Study of the Effect of Different Lay-up Methods on the Composite Mechanical Characteristics

A Senior Project

presented to

the Faculty of the Aerospace Engineering Department

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Bachelor of Science

by

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Abstract

The purpose of this experiment is to investigate and understand composite structures and the effect of different layup methods on the composite structure, particularly a composite I-beam. One must learn the procedure on how to build the composite I-beam and put it together then build the final composite I-beam and enter the I-beam in the 14th Annual Society for the Advancement of Material and Process Engineering (SAMPE) Student Bridge Contest. The competition will be held May 25th, 2011 in Long Beach, CA. The I-beam was entered in the competition and placed 4th out of 5. The goal for this experiment was to hold a 2,000 lbf , the beam held a force of about 1,000 lbf and a moment of about 10,000 lbf-in. The beams final mass was about 418 grams.

I. Introduction

The I-beam is shown, by beam theory, to be a very efficient form for carrying both bending and shear loads in the plane of the web. The inefficiency of the I-beam is that the cross-section has a reduced capacity in the transverse direction, and is also inefficient in carrying torsion. It is important to note that the web resists shear forces while the flanges resist most of the bending experienced by the beam.

The application of aerospace, aircraft, automobile and aviation require the material's characteristic such as high stiffness-to-weight-ratios. Although these are characteristics of composite materials, they are difficult to design and analyze because of their heterogeneous and antisotropic nature. Composite structures are widely used today in aerospace applications.

Humans have been using composite materials for thousands of years. Take mud bricks for example. A cake of dried mud is easy to break by bending, which puts a tension force on one edge, but makes a good strong wall, where all the forces are compressive. A piece of straw, on the other hand, has a lot of strength when you try to stretch it but almost none when you crumple it up. But if you embed pieces of straw in a block of mud and let it dry hard, the resulting mud brick resists both squeezing and tearing and makes an excellent building material. Put more technically, it has both good compressive strength and good tensile strength. Another well-known composite is concrete. Here aggregate (small stones or gravel) is bound together by cement. Concrete has good strength under compression, and it can be made stronger under tension by adding metal rods, wires, mesh or cables to the composite (so creating reinforced concrete). [1]

Composite materials are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct within the finished structure, in this experiment fiber glass and epoxy. There are different molding methods in order to make a composite structure, they are: autoclave molding, resin transfer molding, vacuum bag molding, pressure bag molding, and etc. Autoclave molding is a process using a two-sided mold set that forms both surfaces of the molded product. The lower side is a rigid mold and the upper side is a flexible membrane made from silicone or an extruded polymer film such as nylon. Note that reinforcement materials can be placed manually or robotically. In autoclave molding it is more common to pre-impregnate the mold with the resin in the form of prepreg fabrics or unidirectional tapes. The process is performed at both elevated pressure and elevated temperature. The use of elevated pressure facilitates a high fiber volume fraction and low void content for maximum structural efficiency. The resin transfer molding uses a two-sided mold set that forms both surfaces of the composite structure. In this process the lower side id a rigid mold and the upper side can be a rigid or flexible mold. Resin transfer molding then fits together the two sides to make a mold cavity and this cavity reinforcement materials are placed into it and the mold set is closed prior to the introduction of matrix material. Resin transfer molding can be done at either ambient or elevated temperature. Vacuum bag molding uses a two-sided mold set that shapes both surfaces of the composite structure. The lower side is a rigid mold and the upper side can be a flexible membrane or vacuum bag. The flexible membrane can be a reusable silicone material or an extruded polymer film and the vacuum is applied to the mold cavity. The vacuum bag molding is usually done using a venture vacuum and air compressor or a vacuum pump. The vacuum bag molding technique is usually used to laminate together carbon fiber fabric or fiber glass along with resins and epoxies. The pressure bag molding technique is related to vacuum bag molding except the upper side is inflated with heated compressed air or steam as well as the lower side. This process allows the excess resin and air to be forced out. This process is used for making composite helmets. There are also many other techniques that are

used for composites that are not mentioned because there are too many to name individually but the ones mentioned are the most common used molding techniques.[1]

The experiment was done using the vacuum bag molding technique. The technique was used because it is a very economic way to work with composites and because of its simplicity. Note that vacuum bagging is widely used in the composite industry. In commercial woodworking facilities vacuum bags are used to laminate curved and irregular shaped work pieces. A vacuum bag can be made of strong rubber-coated fabric or a polymer film.

It is important not only to choose your composite material such as fiber-glass and what method to use but it is also important to choose the resin best suited for the project. There are many types of resins, here are a few, polyester resin, vinylester resin and epoxy resin. Polyester resin has a yellowish tint and is used in common projects. Its weaknesses are that it is UV sensitive and can degrade over time; in order to help preserve it a coated is also added. Vinylester resin has a bluish tint. This type of resin has lower viscosity than polyester resin and is more transparent. Vinylester resin is fuel resistant, will melt in contact with gasoline, and is more resistant over time to degradation than polyester resin. Epoxy resin is transparent when cured. In this experiment, as well as in the aerospace industry, epoxy is used as a structural matrix material or as structural glue.

In today's world composite materials are used in high performance products because of the need to be lightweight yet strong enough to take large loading conditions. Composites can also be molded into complex shapes. Some examples of this are: aerospace components, boat and scull hulls, bicycle frames, racing car bodies, launch vehicles, heat shields for re-entry vehicles, and etc. The downside to using composites is the high cost of manufacturing them.

The competition has seven categories for the beams which are; I-beam carbon and/or aramid fiber, I-beam fiber glass, I-beam natural fiber, square beam carbon and/or aramid fiber, square beam fiber glass, square beam natural fiber, and open design. The competition was notified that a fiber glass I-beam would be made.

As shown in figure 1, I-beams have different parts to it like the web thickness, beam depth, and etc.

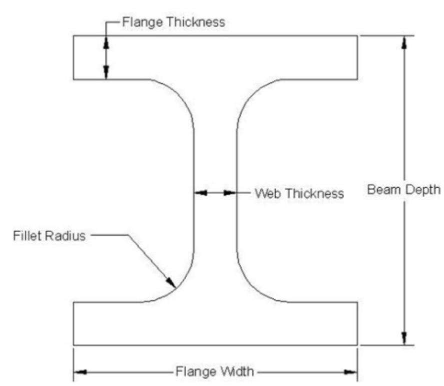

Figure 1. This is a basic schematic of an I-beam[2]

The purpose of this study is to investigate and understand composite structures and the effect of different layup methods on the composite structure, particularly a composite I-beam. The composite I-beam is to be constructed from different fiber material and epoxy resin. Strain gages will be used to measure loading on the I-beam. Theoretical and numerical results will be compared to experimental results.

II. Senior Project Description

The purpose of this senior project is to model and build an I-beam made out of glass fiber with a maximum mass of 600 grams. The beam itself must be a 4"x4" (maximum) by 24" in length. It must have a single web less than or equal to 0.6'' thickness. In order to meet these requirement one must focus in getting the right ratio; therefore one must focus on the manufacturability and optimization of beams. This was done by creating various set ups, changing the materials used, and using different techniques when it came to vacuuming and applying epoxy to the fibers. The final bridge design was submitted to SAMPE Student bridge contest where the design competed with other

universities. In the end, what makes a "good bridge" will be determined by the amount of loading the beam can hold without any types of failure, such as buckling and fracturing.

III. Design

To be able to design an I-beam an overall understanding of the loads and beam behavior must be known. This was done by calculating the reacting forces and moment along the beam. The method selected was Excel for its simplicity and user friendly applications. The length of the beam was modeled in increments of one inch as shown in Figures 2 and 3 below; the diagrams demonstrate the forces and moments seen by the beam at distance x-inches.

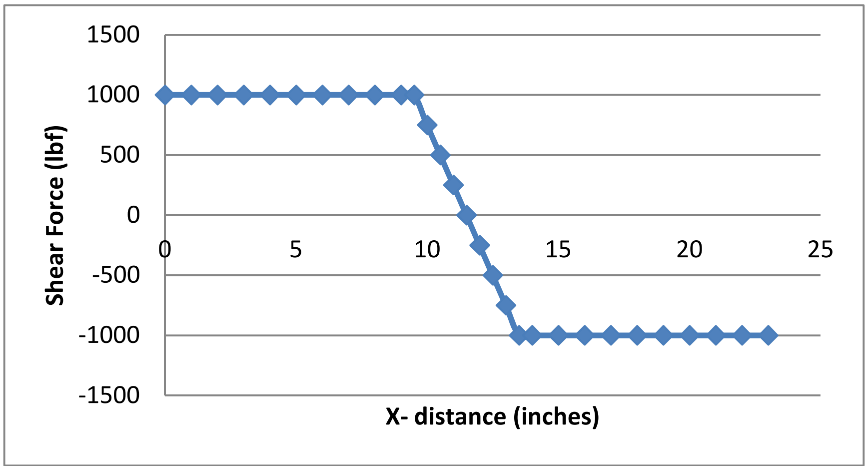

Figure 2. Shear Force along the I-beam

The shear force was calculated using 2000lbf as a minimum requirement in order to model the force seen by the I-beam. The shear force is used to determine what section of the beam saw the most force and thus needed reinforcement. As seen in Figure 2 the greatest shear load is projected at the ends of the beam and at the middle of the beam, a change of shear force direction is seen, going from positive to negative. From the shear calculations one could easily determine the moment force along the I-beam.

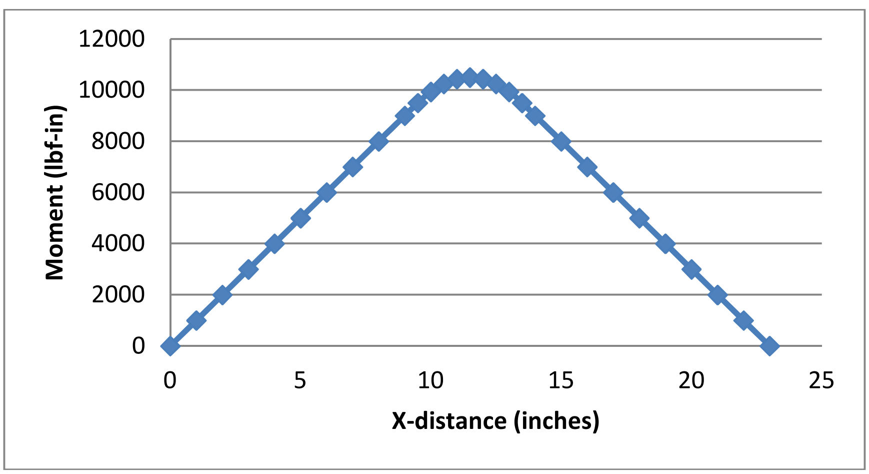

Figure 3. Moment force along the I-beam

Figure 3 demonstrates the maximum moment viewed by the beam. The maximum moment was at its mid-distance where the force was being applied. The moment diagram portrays the behavior of the moment across the I-beam thus which helps in determining which locations of the I beam need less material to reduce mass.

The final design that was chosen was a curved I-beam, this was selected for the weight to force ratio. The curved I beam was accomplished by removing the extra material from the bottom, middle, and the top corners. Figure 4 depicts a schematic of the geometry of the curved I-beam.

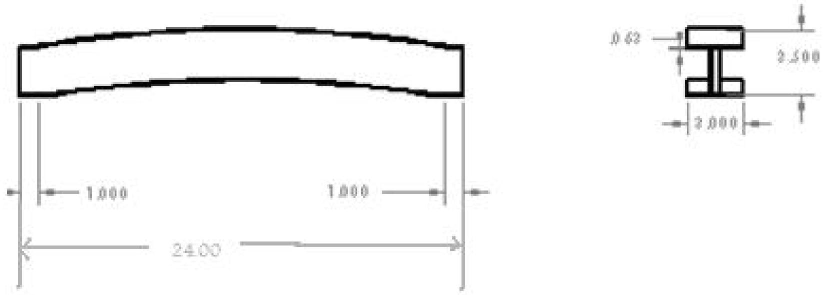

Figure 4. Schematic of Curved I-beam

As seen from the schematic, an inch was given as flat surface to allow enough room for the roll pins to be fixed since it required a span of 23 inches. The beam had an initial height of 3.43 inches and curved up to a total height of 3.5 inches. Both flanges were 0.062 inches thick made of only fiber glass in order to eliminate delaminating issues and in order to reduce mass. The web was 0.534 inches thick with 0.408 inches of foam, and 0.063 inches of fiber glass at each side of the foam as seen in Figure 5.

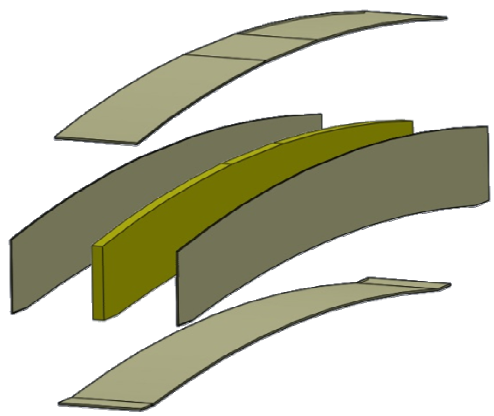

Figure 5. An Extrude View of the I-beam layers

In Figure 5, the gray sections are the fiber glass layers, while the yellow section is the foam placed in the web. This design had an overall mass of 418 grams and was able to hold a load of 990 lbf.

IV. Apparatus and Procedure

The experiment was conducted using a vacuum pump and its tubing. Figure 6 shows the setup for making the composite I-beam in the Structures Laboratory at Cal Poly University. Figure 7 demonstrates the vacuum pump used for making the I-beams. Figure 8 shows the schematic of the process of making the I-beam using the vacuum pump.

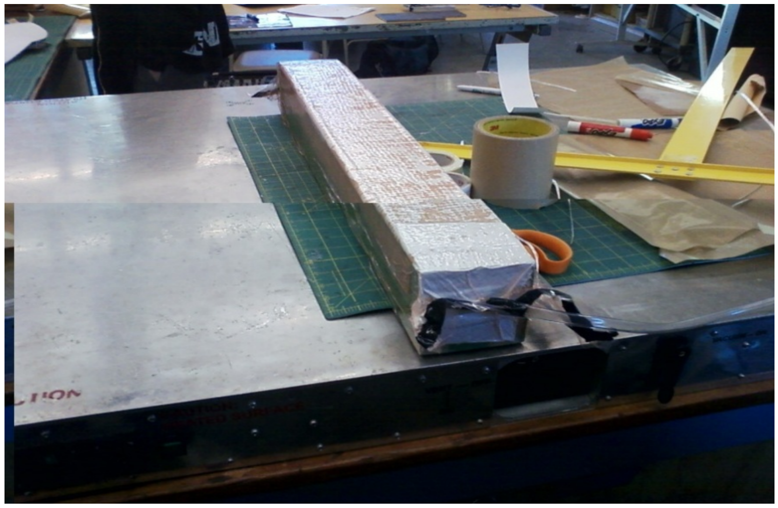

Figure 6. The composite I-beam in a vacuum bag

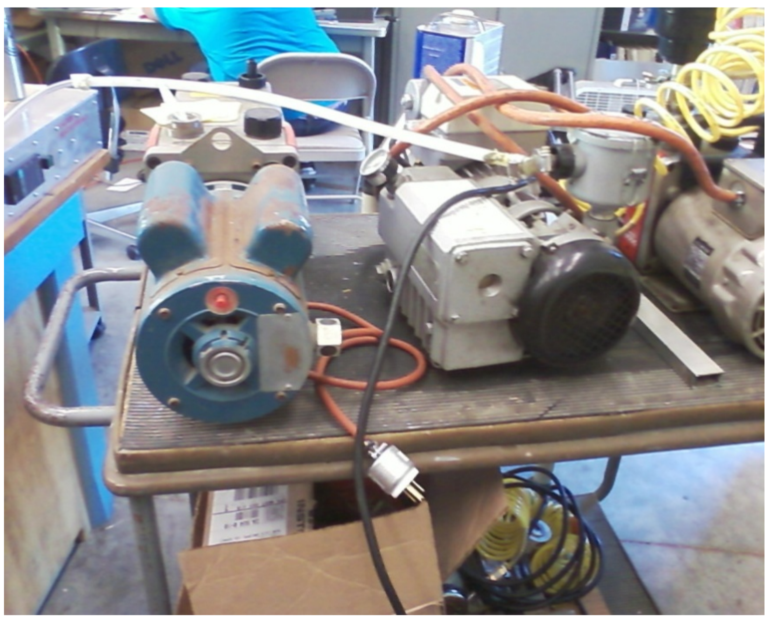

Figure 7. The vacuum pump used to pressurize the I-beam

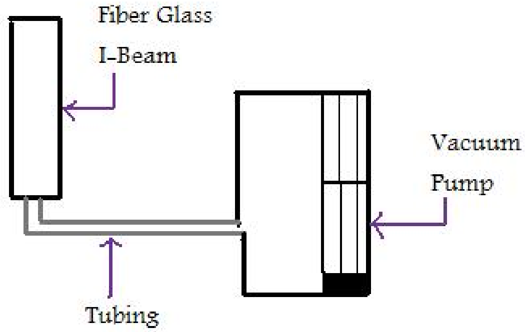

Figure 8. Schematic of the process of making the I-beam

The first iteration I-beam was not be made in one piece, it was made in two. The first half is in the shape of a U as well as the other half, when the two are made they will be put together to make an I-beam. Each half of the I-beam consisted of four pieces of fiber glass (26” by 9”), a flow medium (26” by 4”), one piece of cotton (26”by 9”), tape (32” by 13”), a green bag (32” by 13”), a vacuum bag (36” by 36”), porous material (26” by 9”), tubing, vacuum pump, PR2032 epoxy resin, and PH3660 epoxy hardener. All these materials will be wrapped around one piece of wood 26” x 3” by 3.5.” When all these materials were cut to size the epoxy resin (100 grams for every 100 grams of fiber glass) mixed with the epoxy hardener (27grams for every 100 grams of fiber glass) were spread on the fiber glass, then the fiber glass was set on top of the wood and the rest of the materials except the cotton which went on top of the fiber glass, and finally when this was done it was sealed in a vacuum bag and the vacuum pump was used to pressurize all the materials. The vacuum pump remained on for about 10 hours and when it was turned off, mold was cleaned until only the mold of the fiber glass in the shape of a U was left. The mold was left in the laboratory to dry for a week then the second half was manufactured using the same process. When it was all completed the I beam had a mass of about 1,100 grams, which is almost double of what the competition required. It was determined that this method of manufacturing an I beam was not very efficient because there was a large risk of manufacturing one that was too heavy. In order to improve the design it was determined that a curved I beam would best meet all the requirements.

The next several iterations consisted of making curved I beams and it was determined that several would need to be made in order to determine the weaknesses of the design. The curved I beam was accomplished by removing the extra material from the bottom, middle, the top corners, and removing the foam in the flanges. The curved I-beam was made all at once, meaning, that all the layers and materials needed were put together in one mold. In order to achieve the curved shape for the beam several pieces of foam were taped together and sanded to achieve a curved shape. The pieces of foam were taped together to make two large pieces for the mold; the dimensions for each piece were 4x5x26 inches. The beam had an initial height of 3.43 inches and curved up to a total height of 3.5 inches. Both flanges were 0.062 inches thick made of only fiber glass in order to eliminate delaminating issues and in order to reduce mass. The web was 0.534 inches thick with 0.408 inches of foam, and 0.063 inches of fiber glass at each side of the foam as seen in Figure 5. The same type of epoxy and epoxy hardener were used as the first iteration. Other materials also used to manufacture the mold were a flow medium, cotton, tape, a vacuum bag, porous material, tubing, and the vacuum pump. The vacuum pump also remained on for about 10 hours in order to pressurize each mold. Since the mold for the beam was made of foam, the molds were wrapped with plastic and careful attention was given when wrapping the mold to prevent folds or air pockets within the bag. After wrapping the molds, grease was added to help with the release of the mold after vacuuming process. This is very important, because any deformations would reflect in the I-beam, thus creating a weaker structure. Another critical area of the I-beam structure are the corners. When placing the glass fiber on top of the mold, the material was stretched and double checked to make sure the material curved, was straight along the corners not a wavy. A wavy corner would greatly affect the performance of the I-beam by causing it to collapse at smaller loads. When the curved beams were manufactured (3 total), each had a mass of a little over 400 grams. The curved I-beams were under the mass requirement therefore the design was considered a success.

V. Testing

The final step of the design process is testing. The testing process confirms the assumptions that are made in the beginning of the experiment as well as confirming the calculations done for an ideal case. For this experiment, SolidWorks was used as a simulation of what would occur when the beam was tested. Static loading mode was selected to model a 2000lbf, since that was the design goal, at the center of the beam with reaction forces at the bottom. The same test was done at different geometry for the I-beam, e.g. changing height or thickness as a way to optimize the design. With SolidWorks software we were able to model the stress with the Von Misses Stress Method, the displacement with the Resultant Displacement Method, and the strain with the Equivalent Strain Method. Table 1 shows the values that were assumed from the data base from Solid Works for fiber glass. Figures 9, 10, and 11 below illustrate the result for each test if it were to support the 2,000 lbf.

Table 1. Lists all the values used for simulating the I-beam in Solid Works

Property Name	Value	Units	Value Type
Elastic modulus	7.3e+010	N/m^2	Constant
Poisson's ratio	0.22	NA	Constant
Mass density	2600	kg/m^3	Constant
Tensile strength	2.6e+009	N/m^2	Constant
Yield strength	1.9e+009	N/m^2	Constant
Thermal conductivity	0.2256	W/(m.K)	Constant
Specific heat	1386	J/(kg.K)	Constant

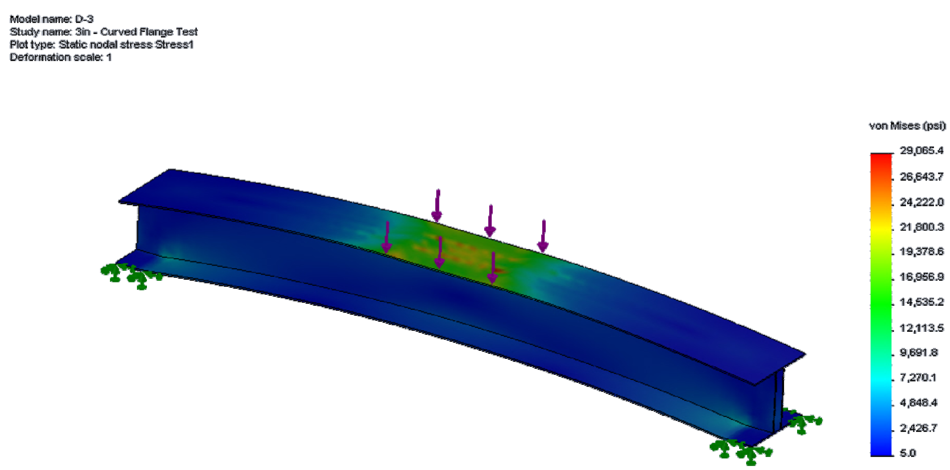

Figure 9. Demonstrates the stress simulation using the Von Misses Stress Method

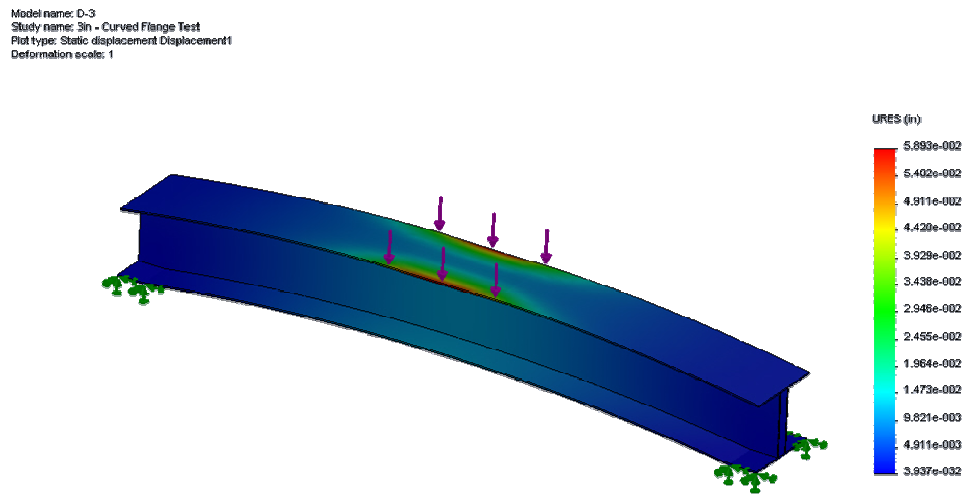

Figure 10. Demonstrates the displacement simulation using the Resultant Displacement Method

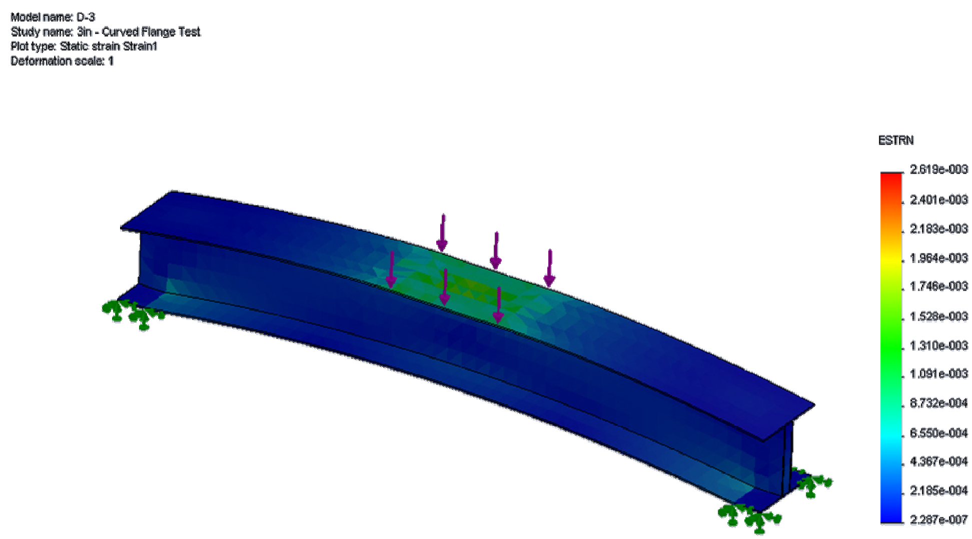

Figure 11. Demonstrates the strain simulation using the Equivalent Strain Method

After multiple iterations a final design was selected. The design consisted of having smaller and thinner fledges, as well as an overall shorter beam than first selected. The actual material property used was unknown because there were no methods of testing for them in the university, thus similar elastic modulus, Poisson's ratio, shear modulus, mass density, tensile strength, yield strength, thermal expansion coefficient, thermal conductivity, and specific head had to be used as the ideal case for these calculations. For the overall picture, the team was looking for the trend of the material behavior instead of the actual numbers seen for stress, strain, and displacement.

Once the first beam was built, a physical test was done. A 4"x4" box would be used to place the force along the beam on the top surface, while roller pins would be applied at each end at the bottom support. The testing was done at the SAMPE competition, where the beam held 990 lbf. Figure 12 depicts a schematic of the testing requirements and placement, while Figure 13 demonstrates the beam being tested at the competition.

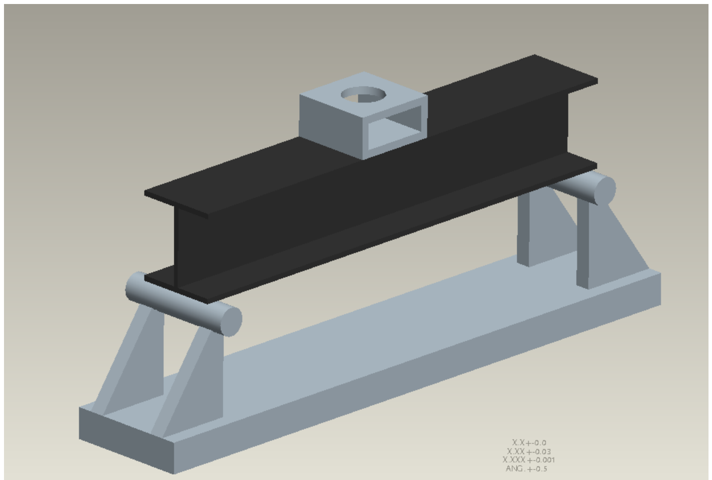

Figure 12. Isometric of a Typical beam with loading fixtures[3]

Figure 13. Demonstrates the machinery and other parts used to apply the loading to the beam.

When the beam is in its correct position, the testing machine slowly increased the force until the beam failed in any way, either by fracturing, buckling, and etc. A large gauge to the side of the machine determined the force applied to the beam; the loads given at the competition were the ones used to calculate the force to weight ratio. Note that the tests for the iterations before the final one were done at the Cal Poly Architectural Engineering lab. The machine used at the Cal Poly Architectural Engineering lab was very similar to the one used in the SAMPE competition except that the loading applied was done read electronically, rather it was read using a dial.

VI. Results and Discussion

Once the fabrication of the first I-beam was completed many errors were detected from the way it was manufactured. After a few iterations a standardized process was formed. The process was obtained after experimenting with different forms of layouts, vacuuming process, and materials used. It was determined that the I-beam would be made out of glass fiber due to it being relatively cost effective compared to other materials. The materials used for the set up process are: green bag material, the peel ply (blue/white material), cotton, and the red bag material. These materials were selected because they produce the best I-beams using the vacuum bag molding technique; the materials produce a clean product, with no dents, and light weight. Thus this method kept excess material usage at a low.

Another important aspect of the beam is its structure. Since the fiber takes the form of the mold, smooth surfaces are ideal. After the initial tests were performed, the weak areas of the design were highlighted, more specifically at the edges of the beam. In the previous iterations the material would first delaminate from the foam at the bottom

corners of the beam, thus losing its strength and causing the beam to buckle. All the iterations demonstrated that any manufacturing error, such as leaving gaps between the foam and the flange or having creases on the fiber glass would lead to some sort of failure. To prevent manufacturing errors and the failures that go with it, three more layers of 4”x4”of fiber glass were added at each bottom corner and the top center piece to the final design. Also, the web edges were wrapped with fiber glass to prevent de-lamination.

Lastly, the best method was determined when it came to material removal and final sizing of the beam. The material removal of the excess layers used to mold the glass fiber can be easily done as a group. One of the two edges is selected to begin peeling off the excess layers of material. When enough leverage is pealed, a team of three is used to continue the peeling. One would hold the beam down, while the other two, with the aid of pliers, can remove the excess material. This method provides a smooth finish throughout the whole beam. When all the layers are removed the final sizing is then done with an electric saw. This process provided was thought to provide the best force to weight ratio needed to produce a competitive beam.

The I-beam performed much lower than expected. The goal of the experiment was to be able to hold a minimum of 2,000 lbf as stated in the SAMPE rules and guidelines. The final I-beam only held a 990 lbf at the competition as shown in Figure 14.

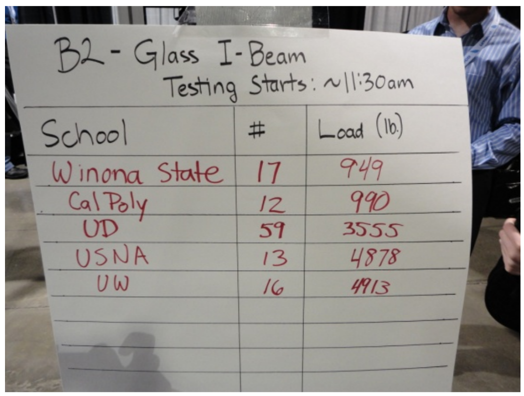

Figure 14. Demonstrates the loading the I-beam withstood at the competition

The final I-beam did not withstand the 2,000 lbf for a number of reasons, including: it was about 200 grams under the maximum mass requirement, the web and flanges were to thin, bad manufacturing, was too tall and etc. The results for the shear and moment are shown in Figures 15 and 16.

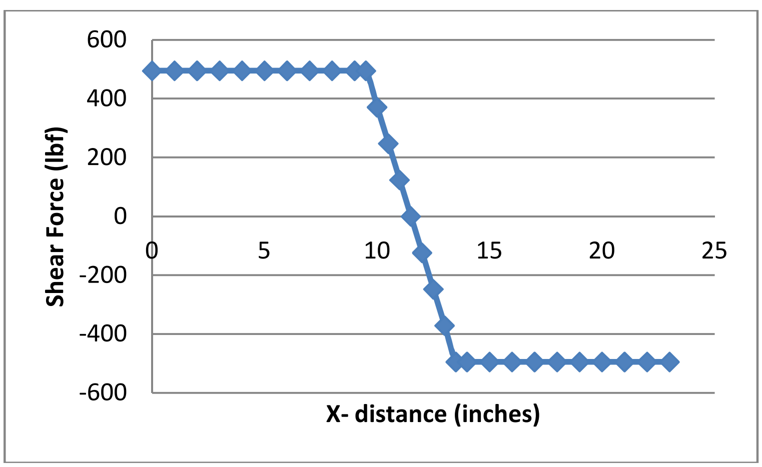

Figure 15. Demonstrates the shear force when the I-beam held a 990 lbf

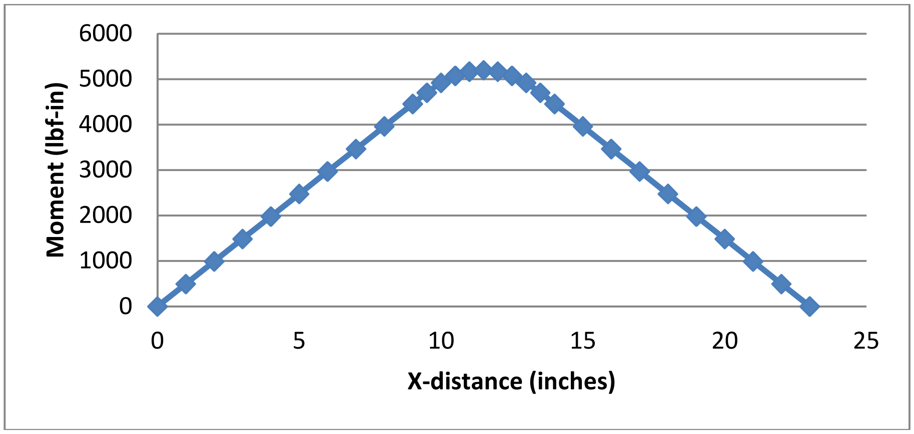

Figure 16. Demonstrates the moment when the I-beam held a 990 lbf

Solid Works simulations were not done for the 990 lbf because it would basically be the same because all the assumptions would stay the same except the amount of loading the beam took. Figure 17 demonstrates that the beam fractured.

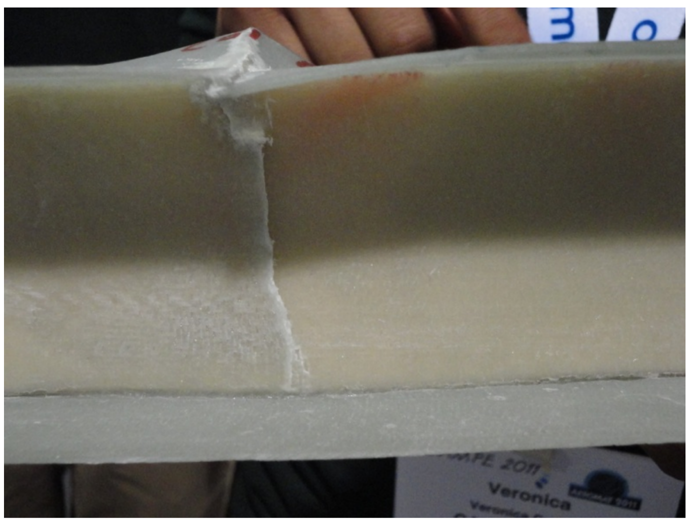

Figure 17. Demonstrates the fracture on the beam which was at the center of the beam

Even though the I-beam did not meet the goal of 2,000 lbf it was considered successful in other ways. The I-beam fractured at about the mi-point of the beam, the beam did not buckle, the beam did not de-laminate, no twisting was involved, and was light weight.

VII. Conclusion

After multiple iterations of the I-beam design, a curved I-beam was determined to be the best because of its lightweight. The problem with the final design was that it only held about half of the intended force; this could have been due to a multiple of issues such as being too lightweight, too tall, and the web and flanges being too thin. From observing the designs that won in the SAMPE competition, it was determined that in order to improve the current design it would be better to make the beam shorter, much thicker at the flanges and web, use autoclave, and use only fiber glass to make the beam instead of including foam. In the future, it would be better to know the material properties of the items used to make the beams or to be able to test for them. For this experiment, it was determined that the values from Solid Works for fiber glass would suffice because it would give the general trend of what would happen when the beam was tested. The data that was determined is not exact but is enough to demonstrate how the beam failed and how it performed.

Appendix

Calculating Shear and Moment Force Along the Beam			
Distributed Load for the 2,000 lbf (w)	**x**	**Shear (V)**	**Moment (M)**
lb/in	**inches**		
300	1	1000	1000
600	2	1000	2000
900	3	1000	3000
1200	4	1000	4000
1500	5	1000	5000
1800	6	1000	6000
2100	7	1000	7000
2400	8	1000	8000
2700	9	1000	9000
3000	9.5	1000	9500
3300	10	750	9937.5
3600	10.5	500	10250
3900	11	250	10437.5
4200	11.5	0	10500
4500	12	-250	10437.5
4800	12.5	-500	10250
5100	13	-750	9937.5
5400	13.5	-1000	9500
5700	14	-1000	9000
6000	15	-1000	8000
6250	16	-1000	7000
	17	-1000	6000
	18	-1000	5000
	19	-1000	4000
	20	-1000	3000
	21	-1000	2000
	22	-1000	1000
	23	-1000	0

Distributed Load for the 990 lbf (w)	x	Shear (V)	Moment (M)
lb/in	**inches**		
247.5	0	495	0
300	1	495	495

600	2	495	990
900	3	495	1485
1200	4	495	1980
1500	5	495	2475
1800	6	495	2970
2100	7	495	3465
2400	8	495	3960
2700	9	495	4455
3000	9.5	495	4702.5
3300	10	371.25	4919.0625
3600	10.5	247.5	5073.75
3900	11	123.75	5166.5625
4200	11.5	0	5197.5
4500	12	-123.75	5166.5625
4800	12.5	-247.5	5073.75
5100	13	-371.25	4919.0625
5400	13.5	-495	4702.5
5700	14	-495	4455
6000	15	-495	3960
6250	16	-495	3465
	17	-495	2970
	18	-495	2475
	19	-495	1980
	20	-495	1485
	21	-495	990
	22	-495	495
	23	-495	0

Acknowledgments

The experiment could not have been done without the Architectural Engineering Department. The Department let us use their machine to test each iteration of the I-beams. Architectural Engineering technician Ray Ward was there every time we needed to use the machine, and made sure that each beam was tested correctly.

Dr. Eltahry Elghandour was a very essential person in the lab and this experimentation could not have been done without him. Dr. Elghandour let us truly learn by doing.

The experiment could not have been done also without the Aerospace Engineering Department because the department let us use as much fiber glass and epoxy as we needed and for the use of the composite lab.

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