Composite sandwich structure with grid stiffened core

Venkata Dinesh Muthyala
Louisiana State University and Agricultural and Mechanical College

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COMPOSITE SANDWICH STRUCTURE
WITH GRID STIFFENED CORE

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
In partial fulfillment of the
requirements for the degree of
Master of Science in Mechanical Engineering

in

The Department of Mechanical Engineering

By
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B.E., Osmania University, Hyderabad, India, 2005
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ABSTRACT

Composite sandwich structures have been widely used in aerospace structures, ship building, infrastructure, etc. due to their light weight and high strength to weight ratio. Traditionally, light-weight core materials such as foam core, truss core, honeycomb core have been used in fabricating sandwich structures with limited success. In this study, a new composite sandwich structure with a hybrid core was proposed, fabricated, tested, and modeled. The hybrid core consists of a fiber reinforced polymer grid skeleton that is filled in by extremely light-weight syntactic foam in the bay areas. The new sandwich structure was manufactured using a new manufacturing process. The behavior of these structures under impact and compression was investigated. Experimental results show that the grid structure with smaller bay area has higher impact resistance compared to grids with larger bay areas. For the hybrid core with a smaller bay area, the damage was localized to a much smaller area as evidenced by ultrasonic inspection. The nodal region was observed to have the highest impact resistance while the bay area was the weakest and had the least impact resistance. Compression testing was done after subjecting the specimens to impact testing. The results obtained show that the residual load carrying capacity decreases as the bay area increases. However, compared to the control group, which was the traditional laminated composite, the sandwich structure with grid stiffened core shows better impact tolerance and higher residual strength, although the fiber volume fraction used was the same. SEM images of impact region were taken and the mechanisms involved in the failure of foam, ribs and nodes were observed.

From impact analysis it was found that grid stiffened sandwich structures with a smaller bay area have a higher impact loading capacity. The damage was localized to a smaller area. The
residual load carrying capacity of grid structures was found to be higher than that of the laminates.

Finite element analysis was conducted on the hybrid structure using ANSYS. A 3-D finite element model was developed and appropriate material properties were given to each component. Boundary conditions similar to those used in compression testing were utilized. The model was firstly validated by the experimental results. Parametric analysis was then performed on the validated model by varying important design parameters like skin thickness, skin modulus, rib width, rib modulus and bay area. Results obtained by changing these parameters were analyzed. The experimental and finite element results were discussed and general conclusions were drawn.

From the impact results it was observed that grid structures with small bay area have a higher impact tolerance. The damage caused by impact was confined to a much smaller area compared to laminate composites. The residual load carrying capacity of grid structures with small bay area was found to be higher compared to large bay area specimens. It was found that for higher energy impacts the grids with smaller bay areas were able to retain higher load carrying ability.
CHAPTER 1. INTRODUCTION

Impact damage has been an epidemic problem for composite structures. Even subjected to a low velocity impact, laminated composites may sacrifice its load carrying capacity considerably due to the various types of damage like delamination, fiber fracture, matrix cracking, and fiber/matrix interfacial debonding. Unless there is a space limitation, composite sandwich structure is a preferred structural form because it can be constructed by using low cost core materials. Also, sandwich structures usually have a higher bending stiffness with the same amount of fiber reinforced polymer materials. In a composite sandwich structure, the core is responsible for separating and fixing the skins, resisting transverse shear, and providing other functionalities like absorbing impact energy, shielding radiation, and insulating heat transfer.

Currently, various types of core materials have been used such as foam core, truss core, 3-D integrated core, etc. While these core materials have been used with a certain success, they are limited in one way or another. For instance, the brittle syntactic foam core absorbs impact energy primarily through macro length-scale damage, sacrificing residual strength significantly.

Therefore, we propose to develop a new sandwich core, a grid skeleton that is filled in by syntactic foam. We believe that this core is better in impact resistance and residual strength because (1) the grid skeleton will be responsible for transferring the impact energy elastically and providing the in-plane strength and transverse shear resistance; (2) the syntactic foam in the bay will be primarily responsible for absorbing impact energy through damage; (3) the grid skeleton and the foam will develop a positive composite action, i.e., the grid skeleton confines the foam to increase its strength and the foam provides lateral support to resist rib local buckling and crippling. The objective in this study is to fabricate, test, and model the impact response and residual strength of this type of new sandwich structures. The hand lay-up technology assisted by
vacuum bagging will be used for manufacturing the specimens. Low velocity impact test per the DynaTup 8250HV impact machine will be conducted to evaluate the impact response of the sandwich structure. Various impact locations, rib, node, and bay, will be selected for testing. Compression after impact (CAI) tests will be conducted to evaluate the residual strength.

A finite element analysis per ANSYS, which is validated by test results, will be utilized to implement a parametric study. The effect of various design parameters like the skin thickness and stiffness, the rib width and stiffness, and the bay area, will be evaluated by the modeling.

In Chapter 2 previous work on laminate and grid structures is reviewed and discussed. The manufacturing process and the calculation of various material properties are given in Chapter 3. The various types of tests conducted in this study i.e. ultrasonic inspection, impact and compression testing and their results are discussed in Chapter 4. The steps involved in creating a finite element model, the boundary conditions and the analysis type are given in Chapter 5. In Chapter 6 the parametric analysis performed on the sandwich structures are discussed and Chapter 7 presents the conclusion and discusses future work.
CHAPTER 2. LITERATURE REVIEW

The behavior of laminated composites subject to impact, tensile and compressive loads has been well documented. The paper by Saito and Kimpara shows the effect of impact on multi-axial stitched composite panels manufactured using vacuum assisted resin transfer molding method [1]. Byun et al conducted low-velocity impact tests on 3-D laminated composites and found that the damage area for 3-D composites was significantly less when compared with 2-D composite panels [2]. The effect of pressure used during resin transfer molding was investigated by Kas and Kaynak using C-scan inspection [3]. The effect of low temperature was studied by Rio et al by varying the temperature from -150°C to 20°C and the damage due to impact was found to increase with decrease in the temperature [4]. Ibekwe et al. studied the effect of low velocity impact on unidirectional and crossply laminated beams under various temperatures. It was found that temperature has a significant effect on the impact response with the extent of damage being greater when subjected to impact at lower temperatures [5].

The effect of ultraviolet radiation on the low velocity impact response and compressive strength of glass fiber reinforced epoxy composite laminates was studied by Pang et al [6]. It was found that while UV radiation has a considerable effect on the compressive strength it does not have significant effect on the impact response. The low velocity impact response of laminates when subjected to moisture cycling at elevated temperatures was studied by Li et al [7]. Impact response was significantly affected by the first moisture cycle with the subsequent cycles having little effect. A study on the behavior of laminated composites manufactured using a hand lay-up process subjected to ballistic impact was conducted by Findik and Tarim using different guns and was found that they offer the same protection as steel armor [8]. A variety of other kinds of tests were conducted on composite panels to better understand their behavior [9-12].
Sandwich structures with various lightweight cores have also been extensively studied. In a study by Li and Jones, low velocity impact response of hybrid syntactic foam with rubber latex coated microballoons sandwiched between two facesheets was studied [13]. It was found that compared to the core which consists of pure epoxy or just the syntactic foam without rubber coating, the impact energy absorbed by rubberized syntactic foam core was much higher. In another study the syntactic foam was modified by using crumb rubber [14]. The impact tolerance of the structure was found to increase with the increase in the rubber content of the core. The impact response of cement based syntactic foams was studied by varying the volume fraction of cement in the core [15]. Impact energy absorption was found to increase with insignificant decrease in the strength of the core as the cement content reduces.

However, laminated composite panels and sandwiched foams have several problems. In order to improve the behavior under impact and other kinds of loading, grid stiffened structures are gaining importance. Various fabrication techniques have been used for manufacturing grid structures. Han et al used interlocked ribs with a slotted joint to create grid structures [17]. The structure was shown to have excellent mechanical properties like high damage tolerance and durability. Vacuum Assisted Resin Infusion Molding (VARIM) process was used by Hosur et al to create integrated core sandwich panels [18]. A comparison of composite structures was made with grid structures by Meink [19] to determine the practicality of replacing sandwich structures with grid structures. It was determined that the advantage of the grid structure lies in the manufacturing since the fabrication can be automated.

Grid stiffened structures are found to have higher impact resistance and the delamination and crack propagation occurring in these structures is less compared to laminated composite panels [16, 20]. Low velocity impact tests were conducted by Hosur et al. on integrated core
sandwich composite samples which show that skin thickness and composition of skin plays a significant role in the impact response of these structures [21]. Hollow core panels having varying thickness of rib were also prepared and the response when subjected to low velocity impact was observed and it was found that these cores provided greater impact resistance due to additional energy absorption mechanisms [22]. The dynamic compression behavior of integrated core sandwich composites was studied by Hosur et al. by fabricating foam filled 3-D integrated core sandwich composites using VARIM process [23]. Split Hopkinson pressure bar setup was used to find the high strain rate response and it was found that foam provides lateral support and prevents buckling of vertical piles and increasing the skin thickness increased the overall modulus.

Compression tests were conducted on cylindrical grid structures by Li et al. and it was found that the strength, ductility and failure mode of the cylinders depend on the fiber orientation [24]. In a study by Li and Maricherla [43] and Velamarthy [25], it was found that grid composite cylinders are effective in carrying load and have a high resistance to failure and deformation compared to normal FRP tubes under compressive loads. The local and global buckling behavior of Iso-Truss composite structures under compression was examined by Jensen et al. through experiments [26]. The results showed that the local buckling depends on bay length, with higher buckling loads observed for shorter bay lengths. Global buckling was found to be independent of bay length. Hybrid composite cylinders made of tubular steel lattice covered with FRP skin were subjected to compression. It was found that these cylinders have the advantages of both steel tubes and FRP confinements [27].

Chen and Tsai developed a finite element model of a grid structure which was found to be reasonably accurate and this model was used to compare the performance of grid structures with laminates and sandwich plates [28]. The model was also used to optimize the grid structure.
Jaunky et al studied the buckling behavior of grid stiffened panels by using smeared stiffener theory for global buckling and Rayleigh-Ritz method for local buckling of skin segments [29]. The design of the grid structure is optimized by varying several design parameters like skin thickness, stiffener spacing etc. Zhang et al created a load reconstruction method for predicting the low-velocity impact response of advanced grid stiffened plates by smearing the ribs onto a continuous unsymmetrical plate [30]. This method was numerically verified by developing a program in MATLAB. The response of low velocity impact on honeycomb structures was modeled by Castanie et al using finite element modeling and a good correlation was found between the experimental and numerical results [31].

The effect of transverse loading on grid-stiffened composite panels was studied by Jadhav et al and a parametric analysis was performed by changing the rib thickness, skin thickness, rib width etc to optimize the panel [32]. Finite element analysis was used for the parametric analysis. It was observed that the energy absorption was higher when the panel was loaded on the skin side. The global buckling load for a grid stiffened composite cylinder was determined by developing an analytical model using the unit cell analysis [33]. This model was validated by comparing the numerical results with the experimental results and a parametric study was conducted after validating the model.

The purpose of this study is to develop a new fabrication procedure for manufacturing composite sandwich structures with a grid stiffened core, to conduct low-velocity impact testing on them and evaluate their impact response and the extent of damage through C-Scan, to perform both pre-and post-impact compression test to determine their residual strength, and to create a finite element model to for parametric study. A list of other useful references [34-52] that were considered during the study can be found in the references section.
CHAPTER 3. MANUFACTURING AND CHARACTERIZATION

3.1 Raw Materials

The materials used in the manufacturing of the grid structures are glass fiber rovings by Saint Gobain, glass microspheres by Potters Industries, DER 332 epoxy resin by DOW Chemicals consisting of Part A (epoxy) and Part B (curing agent) and woven roving fabric by Fiber Glast. Table 3.1 lists the relevant material properties found in the manufacturers’ data sheets. The Young’s modulus of the epoxy varies with the percentage of Part B used. For the composition of Part B used in our case the Young’s modulus of the epoxy was found to be 1.8GPa.

Table 3.1 Material Properties of Raw Materials Used

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Poisson's Ratio</th>
<th>Shear Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Glass Fiber</td>
<td>75.1</td>
<td>0.2</td>
<td>30.6</td>
</tr>
<tr>
<td>Resin</td>
<td>1.8</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Glass Microspheres</td>
<td>73.0</td>
<td>0.2</td>
<td>29.9</td>
</tr>
</tbody>
</table>

3.2 Composition of Materials

In Table 3.2 the volume fraction of each component used in preparing the syntactic foam is listed. The volume fraction of glass microspheres was fixed at 60% and the volume fractions of Part A and Part B of the epoxy were calculated keeping the ratio of Part A to Part B at 85:15.

Table 3.2 Composition of the Syntactic Foam

<table>
<thead>
<tr>
<th></th>
<th>Volume Fraction (%)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Weight (g)</th>
<th>Weight Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part A</td>
<td>34.0</td>
<td>902.5</td>
<td>1.06</td>
<td>956.7</td>
<td>70.8</td>
</tr>
<tr>
<td>Part B</td>
<td>6.0</td>
<td>159.2</td>
<td>1.07</td>
<td>170.4</td>
<td>12.6</td>
</tr>
<tr>
<td>Microballoon</td>
<td>60.0</td>
<td>1592.8</td>
<td>0.14</td>
<td>222.9</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Using this particular composition the density of the syntactic foam was found to be 0.5g/cm³. In this study three groups of grid specimens were prepared with varying grid geometries. Table 3.3 lists the geometry used for the three groups of grid specimens.
Table 3.3 Geometry of the Three Groups of Grids

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Bay Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12.7mm×12.7mm</td>
</tr>
<tr>
<td>3</td>
<td>25.4mm×25.4mm</td>
</tr>
<tr>
<td>4</td>
<td>50.8mm×50.8mm</td>
</tr>
</tbody>
</table>

For comparison purposes, a laminated composite group, Group 1 was also prepared. Group 1 is a laminate composite with six layers of Glass fabric and is used as control. When preparing the Group 1 specimens, the fiber volume fraction was the same as the grid specimens. In such a way, the effect of the grid structure against laminated composite can be identified.

In order to maintain a constant volume fraction of glass fibers for all the three groups of grids the width of the rib was varied. This was achieved by using different number of fiber strands when weaving the grid skeleton. The number of strands in Group 4 was fixed as 7 and the number of strands required for the other two groups was calculated based on the volume fraction of glass fiber in this group. Table 3.4 gives the volume fraction and the number of strands used in the four groups. It can be seen that the volume fraction of glass fiber in Group 2 is slightly less than the volume fraction in Group 3 and Group 4. This is unavoidable because if the number of strands in the Group 2 specimens is increased from 2 to 3 the difference in volume fractions between Group 2 and the other two groups will increase significantly.

Table 3.4 Volume Fraction and Number of Strands

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Number of Fiber strands</th>
<th>Volume Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>10.0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>10.3</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>11.1</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Four additional control sample groups were also made with Group 5 consisting of a sandwiched grid core without foam in the bay area. Group 6 consists of a pure grid core without
facesheets. For Group 7 sandwiched foam without grid was prepared and Group 8 had foam without any facesheets.

3.3 Manufacturing Process

The grid skeleton was created using a dry weaving process in which the glass fiber was weaved without applying any resin during the weaving. In order to do this a wooden mold of appropriate dimension was selected and pins were hammered in at the appropriate locations depending on the geometry of grid as shown in Figure 3.1.

![Figure 3.1 Wooden Mold with pins and non porous Teflon sheet](image1)

Once the pins were placed on the mold a layer of non-porous Teflon sheet was placed on to it in order to facilitate the removal of sample after curing. A glass fabric sheet was then placed on top of the Teflon sheet as shown in Figure 3.2 to form the bottom skin.

![Figure 3.2 Bottom skin placed on top of the Teflon sheet](image2)
From Fig. 3.3, the pins were placed one inch apart so as to form a Group 3 grid. The dry glass fiber rovings were woven around these pins and in each rib there were four strands so as to maintain a constant volume fraction. The grid skeleton at the end of this process can be seen in Fig. 3.3. This mould was then placed on top of the bottom layer of the vacuum bag. A layer of tacky tape was placed all around the mold as can be seen from Fig. 3.3. The foam was prepared by thoroughly mixing Part A of the epoxy and the glass microspheres using a mechanical mixer. Later Part B was added to the mixture. It was then quickly poured into the grid as shown in Figure 3.4. Once the foam was poured into the grid the top skin was placed on the grid and a layer of plastic sheet was put on top of the skin. A quarter inch thick glass sheet was now placed on top of the plastic sheet and then the whole setup was placed under vacuum for a period of 24 hours. The glass sheet was used in order to apply an even pressure on the top skin in order to create a flat upper surface. A few samples were made without the glass sheet and it was found that the upper surface was not even. This process is seen in Figures 3.5 and 3.6.

![Figure 3.3 Grid is dry woven](image-url)
Figure 3.4 Foam is poured into the grid

After allowing the sample to cure under vacuum for 24 hours it was removed from the mold and the samples were cut to 150mm×100mm specimens using a precision cutter.

Figure 3.5 Top skin is placed on the grid
In order to make the control sample (Group 1-Laminate) 6 layers of glass fabric were used and 1/5 of the total foam was placed in between each layer and then the whole setup was placed under vacuum for 24 hours.

**3.4 Burn-Out Test**

The volume fraction of glass fiber in the rib was found by a burn out test. ASTM D2584 was followed for carrying out the test. A dry and clean crucible was chosen, and its weight was recorded. The specimen was then put in the crucible and the overall mass determined. After that, the crucible was placed in a furnace and was heated until the resin burned out completely. Once the crucible was removed from the furnace and cooled to room temperature, its weight was also recorded and the weight fractions and volume fractions were calculated accordingly. The volume fractions were calculated using the following procedure:

\[
\begin{align*}
\omega_{c+s} &= \text{Weight of crucible} + \text{Weight of sample} \\
\omega_s &= \text{Weight of sample} \\
\omega_{c+gf+gm} &= \text{Weight of crucible} + \text{Weight of Glass fiber} + \text{Weight of Glass Microspheres which is obtained after the burnout test.}
\end{align*}
\]
\[ w_r = \text{Weight of resin (} w_{c+s} - w_{c+gf} = \text{gm}) \]

\[ w_r = \text{Weight fraction of resin (} w_r/w_s \) \]

Assuming the volume fraction of epoxy to be 0.4\( v \), the required volume fractions can be calculated using Table 3.5 below.

<table>
<thead>
<tr>
<th>Volume fraction</th>
<th>Density (g/cm(^3))</th>
<th>Weight (g)</th>
<th>Weight Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin</td>
<td>0.4( v )</td>
<td>1.06</td>
<td>0.424( v )</td>
</tr>
<tr>
<td>Glass Microspheres</td>
<td>0.6( v )</td>
<td>0.14</td>
<td>0.084( v )</td>
</tr>
<tr>
<td>E-Glass Fiber</td>
<td>1-v</td>
<td>2.72</td>
<td>(2.72-2.72( v ))</td>
</tr>
<tr>
<td>SUM</td>
<td>1</td>
<td>2.72-2.212( v )</td>
<td>1</td>
</tr>
</tbody>
</table>

Since \( w_r \) has been calculated from the burnout test the value of \( v \) can be easily determined and the volume fractions of each component are calculated. For calculating the volume fraction of fiber in the node the amount of fiber in the rib is doubled and the other components are calculated accordingly. The volume fractions of glass fiber in the skin, rib and node of the Group 2-4 grids are given in Table 3.6. For control samples the volume fraction of glass fiber for the outer skins and inner plys is given in Table 3.7.

<table>
<thead>
<tr>
<th>Group 2</th>
<th>Group 3 &amp; 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rib only</td>
<td>0.36</td>
</tr>
<tr>
<td>Node Only</td>
<td>0.72</td>
</tr>
<tr>
<td>Skin Only</td>
<td>0.51</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fiber Volume Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Layers</td>
</tr>
<tr>
<td>Inner Plys</td>
</tr>
</tbody>
</table>
3.5 Determination of Mechanical Properties

After determining the volume fractions of fiber in the ribs, nodes and skins the material properties can be found by using the rule of mixtures and Halpin-Tsai equation. These properties are used when performing Finite Element Analysis. The values of the elastic modulus in the longitudinal directions, the shear modulus and the major Poisson’s ratio of the composite are calculated using the rule of mixtures as follows:

\[
E_1 = E_f v_f + E_r v_r \tag{3.1}
\]

\[
\nu_{12} = \nu_f v_f + \nu_r v_r \tag{3.2}
\]

\[
\frac{1}{G_{12}} = \frac{v_f}{G_f} + \frac{v_r}{G_r} \tag{3.3}
\]

For finding the properties in the transverse direction the Halpin-Tsai equation given below was used and the resulting values of Group 2 are given in Table 3.8, those of Group 3 & 4 are given in Table 3.9 and Group 1 in Table 3.10.

\[
\frac{E_T}{E_m} = \frac{1+\xi \eta V_f}{1-\eta V_f} \tag{3.4}
\]

Where

\[
\eta = \frac{E_f / E_m - 1}{E_f / E_m + \xi} \tag{3.5}
\]

\[
E_f = \text{Fiber modulus}
\]

\[
E_m = \text{Matrix modulus}
\]

\[
\xi = 2 \text{ for circular fibers}
\]
Table 3.8 Material Properties of Group 2 samples

<table>
<thead>
<tr>
<th></th>
<th>Rib</th>
<th>Node</th>
<th>Skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$</td>
<td>14400 MPa</td>
<td>27956 MPa</td>
<td>20013 MPa</td>
</tr>
<tr>
<td>$E_2$</td>
<td>1850 MPa</td>
<td>27956 MPa</td>
<td>20013 MPa</td>
</tr>
<tr>
<td>$E_3$</td>
<td>1850 MPa</td>
<td>5417 MPa</td>
<td>2761.5 MPa</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>436.7 MPa</td>
<td>963.3 MPa</td>
<td>565.6 MPa</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.269</td>
<td>0.258</td>
<td>0.264</td>
</tr>
</tbody>
</table>

Table 3.9 Material Properties of Group 3 & 4 samples

<table>
<thead>
<tr>
<th></th>
<th>Rib</th>
<th>Node</th>
<th>Skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$</td>
<td>15399 MPa</td>
<td>30075 MPa</td>
<td>20013 MPa</td>
</tr>
<tr>
<td>$E_2$</td>
<td>1989.2 MPa</td>
<td>30075 MPa</td>
<td>20013 MPa</td>
</tr>
<tr>
<td>$E_3$</td>
<td>1989.2 MPa</td>
<td>6807.4 MPa</td>
<td>2761.5 MPa</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>456.2 MPa</td>
<td>1185.6 MPa</td>
<td>565.5 MPa</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.268</td>
<td>0.256</td>
<td>0.264</td>
</tr>
</tbody>
</table>

Table 3.10 Material Properties of Group 1 samples

<table>
<thead>
<tr>
<th></th>
<th>Outer Layers</th>
<th>Inner Plys</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$</td>
<td>20013 MPa</td>
<td>13579.1 MPa</td>
</tr>
<tr>
<td>$E_2$</td>
<td>2761 MPa</td>
<td>1757.3 MPa</td>
</tr>
<tr>
<td>$E_3$</td>
<td>2761 MPa</td>
<td>1757.3 MPa</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>565.5 MPa</td>
<td>423.8 MPa</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.264</td>
<td>0.269</td>
</tr>
</tbody>
</table>
CHAPTER 4. TESTING AND ANALYSIS

4.1 Testing

After fabricating the required number of specimens, a variety of tests were carried out to investigate the behavior of the various groups of specimens when they were subjected to impact at various positions and under compression.

4.1.1 Ultrasonic Inspection

Ultrasonic inspection was performed on all specimens over a 6in×6in area using a 1MHz transducer both before and after they were impact tested. An UltraPac inspection machine shown in Figure 4.1 from Physical Acoustics Laboratory was used in conjunction with UltraWin software to acquire the images and identify damages.

![Figure 4.1 Ultrasonic Testing Machine](image)

4.1.2 Impact Testing

Instron Dynatup Impact testing machine shown in Figure 4.2 was used for carrying out this test. A schematic diagram of the test is shown in Figure 4.3. Energy and Load vs. Time data is acquired by the data acquisition system. The initiation and propagation energy are calculated using this data. Impact energy corresponding to the maximum impact force is defined as initiation...
energy. Propagation energy is defined as the difference between the maximum impact energy and the initiation energy. Three different velocities and two different hammer weights were used for doing the impact testing. Specimens were tested at velocities of 2m/s, 3m/s and 4m/s using hammer weights of both 50lb and 88lb. Each group was tested at three different locations namely Bay, Rib and Node that surrounded the center of the specimen and the response was acquired.
4.1.3 Compression After Impact

After impact the specimens were tested under compression loading and the results obtained from samples subject to impact were compared with those obtained from samples without impact. The testing was done using a MTS 810 machine shown in Figure 4.4 and the specimen was fixed in a “Boeing Compression after impact compression test fixture” shown in Figure 4.5.

![Figure 4.4 MTS 810 Machine](image1)

![Figure 4.5 Boeing Compression After Impact Compression Test fixture](image2)
4.2 Results and Analysis

4.2.1 Ultrasonic Inspection

In Figure 4.6 a C-Scan image of a Group 4 of 6in×6in specimen before impact is shown. The red region depicts the area with foam and the blue region shows the presence of glass fiber. Pulse-Echo transmission method was used to capture the signal and the color of the image changes with the strength of signal which is received by the transducer. Red color represents an excess of 80% of the signal returning to the receiver, whereas blue color represents that 50-80% of the signal is being received by the receiver and green color indicates that less than 50% of the signal is being received. During Ultrasonic inspection the settings were fine tuned till this kind of image could be obtained. Once the pre-impact image is acquired the settings are retained till the post-impact image of the same specimen is obtained.

![C-Scan image of pre-impact Group 4 specimen](image)

Figure 4.6 C-Scan image of pre-impact Group 4 specimen
C-Scan provides qualitative data as to the extent of damage occurring in a sample upon impact. As mentioned earlier impact testing was done using three different velocities on three locations on the specimen: Rib, Node and Bay. A 6in×6in area was inspected and the images obtained are shown in Figures 4.7-4.36. The pre and post impact C-Scans of Groups 1-4 specimens are shown in the Figures below.

For Group 1 (laminate) it can be seen that as the impact velocity increases the area of damage is also increasing as shown in Figures 4.7-4.9. From Figures 4.10-4.12 the damage caused by impact at bay, rib and nodal regions of Group 2 samples with a 50lb hammer weight and 2m/s velocity is shown. Figures 4.13-4.15 show the pre and post impact images of Group 2 specimens at various locations with an impact velocity of 3m/s. The damage caused by an impact velocity of 4m/s with a 50lb hammer weight is shown in Figures 4.16-4.18. It can be seen from these figures that the area affected by impact increases as the velocity of impact increases. Similar testing was done on Group 3 and Group 4 specimens by increasing the velocity of impact and varying the location of impact and the images obtained are shown in Figures 4.19-4.36. It can be seen from the images that as the bay area size increases the effect of impact are more widespread and the unit cell is not able to confine damage for higher velocity impacts.
Figure 4.7 Pre and Post impact C-Scan image of Group 1 specimen with impact velocity of 2m/s

Figure 4.8 Pre and Post impact C-Scan image of Group 1 specimen with impact velocity of 3m/s

Figure 4.9 Pre and Post impact C-Scan image of Group 1 specimen with impact velocity of 4m/s
Figure 4.10 Pre and Post impact C-Scan image of Group 2 specimen with impact velocity of 2m/s subjected to impact on Bay

Figure 4.11 Pre and Post impact C-Scan image of Group 2 specimen with impact velocity of 2m/s subjected to impact on Rib

Figure 4.12 Pre and Post impact C-Scan image of Group 2 specimen with impact velocity of 2m/s subjected to impact on node
Figure 4.13 Pre and Post impact C-Scan image of Group 2 specimen with impact velocity of 3m/s subjected to impact on Bay

Figure 4.14 Pre and Post impact C-Scan image of Group 2 specimen with impact velocity of 3m/s subjected to impact on Rib

Figure 4.15 Pre and Post impact C-Scan image of Group 2 specimen with impact velocity of 3m/s subjected to impact on Node
Figure 4.16 Pre and Post impact C-Scan image of Group 2 specimen with impact velocity of 4m/s subjected to impact on Bay

Figure 4.17 Pre and Post impact C-Scan image of Group 2 specimen with impact velocity of 4m/s subjected to impact on Rib

Figure 4.18 Pre and Post impact C-Scan image of Group 2 specimen with impact velocity of 4m/s subjected to impact on Node
Figure 4.19 Pre and Post impact C-Scan image of Group 3 specimen with impact velocity of 2m/s subjected to impact on Bay

Figure 4.20 Pre and Post impact C-Scan image of Group 3 specimen with impact velocity of 2m/s subjected to impact on Rib

Figure 4.21 Pre and Post impact C-Scan image of Group 3 specimen with impact velocity of 2m/s subjected to impact on Node
Figure 4.22 Pre and Post impact C-Scan image of Group 3 specimen with impact velocity of 3m/s subjected to impact on Bay

Figure 4.23 Pre and Post impact C-Scan image of Group 3 specimen with impact velocity of 3m/s subjected to impact on Rib

Figure 4.24 Pre and Post impact C-Scan image of Group 3 specimen with impact velocity of 3m/s subjected to impact on Node
Figure 4.25 Pre and Post impact C-Scan image of Group 3 specimen with impact velocity of 4m/s subjected to impact on Bay

Figure 4.26 Pre and Post impact C-Scan image of Group 3 specimen with impact velocity of 4m/s subjected to impact on Rib

Figure 4.27 Pre and Post impact C-Scan image of Group 3 specimen with impact velocity of 4m/s subjected to impact on Node
Figure 4.28 Pre and Post impact C-Scan image of Group 4 specimen with impact velocity of 2m/s subjected to impact on Bay

Figure 4.29 Pre and Post impact C-Scan image of Group 4 specimen with impact velocity of 2m/s subjected to impact on Rib

Figure 4.30 Pre and Post impact C-Scan image of Group 4 specimen with impact velocity of 2m/s subjected to impact on Node
Figure 4.31 Pre and Post impact C-Scan image of Group 4 specimen with impact velocity of 3m/s subjected to impact on Bay

Figure 4.32 Pre and Post impact C-Scan image of Group 4 specimen with impact velocity of 3m/s subjected to impact on Rib

Figure 4.33 Pre and Post impact C-Scan image of Group 4 specimen with impact velocity of 3m/s subjected to impact on Node
Figure 4.34 Pre and Post impact C-Scan image of Group 4 specimen with impact velocity of 4m/s subjected to impact on Bay

Figure 4.35 Pre and Post impact C-Scan image of Group 4 specimen with impact velocity of 4m/s subjected to impact on Rib

Figure 4.36 Pre and Post impact C-Scan image of Group 4 specimen with impact velocity of 4m/s subjected to impact on Node
From impact testing it was seen that upon impact on bay area the damage was caused mainly by microballoon crushing. For impact on the node and rib region the damage was caused by fiber fracture in addition to microballoon crushing in the surrounding region. It can be seen from Figure 4.9 that almost the entire laminate specimen has had some damage when subjected to an impact velocity of 4m/s. A similar trend is followed by all the other groups but it can be seen that the extent of damage is much higher for Group 4 samples than for Group 2 samples. Comparing Figures 4.18, 4.27 and 4.36 we can see that by increasing the bay area the area affected by impact increases even when the impact takes place on the nodal region. This effect is further increased when impact takes place on the bay area as can be seen from Figures 4.16, 4.25 and 4.34. Further it can be noticed that as the impact velocity increases the area affected increases drastically for Group 4 as can be seen from Figure 4.34 where the entire sample is affected; for Group 2 an increase in velocity from 2m/s to 4m/s does not lead to a considerable increase in damage. Impact location also plays an important role in the impact response as can be seen from Figures 4.10-4-15. It can be seen that the area affected by impact gradually decreases as the impact occurs on bay, rib and node, respectively.

4.2.2 Impact Testing

The results obtained from impact testing using a 50lb load on the four Groups are summarized in Tables 4.1-4.3. Typical Load-Time and Energy-Time traces are shown in Figure 4.37. Figures 4.38, 4.40 and 4.42 show the variation in propagation and initiation energy for the four groups with increasing velocity of impact. Figure 4.39, 4.41 and 4.43 show the corresponding variation in the maximum load. From these Tables and figures it is seen that the difference between the Initiation Energy for Group 1 and Group 2 increases with increase in the impact velocity. Also it can be seen that the initiation energy and maximum load are the least for impact at bay and high for impact at node at all three velocities with a few exceptions. We can
also see that the bay region of Group 2 has much higher initiation energy when compared to Group 3 & 4.

![Load-Time and Energy-Time trace for Impact at Node on a Group 4 specimen with an impact velocity of 4m/s](image)

**Figure 4.37 Load-Time and Energy-Time trace for Impact at Node on a Group 4 specimen with an impact velocity of 4m/s**

**Table 4.1 Impact test results with an impact of 2m/s**

<table>
<thead>
<tr>
<th>Group</th>
<th>Region</th>
<th>Initiation Energy (J)</th>
<th>Propagation Energy (J)</th>
<th>Maximum Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Standard Deviation</td>
<td>Average</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>43.5</td>
<td>1.1</td>
<td>13.0</td>
</tr>
<tr>
<td>2</td>
<td>Bay</td>
<td>44.5</td>
<td>1.0</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>40.6</td>
<td>1.2</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>48.7</td>
<td>0.8</td>
<td>8.6</td>
</tr>
<tr>
<td>3</td>
<td>Bay</td>
<td>37.0</td>
<td>1.0</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>44.6</td>
<td>1.2</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>48.5</td>
<td>0.9</td>
<td>7.6</td>
</tr>
<tr>
<td>4</td>
<td>Bay</td>
<td>33.8</td>
<td>1.5</td>
<td>20.9</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>46.4</td>
<td>1.3</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>45.3</td>
<td>0.6</td>
<td>11.0</td>
</tr>
</tbody>
</table>
Figure 4.38 Initiation and Propagation Energy with impact of 2m/s

Figure 4.39 Variation of Maximum load for a 2m/s impact velocity
Table 4.2 Impact test results with an impact velocity of 3m/s

<table>
<thead>
<tr>
<th>Group</th>
<th>Region</th>
<th>Initiation Energy (J)</th>
<th>Propagation Energy (J)</th>
<th>Maximum Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Standard Deviation</td>
<td>Average</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>69.5</td>
<td>3.1</td>
<td>51.9</td>
</tr>
<tr>
<td>2</td>
<td>Bay</td>
<td>72.3</td>
<td>3.7</td>
<td>50.5</td>
</tr>
<tr>
<td></td>
<td>Node</td>
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<td>1.1</td>
<td>15.8</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>102.7</td>
<td>2.1</td>
<td>17.9</td>
</tr>
<tr>
<td>3</td>
<td>Bay</td>
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<td>9.0</td>
<td>90.3</td>
</tr>
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<td>Node</td>
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<td>3.6</td>
<td>54.4</td>
</tr>
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<td>Rib</td>
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<td>5.6</td>
<td>53.6</td>
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<td>Bay</td>
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<td>7.7</td>
<td>85.9</td>
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<td>Node</td>
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<td>1.9</td>
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<td></td>
<td>Rib</td>
<td>76.1</td>
<td>3.8</td>
<td>45.0</td>
</tr>
</tbody>
</table>

Figure 4.40 Initiation and Propagation Energy with impact of 3m/s
Figure 4.41 Variation of Maximum load for a 3m/s impact velocity

Table 4.3 Impact test results with an impact velocity of 4m/s

<table>
<thead>
<tr>
<th>Group</th>
<th>Region</th>
<th>Initiation Energy (J)</th>
<th>Propagation Energy (J)</th>
<th>Maximum Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Standard Deviation</td>
<td>Average</td>
</tr>
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<td>-</td>
<td>82.5</td>
<td>6.8</td>
<td>111.9</td>
</tr>
<tr>
<td>2</td>
<td>Bay</td>
<td>102.4</td>
<td>7.4</td>
<td>91.8</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>160.6</td>
<td>4.0</td>
<td>34.6</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>105.1</td>
<td>3.6</td>
<td>90.5</td>
</tr>
<tr>
<td>3</td>
<td>Bay</td>
<td>46.7</td>
<td>13.8</td>
<td>147.5</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>97.1</td>
<td>9.0</td>
<td>97.8</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>66.4</td>
<td>11.9</td>
<td>126.7</td>
</tr>
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<td>Bay</td>
<td>50.3</td>
<td>5.5</td>
<td>142.9</td>
</tr>
<tr>
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<td>Node</td>
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<td>4.4</td>
<td>54.4</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
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<td>16.8</td>
<td>124.0</td>
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</tbody>
</table>
The variation of propagation energy is significant for impact velocity of 4m/s. It is the highest for impact at bay region and lowest for nodal impact. At lower velocities this trend is not so apparent. In order to further investigate the effect of impact on the structures the hammer weight was increased to 88lb and a velocity of 4m/s was used. The results obtained are shown in Table 4.4. Figures 4.44-4.45 show the initiation, propagation and maximum load variation. From
Table 4.4 and Figures 4.44-4.45 it can be seen that the initiation energy of the laminate (Group 1) is higher than that of Groups 3 and 4 at all impact positions and only the node of Group 2 has higher initiation energy.

Table 4.4 Impact Results with a load of 88lb and velocity of 4m/s

<table>
<thead>
<tr>
<th>Group</th>
<th>Region</th>
<th>Initiation Energy (J)</th>
<th>Propagation Energy (J)</th>
<th>Maximum Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Standard Deviation</td>
<td>Average</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>178.8</td>
<td>21.4</td>
<td>147.3</td>
</tr>
<tr>
<td>2</td>
<td>Bay</td>
<td>144.0</td>
<td>19.3</td>
<td>167.1</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>255.4</td>
<td>11.6</td>
<td>59.9</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>168.0</td>
<td>20.8</td>
<td>142.5</td>
</tr>
<tr>
<td>3</td>
<td>Bay</td>
<td>105.2</td>
<td>17.0</td>
<td>213.1</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>128.4</td>
<td>15.9</td>
<td>196.3</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>106.3</td>
<td>19.7</td>
<td>217.8</td>
</tr>
<tr>
<td>4</td>
<td>Bay</td>
<td>61.7</td>
<td>4.9</td>
<td>260.4</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>129.1</td>
<td>5.6</td>
<td>181.2</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>124.9</td>
<td>17.7</td>
<td>202.8</td>
</tr>
</tbody>
</table>

Figure 4.44 Initiation and Propagation Energy with impact of 4m/s with an 88lb load
4.2.3 Compression After Impact

Groups 1-4 were tested for their load carrying capacity before and after impact using a Compression after impact test fixture. Figure 4.46 shows Group 3 and Group 6 specimens under compression after impact testing. The Stress-Strain curves of Group 3 and control samples of Group 5-8 are shown in Figure 4.47. From Table 4.5 we can see that the load carrying capacity of Grid without skin and foam in the bay area (Group 6) is 32489N and that of sandwiched foam (Group 7) is 18034N. The combination of the above gives us Group 3 whose load carrying capacity is 60880N, which is 1.21 times the sum of Group 6 and Group 7 specimens, showing that a positive composite action is taking place in Group 3.

Figure 4.45 Variation of Maximum load for a 4m/s impact velocity and 88lb load
Figure 4.46 Compression testing of Group 3 and Group 6 specimens

Table 4.5 Load carrying capacity of Group 3 and 5-8

<table>
<thead>
<tr>
<th></th>
<th>Maximum Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 3</td>
<td>60880.4</td>
</tr>
<tr>
<td>Grid with Skin (Group 5)</td>
<td>48193.5</td>
</tr>
<tr>
<td>Grid without Skin (Group 6)</td>
<td>32489.0</td>
</tr>
<tr>
<td>Foam with Skin (Group 7)</td>
<td>18034.2</td>
</tr>
<tr>
<td>Pure Foam (Group 8)</td>
<td>7495.1</td>
</tr>
</tbody>
</table>

The initial and residual load values of Groups 1-4 are summarized in Tables 4.6-4.9. Residual load carrying capacity which is the percentage of initial load which the sample can carry after impact is also given in the tables. It can be seen that, for Group 1 specimens, the residual load carrying capacity after a impact of 4m/s falls to just 39.1% of its initial load carrying capacity, whereas Group 2 samples retain 67.3% of its initial load carrying capacity after a 4m/s impact at node and 43.6% after impact at bay, which is significantly higher than Group 1. Comparing Group 1 with Group 3 and 4 it is found that although the initial load carrying capacity of Group 3 and 4 is quite high their residual load carrying capacity is very low. After an impact of 4m/s at node the load carrying capacity of Group 3 specimen is 53.3% and for Group 4 it is just 33.2% of their corresponding initial strength.
Figure 4.47 Stress-Strain Curves of Group 3 and Group 5-8 specimens

Table 4.6 Load Carrying capacity of Group 1 specimens

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Average Load (N)</th>
<th>Standard Deviation</th>
<th>Residual Load Carrying capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>52317.2</td>
<td>2377.5</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>45942.7</td>
<td>1628.5</td>
<td>87.8</td>
</tr>
<tr>
<td>3</td>
<td>26404.3</td>
<td>876.9</td>
<td>50.4</td>
</tr>
<tr>
<td>4</td>
<td>20457.8</td>
<td>537.0</td>
<td>39.1</td>
</tr>
</tbody>
</table>
Table 4.7 Load Carrying capacity of Group 2 specimens

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Region</th>
<th>Average Load (N)</th>
<th>Standard Deviation</th>
<th>Residual Load Carrying capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>51345.2</td>
<td>840.4</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Bay</td>
<td>26786.6</td>
<td>1060.2</td>
<td>52.1</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>46586.2</td>
<td>1396.3</td>
<td>90.7</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>38903.5</td>
<td>1701.4</td>
<td>75.7</td>
</tr>
<tr>
<td>3</td>
<td>Bay</td>
<td>24368.0</td>
<td>1096.2</td>
<td>47.4</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>40807.3</td>
<td>1870.3</td>
<td>79.4</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>26286.7</td>
<td>898.6</td>
<td>51.1</td>
</tr>
<tr>
<td>4</td>
<td>Bay</td>
<td>22406.2</td>
<td>1053.2</td>
<td>43.6</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>34581.3</td>
<td>1261.1</td>
<td>67.3</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>28079.0</td>
<td>945.7</td>
<td>54.6</td>
</tr>
</tbody>
</table>

Table 4.8 Load Carrying capacity of Group 3 specimens

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Region</th>
<th>Average Load (N)</th>
<th>Standard Deviation</th>
<th>Residual Load Carrying capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>60879.8</td>
<td>2772.1</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Bay</td>
<td>32890.3</td>
<td>964.80</td>
<td>54.0</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>50847.7</td>
<td>2243.6</td>
<td>83.5</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>42568.6</td>
<td>906.4</td>
<td>69.9</td>
</tr>
<tr>
<td>3</td>
<td>Bay</td>
<td>25103.4</td>
<td>717.2</td>
<td>41.2</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>47259.4</td>
<td>2100.6</td>
<td>77.6</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>32822.3</td>
<td>1376.9</td>
<td>53.9</td>
</tr>
<tr>
<td>4</td>
<td>Bay</td>
<td>20074.5</td>
<td>671.4</td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>32467.0</td>
<td>281.4</td>
<td>53.3</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>25299.6</td>
<td>578.4</td>
<td>41.5</td>
</tr>
</tbody>
</table>
From the compression results it can be seen that even though the load carrying capacity of Group 2 is much lower than Groups 3 and 4 before impact damage the residual load after impact is much higher. This suggests that under impact Group 2 samples have a much higher probability of retaining more load carrying capacity.

Table 4.10 gives the load and residual load carrying capacity of the four Groups of specimens after a 4m/s impact using an 88lb load. This test further highlights the property of Group 2 specimens to retain load carrying capacity even after impact. It can be seen that even after impact at bay region it carries a load of 16594N whereas a Group 4 sample can only carry a marginally higher load of 18601N after impact at Nodal region and a load of only 11611N with impact at bay area. Further the load carrying capacity of Group 2 at Nodal region stays at around 55% even after a 4m/s impact which is the highest in that table.
Table 4.10 Load Capacity after impact of 4m/s with 88lb load

<table>
<thead>
<tr>
<th>Group</th>
<th>Region</th>
<th>Load (N)</th>
<th>Residual Load Carrying Capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>9292</td>
<td>17.7</td>
</tr>
<tr>
<td>2</td>
<td>Bay</td>
<td>16594</td>
<td>32.3</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>28409</td>
<td>55.3</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>18698</td>
<td>36.4</td>
</tr>
<tr>
<td>3</td>
<td>Bay</td>
<td>14293</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>23870</td>
<td>39.2</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>18170</td>
<td>29.8</td>
</tr>
<tr>
<td>4</td>
<td>Bay</td>
<td>11611</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>Node</td>
<td>18601</td>
<td>26.3</td>
</tr>
<tr>
<td></td>
<td>Rib</td>
<td>13790</td>
<td>19.5</td>
</tr>
</tbody>
</table>

4.2.4 SEM Observation

In order to understand the failure mechanisms involved in the grid structure when subjected to impact SEM photographs of the rib and foam region were taken by cutting a small cross section of the sample at the rib and bay regions. In Figure 4.48 we can see the microballoon crushing and also the crack propagation through the matrix of the foam.

![Microballoon Crushing and Matrix crack propagation](image)

In Figure 4.49 we see the upper layer glass fiber peeling off from the rib. Figure 4.50 shows the fiber pullout resulting from impact and in Figure 4.51 fiber fracture can be seen.
Figure 4.49 Fiber peeling off the rib

Figure 4.50 Fiber pullout
Figure 4.51 Fiber fracture
CHAPTER 5. FINITE ELEMENT MODELING OF GRID STRUCTURES

The finite element analysis of the grid stiffened structures was done on ANSYS Version 11.0. Analytical solution of an ortho-grid structure was provided by Li and Cheng [44]. The discontinuity in the material properties was taken into account using Heaviside unit step function. But this model can only be used to solve ortho-grid problems and is not applicable when the ribs are placed at an angle such as in iso-grid or angle-grid. Hence in this study FEM was used to get numerical verification of experimental results. In this chapter the modeling and analysis of the four groups of specimens are presented. Figure 5.1 shows an unmeshed Group 2 specimen. Once an accurate model was developed, it was validated using experimental results. Parametric analysis was then conducted on the model in order to evaluate the effect of different parameters.

Figure 5.1 Finite element model of Group 2 specimen
5.1 Modeling Procedure

The dimensions of all Groups are 150mm×100mm×13mm and are exactly the same as those used in the experiments. For creating the model first keypoints were created at all the places where the ribs ended as shown in Figure 5.2. Then areas were created through these keypoints and extruded to create the ribs. Then the resulting volumes were overlapped in order to get separate volumes for ribs and nodes as shown in Figure 5.3. After that areas were created in the bay region and extruded and finally skin was placed on both sides.

![Figure 5.2 Position of Keypoints](image)

Afterwards all the volumes were glued together and material properties were given to all the different components based on Tables 3.8-3.10. For Group 2 specimens the material properties were given based on the values in Table 3.8. We can see from Table 3.8 that the value of $E_1$ is higher than $E_2$ i.e. the fibers are in the direction of $E_1$. The values of Young’s modulus, Poisson’s ratio and shear modulus of the vertical and horizontal ribs are given such that the values
reflect the orientation of the fibers. For Group 3 and Group 4 specimens material properties were given based on values in Table 3.9. Group 1 samples which are laminates were modeled using values in Table 3.10. The properties of foam were found experimentally. It was assumed to be an isotropic material with a Young’s Modulus of 723MPa and a Poisson’s Ratio of 0.28.

Figure 5.3 Ribs and Nodes of Group 2 specimens

**5.2 Meshing**

In this study SOLID45 element was used. SOLID45 is used for 3-D modeling of solid structures. This element has eight nodes with three degrees of freedom at each node: translations in the nodal x, y, and z directions. Once all the element attributes were given the model was meshed using the mesh tool. The meshed model is shown in Figure 5.4.
5.3 Boundary Conditions and Loading

In order to accurately replicate the actual testing conditions in the Finite element model boundary conditions were specified as:

1. The bottom face as shown in Figure 5.4 was fully constrained.
2. The two sides were constrained only in the z-direction and x and y directions are left free.
3. On the top surface a compressive pressure was applied.

5.4 Convergence Check

Convergence analysis was performed to verify the accuracy of the results obtained from finite element analysis. In this study convergence analysis was performed on the finite element model of a Group 4 specimen. For convergence analysis the finite element model was meshed using three different mesh sizes, in this case mesh size of 3mm (fine), 3.5mm (medium) and 4mm (coarse) were used. The values of stress obtained in the Y-direction from the three different
analyses are denoted by $\sigma_F$, $\sigma_M$ and $\sigma_C$. The results are said to converge if the following criterion is satisfied:

$$|\sigma_F - \sigma_M| \leq |\sigma_M - \sigma_C|$$

From finite element analysis using a uniform pressure of 55N/mm$^2$ the following values were obtained for stress in the Y-direction using the three different meshes:

$\sigma_F = 420.7$MPa, $\sigma_M = 417.4$MPa and $\sigma_C = 413.3$MPa

$$|\sigma_F - \sigma_M| = 3.3$MPa and $|\sigma_M - \sigma_C| = 4.1$MPa

As the condition for convergence has been satisfied we can say that the results obtained from this analysis are accurate.

**5.5 Analysis**

Linear static analysis was conducted on all four Groups (1-4) and the results obtained were compared with the experimental values. The results obtained from linear analysis applying a load of 39000N are given in Table 5.1. It can be seen that though the values for Group 1, 3 and 4 are close to the test results, the difference for Group 2 is 34%. One reason for this could be the buckling of ribs. In order to see the effect of buckling for all three Groups a simple 2-D buckling analysis was implemented on a single rib using the appropriate material properties and geometry. The results obtained from the three analyses are shown in Figures 5.5-5.7.

<table>
<thead>
<tr>
<th>Group</th>
<th>Experimental Value (mm)</th>
<th>FEM Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

It can be seen from the basic buckling analysis of the rib that a Group 2 rib buckles at a load of 300N whereas Group 3 and Group 4 ribs buckle at 2100N and 2500N respectively.
Figure 5.5 Displacement (in Y-direction) vs. Load Curve of Group 2 Rib

Figure 5.6 Displacement (in Y-direction) vs. Load Curve of Group 3 Rib
From the buckling analysis it can be seen that the ribs of Group 2 specimens are much more susceptible to buckling than Group 3 and Group 4 specimens. Figure 5.8 shows the comparison of Stress-Strain curves of the four groups obtained from Finite Element Analysis and experimental results. For Group 1 the FEM results are very close to the experimental result in the linear region and later it diverges away from the experimental value. For Groups 3 and 4 the FEM result is almost the same as the experimental result in the linear portion and then it diverges away and the predicted strain for a particular stress is higher than the test results. The reason for this is that the materials behave non-linearly or even have plastic deformation at a higher stress during testing; however, only linear elastic analysis was conducted in the FEM. Therefore, the close proximity between the test and FEM in the linear elastic region suggests that the FEM analysis is reliable.
Figure 5.8 Stress vs. Strain Curves of Experimental and FEM results
CHAPTER 6. PARAMETRIC STUDY

Once the finite element model was found to have a response similar to the actual experimental values, parametric studies were conducted to investigate the behavior of the grid structures by varying the skin thickness, material properties of the skin and ribs, the rib width and the area of the bay region. In the parametric study the volume fractions of each component were kept constant so that the results could be compared for the different configurations. An iso-grid with a bay-area of 1 inch$^2$ was also modeled and its response is compared to ortho-grids.

6.1 Ortho-Grid Structures

6.1.1 Effect of Skin Thickness

The foam and ribs are confined by using the skin and its thickness plays a significant role in the load carrying capacity of the sandwich structure. In this study the thickness of the skin was varied from 0.5mm to 1.5mm for groups 3 and 4 and its effect on the compressive displacement of the sample under a load of 71500N was investigated. The results are shown in Figures 6.1-6.3. From Figure 6.1 we can see that, although the Group 4 has a higher displacement when the skin thickness is low, as the skin gets thicker the difference in the compressive displacement for the two groups decreases, and for a skin thickness of 1.5mm it is equal. This indicates that skin plays a major role in Group 4 in confining the ribs and foam. In Group 3 the ribs are closer; they provide considerable confinement to the foam. In Figure 6.2 & 6.3 the effect of each skin thickness on the overall stiffness of the structure can be found. It is seen that in both cases the overall stiffness increases with the increase in skin thickness.
Figure 6.1 Effect of Skin Thickness on Ortho-Grid samples

Figure 6.2 Effect of variation of skin thickness on the Stress-Strain Curves of Group 3 specimens
6.1.2 Effect of Skin Modulus

The modulus of the skin in this section was varied from 10GPa to 70GPa using a 0.5mm thick skin and a load of 71500N. The results are shown in Figures 6.4-6.6. It can be seen from Figure 6.4 that the value of compressive displacement decreases with the increase in the value of the skin modulus. Both Groups 3 and 4 follow nearly the same tendency, indicating that the effect of the skin stiffness on reducing the displacement is equal on both groups. Figures 6.5 & 6.5 show the change in the Stress-Strain curves of the two groups with the change of the skin modulus.
Figure 6.4 Effect of Skin Modulus on Ortho-Grid samples

Figure 6.5 Effect of skin modulus on the Stress-Strain curve of Group 3 specimens
6.1.3 Effect of Rib Modulus

The modulus of the rib was varied from 5GPa to 70GPa and the sample was subjected to a 71500N load. The results obtained are shown in Figures 6.7-6.9. From Figure 6.7 it can be seen that these curves also follow a trend similar to the effect of skin modulus because the compressive displacement decreases with the increase in the rib modulus. Further both Groups follow the same tendency, indicating that the effect of the rib modulus on the structure is equal for both the groups. Figures 6.8 & 6.9 show the change in the Stress-Strain curve of the two groups with the change in the rib modulus.
Figure 6.7 Effect of Rib modulus on Ortho-Grid samples

Figure 6.8 Effect of Rib modulus on the Stress-Strain curve of Group 3 specimens
6.1.4 Effect of Rib Width

Rib width is an important variable which has a considerable effect on the behavior of the structure. The effect of rib width was analyzed by varying the width from 2mm to 5mm for Group 3 and 4mm to 7mm for Group 4. The results are shown in Figure 6.10. In Group 3 the displacement increases till it reaches a width of 4mm and then starts to decrease; in Group 4 the increase is quite drastic till a rib width of 6mm and then it starts to decrease. The initial increase in displacement is caused due to the fact that since the total amount of glass fiber in the rib is kept constant, the volume fraction of fiber in the rib decreases as the rib width increases, reducing the modulus of the rib. Once the rib width reaches a certain value, the distance between the ribs is so small that the grid structure behaves like a laminated plate (fibers uniformly distributed). Therefore, further widening the ribs only has a minimal effect on the displacement of the panel.
Figures 6.11 & 6.12 show the change in the Stress-Strain curves of the two groups with the change in the rib width. It can be seen that with the increase in rib width the overall stiffness of the structure decreases drastically but after a certain point it remains almost constant.
Figure 6.11 Effect of Rib width on the Stress-Strain curve of Group 3 specimens

Figure 6.12 Effect of Rib width on the Stress-Strain curve of Group 4 specimens
6.1.5 Effect of Bay Area

Bay area has a considerable impact on the overall behavior of the grid. In this study the Bay area of Group 3 samples was varied from 360mm\(^2\) to 510mm\(^2\) and for Group 4 samples it was varied from 1606mm\(^2\) to 1965mm\(^2\). The results of Group 3 are shown in Figure 6.13. It is seen that, as the bay area increases, the displacement increases initially but afterwards it starts to decrease. This is because with the increase in the bay area the fibers in the ribs are densely packed and the fiber volume fraction and thus the stiffness of the ribs are increased. Figure 6.14 shows the variation in the stiffness of the structure with the change of the bay area. For Group 4 a similar trend to Group 3 is seen. However, once the bay area is over 1900mm\(^2\) further increasing the bay area has minimal effect on the displacement; see Figures 6.15 and 6.16. The reason is similar to widening the ribs.

![Figure 6.13 Effect of Bay Area on Group 3 samples](image)

Figure 6.13 Effect of Bay Area on Group 3 samples
Figure 6.14 Effect of Bay Area on the Stress-Strain curve of Group 3 samples

Figure 6.15 Effect of Bay Area on Group 4 samples
6.2 Iso-Grid Structures

An iso grid is made using a triangular pattern of ribs such that each side has equal length. In this study an iso-grid structure was modeled using a side length of 38.4mm. The keypoints of the model were created keeping in view the fact that the structure has to maintain symmetry about the Y-Axis. The dimension of the sample was the same as in the other cases at 150mm×100mm×13mm. Once the keypoints were properly located areas were created through the keypoints and then extruded. The resulting volumes were then overlapped to create separate volumes for ribs and nodes. Figure 6.17 shows the grid skeleton of the model.
Areas were then created and extruded as shown in Figure 6.18. Then skin was placed on both sides of the model. Rib width in the model was maintained at 3mm. Since load was not applied axially on the ribs the following equations were used to calculate the effect of angle on the modulus.

\[
\frac{1}{E_X} = \frac{\cos^4 \phi}{E_L} + \frac{\sin^4 \phi}{E_T} + \frac{1}{4} \left( \frac{1}{G_{LT}} \right) \frac{2v_{LT}}{E_L} \sin^2 2\phi
\]

Where \(\phi\) is the orientation of fibers and \(E_L\) and \(E_T\) are the longitudinal and transverse moduli respectively. Since the rib width is equal for Group 3 and iso-grid the material properties of Group 3 (ortho-grid) are used. For calculating \(E_y\) the following equation is used.

\[
\frac{1}{E_Y} = \frac{\sin^4 \phi}{E_L} + \frac{\cos^4 \phi}{E_T} + \frac{1}{4} \left( \frac{1}{G_{LT}} \right) \frac{2v_{LT}}{E_L} \sin^2 2\phi
\]
Figure 6.18 Iso-Grid with foam filled in the structure

The value of $E_x$ and $E_y$ used are 14324MPa and 1854MPa respectively for the angled ribs. The straight ribs have the same values as those of Group 3 ribs. Boundary conditions similar to those on ortho-grid structures were placed and the analysis was conducted for different loads and the resulting displacement of the structure was obtained. The values of load and displacement are given in Table 6.1 and a comparison of the Stress-Strain curves for iso-grid and the ortho-grids is shown in Figure 6.19. From Figure 6.19 we can see that the overall stiffness of the iso grid is lower than Group 3 ortho-grid.

Table 6.1 Load-Displacement values for iso-grid

<table>
<thead>
<tr>
<th>Load (N)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19500</td>
<td>0.7</td>
</tr>
<tr>
<td>39000</td>
<td>1.4</td>
</tr>
<tr>
<td>58500</td>
<td>2.2</td>
</tr>
<tr>
<td>71500</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Figure 6.19 Comparison of iso-grid with ortho-grids
CHAPTER 7. CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

Sandwich structures with grid stiffened core were fabricated using a dry weaving process and the samples were placed under vacuum in order to get high quality specimens. Ultrasonic inspection was conducted on the samples before and after impact to gauge the extent of damage caused by impact. Impact testing was done using three different velocities and two different hammer weights at three different locations on the sandwich structure. The samples were then subjected to compressive loading by placing them in a compression after impact test fixture. The residual load carrying capacity of the specimens was evaluated. Scanning Electron Microscopy was used to understand the micro-length scale failure mechanisms.

The analysis of the impact results shows that the Group 2 specimens are able to withstand impact loading better than the other three groups. It can be seen from the C-Scan images that for Group 2 samples the region affected by impact is much more localized when compared to the rest of the groups. For the laminates the entire specimen is affected by impact whereas the ribs in the grid are able to contain the damage within a certain area. Under compression Group 2 samples have the highest residual load carrying capacity even though its initial load carrying capacity is low.

Finite Element Analysis was implemented by creating a 3-D finite element model in ANSYS and the results obtained were compared with the experimental results. It was observed that except for Group 2 the response of the other groups was very close to the test results. The reason for such a big difference in the finite element result obtained for Group 2 could be because of the very high susceptibility of the ribs in this group to buckle when compared with the other ribs. Parametric analysis was conducted on Group 3 and Group 4 samples by changing some
important parameters. Skin thickness, Skin modulus, Rib width, Rib Modulus and the Bay area were varied and the effect of these variables on the load carrying capacity was observed. The load carrying capacity increases with skin thickness and this effect is more prominent in Group 4. Increasing the skin and rib modulus increases the load carrying capacity of both groups. As rib width increases it was observed that the load carrying capacity decreases quite drastically and after a certain thickness starts increases slowly. With increase in the bay area it was observed that the load carrying capacity first decreases and then increases for higher bay areas, similar to widening the ribs.

7.2 Future Work

In the current study the rib thickness could not be decreased beyond a certain level due to physical constraints placed by the manufacturing method. In the future a more efficient method should be developed so that the volume fraction of fibers in the ribs could be increased. Vacuum assisted Resin infusion method could be implemented for introducing the foam into the bay area so as to get very high quality specimens. An accurate finite element model should be developed for Group 2 specimens in order to get more accurate results. Different element types and better boundary conditions should be used in the finite element modeling to further increase the accuracy.
REFERENCES


VITA

Venkata D. Muthyala completed his schooling in April 2000, at Andhra Education Senior Secondary High School, New Delhi, India. He received the degree of Bachelor of Engineering in Mechanical Engineering from Osmania University, Hyderabad, Andhra Pradesh, India in 2005. He then joined the graduate program at Louisiana State University, Baton Rouge, Louisiana in August 2005. He will be graduating in December 2007 with the degree of Master of Science in Mechanical Engineering.