STUDY OF THE EFFECT OF UNIDIRECTIONAL CARBON FIBER IN HYBRID GLASS FIBER / CARBON FIBER SANDWICH BOX BEAMS

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By
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STUDY OF THE EFFECT OF UNIDIRECTIONAL CARBON FIBER IN HYBRID GLASS FIBER / CARBON FIBER SANDWICH BOX BEAMS

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ABSTRACT

STUDY OF THE EFFECT OF UNIDIRECTIONAL CARBON FIBER IN HYBRID
GLASS FIBER / CARBON FIBER SANDWICH BOX BEAMS

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University of Dayton

Advisor: Steven L. Donaldson, Ph.D.

This study investigated the effect of carbon fiber placed in different amount at
different location in a square box beam. In total 8 designs were selected and 3 beams
were fabricated for each design using hand layup and vacuum bagging technique. The
beams were tested using a four point bending test. The stiffness were calculated and
compared with all glass fiber beams. The beams were analyzed using finite element
method in Abaqus.

It was found that the location of the carbon fiber has an effect on the increase in the
stiffness of the beam. Beam with 29.6% carbon fiber by volume gave maximum increase
in stiffness. The maximum load carried by the beams showed a different trend. It was
found that the maximum load carrying capacity decreased with increase in the amount of
carbon fiber.

Carbon fiber effectiveness index (ratio of percentage increase in stiffness of beam
and volume percent of carbon fiber) was calculated for each design and it was found that
the design D3; which has one layer of carbon fiber on the top and bottom face utilized carbon fiber most effectively.
Dedicated

To my late grandfather for all the inspiration

And my parents for all the support
ACKNOWLEDGEMENT

I would like to express my thanks and appreciation to Dr. Steve Donaldson, my advisor, for giving me the opportunity to work on this project and providing the time and equipment necessary and funding for the work contained herein, and for directing this thesis and bringing it to its conclusion with patience and expertise.

I would like to specially thank Paul Ubrich of Momentive for generously donating the resin and curing agent and Matthew Bodoff of Gurit for donating the foam core. Without support from Paul Ubrich and Matthew Bodoff this project would not have happened.

I would also like to thank everyone who has helped me over the past year with my thesis and graduate degree. This includes Bernard Glasco, for helping me to cut the foam core, set up the testing jig and doing the testing, Garry Andrews for teaching me how to make composite flat panels, Karen Barrett for her help in ordering the material required for the project and coordinating with materials suppliers and Mike Green for making wooden core for beam fabrication trials.

I would also like to thank Dr. Rebecca Hoffman for her help in FEA modeling and giving her precious time and patience to debug the model.

I am grateful for support from my friends for being my family far from home, especially my roommate Sidaard Gunasekaran for his help in taking pictures of the beam fabrication process.
Last but not the least; I would like to thank my family for being there for me. I am grateful for my parent’s support and giving me a chance and inspiration to follow my dreams. I would like to thank my girlfriend, for believing in me and supporting me with patience throughout my masters.
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CHAPTER 1
INTRODUCTION

Materials have been such an influence on our lives that the historical periods of human kind have been dominated, and named, after materials. Over the last forty years, composite materials, plastics and ceramics have been the dominant emerging materials. (1).

A composite material is a macroscopic combination of two or more distinct materials, having a recognizable interface between them. Composites are used not only for their structural properties but also for electrical, thermal, tribological, and environmental applications (2). The applications of composites range from pressure vessels to a full scale aircraft such as the Boeing 787 Dreamliner. The attractive quality of composite materials is high stiffness-to-weight ratio and high strength-to-weight ratio, i.e. higher structural efficiency relative to previously available structural materials. Because of the chemical and environmental stability of the matrix in the composite material, they can last longer than metals. Due to advancements in composite processing and reduce cycle times, composites are making headway into the automobile and other industries.
Carbon fiber composites are readily replacing steel and other metallic components resulting in lightweight, durable, fuel-efficient structures. But the use of carbon fiber is often limited to high end applications as the initial material cost of carbon fiber is very high as compared to other materials. Efforts are being made to compensate the higher cost of the carbon fiber by having multiple parts made simultaneously and by part integration. Another approach to reduce the cost of composites would be to use glass fiber and carbon fiber simultaneously. By using carbon fiber in strategic structural locations, it is possible to reduce the cost of the composite components with very little compromise in performance.

The purpose of this research is to study the effect of amount and position of unidirectional carbon fiber in a glass fiber / carbon fiber box beams. In this study, different beams are made using glass fiber and carbon fiber with a foam core. Each beam has a different amount of carbon fiber placed at different locations in the beam. In total eight such designs are selected. Three beams per design are fabricated using a hand layup technique. All 24 beams are tested under four point bending test and the stiffness of the beams is found.
CHAPTER 2
LITERATURE REVIEW

Most composite structures are designed as assemblies of beams, columns, plates and shells. Beams are structural members that carry mainly bending and transverse shear loads. Composite beams are usually thin-walled. They are produced by pultrusion, filament winding, hand layup etc. To reduce cost and weight, the amount of material used in the beam should be as small as possible. The required bending stiffness is achieved by increasing the moment of inertia as much as possible. This can be accomplished by enlarging the dimensions of the cross section while reducing the thickness of the wall (1).

For higher stiffness beams, material with higher stiffness can be used. Carbon fiber composites have very high stiffness and high strength to weight ratio. For this reason carbon fiber is a material of choice in applications where high stiffness, strength and lower weight are required. These applications include aerospace applications, high end automobiles and in the field of defense. Even though the carbon fiber composites have exceptional properties, the cost of carbon fiber is very high. Even after considering the advancements in the molding technologies and the advancements in the resins which can be formulated to give a gel time as low as 1 min, the cost of carbon fiber composite parts is still very high as compared to their metal counterparts. Another way to reduce the cost
of composite parts is to use expensive fibers like carbon fiber in combination with less expensive fibers like glass fiber. The hybridization of glass fiber and carbon fiber is cost beneficial and can yield improved balanced properties (including cost) than all carbon or all glass beam.

Chenson Dong et al did flexural testing of four different combinations of s-glass and T700 carbon fiber. They found out that the flexural modulus decreased with increased amount of glass fiber in a carbon fiber sample but the flexural strength of a sample increased by 8% by replacing 1 layer out of 5 layers of carbon by s-glass layer (3).

Valenza et al tested hybrid composite of glass mat with randomly oriented fibers and UHM carbon fiber. By replacing only one outer layer of the glass mat with unidirectional carbon fiber, they were able to achieve flexural stiffness equal to aluminum alloy 6061-T4 which is used in marine applications (4).

Wael F. Ragheb used hybridization to improve local buckling capacity of pultruded I-beam. In his research, carbon fiber was placed in different amounts and positions in the pultruded I-beam. It was found that placement of carbon fiber mat on all of the outer faces of the I-beam gave best properties and was one of the economical solution (5).

Nguyen Duc Hai et al, tested several small flanges and wide flanges I-beams. The web of I-beams consisted of only glass fiber and the flanges contained glass fiber and carbon fiber. Event though the beams with 52% carbon fiber showed higher stiffness it was found that the maximum strength of hybrid beams can be obtained with the volume content of carbon fiber to be 25% to 33% (6).
James W. Giancaspro et al investigated the hybridization with inorganic geo polymer. The research included testing of hybrid composite specimens with woven and unidirectional 1k and 3k carbon fiber. They found out that placing carbon on tension and compression faces of the specimen in bending yielded almost same stiffness as the specimen with carbon on the tension face. They also observed that the unidirectional carbon gave same additional stiffness as woven plane weave carbon fiber (7).

The references (3)-(7) show that the placement of carbon fiber in the beam is very important. To attain required stiffness and higher strength it is not required to have a significant amount of carbon fiber, but the right amount placed in the right location, where its properties can be utilized up to its potential. All the references (3-12 and 14-16) talk about a hybridization effect. It was observed that the properties of the hybrid composites predicted by the rule of mixture are different than the actual properties of the hybrid composites.

Previous studies into the effects of hybridization on the flexural properties have shown varied results. Sudarisman and Davis noted the replacement of 33% of E-Glass fiber by S-2 Glass fiber produced an increase in flexural strength by 23% with no significant effects of hybridization to the flexural modulus (8). Dukes and Griffiths found an increase in flexure modulus when carbon fiber was added to the second layer (from each surface) of eight ply unidirectional laminate (9). It was also found that the flexural strength decreased rapidly as all glass reinforcement is progressively replaced by graphite fibers (10).

From CLPT it can be seen that in bending unlike tensile stresses the outer laminate are more stressed than inner laminate. For this reason the bending moduli are different
from in plane moduli. To estimate the apparent bending moduli following formulas can be used.

\[ D_{11} = \frac{t^3 E_x^b}{12\Delta} \]
\[ D_{22} = \frac{t^3 E_y^b}{12\Delta} \]
\[ D_{12} = \frac{t^3 E_x^b \vartheta_{yx}}{12\Delta} = \frac{t^3 E_y^b \vartheta_{xy}}{12\Delta} \]
\[ D_{66} = \frac{t^3 G_{xy}}{12} \]

\[ \Delta = 1 - \vartheta_{xy} \vartheta_{yx} \]
\[ \vartheta_{yx} = \vartheta_{xy} \frac{E_y^b}{E_x^b} \]

It can be seen from the equations the apparent bending stiffness can be calculated using bending coefficients. To calculate bending coefficient the equation used is

\[ D_{ij} = \sum_{k=1}^{N} (\bar{Q}_{ij})_k \left( t_k \bar{Z}_k^2 + \frac{t_k^3}{12} \right); i, j = 1, 2, 6 \]

The \( \bar{Z}_k^2 \) represents the distance of the center of the \( k^{th} \) layer from the mid-plane. From this it can see that the distance of a layer from the mid-plane will affect the apparent bending stiffness. The layer which is farthest from the mid-plane will have the most effect on the bending stiffness. From this it can be concluded that placing a stiff material on the at the outer side of the laminate will give more addition in stiffness as against placing the stiff material like carbon fiber closer to or at the mid-plane.

The concept of hybridization can be used in other variety of applications. P.S. Pravin et. al used hybridization of glass and carbon fiber in epoxy matrix to achieve
low coefficient of thermal expansion for temperature range 300K to 125K and urethane modified epoxy matrix for temperatures as low as 20K. Using different orientation they were also able to get near zero coefficient of thermal expansion for temperature as low as 125K (11).

E. Mahdi et al used hybridization in filament wound cylindrical shells and studied their crushing behavior. They studied carbon/epoxy, glass/epoxy, glass-carbon/epoxy, carbon-glass epoxy and glass-carbon-glass/epoxy cylinders. They found that glass-carbon-glass epoxy gave the best results and due to increase in stiffness, the volume of the cylinder made can be reduced significantly (12).
CHAPTER 3

TEST MATRIX

The goal of this research is to vary the amount and position of the carbon fiber in a glass fiber beam. To get a base line stiffness, designs at the two extremes with all carbon (except for ±45° glass fiber side plies) and all glass fiber are made. The design D0 is all glass fiber beams. The figure below shows the D0 layup.

![Figure 3-1: Layup Representation of Design D0](image-url)
The blue lines represent the unidirectional glass fiber, the red line represents stitched ±45° glass fiber, and the yellow rectangle represents the foam core. The all carbon design, D7, has all the 0° unidirectional glass fiber replaced by 0° unidirectional carbon fiber. The grey lines represent the unidirectional carbon fiber. The ±45° stitched glass fiber was not replaced with carbon fiber as there was not enough carbon fiber to cut carbon fiber in 45°. The figure below shows the layup of design D7.

![Figure 3-2: Layup Representation of Design D7](image)

6 other designs with varying amount and positions of carbon fiber are selected. For ease of understanding, the layers are numbered as shown in following figure. The numbering is similar for the bottom face of the beam.
In design D1 the layer 9, the outside layer which wraps around the beam, is carbon fiber layer. The design D2 has carbon fiber for layer 1 which is the next to the foam and layer 9. In design D3, the layer 7 is omitted. As a result of this, the layers which wraps around the beam is now layer 8 and layer 9 is a single layer of carbon fiber.
The design D4 has carbon fiber at layer 6 and 7; the design D5 has carbon fiber at layer 2, 3 and layer 6, 7. The design D6 has carbon fiber at layer 2, 3 and layer 6, 7, 8 and 9. The design D7 has all 9 layers of carbon fiber. The $\pm 45^\circ$ layers in the web are still glass fiber.

All the designs are shown on the following page.
Figure 3-5: Layup Designs
CHAPTER 4

BEAM FABRICATION

To investigate the effect of the amount and position of carbon fiber, eight different designs were selected. Each design had a specific amount of carbon fiber placed at different positions. Three beams were simultaneously fabricated for each design. The beams were made using a hand layup technique followed by vacuum bagging.

Initially several attempts were made to make a hollow beam. A mold was made out of foam. The foam was covered with Teflon for easy release. A removable foam core covered in Teflon was used. Fiber was laid in the mold and resin was applied using a brush. It was observed that significantly less consolidation was achieved in the composite as there was no pressure acting on the composite walls from the core side. Another attempt was made by using a wooden core. While curing of the epoxy, a considerable amount of heat was generated and once the beam cooled down, the composite shrank on the core. Due to this it was very difficult to remove the core. During the attempts to remove the core, it was badly damaged. After these failed attempts the decision was made to make beams using a foam core and composite skin.
During 4-point bending of a beam the top and bottom faces of the beam are in compression and tension, respectively. The shear load is carried primarily by the sides of the beam and the core. A layup was selected in such a way that the top and bottom faces had 0° unidirectional fiber to resist compressive and tensile loads and the sides had layers of ±45° stitched fiber. This fiber layup presented a challenge to make the beam using a hand layup technique. The beam was made layer by layer and keeping the fiber on the sides in place while laying up fiber on top or bottom was very difficult. Another challenge was to keep the fiber in place while rotating the foam while laying up fiber on different sides of the beam. Once the fibers absorbed resin, it was very difficult to handle the wet fiber as it had tendency to deform. The foam used was a closed-cell; non-porous foam and it did not absorb any resin. This made the application of the first layer of the fiber difficult as it did not stick to the foam unless significant resin was applied. Applying an excess amount of resin was not possible because the target volume fraction of 0.5 was

<table>
<thead>
<tr>
<th>Material Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
</tr>
<tr>
<td>Manufacturer / Product Name</td>
</tr>
<tr>
<td>Area Wight of Fiber</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Longitudinal Modulus (Gpa)</td>
</tr>
<tr>
<td>Transverse Modulus (Gpa)</td>
</tr>
<tr>
<td>In-Plane Shear Modulus</td>
</tr>
<tr>
<td>In-Plane Poisson's Ratio</td>
</tr>
<tr>
<td>Transverse Poisson's Ratio</td>
</tr>
</tbody>
</table>

Table 4-1: Material Properties
to be achieved. To solve the problems mentioned above, the layup used consisted of three layers of unidirectional glass fiber which wrapped around the whole beam. The first such layer was the layer next to the foam. As the glass fiber was wrapped around the foam it stayed in place and provided a good base to further layers. The second such layer was at the midpoint in the layup and the final layer wrapped around the whole beam becoming the outermost layer which held all the layers in place.

As seen in Figure 3-1, the blue line represent the unidirectional 0° glass fiber; the red lines represent a combined layer of +45 and -45 stitched glass fiber. The yellow box represents the foam core. The number 1 represent the inner most layer of fiber which wraps around which provide the base for all other layer. The layers 2 and 3 are the wraps which helped to hold the fibers in place.

![Figure 4-1: Layup Representation](image)
4.1 Procedure

The fiber required for each beam is shown in Table 4-1. The orientation, width and amount of each kind of fiber used are given in the table below.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Glass Fiber</th>
<th>Carbon Fiber</th>
<th>Total layers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Orientation</td>
<td>Width</td>
<td>Amount</td>
</tr>
<tr>
<td></td>
<td>0° Unidirectional</td>
<td>1.5&quot; 2.75&quot; 6.5&quot; 7.25&quot;</td>
<td>1.5&quot; 2.75&quot; 6.5&quot; 7.25&quot;</td>
</tr>
<tr>
<td>D0</td>
<td>8 4 2 1</td>
<td>12 0 0 0 0</td>
<td>27</td>
</tr>
<tr>
<td>D1</td>
<td>8 4 2 0</td>
<td>12 0 0 0 1</td>
<td>27</td>
</tr>
<tr>
<td>D2</td>
<td>8 4 1 0</td>
<td>12 0 0 1 1</td>
<td>27</td>
</tr>
<tr>
<td>D3</td>
<td>6 4 2 1</td>
<td>12 2 0 0 0</td>
<td>27</td>
</tr>
<tr>
<td>D4</td>
<td>4 4 2 1</td>
<td>12 4 0 0 0</td>
<td>27</td>
</tr>
<tr>
<td>D5</td>
<td>0 4 2 1</td>
<td>12 8 0 0 0</td>
<td>27</td>
</tr>
<tr>
<td>D6</td>
<td>4 2 2 0</td>
<td>12 4 2 0 1</td>
<td>27</td>
</tr>
<tr>
<td>D7</td>
<td>0 0 0 0</td>
<td>12 8 4 2 1</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 4-2: Number of Layers Used in Different Beams

The information given in Table 4-1 is the fiber used to make one beam. The fiber was cut using a rotary cutter. The fiber was placed on a cutting board which had markings of the desired fiber lengths and widths. While cutting, the fiber was secured in place with a ruler fixed in place with C-clamps. Safety precautions were taken by wearing hand gloves and mask, after cutting fiber was divided into three sets for three beams.

Before starting the layup, vacuum pump was set up. As three beams were to be made at the same time, appropriate attachments were made to the vacuum pump. A vacuum gauge was attached to measure the vacuum applied.
The target fiber volume fraction was 0.5. The fibers were weighed and accordingly the amount of resin was calculated. Weights of fiber and resin for each beam are given in the tables below.

4.2 Resin Calculations

As the desired fiber volume fraction was 0.5, the volume of resin was equal to the total volume of the glass fiber and carbon fiber. The density of the glass fiber was assumed to be 2.5 g/cc and density of the carbon fiber was assumed to be 1.6 g/cc (1).

\[
\text{Weight of resin} = \left( \frac{\text{Weight of Glass Fiber}}{2.5 \text{ g/cc}} + \frac{\text{Weight of Carbon Fiber}}{1.6 \text{ g/cc}} \right) \times 1.14 \text{ g/cc} \quad \ldots(1)
\]

Resin Density Calculations: Density of the EPON 828 resin at room temperature was 1.16 g/cc and the density of Epikure 3223 at 20°C was 0.95 g/cc. The proportion of the epoxy to curing agent was 12 phr. The density of the final resin mixture was calculated using the rule of mixture.

\[
\text{Density of Resin} = \frac{100 \times 1.16 + 12 \times 0.95}{112} = 1.1375 \approx 1.14 \text{ g/cc}. 
\]

The amount of resin used was calculated using formula (1). The gel time for the resin mixture was around 50 min. As the time required to build one single beam was more than the gel time, the total quantity of resin was split into two batches. The resin required for all the beams was weighed at once to save time. The curing agent was added as required.
<table>
<thead>
<tr>
<th>Beam Fabrication Sheet D0-D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Name</td>
</tr>
<tr>
<td>Target Vf</td>
</tr>
<tr>
<td>Fiber Weight in grams</td>
</tr>
<tr>
<td>Glass 0°</td>
</tr>
<tr>
<td>Glass ±45°</td>
</tr>
<tr>
<td>Carbon 0°</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>Resin Weight in grams</td>
</tr>
<tr>
<td>Epoxy</td>
</tr>
<tr>
<td>Epikure</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>Layup</td>
</tr>
<tr>
<td>Top and Bottom</td>
</tr>
<tr>
<td>Webs</td>
</tr>
<tr>
<td>Foam (mm &amp; g)</td>
</tr>
<tr>
<td>0 Side (mm)</td>
</tr>
<tr>
<td>45 Side (mm)</td>
</tr>
<tr>
<td>Weight (g)</td>
</tr>
<tr>
<td>Total Weight</td>
</tr>
<tr>
<td>Actual Weight</td>
</tr>
</tbody>
</table>

Table 4-3: Fiber and Resin Weight for Beams D0 to D2
<table>
<thead>
<tr>
<th>Beam Name</th>
<th>D3-1</th>
<th>D3-2R</th>
<th>D3-3</th>
<th>D4-1</th>
<th>D4-2</th>
<th>D4-3</th>
<th>D5-1</th>
<th>D5-2</th>
<th>D5-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Vf</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.53</td>
<td>0.53</td>
<td>0.53</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Fiber Weight in grams</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass 0°</td>
<td>270.7</td>
<td>270.1</td>
<td>271.8</td>
<td>252.1</td>
<td>252.6</td>
<td>252.4</td>
<td>212.0</td>
<td>212.4</td>
<td>211.9</td>
</tr>
<tr>
<td>Glass ±45°</td>
<td>125.0</td>
<td>113.8</td>
<td>124.5</td>
<td>116.8</td>
<td>117.9</td>
<td>118.3</td>
<td>117.7</td>
<td>117.5</td>
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Table 4-4: Fiber and Resin Weight for Beams D3 to D5
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<td>455.7</td>
<td>455.7</td>
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</table>

Table 4-5: Fiber and Resin Weight for Beams D6 and D7
4.3 Fiber Lay up

First a Teflon sheet was spread on the table to avoid any damage to it. The curing agent was added to the resin in the right amount and mixed thoroughly using a wooden stick. The mixed resin was applied to the foam core using a 1.5” china bristle brush.

![Resin Application to Foam Core](image)

Figure 4-2: Resin Application to Foam Core

After the resin application the first layer of 0° glass fiber was placed. In all the designs the fiber layer immediately next to the foam wraps around the foam. The edge of the layer was placed in middle of the foam, since if the two edges of the fiber were joined near the edge of the foam it could act as a weak zone.
After laying up the first layer the next layers placed were the ±45° fibers. To keep the fibers in place a foam core wrapped in Teflon sheet was used. Using this foam core a constant pressure applied on the fibers to keep them in place.

For the ±45° layers, a stitched fabric was used. Three layers of this stitched fabric were laid in place, one by one, applying resin to each layer. After placement of ±45°
layers, the core was rotated 90° and 0° layers were laid in place. There are three 0° layers. Two of the layers had the same width as the foam and the third layer overlapped the ±45° fibers on the sides. The overlap was around 0.5” on each side. As at this point the ±45° was only on one side, and the overlapping 0° was only on one side. The other side was kept dry. Once again the foam was rotated by 90° and three layers of ±45° were put in place and the overlapping 0° was put in place. Once again the beam was rotated 90°, the 0° fiber was put in place and the third layer was overlapped on the both ±45° sides. After that to keep all the layers laid until this time, everything was wrapped in a 0° unidirectional layer. Most of the times the 1st batch of the resin mixed with the curing agent was used up. The next batch of resin was mixed. The same procedure was followed for the next layers, starting with ±45° and ending with the final 0° layer; either glass or carbon depending on the design. All the designs except D3 contained a 0° layer which was wrapped around the beam. The design D3 had a single layer of carbon fiber on top and bottom which went on top of the layer which wrapped around the layup. The figure 4-6 shows the layup sequence up to the middle 0° layer which was wrapped around the layup. The yellow box represents the foam core, the blue lines represent the 0° unidirectional glass fiber and the red lines represent the ±45° stitched fiber. The figure is just a representation and is not drawn to the scale.
Once all the layers were laid in place the beam was wrapped in a non-porous Teflon sheet. The Teflon kept the beam from sticking to the breather cloth and ensured easy release. It was made sure that the surface of the Teflon sheet was clean and wrinkle free.
A slight pressure was applied while wrapping the beam to make sure the fiber stay in place; too much pressure may cause the fibers to move or form wrinkles.

![Figure 4-7: Beam Being Wrapped in a Non-Porous Teflon Sheet](image)

After being wrapped in the Teflon sheet the beam was wrapped in a breather cloth. From previous trials it was found that if more than one layer of breather cloth was used, the pressure applied was more uniform and the surface of the beam had less wrinkles and waviness. Hence the beam was wrapped in at least 2-3 layers of breather cloth.

![Figure 4-8: Beam Being Wrapped in Breather Cloth](image)
4.4 **Vacuum Bagging**

To cure the beam, room temperature vacuum bag method was used. For this purpose a bag sealed on the sides was used instead of a plastic sheet. To seal the open sides of the vacuum bag, 3M Scotch tape was used. Scotch tape was easier to use and easy to take off. Before layup of the beam, the vacuum bag was cut to the desired size and sealed at one end. A piece of scotch tape was applied at the open end to seal it afterwards. The size of the bag was at least 1.5 times the length of the beam to avoid any wrinkles on the beam. It was necessary to have a smooth surface, at least on the flanges because while testing the beams in four point bending test, the supports and the loading nose were in contact with the top and bottom flanges. If the top and bottom surface were not smooth, there was a possibility of stress concentrations at the surface irregularities which might have affected the results. To save time, the vacuum port was attached to the vacuum bag before the layup. It was observed that, even with 3 layers of breather cloth, the vacuum port left an impression on the beam. To avoid this extra breather cloth was taped to the vacuum port.

![Figure 4-9: Vacuum Port](image)

Figure 4-9: Vacuum Port
As three beams were made at the same time, it was required to attach the necessary joints to the vacuum port. A three way connector was used to attach a vacuum gauge to the vacuum pump. A T-connector was attached to one of the ports of the 3-way connector.

![Figure 4-10: Vacuum Bagging Arrangement](image)

When beam 1 was being vacuum bagged the ports for beam 2 and 3 were sealed using sealant tape. During vacuum bagging beam 2, the vacuum in the bag of beam 1 was lost. The time difference between vacuum bagging of the two beams was more than 1 hour which was greater than the gel time of the resin; hence no damage was done to the beam. Similarly while bagging beam 3 the vacuum in the vacuum bags of the beams 1 and 2 was lost momentarily. The vacuum achieved was around -60 KPa. It took around 4 minutes to achieve this vacuum. The beams were kept under vacuum at room temperature for 24 hours and then removed.
Once the beams were removed from the vacuum bag, they were weighed and left to cure at room temperature for 15 additional days.
CHAPTER 5
EXPERIMENTAL SETUP AND PROCEDURE

5.1 Machine Setup

After fabrication of the 24 beams, they were tested under four point bending. The machine used for this purpose was an Alliance RF 300 (tall configuration) which was made by MTS Systems Corporations.

Figure 5-1: MTS RF 300 Machine
The machine had a maximum load capacity of 300 KN, maximum crosshead travel of 1690 mm and maximum speed of 580 mm/min. For this testing a 300 kN load cell was selected. The load cell was capable of measuring force within ± 1% of the applied force.

5.2 Experimental Setup

The four point loading setup can be seen in the Figure 6.1. The four point loading head was attached to the machine loading head. The loading head had two loading noses with center distance (loading span) of 279.4 (11 in) mm. The diameter of the loading nose was 12.7 mm. The supports were mounted on an aluminum I beam with markings for adjusting the support distance. The test involved measurement of the midpoint deflection of the bottom face. For this purpose a dial gauge was used. To provide enough room for the dial gauge underneath the beam, two metal slabs of thickness 12.7 mm were placed under each support. The supports were held in place on the aluminum I beam using C-clam. The clamps were placed in diagonally opposite corners. It was made sure that there was enough space between the C-clamps to fit the beam. The center distance between the supports (supporting span) was 558.8 mm (22 in).

During trials it was observed that the failure took place directly under the loading nose. This was due to high stress concentration under the loading nose. To reduce this stress concentration, two rubber sheets were placed under each loading nose while testing. Similarly, two rubber sheets were placed on the supports.

To measure the midpoint deflection of the bottom face of the beam a dial gauge was used. The dial gauge was made by Chicago Dial Indicator. The dial gauge had a range of 1” with accuracy of 0.01”. A digital SLR camera Canon EOS 550 with an 18-55mm lens was used to take dial gauge readings.
5.3 Specimen Preparation

Before testing, the beams were visually inspected. As the beams were fabricated using a vacuum bag method, some of the beams had irregularities on the surface. During fabrication it was made sure that at least the top and bottom surfaces of the beam; which were the loading surfaces; were flat and smooth. Even after the best efforts, some irregularities or waviness were observed on the top and bottom surfaces. For this reason top and bottom surface of the beams were inspected and the surface with less irregularities was selected as the loading surface.

Once the top surface was selected, markings were made on the bottom surface. First the length of the beam was measured and center of the beam located. Once the center was located, the supporting span of length 558.8 mm was marked on the bottom surface. The width of the beam was measured at the center for the bottom face was located and marked using a black marker. This was the point where the needle of the dial gauge would be placed to measure the deflection of the bottom face. The side facing the digital camera was marked indicating the front side. This helped in remembering the position of the beam for later analysis.

5.4 Digital Camera

The digital camera was placed on a tripod. It was made sure that the all the legs of the tripod were of same length ensuring horizontal level of the camera. This was achieved with the help of a level provided on the tripod. The camera was mounted on the tripod using an attachment. The attachment then went into the head of the tripod which could be rotated in $360^\circ$ in horizontal plane and $180^\circ$ in the vertical plane. Once the camera was placed on the tripod, it was made sure it was in a horizontal plane using a level provided
on the tripod head. The camera was attached to the laptop via an USB cable. During previous trials it was observed that a typical test took about 600 seconds to either failure or until the first crack. As we were interested in the linear portion of the load deflection curve, it was decided to take a picture of the dial gauge every 6 seconds so that the load deflection curve would have close to 100 data points. For this purpose EOS Utility Software by Canon Inc. was used. This software allowed connecting the camera to the laptop and controlling it remotely. The software also allowed taking picture every 6 seconds automatically until a given number of pictures were taken. The number of pictures to be taken was set at 120.

Figure 5-2: Timer Shooting Setting

Figure 5-2 shows the snapshot of the timer setting in the EOS utility software.
5.5 Experimental Procedure

5.5.1 Specimen and Dial Gauge Placement

Once the beam specimen was marked and ready, it was placed on the loading fixture. Before placement of the beam, two rubber sheets were placed on each support. The beam was placed on the supports by aligning the marking for support span with the center of the loading nose. The supports were centered with respect to the loading nose hence the beam was automatically centered with respect to the loading nose. Once the beam was in place, the dial gauge was placed under the beam in such a way that the needle of the dial gauge coincided with the marking on the bottom face of the beam at the center. After placement of dial gauge, it was set to zero.

5.5.2 Placement of Camera

Once the beam and the dial gauge were in place, the camera was set in such a way that there was no parallax between the camera and the dial gauge. Once the camera was setup, it was focused on the dial gauge. Using digital magnification in the EOS Utility software, the alignment between the 0 on the face of the dial gauge and the needle was rechecked and fine tuning was done as needed. Once again the camera was focused on the dial gauge and the auto focus function was disabled.

5.5.3 Loading of the Beam

Once the camera was setup, the loading head of the machine was brought down. Two rubber sheets were placed under the loading nose. To correct the compression of the
rubber pads, a pre-load of 50N was applied on the beam. The timer and the displacement in the software were set to 0. The beam dimensions were entered in the software. First the start button on the EOS utility software was pressed, which had a delay of 5 seconds. The 5 seconds were counted down and at the end of 5 seconds the start button on the machine software was pressed. As the beam was preloaded the dial gauge shows some displacement. Once the loading was started the camera took pictures every 6 seconds. Once the dial gauge reached the displacement of 0.5” it was removed to avoid damage if the beam failed and hit the dial gauge. After the dial gauge was removed the software taking pictures was stopped. The beam was loaded until the load dropped 50-55% of the maximum load.

Figure 5-3: Support and Loading Assembly with Dial Gauge
5.5.4 Data Collection

Once the test was done the data was collected manually from the pictures of the dial gauge. The machine data contained time of each data point. The displacement data collected from the dial gauge was plotted against the corresponding load.
CHAPTER 6

FINITE ELEMENT ANALYSIS

In this research, for finite element modeling, Abaqus CAE was used. Deformation and stress analysis of laminated composites can be done at different levels; a) micromechanics b) lamina level c) laminate level.

When a great level of detail is necessary, micromechanics approach is used. In micromechanical approach, the properties are calculated at the fiber/matrix constituent level. For this it is necessary to describe the microstructure including fiber shape, geometric distribution and material properties of the constituents.

In the lamina level approach, the properties of the lamina are defined. The composite is modeled as layers of the lamina. While defining the composite, thickness of lamina, lamina material and material orientation angle is defined.

In laminate level approach, composite material is defined as a homogenous equivalent material with laminate properties. In this case structural behavior can be analyzed by using orthotropic properties (13).
6.1 Modeling of the Beam

In this research, lamina level approach was used. The beam has a foam core and a composite skin. The foam core was modeled using 3D stress elements C3DI, which is an 8-node linear brick element with incompatible modes. The composite skin was modeled as a one single skin.

![Figure 6-1: Layup Representation for Beam D0](image)

In the above figure, the blue color represents 0° unidirectional glass fiber, Red color represents ±45° stitched fabric and yellow color represents the foam core. It can be seen from the representation of the beam shown above that there are layers on the top and bottom face which overlap the ±45° stitched fiber on the webs. To model these overlaps the sides of the beam were partitioned in 3 faces as shown in the figure below.
There are three layers which wrap the beam. It was observed during the fabrication of the beam that the fiber does not follow the 90° corner of the foam core. To take this fact into account a radius of 1mm is introduced at the corners.
The foam core was modeled as an isotropic material. The composite skin, as mentioned above, was modeled as continues skin. For this purpose composite layup method was used. The composite layup method allows selecting number of layers. The composite layup dialog box allows selecting different materials, thicknesses and regions and orientations.

The layers were modeled as shown in the represented as shown in the layup representation. The figure 6-4 shows the composite edit layup box. The figure 6-5 shows the 0° unidirectional layer which wraps around the beam. The figure 6-6 shows the 0° unidirectional layer which goes on top and bottom. Figure 6-7 shows the ±45° layer in the webs and the figure 6-8 shows the 0° unidirectional layer which top layer which overlaps on the sides.
Figure 6-4: Edit Composite Layup

Figure 6-5: 0° Degree Wrap Layer
Figure 6-6: Top and Bottom 0° degree layer

Figure 6-7: +/− 45 Layers

Figure 6-8: 0 Degree Layers Overlapping on Sides
6.2 Boundary Conditions

The beam was loaded in four point bending. In the actual testing the beam was supported on Supports with 12.7 mm diameter (0.5"). The diameter of the loading nose was also 12.7mm (0.5"). For simplicity, the four point loading was modeled as a uniform pressure on the top face of the beam. The pressure applied was 0.5 MPa. The figure 6-9 shows the applied pressure.

![Uniform Pressure](image)

Figure 6-9: Uniform Pressure

As it can be seen from the figure above, the supports are constrained to the reference points RP3 and RP4. The boundary conditions were applied to the reference points. Reference points RP3 and RP4 have all the degrees of freedom fixed. The beam was restrained in x and z direction by applying boundary conditions to the nodes at the center. The supports prevented the rigid body motion of the beam in the y-direction.
6.3 Meshing

The beam was meshed with two different kinds of elements. The foam core was modeled as solid and meshed with hex elements, with C3DI which is an 8 node linear brick element with incompatible mode. The composite skin was meshed with S8R elements which are general purpose shell elements. The approximate global size used was 6.35.

Figure 6-10: Meshing

6.4 Data Collection

To plot the load vs. displacement, data was collected from the model. The load data was collected from RP1 and RP2 and deflection data was collected from the node at the center of the bottom face of the beam. To calculate the total load, RP1 and RP2 are added and plotted against the deflection data. The figure below shows a sample of the graph.
6.5 Result

The step size used in analysis was 0.05 starting from 0.01. The analysis took place in 28 steps, which means there were 28 data points. The figures below show the different results represented on the beam.
**Figure 6-12:** Visualization of Displacement in y-Direction

**Figure 6-13:** FEA: Stiffness vs. Volume Percent of Carbon Fiber
7.1 Results

The data collected from the machine was filtered to show data for time intervals of 6 seconds, corresponding to the photographic images. Since the machine did not collect data at exact time intervals of 6 seconds, data points close to multiples of 6 were selected. On an average each test had 60-70 data points taken from the dial gauge pictures, out of those 45-50 were in the linear region. Using Excel the data was plotted and the slope of the linear region was calculated. It was made sure that the r square value for the curve fitting was above 0.999. If it is below 0.999 data points were reselected. Sample graphs are shown in Figures 7.1-7.3 for load vs. machine head displacement and load vs. displacement captured from the dial gauge.
Figure 7-1: Sample Load vs. Machine Head Displacement

Figure 7-2: Sample Load vs. Dial Gauge Displacement
Figure 7.1 shows the data from the machine. The machine collected data every 0.8 seconds. Figure 7.2 shows the data collected from the dial gauge images with 6 second time intervals. Figure 7.3 shows the curve fitted data with the equation for the curve, in this case this is a straight line with the $r^2$ value indicated. The equation is in the form of $y = mx + c$. The ‘m’ in this equation is the ratio of load and displacement.
Figure 7.4 shows the average stiffness of each design with error bars. The design D0 was the all glass fiber design and the design D7 was the all carbon design. These designs were used as the reference designs. From the graph, it can be observed that all the stiffness were above the D0 design. The addition of carbon fiber increased the stiffness but the increase in stiffness depended on the amount and positions of the carbon fiber. The stiffness of the beam D6 was the highest and the stiffness of the D0 which is the all glass beam was the lowest. All the stiffness were within ±7%.
Figure 7.5 shows average peak loads for different designs. It can be observed the design D1 showed the highest peak load and the design D7 showed the lowest peak load. The peak load increased with addition of the carbon fiber in the D1 design and it reduced for design D2, increased for D3 and then reduced as the amount of carbon fiber was increased. These observations are in agreement with reference (10). All the data except peak loads for D1 were within 8%. For D1 it was within 12%. 
Figure 7.6 shows the variation of stiffness with the volume percent of carbon fiber. It can be seen that the volume percent of carbon fiber varies from 0% in design D0 to 60% in design D7. The design D7 was mentioned as “all carbon design but does not have 100% carbon fiber because as it can be seen in the D7 design representation, D7 has all unidirectional 0° glass fiber is replaced by unidirectional 0° carbon fiber. The webs have ±45° stitched fiber. From the figure we can observe that any addition of the carbon fiber to the glass fiber beam adds to stiffness.

The figure 7.7 shows the increase in stiffness with increase in amount of carbon fiber. The design D0 was used as the base. The increase in the stiffness was compared with the stiffness of the design D0.
Figure 7-7: Change in Stiffness vs. Change in Volume % of Carbon Fiber

It can be observed that the designs D1 and D4 have almost the same amount of carbon fiber, which is 7% and 6.3% respectively. But it can be observed that D1 has higher stiffness than D4. D1 has 7% carbon fiber and the increase in stiffness is 7.3%. D4 has 6.3% carbon fiber and the increase in stiffness achieved was 5.77%. Similarly design D2 and D5 have 15.3% and 13.05% respectively. Design D2 showed 3.6% increase in stiffness and design D5 showed 6.8% increase in stiffness. The design D3 which has only 3.2% carbon fiber and the increase in the stiffness achieved is 11.5%. The design D6 has 29.7% carbon fiber and increases the stiffness of the beam by 20% which is the maximum increase in stiffness achieved. The design D7 has 60% carbon fiber and showed 16% increase in stiffness.
The figure 7-8 shows the variation of peak load vs. volume percent of carbon fiber. It can be seen that the design D1 had the highest peak load. It also can be observed that the general trend was that as the volume percent of the carbon fiber increased the maximum load carrying capacity decreased.
Figure 7-9 shows the percentage variation in the peak load with increasing volume percent of carbon fiber. The percent change in the peak load was compared to the peak load of all glass design, design D0. It can be seen that the design D1 with 7% carbon fiber showed 9.1% increase in the peak load which was the highest. Design D2 which had 15% carbon fiber showed 11.67% decrease in the peak load. The design D3 had 3.2% carbon fiber showed a 4.67% increase in the peak load. Design D4 which had 6.3% carbon fiber showed 7.8% decrease in the peak load. Design D5 had 13.03% carbon fiber showed a 6.8% decrease in the peak load. Design D6 had 29.7% carbon fiber and showed a 16.97% decrease in the peak load. The design D7 had 60.3% carbon fiber and showed 32.8% decrease in the peak load.
<table>
<thead>
<tr>
<th>Design</th>
<th>Peak Load (N)</th>
<th>P/δ (N/mm)</th>
<th>Weight of Carbon</th>
<th>Carbon %</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D0-1</td>
<td>13795.439</td>
<td>1339.5</td>
<td>0.0</td>
<td>0.00%</td>
</tr>
<tr>
<td>D0-2</td>
<td>13414.28</td>
<td>1376.5</td>
<td>0.0</td>
<td>0.00%</td>
</tr>
<tr>
<td>D0-3</td>
<td>16428.146</td>
<td>1358.2</td>
<td>0.0</td>
<td>0.00%</td>
</tr>
<tr>
<td>D1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1-1</td>
<td>15772.555</td>
<td>1445.1</td>
<td>17.6</td>
<td>7.07%</td>
</tr>
<tr>
<td>D1-2</td>
<td>18383.216</td>
<td>1425.3</td>
<td>17.4</td>
<td>6.92%</td>
</tr>
<tr>
<td>D1-3</td>
<td>13462.74</td>
<td>1500.1</td>
<td>17.6</td>
<td>6.96%</td>
</tr>
<tr>
<td>D2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D2-1</td>
<td>12217.967</td>
<td>1421.7</td>
<td>36.6</td>
<td>15.35%</td>
</tr>
<tr>
<td>D2-2</td>
<td>12431.67</td>
<td>1427.2</td>
<td>36.3</td>
<td>15.25%</td>
</tr>
<tr>
<td>D2-3</td>
<td>13892.596</td>
<td>1374.2</td>
<td>36.6</td>
<td>15.34%</td>
</tr>
<tr>
<td>D3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D3-1</td>
<td>13637.863</td>
<td>1561.2</td>
<td>8.0</td>
<td>3.06%</td>
</tr>
<tr>
<td>D3-2R</td>
<td>16745.174</td>
<td>1393.8</td>
<td>8.6</td>
<td>3.38%</td>
</tr>
<tr>
<td>D3-3</td>
<td>15291.066</td>
<td>1589</td>
<td>8.6</td>
<td>3.28%</td>
</tr>
<tr>
<td>D4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D4-1</td>
<td>13132.531</td>
<td>1473.6</td>
<td>16.2</td>
<td>6.42%</td>
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<tr>
<td>D4-2</td>
<td>13801.73</td>
<td>1415.8</td>
<td>16.2</td>
<td>6.40%</td>
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<tr>
<td>D4-3</td>
<td>13282.411</td>
<td>1419.9</td>
<td>15.8</td>
<td>6.24%</td>
</tr>
<tr>
<td>D5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D5-1</td>
<td>12963.047</td>
<td>1457.5</td>
<td>31.2</td>
<td>12.88%</td>
</tr>
<tr>
<td>D5-2</td>
<td>12733.345</td>
<td>1498.5</td>
<td>32.0</td>
<td>13.16%</td>
</tr>
<tr>
<td>D5-3</td>
<td>14956.224</td>
<td>1394.9</td>
<td>31.7</td>
<td>13.06%</td>
</tr>
<tr>
<td>D6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D6-1</td>
<td>11408.352</td>
<td>1611.8</td>
<td>66.1</td>
<td>29.71%</td>
</tr>
<tr>
<td>D6-2</td>
<td>12557.446</td>
<td>1653.8</td>
<td>66.5</td>
<td>29.87%</td>
</tr>
<tr>
<td>D6-3</td>
<td>12266.261</td>
<td>1608.8</td>
<td>66.6</td>
<td>29.66%</td>
</tr>
<tr>
<td>D7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D7-1</td>
<td>10568.307</td>
<td>1493.2</td>
<td>113.7</td>
<td>60.42%</td>
</tr>
<tr>
<td>D7-2</td>
<td>9410.667</td>
<td>1612</td>
<td>115.1</td>
<td>60.30%</td>
</tr>
<tr>
<td>D7-3</td>
<td>9313.918</td>
<td>1620.8</td>
<td>114.1</td>
<td>60.38%</td>
</tr>
</tbody>
</table>
7.2 Discussion

7.2.1 Beam Stiffness

Figure 7-7 shows the change in stiffness vs. the volume percent of the carbon fiber. The designs D1 and D4 had almost same amount of carbon fiber. But the stiffness increase for D1 was 7.3% and stiffness increase for D4 was 5.77%. The higher increase in stiffness for design D1 can be attributed to the location of the carbon fiber placed. D1 had carbon fiber wrapped on the outside and D4 had 2 layers of carbon fiber on top and bottom faces 2 layers below the outside layer. The outside layers were unidirectional glass layers.

The designs D5 and D2 had similar amount of carbon fiber. D2 had 15.3% carbon fiber and D5 had 13.05% carbon fiber. The increases in stiffness were 3.6% and 6.8% respectively. As the design D1 has one layer on the outside and gives 7.3% increase. It might seem logical to assume that the design D2 will yield higher stiffness as it had additional layer of carbon fiber next to the core. But in reality the design D2 was the worst design with minimum increase in the stiffness. It can be seen from the CLPT that the stiff material is more effective away from the neutral access. The design D5 had twice the amount of carbon fiber than D4. The increase in stiffness for design D5 was 6.8% which is 0.9% higher than design D4. This very small gain in stiffness with almost double amount of carbon fiber can be attributed to the fact that the carbon fiber placed near the core was less effective in increasing the bending stiffness.

The design D3 had only 3.2% carbon fiber and the increase in stiffness achieved was 11.5%. As stated above, the outside of the top and bottom faces of the beam are the
optimal places to place the stiff material. By comparing design D1 and D3 it can be concluded that the placement of carbon fiber in the webs had a deteriorating effect on the beam stiffness.

The design D6 had 29.7% carbon fiber and the increase in stiffness achieved was 20%. This was the maximum increase in stiffness achieved. The design D6 had glass fiber next to the core and two layers of glass fiber near the mid plane of the layup.

The design D7 had 60% carbon fiber. In this design all the unidirectional 0° glass fiber was replaced by unidirectional carbon fiber. The increase in the stiffness achieved in this design is 16%. By comparing D6 and D7 it can be concluded that placement of glass fiber near the core of the beam yields better results than substituting all the unidirectional glass fiber by unidirectional carbon fiber.

Figure 7-10: Carbon Fiber Effectiveness Index

![Carbon Fiber Effectiveness Index](image)
Figure 7-10 shows the effectiveness of the carbon fiber in increasing the stiffness. The ratio of ‘percent increase in stiffness’ and ‘volume percent of carbon fiber’ was taken for each design. It showed the percentage increase in stiffness per percent of carbon fiber added. Design D6 showed the highest increase in the stiffness which is 29% but the amount of carbon fiber added was 20%. It can be seen from the figure 7-10 that the carbon fiber effectiveness index for this design is 0.66 but for design D3 even though the increase in stiffness is 11.5% it was achieved by putting only 3.2% carbon fiber. The carbon fiber effectiveness index is 3.5. Which shows that carbon fiber is utilized in a better way in design D3 than in D6 even though D6 has higher stiffness than D3. The design D1 and D4 which had similar amount of carbon fiber have the carbon fiber effectiveness indices 1.04 and 0.91. This indicates that design D1 utilized carbon fiber in a slightly better way than design D4. Designs D2 and D5 have nearly same amount of carbon fiber and have the effectiveness indices 0.24 and 0.52 respectively. The design D2 and D7 have similar efficiency indices; 0.24 and 0.27 respectively which suggested that in both designs the carbon fiber is utilized in poor way.

7.2.2 Peak Load

The peak load showed different trends than the stiffness. As compared to design D0, D1 show 9.1% increase in the peak load. The design D3 showed 4.66% increase in the peak load. All other designs showed reduction in the peak load. Design D4 and D5 showed 7.8% and 6.8% reduction in the peak load. It should be noted that even though D5 had twice the carbon than D4, they carried similar peak load. Design D2 showed 11.67% reduction in the peak load. This could be because of the presence of
unidirectional carbon fiber on the outside but also on the inside. The design D6 showed 16% decrease in the peak load and design D7 showed 32% decrease. The beams with carbon fiber more than 7% except design D4 showed negative effect on the peak load carried by the beam. The design D4 has 6.3% carbon fiber but still it showed decrease in the peak load. The decrease in the load carrying capacity with increase in the amount of carbon fiber can be explained by the way the beams are loaded. The loading nose has a radius of 6.35mm (0.25”). Even though rubber pads are placed under the loading nose to reduce the stress concentration, all the beams failed at the points of loading. Another factor to consider is that the carbon fiber has a very high stiffness. For the same displacement more stress is induced in the carbon fiber than the glass fiber. Considering the high stress concentration under the loading area and the high stress induced in the carbon fiber can explain the reduced load carrying capacity of the beams.

7.2.3 Beam Failure

As previously stated, there was a very high level of stress concentration under the loading nose, the first failure occurred under the loading nose. For most of the beams the beam failed under one loading nose and very little damage was observed under the other loading nose. In all the beams it was observed that the crack stopped just above the bottom face edge or just at the edge. In all the beams the bottom face was always undamaged. The webs of the beams showed different types of cracks. All the failure modes along with pictures are included in the appendix.
7.2.4 Finite Element Analysis

The graph below shows the comparison between the FEA results and experimental results.

![Graph showing FEA vs. Experimental Results](image)

**Figure 7-11: FEA vs. Experimental Results**

It can be seen from the above graph that the FEA results show a different trend than the experimental results. As the materials were not actually tested for material properties, properties from (1) were entered and adjusted to match the properties of the all glass beam (D0) and all carbon beam (D7). The properties for the glass fiber gave results close to the experimental results. The carbon fiber properties were changed to get results close to the experimental results.
It can be seen that, the FEA model predicted stiffness of the designs D3, D4 and D5 are less than the D0 which is the all glass fiber beam. This is in strong disagreement with the experimental results. The model predicted stiffness of D0, D1 and D2 with good precision. The FEA model underestimated the stiffness of D0 by 3.3%, overestimated stiffness of beam D1 by 3.4% and D2 by 6.4%. The Table below shows the FEA and experimental results.

<table>
<thead>
<tr>
<th>Design</th>
<th>Volume Percent of Carbon Fiber</th>
<th>Stiffness in N/mm</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>EXP</td>
</tr>
<tr>
<td>D0</td>
<td>0%</td>
<td>1358.06</td>
<td>1313.1</td>
</tr>
<tr>
<td>D1</td>
<td>6.983351%</td>
<td>1456.8</td>
<td>1406.8</td>
</tr>
<tr>
<td>D2</td>
<td>15.3159271%</td>
<td>1407.7</td>
<td>1497.8</td>
</tr>
<tr>
<td>D3</td>
<td>3.2412163%</td>
<td>1514.66</td>
<td>1302.6</td>
</tr>
<tr>
<td>D4</td>
<td>6.3533258%</td>
<td>1436.43</td>
<td>1283.6</td>
</tr>
<tr>
<td>D5</td>
<td>13.0357519%</td>
<td>1426.2</td>
<td>1278.4</td>
</tr>
<tr>
<td>D6</td>
<td>29.7464979%</td>
<td>1624</td>
<td>1443.5</td>
</tr>
<tr>
<td>D7</td>
<td>60.3644749%</td>
<td>1575.33</td>
<td>1789</td>
</tr>
</tbody>
</table>

Table 7-1: FEA vs. Experimental Results

It can be seen from the table that for designs D3 to D7 the difference between the FEA and the experimental results is 10% or higher. A close look at the results revealed that if the carbon fiber wrapped around the beam, the stiffness was higher than the reference D0 beam. This was observed for designs D1, D2, D6, and D7. Designs D3, D4 and D5 show reduction in stiffness because the carbon fiber did not overlap on the webs.
CHAPTER 8
CONCLUSION

The objective of this research was to study the effect of the amount and position of unidirectional carbon fiber in carbon fiber/glass fiber hybrid sandwich box beams. Eight designs with different amounts of carbon fiber placed in different locations were selected. Three beams were made for each design using a hand layup method. The beams were tested under four point bending. The results obtained were within the of ±8% of the average.

The stiffness of the glass fiber beam, design D0, was used as reference to compare the stiffness of other designs. It was found out that the design D6 showed the maximum increase (20%) in the stiffness with 29.7% of carbon fiber and the design D2 showed the minimum increase in the stiffness (3.6%) with 15.3% carbon fiber. The design D7 had the maximum amount of carbon fiber (60%) and showed 16% increase in stiffness which is 4% lower than the design D6.

To understand the effectiveness of the utilization of the carbon fiber, carbon fiber effectiveness index was used. It was observed that even though the beam D6 had showed the highest increase in the stiffness, the carbon fiber was utilized in a much better way in design D3, in which only with 3.2% of carbon fiber 11.5% increase in stiffness was achieved.
The peak load carrying capacity of the beams showed a different trend. As compared to design D0, D1 showed the maximum increase of 9.1% in the peak load. The beam D7 showed 32% decrease in the peak load carrying capacity. It was observed that beams with carbon fiber more than 7% showed a decrease in the peak load except design D4. D4 had 6.4% carbon fiber but still showed a decrease in the peak load carried. The decrease in the peak load can be attributed to the high stress concentration under the loading nose and the brittle nature of the carbon fiber composite.

FEA analysis of the beams was done using Abaqus. The results for the designs D0, D1, D2 were in good agreement with the experimental results. The results for designs D3, D4, D5, D6 and D7 differed from the experimental results by 10% or more. The FEA model predicted reduction in stiffness for design D3, D4, D5 which was in discord with the experimental results. According to FEA model D7 design is the best design and D5 is the worst design whereas experimental results show that D6 is the best design and D2 is the worst design.

As in this research only three beams of each design were tested, the variation in the results was higher. The hand layup method with vacuum bagging to fabricate the beams does not produce a smooth surface. The variation in the results can be due to lack of smooth surfaces.
BIBLIOGRAPHY


APPENDIX

Load - Deflection Plots

![Load vs. Displacement for D0-1 graph]

The graph shows the linear relationship between load and bottom face displacement for D0-1. The equation of the line is:

\[ y = 1339.5x - 2181.3 \]

with a determination coefficient of 0.9979, indicating a strong correlation between the load and displacement.
Load vs. Displacement for D0-2

\[ y = 1376.5x - 1349.9 \]
\[ R^2 = 0.9989 \]

Load vs. Displacement for D0-3

\[ y = 1364.5x - 1646.8 \]
\[ R^2 = 0.9994 \]
Load vs. Displacement for D1-1

\[ y = 1445.1x - 2399.3 \]

\[ R^2 = 0.9992 \]

Load vs. Deflection for D1-2

\[ y = 1425.3x - 1499.2 \]

\[ R^2 = 0.9991 \]
Load vs. Deflection D2-2

\[ y = 1427.2x - 1737.2 \]
\[ R^2 = 0.9995 \]

Load vs. Deflection D2-3

\[ y = 1374.2x - 1179.5 \]
\[ R^2 = 0.9994 \]
Load vs. Deflection for D3-1

\[ y = 1561.2x - 2390.7 \]

\[ R^2 = 0.9994 \]

Load vs Displacement for D3-2

\[ y = 1393.8x - 1697 \]

\[ R^2 = 0.9996 \]
Load vs. Deflection for D3-3

\[ y = 1589x - 3593.8 \]
\[ R^2 = 0.9993 \]

Load vs. Deflection for D4-1

\[ y = 1473.8x - 2023.9 \]
\[ R^2 = 0.9995 \]
Load vs. Deflection for D4-2

\[ y = 1415.8x - 2357.3 \]
\[ R^2 = 0.999 \]

Load vs. Displacement for D4-3

\[ y = 1419.9x - 1701.4 \]
\[ R^2 = 0.9995 \]
Load vs. Displacement for D5-3

\[ y = 1394.9x - 1694.7 \]

\[ R^2 = 0.9991 \]

Load vs. Displacement for D6-1

\[ y = 1611.8x - 3098.3 \]

\[ R^2 = 0.9986 \]
Load vs. Deflection for D6-2

$y = 1653.8x - 3687.6$

$R^2 = 0.9974$

Load vs. Deflection for D6-3

$y = 1608.8x - 2608.5$

$R^2 = 0.9991$
Load vs. Displacement for D7-1

\[ y = 1493.2x - 1892.8 \]
\[ R^2 = 0.9978 \]

Load vs. Displacement for D7-2

\[ y = 1612x - 2207 \]
\[ R^2 = 0.9957 \]
Load vs. Displacement for D7-3

\[ y = 1620.8x - 2790 \]

\[ R^2 = 0.9988 \]
# Description of the Fractures

<table>
<thead>
<tr>
<th>Design</th>
<th>Specimen No.</th>
<th>Left Side</th>
<th>Right Side</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Top</td>
<td>Bottom</td>
</tr>
<tr>
<td>D0</td>
<td>D0-1</td>
<td>Step Crack across the top face</td>
<td>No Damage</td>
</tr>
<tr>
<td></td>
<td>D0-2</td>
<td>Crack across top face</td>
<td>No Damage</td>
</tr>
<tr>
<td></td>
<td>D0-3</td>
<td>Small cracks</td>
<td>No Damage</td>
</tr>
<tr>
<td>D1</td>
<td>D1-1</td>
<td>Curved crack across the face</td>
<td>No Damage</td>
</tr>
<tr>
<td></td>
<td>D1-2</td>
<td>Straight Crack across the top face</td>
<td>No Damage</td>
</tr>
<tr>
<td></td>
<td>D1-3</td>
<td>Thin crack across the surface</td>
<td>No Damage</td>
</tr>
<tr>
<td>Design No.</td>
<td>Specimen No.</td>
<td>Left Side</td>
<td>Right Side</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td></td>
<td>Top</td>
<td>Bottom</td>
<td>Side 1</td>
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<tr>
<td>D2</td>
<td>D2-1</td>
<td>Curved crack across the face</td>
<td>No Damage</td>
</tr>
<tr>
<td></td>
<td>D2-2</td>
<td>No Damage</td>
<td>No Damage</td>
</tr>
<tr>
<td></td>
<td>D2-3</td>
<td>Small crack across the top face</td>
<td>No Damage</td>
</tr>
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<td>D3-1</td>
<td>No Damage</td>
<td>No Damage</td>
</tr>
<tr>
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<td>D3-2</td>
<td>Very thin crack along the top face</td>
<td>No Damage</td>
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<tr>
<td></td>
<td>D3-3</td>
<td>Curved crack across the face</td>
<td>No Damage</td>
</tr>
<tr>
<td>Design</td>
<td>Specimen No.</td>
<td>Left Side</td>
<td>Right Side</td>
</tr>
<tr>
<td>--------</td>
<td>--------------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td></td>
<td>Top</td>
<td>Bottom</td>
<td>Side 1</td>
</tr>
<tr>
<td>D4</td>
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<tr>
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<td>Step like crack</td>
<td>No Damage</td>
<td>No Damage</td>
</tr>
<tr>
<td>D4-2</td>
<td>Straight Crack across the top face</td>
<td>No Damage</td>
<td>Straight Crack</td>
</tr>
<tr>
<td>D4-3</td>
<td>Crack across top face</td>
<td>No Damage</td>
<td>No Damage</td>
</tr>
<tr>
<td>D5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D5-1</td>
<td>Thin step shaped crack</td>
<td>No Damage</td>
<td>Straight Crack, delamination along the crack</td>
</tr>
<tr>
<td>D5-2</td>
<td>Straight Crack across the top face</td>
<td>No Damage</td>
<td>Crack strats straight turns to 45, Delamination in top part of crack</td>
</tr>
<tr>
<td>D5-3</td>
<td>Step shaped crack, thin</td>
<td>No Damage</td>
<td>Little compressive damage at the point of contact</td>
</tr>
<tr>
<td>Design</td>
<td>Specimen No.</td>
<td>Left Side</td>
<td>Right Side</td>
</tr>
<tr>
<td>--------</td>
<td>--------------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Top</td>
<td>Bottom</td>
</tr>
<tr>
<td>D6</td>
<td>D6-1</td>
<td>Crack across top face, edges are crushed and delamination at the foam</td>
<td>No Damage</td>
</tr>
<tr>
<td>D6</td>
<td>D6-2</td>
<td>Straight Crack across the top face</td>
<td>No Damage</td>
</tr>
<tr>
<td>D6</td>
<td>D6-3</td>
<td>Straight Crack across the top face, edges are crushed</td>
<td>No Damage</td>
</tr>
<tr>
<td>D7</td>
<td>D7-1</td>
<td>Straight crack across the top face</td>
<td>No Damage</td>
</tr>
<tr>
<td>D7</td>
<td>D7-2</td>
<td>Straight crack across the top face</td>
<td>No Damage</td>
</tr>
<tr>
<td>D7</td>
<td>D7-3</td>
<td>Little Damage</td>
<td>No Damage</td>
</tr>
</tbody>
</table>
Images of Beam Fracture

D0-2 Left

D0-3 Right

D1-2 Left
D1-2 Left

D1-3 Right

D3-2 Right
Beam Cross Sections

D0

D1