength to cost ratio compared to its carbon fiber or fiberglass counterparts.
VI. References

1. 2013 SAMPE Student Bridge Contest Rules. SAMPE Document.

2. ASTM D790 Plastic Flexural 3 Point Bending Test.