Abstract

MOTLEY, DAVID RICHARD. Analysis of Low Velocity Impact on Pultruded Fiber Reinforced Polymer Plates (Under the direction of Dr. Eric Klang.)

Impact is one of the greatest design limitations involved in designing new composite products. The purpose of this research was to gain an initial understanding of the impact behavior of fiberglass reinforced pultruded laminates with vinylester and isopolyester resins. The effect of adding a protective layer of rubber to the laminates was also investigated.

Several drop tower impact test were performed with a relatively high mass (12 lbs.) and a low velocity (80-150 in/s). These impacts produced severe damage in some of the laminates with only one impact. The 3D stitched laminates and the Duraspan™ laminates, which are used in Martin Marietta Composite’s bridge decks, showed the least amount of visible damage of the laminates tested. The Duraspan™ laminates however, had two interlaminar delamination regions while the others only had one. This delamination was seen with C-scan images of the impacted laminates. This extra delamination region did not decrease the tensile strength at all. Tensile tests were performed with a 1 in. strip from the center of the impacted samples in order to test the residual tensile strength.

Finite element models were created with ANSYS/ls-Dyna nonlinear finite element software. These models were used to simulate the drop tower tests and then were extended to thicker laminates as well as different impact speed and impactor mass. Several models were also created to predict the effects of the rubber protective layer.
These models were able to predict approximate stresses and strains induced in the laminates during the impact which were compared to the damage from the drop tower tests. The models predicted that the rubber layer decreased the stress and strain in the laminate up to 50%. The drop tower tests confirmed that the rubber aided the impact resistance significantly.
ANALYSIS OF LOW VELOCITY IMPACT ON PULTRUDED FIBER
REINFORCED POLYMER PLATES

by

David Richard Motley

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Department of Mechanical and Aerospace Engineering

Raleigh
2002

Approved by:

Dr. Jeffrey W. Eischen
Dr. Larry M. Silverberg

Dr. Eric C. Klang
Chairman of Advisory Committee
Biography

David was born in Winston-Salem North Carolina and has one younger brother, Eric. His parents are Pharris and Cathy Motley who still reside in Winston-Salem. He graduated from high school in 1995 and came to NC State to study engineering. He earned a Bachelor of Science degree in Mechanical Engineering in 2000 and continued with the pursuit of his Master of Science in Mechanical Engineering.
Acknowledgements

I would like to thank the following people:

My parents, Pharris and Cathy Motley, for their continuous love and support.

Dr. Klang for his guidance through the last two years and for reminding me to keep the most important things first in my life.

Dr. Dan Richards and Greg Solomon at Martin Marietta Composites for their assistance and for making this research possible.

My committee members: Dr. Eischen and Dr. Silverberg.

Jared Baucom, Rolin Barrett, and Dr. Zikry for their assistance with the impact laboratory.

Richard Wood, Chris Holder, and Greg Sabin at Cherry Point Naval Aviation Depot for graciously allowing me to use their ultrasonic C-scan equipment.

Lastly and most importantly, I would like to thank my wife Arica for her unending love and patience during the last few years.
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1. Introduction

The fiberglass reinforced plastic (FRP) bridge deck, figure 1.1, was created in 1992 by Lockheed Martin Missiles & Space Company at the Palo Alto Research and Development Laboratory. In 1995, Lockheed Martin sold the technology to its spin-off company, Martin Marietta Materials, Inc. (MMM). Martin Marietta Composites, Inc. (MMC) was then created to further engineer and manage this technology. MMC [1] has since installed several decks across the United States. The major benefit of these bridge decks is a longer life mostly due to much higher corrosion resistance than steel and concrete.

![Pultruded Duraspan™ deck section.](image)

Composite material can also be very advantageous in many other places such as in the automotive, marine, and construction industries. The benefits of composites in
these fields include a significant reduction in weight, enhanced fatigue properties, and the ability to adjust the material properties for each application.

MMC has been continually investigating new composite products in order to enlarge their product line. Many of these new and innovative products are influenced by impact damage, whether by design or by accident. Impact properties such as damage resistance are crucial to product design due to the significant deterioration of the material properties of composite materials after impact damage has occurred. This damage can be visible damage such as cracks or invisible damage such as delamination between layers. This delamination is common because of the low strength of the bond between the layers since there are no fibers in that direction.

This research was initiated by the interest in creating a composite dump bed for quarry trucks, figure 1.2. MMM’s main product is aggregate for the construction industry. MMM mine and crush rock, which requires a significant amount of transportation of rock. These quarry trucks are limited by the weight that they are allowed to carry therefore, by reducing the weight of the truck itself, more material can be transported per trip. This could result in fewer trips per day for the trucks or more rock carried per day, both have the potential to increase profits for MMM considerably.
Impact is a considerable design limitation for these beds. Large rocks are dumped into these beds from loaders on a daily basis. These rocks can be as large as 4 ft. in diameter and weight as much as 2400 lbs. The sharp edges on these rocks can create considerable damage to steel beds, but composite materials can hold up to this task if properly designed. Rubber mats are currently used in the steel beds to absorb some of the shock from the rock and would most likely be an essential part of the composite design as well.

1.1 Purpose and Scope

The purpose of this research was to characterize the damage done to pultruded fiberglass laminates subjected to low velocity, high mass impact. This subject is a crucial design question that appears frequently in the design of new composite products. Impact loads affect almost all commercial composite products whether by design or by accident. This investigation attempted to provide initial insight into impact damage of the
pultruded fiberglass laminates by performing several tests with a drop weight tower. These impact tests were then analyzed with finite element models that were later used to predict the behavior of the laminates under different impact situations not included in the testing. These results were summarized and several conclusions were made about the damage induced by the impact. Further research is needed to evaluate the effects of impact damage on specific applications.

2. Background

2.1 Impact

Early work on impact mechanics was inspired by the railroad industry, specifically the cars impacting the steel rails [2]. Thomas Young was one of the first to investigate impact on perfectly elastic material in the early 1800’s. Young concluded that the energy absorbed by the beam was proportional to its volume. Saint-Venant [2] was also developing theories about impact around this time. Saint-Venant looked at a beam fixed at one end subjected to an impact blow at the other end. He simplified this problem to a vibrating beam with a mass attached to one end. Saint-Venant never fully solved this problem but laid the groundwork for the research that followed.

H. Lee [3] also followed Saint-Venant and others to come up with very detailed equations of motion related to impact in 1932.

J. D. Winkel and D. F. Adams [4] conducted some of the first experimentation with modern drop weight test fixtures in 1985. They used this test fixture to characterize the difference in impact damage between several types of composite laminates. They were able to gain time histories of the impact force by using a piezoelectric force transducer. Before the piezoelectric force transducers, strain gages were the most common tool for instrumenting these tests.

In 1994, G. Zhou [5] performed a study to determine the influence of impact force and incident kinetic energy during impact on composite plates. He performed this study using glass-fiber reinforced laminates with low velocity impact. A flat-ended impactor was used with energy ranging from 15-3000 J. After the samples were impacted they were C-scanned and cross-sectioned to determine their damage mechanisms. The damage mechanisms that absorbed the energy and controlled the load bearing capabilities were delamination, fiber shear-out, and fiber tear. Zhou determined that these damage mechanisms were geometry dependent and happens in a sequential order. He matched these sequences to the corresponding section of the force time curve from the drop tower tests. Zhou also concluded that the load and energy needed for damage was most affected by the laminate thickness and the load bearing capability was most affected by the in-plane dimension. G. Zhou along with G. A. O. Davies and D. Hitchings [6] also studied the post impact compressive strength of delaminated composites and concluded that their strength suffered greatly when delaminations were present. He also matched
reasonably well the force-time characteristics of impact on 10 mm laminated plated with an FE model which accounted for geometric non-linearity.

Also 1994, Chun and Lam [7] solved the non-linear, second order differential equations governing the dynamic response of laminated composite plates. This was done in order to propose a numerical method for the calculation of the dynamic response of these plates under low velocity impact. Their results included stress, deflection, contact force, and energy transferred vs. time for several different stacking sequences. They compared their results to literature and stated that their proposed method could be used to analyze laminated plate with any stacking sequence.

2.2 Thick Laminate Impact

In 1994 G. Zhou and G. A. O. Davis [8] used a drop weight test rig to investigate the impact response of thick glass/polyester laminates plates. Impact tests were conducted with a high mass (8-75 kg) and a low velocity impactor. This allowed more kinetic energy to be absorbed by the sample since there was a relatively long contact duration. They determined the impact response and energy absorbing characteristics by studying the absorbed energy histories and the force-displacement relationships. Visual inspection, ultrasonic C-scan, and an optical microscope were used to observe the damage. The conclusions of this study was that the maximum static and impact forces, and the incident kinetic energy could be scaled by a thickness ratio if the samples have the same diameter and their behavior is dominated by shear. The major failure modes
that they observed included matrix cracking, surface microbuckling, delamination, fiber shear-out, and fiber fracture.

Zhou and Davies proposed an empirical scaling method to apply to strain rate sensitive composite materials. They used radius to thickness ratios of 5 and 2 for their tests and observed that shear dominated these samples when loaded. Their method began with an indentation law for flat ended impactors and then after making some assumptions came up with a simple relationship between the two thickness:

\[
\frac{(mv^2)_{25}}{(mv^2)_{10}} = \frac{t_{25}}{t_{10}}
\]  

(1)

Where the subscripts denote the thickness of the plate in mm. This relationship was then used to compare the force per unit thickness to the damage area for both plates with relatively good agreement. This relationship was also found useful in scaling the absorbed energy in the two plates.

2.3 Finite Element Analysis

Some of the first research on the modeling of impact damage resistance in composite materials was on the subject of bird strikes. In 1981, R.E McCarty [9] used the nonlinear finite element software MAGNA to model birds striking the canopy of the F-16A and in 1982, M.S. Hirschbein [10] used NASTRAN to model the effects of bird strikes on turbine blades. Both of these authors claimed reasonable results.

There have been many damage criterions created for composite damage analysis in Livermore’s ls-Dyna transient non-linear FEA software [11]. One of the earliest was
established by Chang and Chang [12] in 1985. They created a damage model to predict damage in notched laminate composites under tensile loading. The model could be used to assess the type and the extent of the damage, evaluate residual strengths, and predict ultimate strengths. The damage was assessed with a proposed failure criteria and proposed property degradation model. They found excellent agreement between their predicted results and experimental data. The current composite damage model that is used by ls-Dyna is based on this model.

They identified the three main inplane failure modes as matrix cracking, fiber-matrix shearing, and fiber breakage. The following failure criterion (equation 1) was used to predict matrix cracking:

\[
\left( \frac{\sigma_y}{Y_t} \right)^2 + \frac{1}{\gamma_{xy}^m} \int_0^{\gamma_{xy}^m} \sigma_{xy} d\gamma_{xy} = e_m^2
\]  

Where \( s_y \) is the transverse tensile stress and \( s_{xy} \) is the shear stress in each layer. \( Y_t \) is the transverse tensile strength, \( \gamma_{xy}^u \) is the ultimate shear strain, and \( e_m \) is the failure strain of the matrix material. By adding the shear stress-shear strain relationship:

\[
\gamma_{xy} = \left( \frac{1}{G_{xy}} \right) \sigma_{xy} + \alpha \sigma_{xy}^3
\]  

Equation 2 can be written as:

\[
\left( \frac{\sigma_y}{Y_t} \right)^2 + \frac{\sigma_{xy}^2}{2G_{xy}} + \frac{3}{4} \alpha \sigma_{xy}^4 + \frac{S_c^2}{2G_{xy}} + \frac{3}{4} \alpha S_c^4 = e_m^2
\]
Where $S_c$ is the ply shear strength. For laminates with linear elastic behavior ($a = 0$), equation 4 can be written as:

$$\left(\frac{\sigma_y}{Y_t}\right)^2 + \left(\frac{\sigma_{xy}}{S_c}\right)^2 = e_m^2 \quad (5)$$

This failure criterion states that when the stresses $s_y$ and $s_{xy}$, in any one of the plies, satisfy one of the previous equations ($e_m = 1$), matrix cracking occurs in that layer.

A failure criterion created by Yamanda-Sun [13] was modified by Chang and Chang for use with fiber-matrix shearing and fiber breakage.

$$\left(\frac{\sigma_x}{X_t}\right)^2 + \int_0^{\gamma_{xy}} \sigma_{xy} d\gamma_{XY} + \int_0^{\gamma_{Xc}} \sigma_{XY} d\gamma_{XY} = e_f^2 \quad (6)$$

or

$$\left(\frac{\sigma_x}{X_t}\right)^2 + \left( \frac{\sigma_{xy}^2}{2G_{xy}} + \frac{3\alpha \sigma_{xy}^4}{4} \right) \left( \frac{S_c^2}{2G_{xy}} + \frac{3\alpha S_c^4}{4} \right) = e_f^2 \quad (7)$$

Where $s_x$ is the longitudinal tensile stress and $X_t$ is the tensile strength in each ply. As before, for linear elastic materials the equation can be reduced to:

$$\left(\frac{\sigma_x}{X_t}\right)^2 + \left(\frac{\sigma_{xy}}{S_c}\right)^2 = e_f^2 \quad (8)$$
This failure criterion states that when the stresses $s_x$ and $s_{xy}$, in any one of the plies, satisfy one of the previous equations ($e_f = 1$), either fiber breakage or fiber-matrix shearing occurs in that layer.

Once damage has occurred the material looses strength in that area and the reduction is dependent on the mode of failure. For matrix cracking in a layer, the transverse modulus $E_y$ and Poisson’s ratio $\nu_y$ are reduced to zero. The longitudinal modulus $E_x$ and the shear-stress strain relation of that layer are unchanged.

When fiber breakage and/or fiber-matrix shearing are predicted, the extent of the property degradation depends on the size of the damage. For fiber failure, both $E_y$ and $\nu_y$ are reduced to zero. The longitudinal modulus $E_x$ and the shear modulus $G_{xy}$ degenerate according to the Weibull distribution:

$$\frac{E_x^d}{E_x} = \exp \left[ 1 - \left( \frac{A}{A_0} \right)^\beta \right]$$ \hspace{1cm} (9)

$$\frac{G_{xy}^d}{G_{xy}} = \exp \left[ 1 - \left( \frac{A}{A_0} \right)^\beta \right]$$ \hspace{1cm} (10)

Where $E_x^d$ and $G_{xy}^d$ are the reduced tensile and shear modulii. $A$ is the predicted damage zone and $A_0$ is the fiber failure interaction zone associated with the measured ply tensile strength $X_t$. $\beta$ is the shape parameter of the Weibull distribution for the property degeneration.

In 1992, Tian and Swanson [14] used ANSYS to model delamination caused by impact and the residual strength of the composite. They used solid anisotropic elements.
with one element per layer to model the laminates. They were able to incorporate a failure criterion and reasonably correlate their FE results to experimental results.

In 1996, Francis Collombet (et. al.) [15] combined experimental and numerical analysis of low velocity, heavy mass impact to develop another method of predicting damage in composite laminates. They used drop tower experiments to gather data about the force and damage mechanisms resulting from low velocity impact. Finite element analysis was then used to evaluate and predict local damage in the laminates. They developed a damage criterion for stresses to cause cracking and loads to cause delamination.

One of the more recent models created for Ls-Dyna3D was by Williams and Vaziri in 1999 [16]. They have built upon previous plane-stress continuum damage mechanics models and made comparisons with previous numerical results and experimental data. The purpose of their model was to predict the damage progression in laminated composite plate subjected to impact loads. They showed that their model made improvements upon the previous damage models.

Another recent model was created for Ls-Dyna3D by Hou, Pentrinic, and Ruiz [17]. They improved the delamination criterion by including more of the stresses that contribute to the failure. They included interlaminar shear and through-thickness compression stresses as well as fiber failure and matrix cracking. They also stated that their model showed improvements in the damage prediction in composite laminates.
2.4 Improving Impact Properties

Several different ways of improving the impact properties of composite materials have been studied. Some of these include 3D weaving, 3D stitching, optimal stacking sequences, and combining fibers with different properties. It was found very early that unidirectional fibers will split at very low energies and are therefore not recommended for use on the outside edge of laminates. Laminates with -/+ 45° and 0°/+ - 45° surface plies have shown much better impact resistance and residual strengths (18). However, it has also been found that delamination is more likely between abrupt ply angle changes such as -/+ 45° [19].

The introduction of lower modulus fibers has also been shown to improve the energy absorption of the composites. Hancox and Wells [20] showed a 500% increase in energy absorption by introducing E-glass fibers with carbon fibers.

Cantwell, Curtis, and Morton [21] showed in 1983 that three-dimensional weaving and stitching significantly reduced the delamination in layered materials. This reduced delamination improved the impact response, the strength, and the residual properties of the laminate.

In 2000, Shankar and Zhu [22] published the results of a study about the effects of stitching on the low-velocity impact response of composite beams. They used numerical analysis to look at the response of the beams (which were already delaminated) reinforced with stitching. The stitches were modeled as shear tractions to provide shear resistance between the layers. The analysis consisted of a rigid ball impacting a simply supported beam. They also analyzed unstitched laminates for a comparison. They found
that the stitching does not affect the load at which the delamination begins but it greatly reduces the spreading of the delaminations.

2.5 Ultrasonic scanning

Ultrasonic scanners use piezoelectric transducers to generate and detect ultrasonic waves traveling through specimens. These waves are sent through the specimen being scanned and then reflected off of the front surface, back surface, and any flaws or damage that may be in the specimen. The amplitude, the distance that the wave travels, and the attenuation, the travel time of the wave, are recorded and displayed graphically to locate flaws, damage, and material properties such as density. Other types of non-destructive ultrasonic scanning include acoustic ultrasonic, ultrasonic spectroscopy, and ultrasonic microscopy [23].

The most widely used method of ultrasonic scanning of composite materials is C-scanning. The letter designation of A, B, and C-scanning represent how the ultrasound data is presented [24]. This type of scanning can be used to detect imperfections and damage in various materials including composites. With ultrasonic A-scanning, the data is presented as a single amplitude versus time wave on an oscilloscope or similar device. This information only gives the location of the flaw or damage on the specimen. B-scan represents the data as a depth profile versus position along a specimen. This is accomplished by determining the travel time of the ultrasonic wave through the material. B-scans only give depth information about the flaw or damage. C-scan is the presentation of the depth profile in two dimensions relative to the surface of the specimen, or simply a combination of A and B-scans. C-scans are able to represent the
damage location and the damage depth with different shades of gray or different colors. A disadvantage of piezoelectric transducers is the need for a coupling agent such as water or gel to allow the wave to travel to the specimen. More current innovations include the use of lasers to guide the wave to the specimen. These however require special equipment to contain the powerful laser beam [25].

The first C-scan technology was created in 1956 in the Automation Instruments Power Plant Inspection Division test lab in Paramount, California. This system was made up of a Sperry Reflectoscope, a camera, and an emersion tank [26]. Martin [27] was one of the first to publish research related to the ultrasonic scanning of composite materials in 1970. His research consisted of scanning for defects in metal matrix composites of thickness ranging from 0.5 to 2.5 mm.

More recent research has been focused on making the scanning process more automated. Several automated techniques were created in the 80’s that reduced the need for highly trained technicians in order to produce quality ultrasonic scans. These systems were created for the US Air Force and McDonnell Aircraft Co. [24]

2.6 Composite trucks

There has been very little information published thus far on the implementation of composite materials to truck beds. The first application was the light duty passenger truck beds designed for easy replacement. In 1996, Rieter Industries developed a plastic dump bed for on-highway dump trucks [28]. These beds were designed with polyethylene. The advantages of this bed include less maintenance as well as dent and
corrosion resistance. They also claim that this plastic body applies less strain to the truck when unloading because the material slides out easier and the load that the cylinders are required to lift is lighter.

3. Drop Tower Testing

3.1 Introduction

The most common method of performing drop tower impact test consists of dropping a weighted impactor from a specific height and allowing it to strike a fixed target. Figure 3.1 shows the drop tower used for these tests [29]. The clamp, which holds the impact sample in place, is made up of thick aluminum rings, which are secured to the base of the tower with threaded studs and nuts.
Figure 3.1: Drop tower test apparatus.

The impact tup has a 0.375 in. end diameter and the unsupported region of the samples is 3 in. in diameter. Figure 3.2 shows the clamp with a laminate secured in place. This drop tower could produce impact velocities of 19.6 – 196.8 in/s (0.5 – 5 m/s) and impact energies up to 1,710,000-lbm in²/s² (500 J).
The dynamic tup position was monitored with a MTS Temposonic Transducer and the acceleration history was recorded during the freefall with a piezoelectric accelerometer. The acceleration vs. time was used to determine the impact force and the position signal was used to determine the velocity of the impactor just before and after impact. The calibration factors for the impact tower instrumentation are given in table 3.1. These factors were used to convert the voltage signals to force (lbf) and height (in).
Table 3.1 Calibration factors

<table>
<thead>
<tr>
<th>Charge Amp</th>
<th>Sensitivity</th>
<th>mV/pC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Calibrated Accelerometer Sensitivity</td>
<td>100</td>
<td>pC/g</td>
</tr>
<tr>
<td>Acceleration Factor</td>
<td>490</td>
<td>(m/s²)/V</td>
</tr>
<tr>
<td>Impact Mass</td>
<td>5.5</td>
<td>Kg</td>
</tr>
</tbody>
</table>

The impact samples were 5 in. x 5 in. pultruded plates consisting of E-glass fibers, some with vinylester and some with isopolyester resin. The layers and approximate layer thickness of each material are given in the following sections of this thesis. These properties were determined using the shareware laminate code *The Laminator – Classical Analysis of Composite Laminates* [30] and previous material testing. For this research, thirty-two samples were impacted in the drop tower as shown in table 3.2.

Table 3.2: Breakdown of impact test performed.

<table>
<thead>
<tr>
<th></th>
<th>Vinylester</th>
<th>Isopolyester</th>
<th>Isopolyester (Duraspan)</th>
<th>3D Stitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast</td>
<td>5</td>
<td>5</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>With Rubber</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The incident kinetic energy, IKE (kinetic energy just before impact) for each test was also determined for each test with the equation 11 and used as a comparison between tests.

\[ IKE = \frac{1}{2} m_i v_i^2 \]

(11)

### 3.2 Drop Tower Tests

#### 3.2.1 Test 1 – Vinylester Resin

The first set of test samples was impacted once with a velocity of 149.6 in/s (3.8 m/s) and an impactor mass of 12.13 lbs. (5.5 kg). This resulted in an IKE of 136,500 lbm-in/s² (40 J). Figures 3.3 & 3.4 show the data reordered during the impact tests. Figure 3.3 shows the force history with a 5\(^{th}\) order polynomial curve fit.

![Figure 3.3: Force history for test 1.](image)
The average maximum impact force was taken from these curve fits on all test data. For this test, a maximum average impact force of 2400 lbf. was observed. The oscillations on the front side of the force history data occurred in every sample. It was not entirely clear why the oscillations occurred but mechanical noise in the system was ruled out. These oscillations could be an indication of the amount of damage occurring in the sample because there was a difference in the frequency of the oscillations as the amount of damage changed from test to test.

Figure 3.4 shows the height history from which the velocities before and after impact were calculated by taking the derivative immediately before and after impact. The discrepancy in the data on the rebound side of the signal did not effect the velocity measurement since it could be taken in the lower section or by taking several points near the bottom and several points at the top of the rebound. It was not known why this discrepancy occurred in the data but it was common with almost all of the data.
The material for test 1 consisted of pultruded E-glass and a vinylester resin which was pultruded by Creative Pultrusions [31]. In these samples there were three layers of 2 Oz. per foot$^2$ continuous E-Glass Mat and three layers of 113 yield roving, 42 and 84 rovings per layer. 113 yards of this roving material weighs 1 lb. The lay-up and approximate layer thickness is shown in table 3.3. This layer thickness was based on visual inspection of the cross-section and an approximate fiber volume fraction of 50%. The apparent material properties for this material are found in the finite element section of this thesis.
Table 3.3: Lay-up of vinylester laminate.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 1/2&quot; Nexus</td>
<td>0</td>
</tr>
<tr>
<td>12 1/4&quot; - 2 oz. OC</td>
<td>0.015</td>
</tr>
<tr>
<td>Resin</td>
<td>0.019</td>
</tr>
<tr>
<td>84 -113 yield roving</td>
<td>0.031</td>
</tr>
<tr>
<td>Resin</td>
<td>0.019</td>
</tr>
<tr>
<td>12 1/4&quot; - 2 oz. OC</td>
<td>0.015</td>
</tr>
<tr>
<td>Resin</td>
<td>0.019</td>
</tr>
<tr>
<td>42 -113 yield roving</td>
<td>0.016</td>
</tr>
<tr>
<td>Resin</td>
<td>0.019</td>
</tr>
<tr>
<td>12 1/4&quot; - 2 oz. OC</td>
<td>0.015</td>
</tr>
<tr>
<td>Resin</td>
<td>0.019</td>
</tr>
<tr>
<td>84 -113 yield roving</td>
<td>0.031</td>
</tr>
<tr>
<td>Resin</td>
<td>0.019</td>
</tr>
<tr>
<td>12 1/4&quot; - 2 oz. OC</td>
<td>0.015</td>
</tr>
<tr>
<td>13 1/2&quot; Nexus</td>
<td>0</td>
</tr>
</tbody>
</table>

Total 0.24

Damage

All five samples were impacted with the same impact force and exhibited identical damage, figure 3.5. This impact produced an indentation on the top surface of the samples and a backside crack approximately 2.4 in. in length running in the pultruded direction. Clearly, matrix cracking and delamination were the dominant failure mechanisms, which was expected due to the brittleness of the matrix material and the low interlaminar shear strength between the layers.
Figure 3.5: Top and bottom damage on samples from test 1.

The matrix cracking in these samples initiated in the bottom surface of the laminate, which agrees with previous researcher’s observations. W. J. Cantwell and J. Morton [32] found that the laminate thickness and stiffness determined which surface the damage would initiate on. For thick, stiff targets, the damage initiated on the top surface where the high contact stress occurred. For thin, flexible targets, the damage initiated on the bottom surface where the in plane stresses are the highest. It was also found that there was an optimum target stiffness in which damage initial damage occurred on the top and bottom surfaces simultaneously. This optimum thickness was found to give the highest resistance to damage initiation. Table 3.8 in section 3.2.8 gives a summary of the damage in all seven tests.
**Ultrasonic C-scan**

Several ultrasonic C-scans of the impacted test samples were performed with the help of Cherry Point Naval Aviation Depot (NADEP) [33]. These scans were performed with a Panametrics model 9100 high-speed ultrasonic flaw detector and an ultrasonic immersion tank. This instrument used a piezoelectric transducer to emit an ultrasonic wave that traveled through the sample and was reflected back from the sample and a reflector plate. This created a picture of the internal damage (delamination) created by the impact to the composite, figure 3.6. The dark oval shaped region in the center of the specimen is the delaminated region. The long length of the oval runs in the pultruded (strong) direction, which was also the direction of the backside crack. A summary of this damage is presented at the end of this section, and C-scan images accompany each test section.

![Ultrasonic scan of delamination in sample from test 1.](image)

**Figure 3.6:** Ultrasonic scan of delamination in sample from test 1.
3.2.2 Test 2 – Vinylester Resin

The second set of test samples was impacted once with a velocity of 81 in/s (2 m/s) and an impactor mass of 12.13 lbs. The material for test 2 was the same as in the first test. This velocity and mass resulted in an IKE of 40,700 lbm-in$^2$/s$^2$ (11.9 J). Figure 3.7 shows the force history vs. time for the five samples.

![Figure 3.7: force histories of all samples from test 2.](image)

This graph shows all five acceleration signals for test 2 converted to force (lbf). The scatter in the data occurred with every test and was fairly regular. This data could have been run through filters to eliminate certain frequencies but some of the data could have been lost in the process. Other than the difference in the initial times, the curves are
all nearly identical in height and length. The average length of the impact for this test was 0.00521 sec., and the average maximum force was 1577 lbf.

**Damage**

These samples exhibited far less damage than the samples in test 1 due to the lower impact velocity. As before, the only visible damage was a backside crack approximately 0.6 in. in length, figure 3.8, and a small indentation at the point of impact. The crack on these samples did not extend far enough to clearly show the pultruded fiber direction as seen in the first set of samples.

![Figure 3.8: Top and bottom damage on sample from test 2.](image)

The delamination region observed in the C-scan was also much smaller in size than the first test, figure 3.9. The region was still oval shaped but was approximately 75% smaller than for test 1.
3.2.3 Test 3 – Isopolyester Resin With Rubber Covering

The third set of test samples was impacted once with a velocity of 149 in/s (4 m/s) and an impactor mass of 12.13 lbs. This resulted in an IKE of 136,500 lbm-in$^2$/s$^2$ (40 J). The average maximum impact force was 1612 lbf, as seen in figure 3.10. Again, the oscillations seen in the force histories may be related to the amount of damage occurring in the sample during impact but more investigation is needed before a conclusion can be reached. The oscillations for this test had a higher amplitude and were closer together than for many of the other tests.
Figure 3.10: Force history from test 3.

The material for test 3 consisted of pultruded E-glass and an isopolyester resin and a 3/16 in. neoprene rubber pad placed on top of the composite, figure 3.11, and clamped in the fixture. The neoprene was not adhered to the laminate in any way although using an adhesive between the layers may improve the impact resistance.
There were three layers of 2 Oz. per Foot\textsuperscript{2} continuous E-Glass Mat and two layers of 113 yield roving in this laminate. The lay-up and approximate layer thickness is shown in table 3.4.

Table 3.4: Lay-up of isopolyester laminate

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 1/2&quot; Nexus</td>
<td>0</td>
</tr>
<tr>
<td>12 1/4&quot; - 2 oz. OC</td>
<td>0.0165</td>
</tr>
<tr>
<td>Resin</td>
<td>0.019</td>
</tr>
<tr>
<td>90 -113 yield roving</td>
<td>0.031</td>
</tr>
<tr>
<td>Resin</td>
<td>0.019</td>
</tr>
<tr>
<td>12 1/4&quot; - 2 oz. OC</td>
<td>0.0165</td>
</tr>
<tr>
<td>Resin</td>
<td>0.019</td>
</tr>
<tr>
<td>90 -113 yield roving</td>
<td>0.016</td>
</tr>
<tr>
<td>Resin</td>
<td>0.019</td>
</tr>
<tr>
<td>12 1/4&quot; - 2 oz. OC</td>
<td>0.0165</td>
</tr>
<tr>
<td>13 1/2&quot; Nexus</td>
<td>0</td>
</tr>
</tbody>
</table>

Total: 0.1875
Damage

The damage to this set of samples consisted of a small indentation and a small crack on the top surface and a larger backside crack. The topside crack was approximately 0.8 in., figure 3.12, and the backside crack was approximately 2.9 in. in every sample. The visible damage to all samples in the set was nearly identical.

![Figure 3.12: Top and bottom damage on samples from test 3.](image)

The delamination image of the damage to this set of samples was an oval shape as before but also resembled a figure eight, figure 3.13. The overall size of the delaminated region was similar to that seen in test 1 and as before, the oval extended in the pultruded direction.
3.2.4 Test 4 – Isopolyester Resin without Rubber Covering

This set of samples included the same composite material as in test 3 (isopolyester resin) but without the rubber protective layer. The samples were hit with the same impactor mass of 12.13 lbs and a velocity of 150 in/s.

Damage

The damage to this set of samples was significantly worse than the previous set with the rubber covering. The topside crack was approximately 1 in. long and there was a considerable area of crushed material, figure 3.14. The backside crack was 3.25 in. long running in the pultruded direction. The length of this crack may have been limited by the clamp fixture which had a diameter of 3 in. The topside of the laminate did not crack in every laminate, but the backside cracks were all very similar in length.
The delamination region in test 4, figure 3.15, was only slightly larger than that for test 3. The long length was approximately the same but the width, weak direction, increased slightly. The length remaining the same may have been due to the damage getting closed to the clamped supports in that direction.
3.2.5 Test 5 – Isopolyester Resin With Rubber Covering (DuraSpan™)

This set of samples consisted of the web material of Martin Marietta Composite’s DuraSpan™ FRP bridge deck with a protective rubber covering. The material properties [34] are shown in table 3.5 and the lay-up is shown in table 3.6 with approximate layer thickness. The matrix is an isopolyester resin and the fabric material used in this laminate was made up of approximately 30% -45°, 30% 45°, and 40% 90° material. The Nexus is a coating used to help the pultrusion process and did not affect the properties. This material was impacted with a velocity of 150 in/s and a mass of 12.13 lbs.
Table 3.5: Stacking of DuraSpan™ laminate

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nexus</td>
<td>0.001</td>
</tr>
<tr>
<td>-45/+45/90</td>
<td>0.038</td>
</tr>
<tr>
<td>Resin</td>
<td>0.010</td>
</tr>
<tr>
<td>Roving</td>
<td>0.027</td>
</tr>
<tr>
<td>Resin</td>
<td>0.010</td>
</tr>
<tr>
<td>-45/+45/90</td>
<td>0.038</td>
</tr>
<tr>
<td>Resin</td>
<td>0.010</td>
</tr>
<tr>
<td>Roving</td>
<td>0.027</td>
</tr>
<tr>
<td>Resin</td>
<td>0.010</td>
</tr>
<tr>
<td>-45/+45/90</td>
<td>0.038</td>
</tr>
<tr>
<td>Nexus</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.210</strong></td>
</tr>
</tbody>
</table>

Table 3.6: Material properties

<table>
<thead>
<tr>
<th></th>
<th>Tensile</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>2.70 Msi</td>
<td>2.94 Msi</td>
</tr>
<tr>
<td>E2</td>
<td>2.46 Msi</td>
<td>2.50 Msi</td>
</tr>
<tr>
<td>V12</td>
<td>0.27</td>
<td>N/A</td>
</tr>
<tr>
<td>Ultimate Strength 0°</td>
<td>33.2 Ksi</td>
<td>38.3 Ksi</td>
</tr>
<tr>
<td>Ultimate Strength 90°</td>
<td>24.3 Ksi</td>
<td>26.8 Ksi</td>
</tr>
<tr>
<td>Interlaminar shear 0°</td>
<td>2.92 Ksi</td>
<td>N/A</td>
</tr>
<tr>
<td>Interlaminar shear 90°</td>
<td>3.42 Ksi</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Damage**

This material exhibited the least visible damage of any of the samples impacted with this velocity. There was only a small mark on the front where the impactor hit and only slightly more visible damage on the backside and still no visible cracks, as seen in figure 3.16. The line down the front of the sample was from the removal of a ridge needed for the bridge structure. There was no apparent effect of this line in the impact damage. The red line on the back indicated the pultruded direction of the laminate.
Figure 2.16: Top and bottom damage on samples from test 5.

The delamination region of test 5, figure 3.17, varied greatly from the others. Instead of an oval shape, the delamination region resembled a circle. This circular shape was created by two overlapping ovals 90° from each other. These delaminations occurred between several different layers. This was the only group of samples tested that had more than one delamination. Once the samples were cut open, the delaminations were slightly visible. These delaminations appeared to be on the top of the 2nd and 3rd layer of fabric material. These delaminations most likely occurred here due to the severe angle changes created by placement of the +/- 45° layers.

Several researchers [35] have observed that the oblong, “peanut-shaped”, delamination region almost always extends in the direction of the fibers of the lower layer of the interface. They also noted that these delaminations rarely occurred between layers running in the same direction. These delamination regions were as large as most of the
other tests which was very surprising since there was very little visible damage to these samples.

![Ultrasonic scan of delamination from test 5.](image)

**Figure 3.17: Ultrasonic scan of delamination from test 5.**

### 3.2.6 Test 6 – 3D Stitch

This set of samples consisted of a 3D stitched material developed by Ebert Composites, Inc., figure 3.18. There was a top and a bottom fiberglass reinforced laminate with a foam material sandwiched in the middle and glass stitching material. The stitching consisted of E-glass threaded through all three layers of the material in the out of plane direction. This extra stitch significantly strengthened the laminate in its weakest direction by tying the layers together. This decreases the interlaminar debonding which is one of the major causes of laminate failure. This additional stitch also adds considerable cost to the manufacturing process and therefore is rarely used when cost is a
major issue. The laminates were impacted with the same 150 in/s and 12.13 lbs once on the top plate and once on the bottom plate in order to get more data points. The two impacts did not appear to affect each other.

![Figure 3.18: 3D stitched laminate and foam core.](image)

**Damage**

This set of sample exhibited very little visible damage to the laminate. The resin used in these samples was more transparent than any of the others so the delamination area was more visible than the other tests, figure 3.19. There were no visible cracks and the delamination size was area was approximately 0.567 in$^2$ on all of the samples. The delamination area and the residual indentation on the laminates were much smaller than the other tests. The stitching significantly reduced the delaminated region by keeping all of the layers tied together.
Figure 3.19: Damage on sample from test 6.

A C-scan image of these samples was not achievable due to the foam core between the panels. This foam absorbed the ultrasonic wave created by the transducer therefore no image could be generated. However, a reasonably accurate measurement was obtainable by observation since this resin was more transparent than the others.

3.2.7 Test 7 – Vinylester Without Rubber Covering

This set of samples included the vinylester laminates as in tests 1 and 2, with no rubber covering. The laminates were impacted at 115 in/s and the same mass of 12.13 lbs. The purpose of this test was to get an addition data point in between 80 and 150 m/s.
Damage

There was no crack on the topside of these samples, only a small indentation. The backside crack was approximately 2 in. in length running in the pultruded direction on all samples.

![Figure 4.20: Damage on top and bottom on samples from test 7.](image)

The delamination region of these samples, figure 3.21, was very similar to the other vinylester tests with the size in between the higher and the lower velocity impacts.
3.2.8 Summary of Tests

Table 3.7 is a comparison of all of the impact tests performed.

Table 3.7: Test Summary

<table>
<thead>
<tr>
<th>Test</th>
<th>Resin</th>
<th>Rubber</th>
<th>Impact speed (in/s)</th>
<th>IKE (lbm-in^2 / s^2)</th>
<th>Delta KE</th>
<th>Force (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vinylester</td>
<td>no</td>
<td>157</td>
<td>136450</td>
<td>242</td>
<td>2400</td>
</tr>
<tr>
<td>2</td>
<td>Vinylester</td>
<td>no</td>
<td>81</td>
<td>38800</td>
<td>60</td>
<td>1577</td>
</tr>
<tr>
<td>3</td>
<td>Isopolyester</td>
<td>yes</td>
<td>157</td>
<td>136450</td>
<td>235</td>
<td>1612</td>
</tr>
<tr>
<td>4</td>
<td>Isopolyester</td>
<td>no</td>
<td>157</td>
<td>136450</td>
<td>242</td>
<td>1640</td>
</tr>
<tr>
<td>5</td>
<td>Isopolyester (Duraspan)</td>
<td>yes</td>
<td>157</td>
<td>136450</td>
<td>221</td>
<td>2020</td>
</tr>
<tr>
<td>6</td>
<td>3D stitch (Resin unknown)</td>
<td>no</td>
<td>157</td>
<td>136450</td>
<td>N/A</td>
<td>3168</td>
</tr>
<tr>
<td>7</td>
<td>Vinylester</td>
<td>no</td>
<td>118</td>
<td>84500</td>
<td>242</td>
<td>1960</td>
</tr>
</tbody>
</table>
Table 3.8 is a summary of the damage observed in the test samples. The amount of damage was rated from 1 to 5 with 5 being the worst.

### Table 3.8: Damage Summary

<table>
<thead>
<tr>
<th>Test</th>
<th>Resin</th>
<th>Rubber</th>
<th>Impact speed (in/s)</th>
<th>Upper visible damage</th>
<th>Lower visible damage</th>
<th>Delamination area (in^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vinylester</td>
<td>no</td>
<td>157</td>
<td>4</td>
<td>4</td>
<td>3.78</td>
</tr>
<tr>
<td>2</td>
<td>Vinylester</td>
<td>no</td>
<td>81</td>
<td>2</td>
<td>2</td>
<td>0.94</td>
</tr>
<tr>
<td>3</td>
<td>Isopolyester</td>
<td>yes</td>
<td>157</td>
<td>4</td>
<td>4</td>
<td>4.71</td>
</tr>
<tr>
<td>4</td>
<td>Isopolyester</td>
<td>no</td>
<td>157</td>
<td>5</td>
<td>5</td>
<td>5.76</td>
</tr>
<tr>
<td>5</td>
<td>Isopolyester (Duraspan)</td>
<td>yes</td>
<td>157</td>
<td>1</td>
<td>1</td>
<td>6.37</td>
</tr>
<tr>
<td>6</td>
<td>3D stitch (Resin unknown)</td>
<td>no</td>
<td>157</td>
<td>2</td>
<td>2</td>
<td>0.57</td>
</tr>
<tr>
<td>7</td>
<td>Vinylester</td>
<td>no</td>
<td>118</td>
<td>3</td>
<td>3</td>
<td>2.42</td>
</tr>
</tbody>
</table>

### 3.3 Residual Tensile Strength

A 1 in. strip was cut out of the center of each sample in order to test the residual strength of the laminate. These samples were tested in tension on an Instron universal testing machine at a rate of 0.2 in/min. The ultimate failure loads are shown in table 3.9.

### Table 3.9: Residual strength of impacted laminates

<table>
<thead>
<tr>
<th>Test</th>
<th>Resin</th>
<th>Rubber</th>
<th>Impact speed (in/s)</th>
<th>Average strength without damage (ksi)</th>
<th>Average strength with damage (ksi)</th>
<th>Percentage of strength lost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vinylester</td>
<td>no</td>
<td>157</td>
<td>12.87</td>
<td>10.19</td>
<td>20.82</td>
</tr>
<tr>
<td>2</td>
<td>Vinylester</td>
<td>no</td>
<td>81</td>
<td>12.87</td>
<td>12.49</td>
<td>0.64</td>
</tr>
<tr>
<td>3</td>
<td>Isopolyester</td>
<td>yes</td>
<td>157</td>
<td>8.29</td>
<td>8.33</td>
<td>0.36</td>
</tr>
<tr>
<td>4</td>
<td>Isopolyester</td>
<td>no</td>
<td>157</td>
<td>8.29</td>
<td>5.91</td>
<td>29.31</td>
</tr>
<tr>
<td>5</td>
<td>Isopolyester (Duraspan)</td>
<td>yes</td>
<td>157</td>
<td>6.54</td>
<td>6.66</td>
<td>+1.83</td>
</tr>
<tr>
<td>6</td>
<td>3D stitch (Resin unknown)</td>
<td>no</td>
<td>157</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>7</td>
<td>Vinylester</td>
<td>no</td>
<td>118</td>
<td>12.87</td>
<td>10.45</td>
<td>18.80</td>
</tr>
</tbody>
</table>
The rubber appeared to make a large difference with the residual strength of damaged laminates. None of the specimens with the rubber layer had more than a 1% loss in strength. The Duraspan laminates were even stronger after impact, although this difference is more than likely scatter in the data. Tests 3 and 4 were exactly the same except for the rubber layer on the laminate. The samples without the rubber showed a 30% drop in tensile strength while the samples with the protective layer showed practically no difference after impact. Comparing tests 1, 2, and 7 (which were identical except for the impact speed) also shows that most of the loss of strength comes somewhere after 80 in/s. Figure 3.22 shows a comparison of the percentage of strength lost to the impact speed. There needs to be more data between these points to verify, but the majority of the loss in strength appears to come immediately after 80 in/s with this 12 lb. impactor.

![Figure 3.22: Lost Tensile strength in test 1, 2, and 7.](image)
Due to the unavailability of a compression test jig, the compression after impact (CAI) tests could not be performed. The residual compressive strength would most likely be affected more by this damage than the residual tensile strength.

4. Finite Element Analysis

4.1 Introduction

Due to the cost of impact testing and a short time period, finite element analysis was used to gain additional information about the behavior of the composite laminates subjected to impact loading. Simple models were verified with testing and more complex models were used to simulate additional parameters such as thick laminates and rubber protecting the composite. FEA was used to predict the stresses and strains induced in the laminate by a low velocity projectile. These stresses and strains can later be used to predict the life span of the composite under various loading conditions. ANSYS and ANSYS/ls-Dyna finite element codes were used for the simulations.

4.2 Static Model

A static model was created to get an idea of the loads caused by a 4 ft. diameter granite rock. Several simple shell models were made with pressures in various locations. The resulting stresses and strains were very low and well within the capability of the composite even without a rubber liner. From this it was decided that the impact was going to be the limiting factor in the design.
4.2.1 Impact factor

From Mechanics of Materials [36] the impact factor is the ratio of the dynamic response of a structure to the static response of the structure with the same load. Once this factor is known for a certain structure and loading condition, a much simpler static model can be used to analyze the behavior.

A suddenly applied load is a load that is released from a point very close to the target and has no initial velocity. The object is lowered until it is in contact with the target and then released. Since the object is in contact with the target it has no initial velocity, but as it moves through $d_s$ it gains a small amount of kinetic energy. The maximum deflection from this loading condition is shown to be $d_{\text{max}} = 2d_s$.

This simple concept was used as an initial check of the dynamic finite element model. A static model was first created using a pressure load of 19.8 lbs. This weight is equivalent to 9 kg and is not related to the mass of 12.13 lbs in the testing section of this thesis. This pressure was applied to shell elements with fiberglass properties and the maximum deflection was observed, figure 4.1. The maximum deflection in the center of the shell was found to be –0.548 micro inch.
Figure 5.1: Static pressure on shell elements.

The dynamic model was then created with a square impactor hitting a shell with the same properties, figure 4.2.
The block was placed at several distances from the shell and dropped onto it. The maximum deflection in the center of the shell converged to –1.2 micro inch as initial distance was decreased, table 4.1. This final deflection compared to the static deflection represents an impact factor of 2.2, which was close to the 2.0 predicted by mechanics of materials.

Table 4.1: Convergence of deflection and stress

<table>
<thead>
<tr>
<th>Distance from target (in.)</th>
<th>Deflection (micro inch.)</th>
<th>Stress Intensity (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>-4.6</td>
<td>3100</td>
</tr>
<tr>
<td>0.01</td>
<td>-1.9</td>
<td>1300</td>
</tr>
<tr>
<td>0.001</td>
<td>-1.25</td>
<td>850</td>
</tr>
<tr>
<td>0.0001</td>
<td>-1.2</td>
<td>825</td>
</tr>
<tr>
<td>0.00001</td>
<td>-1.2</td>
<td>815</td>
</tr>
</tbody>
</table>
4.3 Elements

4.3.1 ANSYS/ls-Dyna Shell 163

The ANSYS/ls-Dyna shell 163 element is the general-purpose thin structural shell element for explicit dynamics. It contains all of the features of the implicit shell elements including both bending and membrane capabilities. This element has four nodes and twelve degrees of freedom per node including translations, rotation, accelerations, and velocities.

4.3.2 ANSYS/ls-Dyna Solid 164

The ANSYS/ls-Dyna structural solid element 164 was also used in this investigation. This element has eight nodes and nine degrees of freedom per node including translations, velocities, and accelerations. The solid element 164 could not be used for the interlaminar stress prediction models. A problem was encountered with the layer ability of the solid element so this element was not used to determine interlaminar stresses. This solid element uses an effective modulus through the thickness of the layer by averaging the elastic modulus of all the layers (ANSYS theory reference). This becomes a problem when the layers have drastically different moduli from layer to layer as in fiberglass laminates. This element will not take into effect the position in the laminate of the very high or very low modulus layers, which plays a key role in the bending of the laminate. It will also give inaccurate interlaminar stresses since the adjoining modulii are the key parameter for that calculation. Therefore, macroscopic laminate properties were used with this element.
4.3.3 ANSYS shell 99

Shell 99 was used for a static stress comparison of plate bending. This element is a linear layered structural shell which has eight nodes per element and six degrees of freedom per node.

A simple one layer isotropic model was created with the vinylester resin properties and compared to plate theory results [37]. For the symmetric bending of a circular isotropic plate the governing ordinary differential equation is:

$$\frac{1}{r} \frac{d}{dr} \left[ r \frac{d}{dr} \left( \frac{1}{r} \frac{d}{dr} \left( \frac{dW}{dr} \right) \right) \right] = \frac{q}{D} \quad (12)$$

The solution for a uniformly loaded plate is:

$$W = \frac{qr^4}{64D} + \frac{Ca^4}{4} + C_2 \log \frac{r}{a} + C_2 \quad (13)$$

For a circular plate with clamped boundary conditions, the solution reduces to:

$$W_{\text{max}} = \frac{qa^4}{64D} \quad (14)$$

where

D = flexural rigidity

q = uniform pressure (psi)

a = radius

$$D = \frac{Eh^3}{12(1-v^2)} \quad (15)$$

and

$$(\sigma_r)_{\text{max}} = \frac{3}{4} \frac{qa^2}{h^2} \quad (16)$$
where

\[ h = \text{plate thickness} \]

\[ E = \text{modulus of elasticity} \]

Quadrilateral and triangular meshes were used with this model to determine if they had an effect on the results. A 50-psi uniform pressure was applied to the plate which had properties as seen in table 4.2.

**Table 4.2: Isotropic plate properties.**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>( 500000 \text{ psi} )</td>
</tr>
<tr>
<td>v</td>
<td>0.3</td>
</tr>
<tr>
<td>t</td>
<td>0.25 \text{ in.}</td>
</tr>
<tr>
<td>R</td>
<td>1.5 \text{ in.}</td>
</tr>
</tbody>
</table>

The deflections and maximum in-plane stresses predicted by ANSYS are shown in table 4.3 along with the deflection and in-plane stress predicted from the above equations.

**Table 4.3: Deflections and stress for isotropic plate.**

<table>
<thead>
<tr>
<th></th>
<th>Deflection (in)</th>
<th>Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANSYS Quadrilateral mesh</td>
<td>0.00623</td>
<td>1351</td>
</tr>
<tr>
<td>ANSYS Triangular mash</td>
<td>0.00623</td>
<td>1343</td>
</tr>
<tr>
<td>Predicted from theory</td>
<td>0.00553</td>
<td>1350</td>
</tr>
</tbody>
</table>

The stresses compared very well, however, there was a difference in the predicted deflections of the two methods. The difference in the deflection can be attributed to the different bending theories used. ANSYS used Mindlin theory, which does include transverse shear strain, and classical plate theory is based on Kirchoff theory, which does
not include transverse shear strain. Kirchhoff theory is usually used with thin plates and Mindlin is used with thick plates.

4.4 Drop Tower Model

The next step was to model the drop tower test in order to predict stress and strain information which was not obtained from the tests. Two separate ANSYS/ls-Dyna models were created in order to compare the results of the two and pick one to use to model the tests. One target was created with shell 163 elements and one with solid 164 elements. The shell element has the advantage of fewer elements and degrees of freedom, which lowers the required computer time. The solid elements are advantageous due to their capability to capture the through thickness effects of the deflection and stress since more than one element was placed in the thickness direction.

4.4.1 Shell 163 Model

A 5 in. x 5in. shell target with the correct laminate properties was used for the target and a sphere was used to represent the round end of the impactor tup, figure 4.5. The shell was constrained in the Z direction around the edges to simulate the clamp device and also constrained in all directions along two sides to prevent rigid body motion. A spherical solid was given an initial velocity from just above the shell surface to lower the processor time required.
This model used very similar boundary conditions as the test jig in the drop weight tower. However, these boundary conditions gave some strange results in the clamped region due to the bending and membrane actions of the shells. A new model was created to remove the possibility of these effects and also to lower the number of degrees of freedom in the model. This model consisted of a flat cylindrical shell with the \( z \) displacements and out-of-plane rotations fixed around the outer edge, figure 4.6. A uniform mesh is often difficult with a cylindrical mesh. If a triangular mesh is used, singularities are created at the center of the circle where the elements internal angles are very small. ANSYS also does not recommend the triangular mesh option with shell 163.
elements therefore the quadrilateral mesh was used for all models. With the quadrilateral mesh the center elements have a slightly different shape than the elements on the outer rings of the circle, however, no irregularities were noticed with this mesh.

![Cylindrical target mesh](image.png)

**Figure 4.6: Cylindrical target mesh.**

In order to verify the accuracy of the model, the impact force and the total energy was compared with the experimental results. Both were within 15% of the test results. Figure 4.7 shows the impact force predicted along with the force history from test 2 with an impact velocity of 80 in/s.
In dynamic finite element analysis, the hourglass energy is a large concern. Hourglass modes are unnatural modes that do not produce strain energy even though the element is deforming. These modes are very common in impact analysis but should be kept to minimum. As a general rule the hourglass energy should be kept below 10% of the total energy of the model. Flanagan-Belytscko stiffness form of hourglass control was used to lower the hourglass energy throughout all analyses. A representative energy plot from ANSYS/ls-Dyna is shown in figure 4.8.

Figure 4.7: Force history and predicted FEA force for test 2.
Figure 4.8: Energy history from ANSYS/ls-Dyna.

4.4.2 Solid 164 Model

A 3 in. diameter solid cylinder was used for the composite target and a sphere was used for the steel impactor, figure 4.9. The solid elements were constrained with all translations fixed around the edges to simulate the clamped boundary conditions in the drop tower tests. The spherical solid was given an initial velocity in the direction of the target as in the other models.
In order to verify the accuracy of this model, the impact force and the total energy was compared with the experimental results. The ANSYS model over predicted the impact force, which was expected since no energy release due to damage was predicted. The predicted impact force was approximately 10-30% higher than the measured force from the tests. This solid model did not predict the impact force as well as the shell model but the thickness effects of the solid elements were a large advantage. This thickness effect included different stresses and deflections predicted on the top and the bottom of the composite. This situation was closer to the actual tests since there was some compression of the composite done by the impactor. The stresses also appeared to be different since there was a difference in the damage on the top and the bottom of the impacted laminates.
4.4.3 Comparison of Shell and Solid Models

The results of the shell element target model were compared to the results of the solid element target to determine which one would be used to predict the effects of various changes to the parameters of the impact. The shell model came very close to matching the impact force of the preliminary tests. However, the aspect ratio of the unsupported region of the test was far below what is accepted for thin shells. The aspect ratio was 12.5 and the general rule is for the length to be 100 times the thickness of the shell. The solid model did not match the impact force as well but it was acceptable for this investigation. However, far more information could be retrieved through post processing with the solid elements rather than the shell elements. With these solid elements a difference can be seen between the deflection and stresses on the top of the target and the bottom of the target. This more closely resembles the actual test since there is a slight amount of compression of the target and the majority of the damage occurs on the backside of the target. The solid models show the highest in-plane stresses on the backside of the target. The solid element model was also more flexible when changing the parameters such as laminate thickness and adding the protective rubber layer.

The in-plane stresses and deflections predicted from the two models were compared using the test setup with the vinylester resin and an impact velocity of 81 in/s (test 2). Due to the macroscopic nature of this investigation, these stress results were not taken to be exact. Once a model was chosen, the differences in stresses were mainly used
in order to make conclusions about the effects of changing the parameters of the composite and the impact.

### 4.4.4 Convergence

Convergence of the solid 164 model was checked with the second test results to verify that enough elements were being used in these models. Five models were made with different numbers of elements in the target mesh. The targets had 107, 299, 863, 1535, and 5183 elements. Figure 4.10 shows the deflection vs. number of elements used in the model.

![Figure 4.10: Convergence of solid model.](image)

The model with 1535 elements was used in the rest models in order to get accurate results and keep the processor time to a minimum. The model with 5183
elements required a considerable amount of computer time to run. The model with 1535
elements had two elements through the thickness and the model with 5183 elements had
three elements through the thickness, hence the large difference in elements. For the
models with a different thickness, the overall mesh coarseness was kept relatively the
same. Several checks were done throughout the analysis to insure that the number of
elements still gave accurate results.

4.5 Drop Tower Tests Simulations

4.5.1 Test 1 – Vinylester Resin

For this drop tower test, the impact mass was 12.13 lbs. and the impactor velocity
just before impact was 150 in/s. In the FEA model, the density of the sphere was
adjusted to achieve the same mass as the impactor. The target was modeled with solid
164 elements with a thickness of 0.24 in. A linear orthotropic material model was used
for the composite laminate and linear isotropic properties for the steel impactor. These
properties are listed in table 4.5 and 4.6.
Table 4.5: Material properties used for composite laminate.

<table>
<thead>
<tr>
<th>Apparent Laminate Properties</th>
<th>Ex</th>
<th>3.94E+06 psi</th>
<th>Strong direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ey</td>
<td>2.16E+06 psi</td>
<td>Weak direction</td>
<td></td>
</tr>
<tr>
<td>Ez</td>
<td>9.55E+05 psi</td>
<td>Out of plane dir.</td>
<td></td>
</tr>
<tr>
<td>Gxy</td>
<td>1.50E+05 psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gyz</td>
<td>9.00E+04 psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gxz</td>
<td>9.00E+04 psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_{xy}$</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_{yz}$</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_{xz}$</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6: Material properties used for steel

<table>
<thead>
<tr>
<th>Ex</th>
<th>3.00E+07 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>0.1420 lbf-s$^2$/in$^4$</td>
</tr>
<tr>
<td>$v_{xy}$</td>
<td>0.30</td>
</tr>
</tbody>
</table>

These material properties were determined with the aid of the shareware program *The Laminator* [30]. The individual martial properties for each layer are given in table 4.7. These layer properties were inputted into the program along with the layer thickness and stacking sequence to determine the apparent material properties.
Table 4.7: Material properties for each layer.

<table>
<thead>
<tr>
<th></th>
<th>E1</th>
<th>E2</th>
<th>G12</th>
<th>v12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roving (E-glass)</td>
<td>1.00E+07</td>
<td>2.00E+06</td>
<td>2.00E+06</td>
<td>0.2</td>
</tr>
<tr>
<td>Mat material (isotropic)</td>
<td>1.00E+06</td>
<td>1.00E+06</td>
<td>4.00E+05</td>
<td>0.28</td>
</tr>
<tr>
<td>Matrix (vinylester)</td>
<td>5.00E+05</td>
<td>5.00E+05</td>
<td>1.00E+05</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The impact force was first compared to the experimental data. From a curve fit of the experimental acceleration data, the maximum impact force was found to be approximately 1600 lbf. Five samples were tested with the same impact velocity and the maximum impact force was almost identical in all samples. Figure 4.11 shows a comparison between the experimental data and the predicted impact force versus time. The higher predicted impact force can be attributed to the model not including the energy release due to the damage (delamination and matrix cracking).

![Figure 4.11: Force history and FEA force for test 1.](image)
4.5.2 Test 2 – Vinylester Resin

The second test consisted of the same material with an impactor velocity of 81 in/s. Since the impact velocity was much lower, the impact force was also reduced. Figure 4.12 shows the predicted and actual force data for this test.

![Figure 4.12: Force history and FEA force for test 2.](image)

The predicted time span that the impactor was in contact with the target did not change with different impactor speed in the ANSYS models. The contact time for the tests was 5.3 ms. for the first test (150in/s) and 4.4 ms. for the second test (80 in/s). The FEA model predicted a contact time of 3.7 ms. for all impactor speeds.
5. Comparisons

5.1 Test 1, 2, and 7

Test 1, 2, and 7 were performed with the vinylester resin and impact speeds of 157, 81, and 118 in/s respectively. These three tests were compared in order to examine the effect of velocity on the specimens; all other parameters were kept the same. Finite element models were also created in order to examine trends in stresses and deflection of these three tests. Table 5.1 is a summary of these three tests.

Table 5.1: Comparison between test 2, 7, and 1.

<table>
<thead>
<tr>
<th>Test</th>
<th>Impact velocity (in/s)</th>
<th>Predicted maximum in-plane stress on top (ksi)</th>
<th>Predicted maximum in-plane stress on bottom (ksi)</th>
<th>Backside crack Length (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>81</td>
<td>42.9</td>
<td>-33.1</td>
<td>0.6</td>
</tr>
<tr>
<td>7</td>
<td>118</td>
<td>68.2</td>
<td>-41.8</td>
<td>2.1</td>
</tr>
<tr>
<td>1</td>
<td>157</td>
<td>93.1</td>
<td>-45.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Based on visual comparisons of the predicted stress patterns on the bottom of the FEA models and the crack length, the cracks extend to the 25-35 ksi range on all three of these models. Further work could determine a stress range that initiates and continue matrix cracking and debonding. The following plots compare the crack length and debonded area to the impact speed, impact force, kinetic energy, and maximum in-plane stress on the bottom surface. From these graphs, the damage appears to be somewhat proportional to the speed and force of the impactor.
Figure 5.1: Effect of impact speed on the damage.

Figure 5.2: Effect of impact force in the damage.
From these graphs, the impact speed, impact force, kinetic energy, and maximum stress in the laminate all seem to have the same effect on the amount of damage in the composite after impact.
Stress and Strain

The maximum predicted stress in the z direction for these three impactor speeds is shown in figure 5.5.

Figure 5.5: Maximum in-plane stress in test 1, 2, and 7 (81, 118, and 157 in/s).
As before, the predicted stress jumped quickly from the 81 to the 118 in/s case then leveled off as the speed went to 157 in/s. The stress contour patterns were almost identical in each case with only the values of the stress regions changing.

The strain in the X direction (maximum in-plane) also showed nearly identical contour patterns for all three cases. These strains are shown in figure 5.6.
The “wavy” pattern in the high strain area was very interesting. This pattern was also seen in the external backside crack on some of the test samples (see figure 3.14). This was most likely due to the anisotropic nature of the laminate.

### 5.2 Rubber Protection on Laminate

In many cases, such as in the dump truck beds, a rubber liner or mat can be used to absorb much of the impactor energy and decrease the amount of damage sustained by the composite. The solid model used to simulate the drop tower tests was modified to include a rubber protective layer, figure 5.5.

![Figure 5.5: Laminate and rubber protective layer.](image)

The material properties used for the rubber are shown in table 5.2. 500 psi was used for the shear modulus even though most references use 150 psi as the upper limit. Several contact problems were encountered with the model due to the soft material not
being stiff enough to avoid penetration by the steel impactor, so the shear modulus was increased to avoid this problem.

Table 5.2: Material properties used for rubber

| Rubber Properties |  
|-------------------|---
| $\rho$            | 0.00127 lbf-s$^2$/in$^4$  
| $G_{xy}$          | 500 psi  

A quarter model was used for this analysis to save processor time and allow more elements to be used in the target. Figure 5.6 shows a comparison of $\sigma_z$ (maximum in-plane stress) for the quarter model and the full model. This was to ensure that the quarter model gave the same results as the full model. The maximum stress in the tip of the quarter model was only slightly higher than the stress in the full model.

![Figure 5.6: Comparison of full and quarter models.](image)
This quarter model was able to cut the processor time by 50-75%. The outside edge of the rubber and composite were fixed in all directions to simulate the clamped boundary conditions and the sides were held in place to for symmetry boundary condition, figure 5.7. The fiber orientation in all of the models was aligned with the X, Y, and Z coordinate system. In these cylindrical models the strong direction of the laminate corresponds to the Z direction, the weak direction corresponds to the X direction, and the Y direction is the out of plane direction. Aligning the principal directions of the laminate with the coordinate system allowed for symmetry to be used.

The ls-Dyna material model used for the rubber was the nonlinear Blatz-Ko rubber elastic model. This model was defined by Blatz and Ko and used the second
Piola-Kirchoff stress, equation 17, where $G$ is the shear modulus, $V$ is the volume, $\nu$ is the Poisson’s ratio, $C_{ij}$ is the Cauchy-Green strain tensor, and $\delta_{ij}$ is the Kronecker delta.

$$S_{ij} = G\left(\frac{1}{V}C_{ij} - V\left(\frac{1}{1-2\nu}\delta_{ij}\right)\right)$$

(17)

The shear modulus for rubber materials can vary widely depending on the type of rubber and the hardness. By varying the shear modulus of the rubber the results were changed significantly. The stress in the composite and the deflection were decreased the most when the rubber mat was firm enough to only allow the impactor to compress it approximately half of its thickness, figure 5.8. When the rubber was too soft the impactor would hit the composite and increase the stresses. When the rubber was too soft, it would not absorb enough of the energy to protect the composite. The best results were seen when the shear modulus was around 500 psi.
Figure 5.8: Protective rubber compressed.

Figure 5.9 shows the effects of thickening the rubber protective pad. Three pad thicknesses were modeled, 0.24”, 0.36”, and 0.48”. Only a few impact velocities with each rubber thickness could be modeled with ANSYS/ls-Dyna due to the penetration problems at the higher speeds. These results show a significant reduction in stress with the rubber protective pad at these speeds.
The reduction in stress and deflection was seen to vary widely depending on the material properties used. These reductions seen in this section are only examples of the reduction possible and not exact figures.

The material tests verified that the rubber aids the composite greatly. Tests 3 and 4 were exactly the same except for the rubber protecting the composite laminate. A significant decrease in damage on both the top and bottom surface could be noticed on the specimens. There was also a significant decrease in the crushing of the laminate and the total deflection predicted by the models when the rubber pad was used. This was observed by the decrease in the damage to the top surface of tests 3 and 4. The set of samples without the rubber showed significant damage to the top of the laminate. The rubber significantly decreased the amount of damage to the top layer, figure 5.10.
A decrease in the amount of delamination was also seen with the C-scan images of the samples from the two tests, figure 5.11. The length of the oblong shape was similar in both specimens but the width was larger in the non-protected laminate.
ANSYS/ls-Dyna also predicted a significant reduction in stress and strain with the addition of the rubber layer. Figure 5.12 shows the difference in the maximum in-plane stress between the model with rubber and the model without the rubber layer. A 45% reduction in the maximum stress was predicted on the bottom surface and a 30% reduction on the top surface.

Figure 5.12: Difference in maximum in-plane stress with and without rubber protective layer.
Figure 5.13 shows the difference in the maximum in-plane strains between the two models. A reduction of 35% was predicted in the maximum strain values on the bottom surface and a reduction of 55% on the top surface. The rubber was removed from the figure to keep the strain values in the same range as laminate without the rubber.

![Figure 5.13: Difference in maximum in-plane strain with and without rubber protective layer](image)

Figure 5.13: Difference in maximum in-plane strain with and without rubber protective layer
6. Parametric Study

In order to predict how the pultruded composite material would behave under different impact situations, a study was performed using finite element models. The models were adjusted to simulate different impact energies by varying the impactor mass and speed. Four models (without rubber) were constructed to look at the effects of the mass and four were created for the impactor speed. The models with the varied mass included 5, 12, 20, and 50-pound impactors and the velocities included 40, 81, 103.5, and 150 in/s impact speeds. The speed of 103.5 in/s was used to create a situation where a different combination of mass and velocity resulted in the same kinetic energy \((1/2 mv^2)\) in the two simulations. The mass of 12 lbs., and the velocities of 80, and 150 in/s correspond to the drop test conditions. This study was performed in the same regions as the test in order to correlate the two together and look for relationships between force, energy, and damage.

Interlaminar stresses are the most useful parameters in laminated composites subjected to impact loading. However, this model does not include layer data therefore interlaminar stresses were not computed by ANSYS/ls-Dyna. Von Mises stresses also are not as useful in this situation due to the anisotropic nature of the composite. For this study it was decided to compare \(s_z\) stresses since they were the highest in-plane stresses in the laminates due to the anisotropic nature of the composite.
6.1 Adjusted Mass

The mass was adjusted in the solid 164 models in order to look at how the stress and strain in the target change as the mass is increased. Since energy is the most common basis for comparison, a graph of stress and strain vs. energy, figure 6.1, was observed for possible connections to damage. The stresses and strains showing similar patterns was not unexpected since they only vary by the material modulus.

![Graph showing stress and strain vs. energy](image)

**Figure 6.1:** Max in-plane stress and strain as impactor mass is increased.

The stress and strain both increase quickly at first as the mass is increased then level off. Damage would most likely occur in all four of these situations, especially the 2\textsuperscript{nd}, 3\textsuperscript{rd}, and 4\textsuperscript{th}.
6.2 Adjusted Speed

The impact speed was also adjusted in the solid 164 model in order to understand the role that the speed plays in the stress and strain in the target. Figure 6.2 shows the maximum stresses and strains in the target laminate as the impact speed is increased from 40 in/s to 150 in/s.

![Graph showing maximum stress and strain as impact speed increases.](image)

**Figure 5.2: Max in-plane stress and strain as impact speed is increased.**

The max stress and strains level off slightly after 100 in/s but not as much as when the mass was increased. Overall the mass and the speed appear to have equal influence on the stress and strain levels seen in the composite.

6.3 Thick Laminates

ANSYS/ls-Dyna models were also used to predict the effect of increasing the laminate thickness from 0.24 in. to 0.5 in. and 0.75 in. The same impact velocity and
mass of 150 in/s and 12.13 lbs. was used in this comparison. Table 6.1 is a summary of these results.

Table 6.1: Maximum in-plane stress and strain in three laminates of different thickness.

<table>
<thead>
<tr>
<th>Thickness (in.)</th>
<th>Maximum Z stress (psi)</th>
<th>Maximum X strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.24</td>
<td>93.1</td>
<td>0.0169</td>
</tr>
<tr>
<td>0.5</td>
<td>36.2</td>
<td>0.00843</td>
</tr>
<tr>
<td>0.75</td>
<td>21.8</td>
<td>0.00541</td>
</tr>
</tbody>
</table>

Figure 6.5 shows the maximum stresses and strains from the models of the laminates. Increasing the laminate thickness lowered both the stress and strain considerably, especially in the first step from 0.24 in. to 0.50 in.

Figure 6.5: Maximum in-plane stress and strain in laminates of different thickness.

The maximum stress penetrated relatively the same distance into the laminate when the thickness was increased. This maximum stress however was significantly
lowered as the thickness was increased. Figure 6.6 shows the difference in the stress patterns in a 0.24 in. laminate compared to a 0.5 in., and a 0.75 in. laminate. The 0.75 in. laminate may hold up to an impact of this caliber (12 lbs and 150 in/s) without noticeable damage since the maximum stress is below 30 Ksi. A test would be needed to verify this assumption.

Figure 6.6: Maximum stress with variation in laminate thickness.
7. Composite Truck Bed

7.1 Introduction

The original purpose of the impact research on theses composite laminate was to design a composite bed for use on quarry trucks. These trucks currently make an average of 50 trips to the crusher each day and the amount of rock being hauled by these trucks is limited by the total gross weight of the truck. If weight is removed from the steel bed, the truck can carry additional rock. The original goal was to allow the trucks to carry an additional 5 tons of rock per trip. The trucks currently being used at the MMM quarries are the Caterpillar 773 off-highway truck. The total weight of the truck is 204,000 lbs. and the payload capacity is 58.4 tons. The current bed weights approximately 20,000 lbs.

There are several options possible to remove weight from the bed with composites. An all-composite bed is the first choice and would remove the greatest amount of weight. If it was determined that the composite could not handle the impact of the rocks steel could be used in certain places, such as the floor section. The simplest option would be to replace panels of the steel with composite sections, such as the sides and the cab cover. Fiberglass is the choice material due to its low cost and toughness. Carbon and Kevlar could be used to make the composite stronger in certain areas if needed. However, the simple addition of these materials does not necessarily make the composite less susceptible to impact damage. These materials also have weaknesses that have to be takes into account such as brittleness, moisture absorption, and differences in thermal expansion. Figures 7.1 – 7.3 show several possible composite designs besides an all composite dump bed.
7.2 Design Ideas

Figure 7.1: Dump bed with composite inserts in side panels

Figure 7.2: Dump bed with outer steel frame and composite panels in side and rear.
Figure 7.3: Dump bed with composite cab protection.

8. Conclusions

The purpose of this research was to examine the impact response of pultruded fiberglass reinforced laminates. Several drop weight tower impact test were performed on 5 in. x 5 in. FRP plates with resins including vinylester and isopolyester. These test simulated high mass (12 lbs) and low velocity (80-150 in/s) impact.

ANSYS/ls-Dyna non-linear finite element analysis program was used to predict the stresses in the laminates during the impact. These stresses were then compared to the damage from the drop tests. The critical stress range for impact damage is in the range of 25-35 ksi, which is very close to the static ultimate strength of the Duraspan laminates.

The observations and conclusions of this research include the following:
8.1 Drop Tower Testing

1. Drop tower tests were an effective way to test pultruded fiberglass laminates subjected to impact loading.
2. The 3D stitched sandwich samples showed the least visible damage and only a small area of delamination after one impact strike.
3. The Duraspan laminates held up the best out of the other laminates. There was very little if any visible impact damage on the outside of these laminates and the residual strength was not affected by the impact.
4. Even though the Duraspan laminates had very little visible external damage, they delaminated between two layers while the other groups only had one delaminated interface.
5. The surface matrix cracks always ran in the pultruded (strongest) direction.
6. A rubber protective laminate significantly reduced the damage induced by the impactor by absorbing a portion of the energy. This rubber layer also significantly reduced the amount of residual strength lost due to damage.
7. There was only a significant loss in the residual tensile strength of the laminates in the tests above 100 in/s with no rubber protective layer.

8.2 Finite Element Analysis

1. Approximate stresses and strains were achievable with ANSYS/ls-Dyna but more specific models are needed for more exact predictions.
2. Shell elements in the target mesh predicted the impact force slightly better than solid elements. However, much more information could be retrieved through post processing with the solid elements.

3. The predicted impact force was approximately 10-30% higher than the force seen in the tests. This was due to the model not taking into account the energy lost due to matrix cracking and delamination damage.

4. By comparing the FEA models to the damaged samples, the damage appears to correspond to an in-plane stress range of 25-35 ksi.

5. The model of the rubber protective layer worked well at low velocities but had problems with penetration at higher velocities.

6. Increasing the mass and speed of the impactor has approximately the same effect on the maximum stress and strain in the target surface.

4. Laminate thickness had a large influence on the predicted stress and strain in the composite. Even small thickness increases significantly lowered the stress predicted stress and strain.

8.3 Further work

From the observation stated in this thesis, the critical stress range on the bottom surface of the laminates seems to be in the 25-35 ksi range. Further investigation could verify and possibly narrow this range for certain laminates and find the stress level at the onset of damage. Once this range was verified, the ANSYS/ls-Dyna models would be an even more valuable tool for designing new composite products.
ANSYS/ls-Dyna also has an element failure option. Ultimate strengths of the materials can be set so that once that stress is encountered, the element is eliminated and the load is transferred to the other elements. This requires more investigation into the failure loads of the laminates and further work with the composite layer option in ANSYS/ls-Dyna.

The rubber protective layer appears to aid the impact properties of the composite significantly. More testing and finite element modeling could further justify the use of a rubber protective layer in specific applications and aid in selecting the correct material and thickness. ANSYS/ls-Dyna, as well as other contact codes, still have some problems with contact between materials with a large difference in material properties. The modeling capabilities presented in this thesis were severely limited by penetration problems with the rubber material.
References

1. Martin Marietta Composites, P.O box 30013, Raleigh, NC 27622.


33. Cherry Point Naval Aviation Depot, Cherry Point, NC 28533.

34. Delsen Testing Laboratories, Inc. 1024 Grand Central Avenue Glendale, California 91201-3011. (818) 247-4106.


Appendix A: Sample FEA Code

/*filename,circular solid*/
/prep7
et,1,SOLID164  ! sphere
edmp,hgls,1,5
mp,ex,1,30.0e6  ! psi
mp,dens,1,0.1406  ! lbf-sec^2/in^4
mp,nuxy,1,0.3

et,2,SOLID164  ! composite plate
edmp,hgls,2,5
mp,ex,2,3.677e6  ! psi strong direction
mp,ey,2,0.955e6  ! psi out of plane
mp,ez,2,1.13e6  ! psi weak direction
mp,dens,2,0.00018  ! lbf-sec^2/in^4
mp,nuxy,2,0.22
mp,nuyz,2,0.22
mp,nuxz,2,0.239
mp,gxz,2,0.9e5  ! psi
mp,gxy,2,0.9e5
mp,gxz,2,2.08e5

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wpro,,90.000000
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FITEM,2,2
FITEM,2,-3
VSBW,P51X
wpro,,90.000000,
FLST,2,4,6,ORDE,3
FITEM,2,1
FITEM,2,4
FITEM,2,-6
VSBW,P51X
VGLUE,all
WPSTYLE,,,,,,,,0
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vatt,1,1,0
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MSHKEY,1
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VMESH,all
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cm,eball,elem
esel,none
nsel,none

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VSBW,3
wpro,,90.000000,
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VSBW,9
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WPSTYLE,......,0
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FITEM,5,3
FITEM,5,8
FITEM,5,10
FITEM,5,-11
VSEL,S, , ,P51X
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nsel,all
esel,all

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finish

!---------------------------------------------
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NSEL,S,,P51X
NSEL,INVE

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nsel,all
esel,all
time, 0.010
edrst, 60
edhtime, 70
edenergy, 1, 1, 1, 1
edout, glstat
edout, matsum
EDOUT, RCFORC

finish
/SOLU
SOLVE
FINISH