CHARACTERISTICS AND IMPACT ANALYSIS OF GLASS FIBER-REINFORCED COMPOSITE PLATES

A Thesis
Presented to the Faculty of
California Polytechnic State University, San Luis Obispo

In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in
Aerospace Engineering

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March 2012

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ABSTRACT

Characteristics and Impact Analysis of Glass Fiber-Reinforced Composite Plates

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The main objective of this study was to examine the effects of matrix composition of laminated woven roving S-glass epoxy composite plates which were subjected to low-velocity impact. The testing was conducted with a transverse drop-weight Instron *Dynatup 9250HV* machine with increasing impact energies of 50, 55, and 60 inch-lb_f and a constant impactor mass of 12.57 pounds. A piezoelectric force transducer affixed to the drop-weight device, localized in the hemispherical impactor nose, yielded the complete force versus time history of the impact event. The contact force between the impactor and the composite plate, as well as the energy during impact, were analyzed as functions of time. Each laminate's Damage Threshold Load (DTL) for the corresponding incident impact energies were also examined to determine the respective matrix composition influences. In addition, a numerical evaluation of these specimens was executed using *Abaqus/Explicit*, which utilized a transient dynamic Finite Element Analysis (FEA) code. The numerical transient energy during impact was used to substantiate the experimental tests.

The epoxy resin system for each specimen was mixed with either a limestone or high-density inorganic filler material, with the quantity of filler ranging between 15 and 20 percent of the total composite weight. The fillers reduced raw material costs, improved mechanical performance, and enhanced the crack resistance properties of the composites. Regardless of filler type, the static tensile tests showed that increasing the quantity of filler material resulted in a higher modulus of elasticity and shear modulus, but a lower strain-to-break. Therefore, increasing the quantity of filler produced a stiffer, more brittle material with a lower threshold of tensile deformation prior to ultimate failure. Increasing the laminate thickness also resulted in a lower average elastic modulus and modulus of rigidity.

The dynamic modal analysis showed that the specimens made with high-density filler had higher resonant frequencies for each bending mode when compared to those made with limestone. The resonances of the test samples were also modified by altering the quantity of filler material mixed in the resin system. Increasing the amount of inorganic filler resulted in a higher resonant frequency for each mode. The thicker laminates were more capable of damping energy in the form of deformation waves. The effects of laminate thickness with respect to modal frequency suggested that thicker materials are less susceptible to low magnitude vibrational issues.

ACKNOWLEDGEMENTS

There are several individuals I would like to thank for providing assistance and motivation so that I could finish this thesis. First, I would like to extend my gratitude to the committee members – Dr. Kolkailah, Dr. Elghandour, Dr. DeTurris and Ms. Nigro – for working with me throughout the project and providing their valuable contributions. Thanks to the Cal Poly Aerospace Department for providing the composite raw materials and access to the test equipment in the Structures/Composites Lab. Thanks to Jason Lumsden for granting use of the static tensile and impact test equipment in the *Seattle Composites Lab*. My sincere appreciation goes out to John Truitt for his patience, expertise, and guidance during the impact testing. I would also like to thank Jay Torres for spending countless hours explaining the intricacies and quirks of *Abaqus*; the numerical analysis would have been impossible without your assistance. Lastly, I would like thank my wife, Abigail, for doing EVERYTHING for me over the past six months so that I could put all of my effort and time into this paper. I love you and don't know what I'd do without you.

TABLE OF CONTENTS

LIST OF TABLES	xi
LIST OF FIGURES	xiv
LIST OF SYMBOLS	xviii
1 INTRODUCTION	1
1.1 Impact Behavior in General	1
1.2 Low-Velocity Impact Behavior	3
1.3 Objective	5
2 MATERIAL SELECTION	7
2.1 Resin System	7
2.2 Fiber	11
2.3 Filler	17
3 TEST SPECIMEN FABRICATION	19
3.1 Composite Materials	19
3.1.1 <i>Fiberglass Cloth</i>	19
3.1.2 <i>Epoxy Resin Systems</i>	21
3.1.3 <i>Inorganic Fillers</i>	23
3.2 Equipment	24
3.2.1 <i>Scale</i>	24

3.2.2	<i>Tetrahedron Composite Press</i>	25
3.2.3	<i>Vacuum Pumps</i>	26
3.2.4	<i>Vacuum Bagging Fixture</i>	27
3.2.5	<i>Post-Cure Oven</i>	28
3.2.6	<i>Tile Saw</i>	29
3.3	<i>Specimen Layup</i>	30
3.3.1	<i>Fiberglass Cloth Preparation</i>	30
3.3.2	<i>Epoxy Resin System Preparation</i>	31
3.3.3	<i>Mixing and Application of Epoxy Resin System</i>	37
3.3.4	<i>Vacuum Bagging</i>	41
3.3.5	<i>Post-Cure</i>	43
4	EXPERIMENTAL EQUIPMENT AND SETUP	47
4.1	<i>Weight Fraction Test</i>	47
4.2	<i>Static Test Equipment</i>	48
4.2.1	<i>Tensile Test Load Frame</i>	50
4.2.2	<i>Tensile Test Extensometer</i>	51
4.2.3	<i>Tensile Test Data Acquisition</i>	53
4.3	<i>Dynamic Test Equipment</i>	54
4.3.1	<i>Modal Analysis Test Equipment</i>	54

4.3.2	<i>Impact Test Equipment</i>	57
5	ANALYSIS OF EXPERIMENTAL RESULTS	62
5.1	Weight and Volume Fraction Results	62
5.1.1	<i>Weight Fraction Calculations</i>	62
5.1.2	<i>Volume Fraction Calculations</i>	65
5.2	Static Test Results.....	71
5.2.1	<i>Tensile Test Theory and Calculations</i>	71
5.2.2	<i>Tensile Test Results for 2-Ply Specimens</i>	73
5.2.3	<i>Tensile Test Results for 10-Ply Specimens</i>	88
5.3	Dynamic Test Results	98
5.3.1	<i>Modal Analysis in General</i>	98
5.3.2	<i>Modal Analysis for 2-Ply Specimens</i>	99
5.3.3	<i>Modal Analysis for 10-Ply Specimens</i>	108
5.3.4	<i>Low-Velocity Impact Testing</i>	112
5.3.5	<i>Impact Test Results</i>	115
6	NUMERICAL ANALYSIS	133
6.1	Finite Element Analysis	133
6.2	Modal Finite Element Analysis	134
6.2.1	<i>Numerical Formulation for Dynamic Vibration Model</i>	134

6.2.2	<i>Numerical Results for Modal Analysis</i>	137
6.2.3	<i>Comparison of Experimental and Numerical Results</i>	141
6.3	Low-Velocity Impact Finite Element Analysis	144
6.3.1	<i>Numerical Formulation for Low-Velocity Impact Model</i>	144
6.3.2	<i>Numerical Results for Low-Velocity Impact</i>	147
6.3.3	<i>Comparison of Experimental and Numerical Results</i>	159
7	CONCLUSION	162
8	FUTURE WORK	166
9	REFERENCES	168
10	APPENDICES	173
	Appendix A: Static Tensile Test Data.....	173
	Appendix B: Dynamic Modal Analysis Pictures	192
	Appendix C: Low-Velocity Impact Test Data.....	200

LIST OF TABLES

Table 3.1: CST GS67813 S-glass Properties	20
Table 3.2: Comparison of Aeropoxy and West System Resin Systems	22
Table 3.3: 2-Ply Specimens with West System Epoxy Resin System	34
Table 3.4: 2-Ply Specimens with Aeropoxy Epoxy Resin System	35
Table 3.5: 10-Ply Specimens with Aeropoxy Epoxy Resin System	36
Table 5.1: Fiber Weight Fractions for 2-Ply Laminates.....	63
Table 5.2: Fiber Weight Fractions for 10-Ply Laminates.....	64
Table 5.3: Calculated Densities for 2-Ply Laminates	67
Table 5.4: Calculated Densities for 10-Ply Laminates	68
Table 5.5: Fiber Volume Fractions for 2-Ply Laminates.....	69
Table 5.6: Fiber Volume Fractions for 10-Ply Laminates.....	70
Table 5.7: Dimensions of 2-Ply Tensile Test Specimens.....	74
Table 5.8: Mechanical Behavior of Tensile Test for All 2-Ply Specimens	87
Table 5.9: Dimensions of 10-Ply Tensile Test Specimens.....	88
Table 5.10: Mechanical Behavior of Tensile Test for All 10-Ply Specimens.....	97
Table 5.11: Natural Frequency Response for 2-Ply Laminates with West System Epoxy Resin System and High-Density Filler	102
Table 5.12: Natural Frequency Response for 2-Ply Laminates with Aeropoxy Epoxy Resin System and High-Density Filler	103
Table 5.13: Natural Frequency Response for 2-Ply Laminates with West System Epoxy Resin System and Limestone Filler	105
Table 5.14: Natural Frequency Response for 2-Ply Laminates with Aeropoxy Epoxy Resin System and Limestone Filler	107

Table 5.15: Natural Frequency Response for 10-Ply Laminates with Aeropoxy Epoxy Resin System and High-Density Filler	110
Table 5.16: Natural Frequency Response for 10-Ply Laminates with Aeropoxy Epoxy Resin System and Limestone Filler	111
Table 5.17: Thickness of 10-Ply Impact Test Specimens	115
Table 5.18: Mechanical Behavior of Impact Test for Laminate A ₁₀ ^{15HD}	122
Table 5.19: Mechanical Behavior of Impact Test for 10-Ply Laminates at Incident Impact Energy of 50 in-lb _f	125
Table 5.20: Mechanical Behavior of Impact Test for 10-Ply Laminates at Incident Impact Energy of 55 in-lb _f	127
Table 5.21: Mechanical Behavior of Impact Test for 10-Ply Laminates at Incident Impact Energy of 60 in-lb _f	128
Table 6.1: Specimen Geometry and Properties Used in Numerical Modal Analysis	135
Table 6.2: Numerical Natural Frequency Response for 10-Ply Laminates with High-Density Filler.....	140
Table 6.3: Numerical Natural Frequency Response for 10-Ply Laminates with Limestone Filler	141
Table 6.4: Comparison of Experimental and Numerical Results – Natural Frequency Response for All 10-Ply Laminates.....	142
Table 6.5: Specimen Geometry and Properties Used in Numerical Low-Velocity Impact Analysis	146
Table 6.6: Comparison of Experimental and Numerical Results for Laminate A ₁₀ ^{15HD} at Incident Impact Energy of 30 in-lb _f	149
Table 6.7: Mechanical Behavior of Numerical 10-Ply Laminates with High-Density Filler at Incident Impact Energy of 50 in-lb _f	153
Table 6.8: Mechanical Behavior of Numerical 10-Ply Laminates with Limestone Filler at Incident Impact Energy of 50 in-lb _f	156

Table 6.9: Mechanical Behavior of All Numerical 10-Ply Laminates at Incident Impact Energy of 50 in-lb _f	158
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Table 6.10: Comparison of Experimental and Numerical Results – All 10-Ply Laminates at Incident Impact Energy of 50 in-lb _f	159
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LIST OF FIGURES

Figure 2.1: Ideal Tensile Stress-Strain Curve for Resin System.....	8
Figure 2.2: Tensile Modulus and Tensile Strength Comparisons of Resin Systems.....	10
Figure 2.3: Comparison of Tensile Strength for Several Common Materials.....	14
Figure 2.4: Comparison of Tensile Modulus for Several Common Materials.....	15
Figure 2.5: Stress-Strain Curve Comparison.....	16
Figure 3.1: CST GS67813 8-Harness Satin S-Glass.....	20
Figure 3.2: Aeropoxy PR2032 Resin and PH3660 Hardener	21
Figure 3.3: West System 105 Resin and 206 Hardener	22
Figure 3.4: LF Manufacturing, Inc., Limestone Filler.....	23
Figure 3.5: West System 404 High-Density Adhesive Filler	24
Figure 3.6: Acculab V-600 Scale	25
Figure 3.7: Tetrahedron Composite Press.....	26
Figure 3.8: Vacuum Pumps	27
Figure 3.9: Vacuum Bagging Fixture	28
Figure 3.10: Post-Cure Oven and Oven Temperature Gauge	29
Figure 3.11: Wet Tile Saw	29
Figure 3.12: Trimmed CST GS67813 S-Glass Cloth	30
Figure 3.13: Mixing Epoxy, Hardener, and Filler.....	38
Figure 3.14: Tools Used for Specimen Layup	38

Figure 3.15: Application of Epoxy Resin and Filler to Fiberglass Plies	39
Figure 3.16: Spreading Epoxy Resin and Filler with Rolling Pin	40
Figure 3.17: Vacuum Bag Stacking Sequence	41
Figure 3.18: Vacuum Bagging Fixture with Wetted Out Specimen and Vacuum Bagging Fixture with Vacuum Applied	42
Figure 3.19: Post-Cure Heat Cycle	44
Figure 3.20: Cured 2-Ply Laminates	45
Figure 3.21: Post-Cured and Trimmed Laminates	46
Figure 4.1: Thermolyne 47900 Furnace	47
Figure 4.2: Surfalloy-Surfaced Grips	49
Figure 4.3: 5-kip MTS Sintec Load Frame	50
Figure 4.4: 10-kip MTS Sintec Load Frame	51
Figure 4.5: MTS Extensometer	52
Figure 4.6: MTS Extensometer Attached to 10-Ply Static Test Specimen	52
Figure 4.7: Stress-Strain Plot Generated by MTS TestWorks 4 Software	53
Figure 4.8: MB Electronics Magnetic Shake Table	54
Figure 4.9: Shake Table with Specimen Loaded in Clamp Fixture	55
Figure 4.10: Function Generator, Signal Amplifier, and Digital Frequency Meter	57
Figure 4.11: Instron Dynatup 9250HV Impact Machine and Controls	58
Figure 4.12: Instron Dynatup 9250HV and Impact Test Fixture	59
Figure 4.13: Transient Force and Energy Plots Generated by Instron Impulse Software	60
Figure 4.14: Mitutoyo ABSOLUTE Digimatic Depth Gauge	61

Figure 5.1: Tensile Strength for Laminate W_2^{15HD}	75
Figure 5.2: Failure Mode for Laminate W_2^{15HD} Under Tensile Load.....	76
Figure 5.3: Tensile Strength for Laminate W_2^{20HD}	77
Figure 5.4: Failure Mode for Laminate W_2^{20HD} Under Tensile Load.....	78
Figure 5.5: Tensile Strength for Laminate W_2^{25HD}	79
Figure 5.6: Failure Mode for Laminate W_2^{25HD} Under Tensile Load.....	80
Figure 5.7: Tensile Strength for Laminate A_2^{15HD}	80
Figure 5.8: Failure Mode for Laminate A_2^{15HD} Under Tensile Load.....	82
Figure 5.9: Tensile Strength for 2-Ply Laminates with High-Density Filler	83
Figure 5.10: Tensile Strength for 2-Ply Laminates with Limestone Filler	84
Figure 5.11: Tensile Strength for All 2-Ply Laminates.....	85
Figure 5.12: Failure Mode for All 2-Ply Laminates.....	86
Figure 5.13: Tensile Strength for Laminate A_{10}^{15HD}	89
Figure 5.14: Failure Mode for Laminate A_{10}^{15HD} Under Tensile Load	90
Figure 5.15: Tensile Strength for Laminate A_{10}^{20HD}	91
Figure 5.16: Failure Mode for Laminate A_{10}^{20HD} Under Tensile Load	92
Figure 5.17: Tensile Strength for 10-Ply Laminates with High-Density Filler.....	93
Figure 5.18: Tensile Strength for 10-Ply Laminates with Limestone Filler	94
Figure 5.19: Tensile Strength for All 10-Ply Laminates.....	95
Figure 5.20: Failure Mode for All 10-Ply Laminates.....	96
Figure 5.21: First Bending Mode of a Cantilever Plate	100

Figure 5.22: First 8 Mode Shapes for Laminate W_2^{15HD}	101
Figure 5.23: First 8 Mode Shapes for Laminate W_2^{15L}	104
Figure 5.24: First 4 Mode Shapes for Laminate A_{10}^{15HD}	108
Figure 5.25: Force-Time and Energy-Time Response for Laminate A_{10}^{15HD} at Incident Impact Energy of 50 in-lb _f	117
Figure 5.26: Force-Time and Energy-Time Response for Laminate A_{10}^{15HD} at Incident Impact Energy of 55 in-lb _f	119
Figure 5.27: Force-Time and Energy-Time Response for Laminate A_{10}^{15HD} at Incident Impact Energy of 60 in-lb _f	121
Figure 5.28: Failure Mode for Laminate A_{10}^{15HD} Due to Impact Test at Incident Energies of 50, 55 and 60 in-lb _f	123
Figure 6.1: First Bending Mode of Laminate A_{10}^{15HD}	138
Figure 6.2: Second Bending Mode of Laminate A_{10}^{15HD}	139
Figure 6.3: Third Bending Mode of Laminate A_{10}^{15HD}	139
Figure 6.4: Fourth Bending Mode of Laminate A_{10}^{15HD}	140
Figure 6.5: Low-Velocity Impact at Incident Energy Equivalent to the Barely Visible Impact Damage Threshold for Laminate A_{10}^{15HD}	148
Figure 6.6: Impact at Incident Energy Greater Than Penetration Threshold of Laminate A_{10}^{15HD}	150
Figure 6.7: Low-Velocity Impact at Incident Energy of 50 in-lb _f for Laminate A_{10}^{15HD}	151
Figure 6.8: Numerical Energy-Time Response for 10-Ply Laminates with High-Density Filler at Incident Impact Energy of 50 in-lb _f	152
Figure 6.9: Numerical Energy-Time Response for 10-Ply Laminates with Limestone Filler at Incident Impact Energy of 50 in-lb _f	155
Figure 6.10: Numerical Energy-Time Response for All 10-Ply Laminates at Incident Impact Energy of 50 in-lb _f	157

LIST OF SYMBOLS

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>
a	Acceleration	ft/s^2
A_c	Cross-Sectional Area	in^2
A_2	2-Ply Fiberglass Laminate Fabricated with <i>Aeropoxy</i> Resin System	-
A_{10}	10-Ply S-glass Laminate Fabricated with <i>Aeropoxy</i> Resin System	-
E	Energy	in-lb_f
E	<i>Young's Modulus</i> of Elasticity	ksi
F	Force Vector	lb_f
g	Gravitational Acceleration	ft/s^2
G	Modulus of Rigidity	ksi
L	Specimen Length	in
m	mass	lb_m
t	Specimen Thickness	in
v	Velocity	ft/s
V	Volume Fraction	%
w	Weight	lb_m
W	Weight Fraction	%
W_2	2-Ply Fiberglass Laminate Fabricated with West System Resin System	-

<u>Greek</u>	<u>Description</u>	<u>Unit</u>
δ (delta)	Tip Deflection of Specimen	in
Δ (capital delta)	Change in Quantity	-
ϵ (epsilon)	Strain	in/in
ν (nu)	<i>Poisson's Ratio</i>	-
ρ (rho)	Density	g/in ³
θ (theta)	Ply Orientation	°
σ (sigma)	Normal Stress	ksi

<u>Subscripts</u>	<u>Description</u>	<u>Unit</u>
c	Composite	-
cb	Composite Bending	-
cd	Composite Damage	-
d	Dissipated	-
e	External	-
f	Fiber	-
i	Impactor	-
k	Kinetic	-
m	Matrix	-
t	Tension	-
tot	Total	-

<u>Superscripts</u>	<u>Description</u>	<u>Unit</u>
15HD	15-Percent High-Density Filler Measured by Weight of Composite's Raw Materials	-
20HD	20-Percent High-Density Filler Measured by Weight of Composite's Raw Materials	-
25HD	25-Percent High-Density Filler Measured by Weight of Composite's Raw Materials	-
15L	15-Percent Limestone Filler Measured by Weight of Composite's Raw Materials	-
20L	20-Percent Limestone Filler Measured by Weight of Composite's Raw Materials	-
25L	25-Percent Limestone Filler Measured by Weight of Composite's Raw Materials	-

1 INTRODUCTION

1.1 Impact Behavior in General

An impact event is characterized as when two or more objects collide, producing a high force over a short period of time. Due to the impulse loading caused by impact events, they typically have a greater effect on a material's residual mechanical properties when compared to lower forces applied over longer periods of time [42]. The impact behavior and resulting damage to the colliding bodies is largely dependent upon the relative mass and velocity of the objects.

A body will typically deform when struck by a projectile and the deformation will absorb most, if not all, of the force of the collision if the impact event is perfectly inelastic. This can be better understood by using the concept of energy conservation. Simply put, the kinetic energy of the projectile is converted into heat and sound energy, which results in deformation to and vibration of the struck object. However, the resulting deformation and vibrations cannot occur instantaneously. High-velocity impacts do not allow sufficient time for the material to deform or for the vibrations to occur. Consequently, the impacted body behaves more brittle than it typically would, and the majority of the applied force goes into fracturing the material.

Based on the same concept of ductility and brittleness as it relates to a material's impact behavior, the impact resistance of a structure is decreased as its modulus of elasticity increases [9]. This infers that stiffer materials have less impact resistance than ductile materials. Furthermore, stiff materials will absorb less energy than ductile materials and reflect more energy back into the impacting object.

Impact behavior of composite materials is often divided into two categories for the purpose of analyzing and understanding the residual damage. The first category is low-velocity impact, which is generally characterized as when the object impacting the composite does not puncture the material or cause through-the-thickness fracture. Even though the damage to the material is not always visible, low-velocity impacts usually decrease the laminate strength and stiffness. The primary damage mode for low-velocity impacts is delamination, which is typically accompanied by matrix cracking [5].

The second category of impact behavior is high-velocity, which is characterized by through-the-thickness fracture or breakout. The damage caused by high-velocity impacts is typically visible and also decreases the laminate strength and elastic modulus [48]. As would be expected, penetration-induced fiber breakage is the primary damage mode of high-velocity impacts. Regardless of impact velocity, the study of the resulting damage on fiber-reinforced composite materials is much more critical than for

metal structures. This is due to the inherent ductility of metals which allows them to absorb more impact energy without significantly reducing their residual mechanical properties.

1.2 Low-Velocity Impact Behavior

There are countless engineering applications where a composite structure may be subjected to an impact that results in damage which does not puncture the material or cause through-the-thickness fracture. These low-velocity impacts can cause fiber breakage, matrix cracking, and delamination, which lead to a decrease in the residual strength of the material. Therefore, it is important to consider impact behavior and impact damage mechanisms when designing composite structures.

The delamination caused by low-velocity impacts is usually increased at laminae interfaces when their ply orientations are different [26]. This is a result of dissimilar laminae elastic moduli due to the varying ply orientations. In addition, the size of delamination is highly dependent upon the incident impact energy. Matrix cracks resulting from low-velocity impact events are initiated by stress concentrations at the fiber-matrix interface which are generated by excessive tensile stress. The occurrence of critical matrix cracks is also due to interlaminar transverse shear stress and transverse in-plane stress [14].

Relating back to the concept of energy conservation once again, it can be understood that the total impact energy is equivalent to the sum of the

initiation and propagation energies. Therefore, the total impact energy of a low-velocity collision between two or more bodies only provides a portion of the information necessary to understand a material's fracture behavior. For this reason, experimental impact tests are often conducted with instrumented impact machines which are capable of recording the complete load history of the event so that the transient energy absorbed during different damage modes can be examined.

Materials with different mechanical properties usually have dissimilar initiation and propagation energies, even when their total impact energies are equivalent [18]. Stiff, high-strength materials generally have a large initiation energy and a small propagation energy. Conversely, materials with a low modulus of elasticity usually have a small initiation energy and a large propagation energy [36]. Low-velocity impact tests are commonly conducted on composite laminates with similar geometries in order to determine the energy absorbed during fracture initiation and propagation. This is done to understand the energy absorption capabilities of the material, which are an indicator of ductility or stiffness. Research conducted by Wyrick and Adams indicates that there is a minimum impact energy required to cause a reduction in a material's tensile strength [48]. This threshold incident impact energy is primarily affected by laminate thickness and the composite's constituent materials.

1.3 Objective

Experimental and theoretical studies of low-velocity impact events generally concentrate on one or more of the following factors: impact force and velocity, energy absorption, type of damage, damage initiation and propagation, and residual material behavior. This project will primarily focus on the impact force and velocity, as well as the energy absorption, of fiber-reinforced laminated composites. Organic matrix fiber-reinforced laminated composites are very susceptible to transverse impacts, especially at low velocities [15]. These types of impact events can cause significant damage in the form of matrix cracks and delamination, which can reduce the compressive strength of a laminate by almost 50 percent [24].

In order to analyze and better understand the effects of matrix composition on low-velocity impact behavior, several test specimens will be fabricated with their resin system mixed with different types and quantities of inorganic filler material. Research conducted by Cantwell and Morton indicates that impact behavior and damage is largely influenced by ply orientation and thickness, as well as the mass of the impactor [13]. Therefore, these variables will be held constant in order to isolate the effects of matrix composition as it relates to the transient impact response.

Impact testing will be conducted with a transverse drop-weight machine with increasing impact energies and a constant impactor mass. A piezoelectric force transducer affixed to the drop-weight device, localized in

the hemispherical impactor nose, was used to capture the transient force of the impact event. The contact force between the impactor and the composite plate, as well as the energy during impact, will be analyzed as functions of time. Each laminate's damage threshold load for the corresponding incident impact energies will also be examined to determine the respective matrix composition influences. A numerical evaluation of these specimens will be conducted using *Abaqus/Explicit*, which utilizes a transient dynamic Finite Element Analysis (FEA) code. The numerical transient energy during impact will be used to substantiate the experimental tests.

A static tensile test and dynamic modal analysis will be investigated for each of the composite specimens prior to the impact testing. The tensile test will be used to obtain each laminate's tensile modulus of elasticity and to better understand the effects of filler material on a composite's stiffness and strain-to-failure. The resonant vibration, which is caused by an interaction between the inertial and elastic properties of a structure's materials, is a contributing factor to many vibrational related problems which occur with composite fabricated designs. These vibrational issues can lead to premature fatigue, material failure, and shortened product life [38]. Therefore, a modal analysis will be conducted for each test specimen to characterize several mode shapes and natural frequencies, and determine the damping effects of the constituent filler material and laminate thickness.

2 MATERIAL SELECTION

The purpose of this section is to provide a general overview of the mechanical properties and comparative costs of common constituent materials used in the fabrication of fiber-reinforced composites. A more detailed description of the methods and materials used for laying up the test specimens is provided in the *Test Specimen Fabrication* section.

2.1 Resin System

The primary goal of the resin system in a polymer matrix composite is to provide adhesion between the reinforcing fibers in order to transfer the applied loads throughout the structure. Acting as a load transfer mechanism, the matrix and reinforcing fibers can prevent cracking and disbonding, disperse the interlaminar stresses, and reduce the effects of shear stress. The resin matrix also helps protect the fibers from abrasion and impact damage. A composite's resin system is not intended to bear the primary design loads, so its mechanical properties are usually subordinate to the reinforcing fiber material.

The resin system can also modify the composite's overall mechanical properties, toughness, and environmental resistance [37]. A composite's resin system is usually more ductile than its reinforcing fibers, meaning that the resin can be subjected to plastic deformation before it fractures. The reinforcing fibers are typically more brittle than the matrix, meaning they fail

with little or no plastic deformation. An ideal resin system has a high ultimate strength, stiffness, and strain-to-failure. In order to obtain the ideal mechanical properties, the resin system must initially be stiff while simultaneously resisting brittle failure. Fig. 2.1, below, shows the tensile stress-strain curve for an ideal resin system.

Figure 2.1: Ideal Tensile Stress-Strain Curve for Resin System [37]

From Fig. 2.1 it can be seen that pure elastic deformation initially occurs as the applied stress and resulting strain increase with a linear relationship. This linear-elastic region is defined by *Hooke's Law*, where the stress-to-strain ratio is constant. The slope of the line in this linear region is significant because it represents the modulus of elasticity, which is a measure of the material's stiffness. The modulus of elasticity, also referred to as *Young's modulus* or E , is used to define a material's properties as it elastically deforms and then returns to its original shape as the material is loaded and then unloaded. The end of the linear region on the stress-strain curve is

known as the elastic limit, and loading the material beyond this limit can result in permanent deformation.

Permanent deformation occurs when the material is loaded beyond its yield stress. The point on the stress-strain curve corresponding to the yield stress is called the yield point and represents the beginning of the plastic deformation region. The material will continue to deform plastically until it fails. The respective strain at that point is referred to as the strain-to-failure and it signifies the maximum percent elongation of the material before it ruptures. The strain-to-failure of a resin system must be considered during the material selection process because it should be equivalent to or higher than the strain-to-failure of the selected fiber material. This prevents the composite's matrix from fracturing as a result of the reinforcing fibers stretching beyond the resin system's maximum percent elongation.

In addition to strain-to-failure, the tensile modulus and strength were considered when comparing the mechanical properties of polyester, vinylester, and epoxy resin systems. These thermosetting resin systems were selected for comparison since they are the most commonly used for hand-layups and because they are readily available [27]. Fig. 2.2 shows the relative tensile modulus and strength of each resin system cured at room temperature (pink), and post-cured at an elevated temperature for five hours (blue):

Figure 2.2: Tensile Modulus (Left) and Tensile Strength (Right) Comparisons of Resin Systems [41]

From the figure, it can be concluded that epoxy resin systems generally have a higher tensile modulus and strength than polyester and vinylester resin systems regardless if they are cured at room temperature or with a post-cure. It is also important to note that the mechanical properties of each resin system improved as a result of the five hour post-cure. The benefits of post-curing will be discussed in further detail in the *Specimen Layup* section.

Polyester is the cheapest of the three resin systems and is the easiest to use, however, it typically has the least favorable mechanical properties. Polyester resins also tend to have a high shrinkage rate during cure, which can result in a pre-stressed composite. Vinylesters have higher mechanical properties than polyesters, but usually require a post-cure in order to obtain the improved performance. Vinylesters also have better environmental resistance, but have a high shrinkage rate during cure like polyester resins.

Epoxy was selected as the resin system for fabricating the experimental test laminates because it has the best mechanical and thermal properties [25]. Since it has the best mechanical properties, it can be used with the most types of reinforcing fibers due to its superior strain-to-failure. Although epoxy is typically more expensive than the other two resin systems, it has the greatest fatigue resistance and withstands the effects of moisture the best. Epoxy also tends to shrink the least during cure, which minimizes the potential of pre-stressing the composite during fabrication.

2.2 Fiber

The reinforcing fibers in a composite are the primary load bearing material and have a higher strength-to-weight ratio than the matrix. Consequently, the fibers increase the overall mechanical properties of the composite laminate. This project used continuous-lamination hand-layup techniques, which are discussed later, to fabricate the test specimens. Continuous-lamination consists of bonding sheets of laminae, which are a flat arrangement of unidirectional or woven fibers in a matrix, under pressure to create a laminate [4]. A laminate consists of a stack of two or more laminae, with the fiber orientation arranged to carry the design loads. The constituent materials in a standard laminate are the same in each layer, whereas a hybrid laminate has layers of laminae with different reinforcing fibers.

Standard laminates were fabricated for the experimental tests in order to concentrate on the effects of each composite's thickness and filler material. Hybrid laminates were purposely excluded from this research project in order to limit the number of variables. It was assumed that introducing laminae with different reinforcing fibers may alter the test results such that the effects of the filler material and laminate thickness could be interpreted incorrectly.

The orientation of a composite's reinforcing fibers can create direction-specific, or anisotropic, properties that should be utilized when designing a fiber-reinforced structure. The majority of fibers should be placed along the orientation of the main load paths, and minimized where there is little or no load. Designing a composite in this manner will maximize the strength-to-weight ratio due to the removal of unnecessary ply orientations. One of the simplest ways to fabricate an anisotropic laminate is by using unidirectional pre-impregnated materials. Pre-impregnated, or pre-preg, materials are manufactured with the resin system infused in the fabric, with a specific resin-to-fiber ratio designed to optimize the mechanical properties and load-transfer mechanism between the fibers and matrix.

Depending on the application, there are certain circumstances where woven fabrics are more favorable than unidirectional fabrics. For example, the increased drapability of woven fabrics make them more advantageous when fabricating a structure with complex curves. Although the fiber orientation of woven fabrics is less tailorable than unidirectional, woven

fabrics are generally easier to work with when using hand layup techniques. This can translate into a final composite structure with fewer voids and flaws. In addition, composites made with woven fabrics typically have less internal damage for a given impact energy than those made with unidirectional fibers. This is a direct result of the interlacing fabric weave which effectively changes the failure mechanics of the material. For example, unidirectional laminates subjected to low-velocity impact usually exhibit fiber breakout on the back face due to flexural tensile loading. This splitting can lead to delamination and damage propagation near the back surface of the material. However, using a woven fabric with interlacing fibers can prevent the composite from splitting on the back surface, and therefore limit the amount of delamination [24].

The most common bi-directional fiber weave is $0^\circ/90^\circ$, where half of the tows are in the warp direction and the other half are in the fill direction. Bi-directional fabrics can be used to create isotropic composites which have stress-strain relationships that are independent of the orientation of the coordinate system at any given point. In addition, only two material properties are required to calculate the deformations of an isotropic material - *Young's Modulus* and *Poisson's Ratio* [25]. These unique characteristics allow designers to significantly reduce the complexity of both analytical and numerical models, which aides in predicting stress, strain, and deformation for given loading conditions.

The most common reinforcing fiber for polymer matrix composites is glass. The main advantages of glass fibers are their low cost and high strength; however, they have poor abrasion resistance and poor adhesion to polymer matrix resins in the presence of moisture [5]. The adhesion between fiberglass and polymer matrix resins can be improved with the use of chemical coupling agents on the surface of the fibers. Fig 2.3, below, provides a comparison of the relative tensile strength of several materials, including composites made with glass, carbon, and aramid fibers.

Figure 2.3: Comparison of Tensile Strength for Several Common Materials [28]

On average, S-glass has a higher tensile strength when compared to steel, titanium, aluminum, wood, and E-glass. The tensile strength for S-glass and aramid fibers are comparable, however, both are lower than that of carbon fiber. Similarly, Fig 2.4 indicates that the average tensile modulus for aramid and both glass fibers is lower than that of carbon fiber.

Figure 2.4: Comparison of Tensile Modulus for Several Common Materials [28]

In consideration of the material comparisons provided above, a designer may be influenced to use a reinforcing material such as carbon fiber. However, the impact toughness of most high-modulus fiber composites has been shown to be relatively low when compared to glass fiber-reinforced composites [5]. According to comparative results from a standard notched Charpy impact test, the impact energy absorbed by S-glass epoxy laminates is nearly 6-times greater than for graphite-epoxy laminates. Similarly, the impact energy absorbed by E-glass epoxy laminates is approximately 4-times greater than for graphite-epoxy laminates [7]. When comparing E- and S- type fiberglass to one another, S-glass fibers have a higher tensile strength and elastic modulus, as well as a lower density. Consequently, S-glass composites have a higher strength-to-weight ratio than E-glass.

Lastly, the strain-to-failure for each of the aforementioned fibers was compared to determine its compatibility with epoxy resin. From Fig. 2.5, below, it was determined that S-glass fibers have the highest elongation-to-break while still being lower than that of epoxy resin. This infers that S-glass and epoxy resin are compatible constituent materials since the maximum elongation of the glass fibers should not directly result in matrix cracking.

Figure 2.5: Stress-Strain Curve Comparison [37]

After comparing the relative impact performance, cost, and mechanical properties of each material, S-glass bi-direction woven roving fabric was selected as the reinforcing material for the static and dynamic test specimens.

2.3 Filler

Inorganic fillers, which can account for up to 65% of a composite's weight, are used in the fabrication of fiber-reinforced structures to reduce the total cost and to improve the mechanical performance [17]. For example, adding filler material to a composite decreases the constituent percentage of organic material, and thereby improves the material's resistance to fire. The mechanical performance of a composite is typically enhanced with the use of inorganic filler due to their inherent ability to help maintain uniform fiber-loading. A composite's crack resistance can also be improved with the use of a filled resin system, especially when the resin is used in structures with sharp corners, or in "resin-rich" areas where the smaller filler particles can help to reinforce the resin.

Resin systems with inorganic filler tend to shrink less than those that are unfilled, so the use of fillers can decrease the likelihood of pre-stressing a composite when using an elevated temperature cure. Limiting the amount of shrinkage during cure can also increase the ease of fabrication when making molded parts. In addition, a composite's water resistance, environmental resistance, surface smoothness, stiffness, and dimensional stability can be improved with the use of fillers [17].

Calcium carbonate (CaCO_3), which is commonly referred to as limestone, is used as inorganic filler more than any other material. This is primarily due to its low cost, range of particle sizes, and the quantity of

chemical treatments available which enable the filler to improve a composite's resin-to-fiber bonding. Kaolin, or clay, is the second most commonly used filler. Similar to limestone, clay is typically used due to its low cost, commercial availability, and wide range of particle sizes. After comparing these inexpensive inorganic fillers, limestone was selected due to its increased use in the composites industry.

Some inorganic fillers are engineered by resin system manufactures and are typically designed to enhance the performance their company's resin products. The fillers can be mixed with other brand resin systems, but the manufactures often state that the filler's performance cannot be guaranteed under those circumstances. In general, engineered inorganic fillers are substantially more expensive than limestone and clay, but their benefits are touted to be worth the cost. Consequently, an engineered filler was selected to compare with the limestone. *West System 404 High-Density Adhesive Filler* was used since it was provided by the Cal Poly Aerospace Composites Lab and because it was manufactured by the same company as one of the epoxy resin systems used during specimen fabrication.

3 TEST SPECIMEN FABRICATION

3.1 Composite Materials

3.1.1 Fiberglass Cloth

S-glass was selected as the test specimen fiber due to its low cost, high strength, and impact performance. The dry fiberglass, *GS67813*, was purchased from Composite Structures Technology (CST). It weighs 8.85 ounces per square yard and is 0.0097 inches thick. The manufacturer specifications state that the fabric has a breaking strength of 235 lb/in in the warp direction and 221 lb/in in the fill direction [20]. This fabric is considered “balanced” since the warp-to-fill breaking strengths are within 15% of each other. A balanced fabric was selected because they generally perform better than “unbalanced” fabrics in applications where the axial and perpendicular loads are expected to be similar. An “unbalanced” fabric is better suited for applications where a much higher load is expected in the axial direction as compared to the longitudinal direction. The fiberglass cloth used to make all of the specimens is shown in Fig. 3.1.

Figure 3.1: CST GS67813 8-Harness Satin S-Glass

The GS67813 S-glass has an eight Harness Satin (8 HS) weave with a volan finish. The volan chemical treatment is added to the fiber during the manufacturing process to improve the bond between the fiber and resin. The 8 HS weave indicates that one fill thread floats over seven warp threads and then under one warp thread. The 8 HS weave typically has the greatest residual strength after impact when compared with other woven fabrics and unidirectional pre-pregs [24]. Composites made with woven roving fabric, such as GS67813, get a significant amount of their strength from their high glass-to-resin ratio [35]. This weave is one of the most pliable out of the standard fiberglass weaves, which makes it easier to use when laying up parts with complex curves. A summary of the fiber properties are shown in Table 3.1.

Table 3.1: CST GS67813 S-glass Properties

Weight (oz/sq yd)	Weave	Thread Count	Breaking Strength		Thickness (in)	Finish
			Warp (lb/in)	Fill (lb/in)		
8.85	8 HS	58 x 54	235	221	0.0097	volan

3.1.2 Epoxy Resin Systems

Two different epoxy resin systems were chosen to fabricate the 2-ply S-glass composite specimens that were used in the initial tensile and vibrational tests. The test results were then used to determine which epoxy resin system should be used to fabricate the 10-ply S-glass composite specimens for impact testing.

The first epoxy resin system, which consisted of *Aeropoxy PR2032* resin and *Aeropoxy PH3660* hardener, was manufactured by PTM&W Industries. *PR2032* is an unfilled resin with medium viscosity and is designed for structural applications. The *PH3660* hardener has a sixty minute working time and can cure completely at room temperature [34]. The *Aeropoxy* resin system is shown below in Fig. 3.2.

Figure 3.2: Aeropoxy PR2032 Resin and PH3660 Hardener

The second epoxy resin system consisted of West System's *105 Epoxy Resin* and *206 Slow Hardener*. The *105* resin has a low viscosity, is

unfilled, and is designed for general coating and bonding applications. The 206 hardener has a 100 minute working time and can cure completely at room temperature (above 72° F) [19]. The West System resin system is shown in Fig. 3.3.

Figure 3.3: West System 105 Resin and 206 Hardener

Although the manufacturers of both the *Aeropoxy* and West System products state that a complete cure is capable if the epoxy mixture is kept at or above room temperature, they still recommend a post-cure when possible. A comparison of the epoxy resin systems' properties is provided in Table 3.2.

Table 3.2: Comparison of Aeropoxy and West System Resin Systems

Epoxy Resin & Hardener	Tensile Strength (psi)	Tensile Modulus (psi)	Flexural Strength (psi)	Flexural Modulus (psi)	Glass Transition Temp (°F)	Specific Gravity (g/cc)
<i>Aeropoxy</i> <i>PR2032</i> with <i>PH3660</i>	9,828	4.18×10^5	16,827	4.63×10^5	196	1.11
West System <i>105</i> with <i>206</i>	7,300	4.60×10^5	11,800	4.50×10^5	139	1.18

The Aeropoxy resin system has a higher tensile strength, flexural strength, and flexural modulus than the West System resin system; however, it has a lower tensile modulus. The Aeropoxy resin system also has a slightly lower specific gravity.

3.1.3 Inorganic Fillers

Two inorganic fillers were chosen to fabricate the S-glass test specimens in order to thicken the resin/hardener mixture and improve the material properties. The first half of the 2-ply and 10-ply specimens was made with a calcium carbonate (CaC_3) filler which was supplied by LF Manufacturing, Inc. The CaC_3 filler has a density of 0.0979 lb/in^3 , specific volume of $10.3 \text{ in}^3/\text{lb}$, *Young's Modulus* of $5.37 \times 10^6 \text{ psi}$, and an ultimate tensile strength of $20 \times 10^3 \text{ psi}$. The limestone filler can be seen in Fig. 3.4.

Figure 3.4: LF Manufacturing, Inc., Limestone Filler

The second half of the 2-ply and 10-ply specimens was made with West System *404 High-Density Adhesive Filler*. This inorganic filler is a thickening additive that was designed to maximize bonding properties in

applications where high cyclic loads are expected. It also increases the strength of composites when it is used for gap filling. The material properties of the 404 filler are proprietary to West Systems, so a direct comparison with the limestone filler was not possible. The West System 404 High-Density Adhesive Filler can be seen in Fig. 3.5.

Figure 3.5: West System 404 High-Density Adhesive Filler

3.2 Equipment

3.2.1 Scale

An Acculab V-600 scale was used to weigh the fiberglass cloth, epoxy resin, epoxy hardener, and fillers used to make the test specimens. The top-loaded scale shown in Fig. 3.6 has a 600 gram capacity.

Figure 3.6: Acculab V-600 Scale

3.2.2 Tetrahedron Composite Press

The fiberglass specimens used for the tensile, vibrational, and impact tests were fabricated in the California Polytechnic State University, San Luis Obispo Structures/Composites Lab. The composite manufacturing tools available in the lab allowed for hand-layup continuous-lamination procedures to be used with two potential curing methods. The first curing method available was a *Tetrahedron* composite press which enables the fabricator to control heat and applied force during the cure cycle. When using the *Tetrahedron* composite press, the dimensions of the test specimen are limited by the size of the aluminum pressure plates which are 12-inches wide by 12-inches long. The uniform pressure and heat applied by the composite press provides a consistent and smooth specimen surface finish and reduces the likelihood of voids or defects within the composite. The *Tetrahedron* composite press is shown in Fig. 3.7 below.

Figure 3.7: Tetrahedron Composite Press

3.2.3 Vacuum Pumps

The second hand-layup method accessible in the Structures/Composites Lab involved vacuum bagging. This process is more labor-intensive than using a composite heat press, but it provides the fabricator with design freedom with respect to specimen size and shape. Vacuum bagging also provides a means to apply uniform pressure over the composite specimen which reduces the likelihood of voids between plies, increases fiber wet-out, and decreases the resin-to-fiber ratio by removing excess resin. Vacuum bagging was chosen as the preferred fabrication method for the test specimens for these reasons.

Figure 3.8: Vacuum Pumps

Two vacuum pumps, which are shown above in Fig. 3.8, were used to fabricate the test specimens. One vacuum was manufactured by Carpanelli (model #MM71B2) and the other was manufactured by Gast (model #MOA-V113-AE).

3.2.4 Vacuum Bagging Fixture

The vacuum pumps were connected to a custom made vacuum bagging fixture which was primarily designed to manufacture composite plates. The fixture consisted of two halves which were separated by a rubber gasket. The bottom half of the fixture was made from a 24-inch by 24-inch sheet of aluminum which had vent holes connected to an air pressure fitting. The top half of the fixture had a square aluminum frame with a flexible rubber membrane stretched across. The fixture was designed to have a tight seal between the top and bottom halves so that the air can be removed from the system when a vacuum is applied to the air pressure fitting. The vacuum bagging fixture is shown in Fig. 3.9.

Figure 3.9: Vacuum Bagging Fixture

3.2.5 Post-Cure Oven

As previously mentioned, post-curing the test specimens was not necessary since they were cured slightly above room temperature. However, the manufacturers of both epoxy resin systems still recommended a post-cure of 120°F for at least four hours in order to improve the ultimate mechanical properties of the composite. An oven located in the Cal Poly Aerospace hangar was used to post-cure the 2-ply and 10-ply fiberglass specimens. The oven, which is shown in Fig. 3.10, had a maximum operating temperature of 300°F and ran at atmospheric pressure.

Figure 3.10: Post-Cure Oven (Left) and Oven Temperature Gauge (Right)

3.2.6 Tile Saw

An electric *Target* wet tile saw was used to trim the cured laminates and cut all necessary test specimens to size. The saw sprayed a continuous mist of water onto the diamond-tipped blade to decrease the heat due to friction during the cutting process. This provided a clean cut and decreased the interlaminar stress, preventing delamination. The tile saw can be seen in Fig. 3.11.

Figure 3.11: Wet Tile Saw

3.3 Specimen Layup

3.3.1 Fiberglass Cloth Preparation

The 50 inches wide roll of CST fiberglass cloth was trimmed into rectangular sections that were 6 inches wide by 14 inches long using standard fabric shears. A total of 84 plies were cut to these dimensions in order to make a total of 18 laminates required for testing. The eighteen specimens consisted of twelve that were 2-ply thick and six that were 10-ply thick. Caution was used during the cutting process in order to minimize the potential of fabric/weave migration. Fig. 3.12 shows a sample of the trimmed S-glass cloth. The weight of the raw fiberglass cloth was recorded for each of the 18 specimens using the Acculab V-600 scale. The average cloth weights for the 2-ply and 10-ply specimens were 33.6 grams and 166.1 grams, respectively.

Figure 3.12: Trimmed CST GS67813 S-Glass Cloth

3.3.2 *Epoxy Resin System Preparation*

Generally, when comparing resin and fiber content of a composite laminate, it is important to use volume ratios rather than weight ratios. Calculating resin-to-fiber ratios with percent volumes, rather than percent weights, eliminates any error that would otherwise be introduced by using resin systems with different densities. This factor was considered early in the fabrication process since multiple resin systems and fillers, which had different densities, were going to be used to make the test specimens. However, it was not possible to accurately measure the percent volume of the raw materials with the equipment available during the hand-layup process. As a result, the percent weights method was used to calculate the necessary amounts of resin, hardener, and filler for each specimen.

Unidirectional fiberglass composites, especially those cured under pressure, should have between 25% and 50% of their volume in resin to maximize their strength [27]. Woven fabrics, however, require slightly more resin than unidirectional fabrics due to the small “gaps” that are created by the fiber weaves. If a composite specimen is laid up with an inadequate amount of epoxy, it could result in premature interlaminar failure. As a result, an ideal resin-to-fiber weight ratio of 1:1 was selected to ensure that the specimen plies would have a sufficient amount of epoxy between each layer. Composites with resin contents higher than 50% can result in structures with mechanical properties that more closely resemble their matrix than their fiber.

In addition, high resin contents decrease the overall strength-to-weight ratio of the composite.

To account for the epoxy used during the mixing and layup processes, the manufacturer of the *GS67813* woven roving S-glass recommends mixing approximately 10% more epoxy than what would be required to obtain the ideal resin-to-fiber ratio. The epoxy manufactures also suggest using a higher resin-to-fiber ratio if filler material will be added to the resin system. An increased quantity of resin is necessary since filler material increases the viscosity of the epoxy resin system and makes it more difficult to apply to fiberglass cloth. In addition, findings made by Haddad and Feng showed that composites with lower fiber volume fractions have superior energy absorbing capabilities when compared with composites that have a high fiber volume fraction [22]. Consequently, a final resin-to-fiber ratio of 3:2 was used to determine the amount of raw materials necessary to fabricate the test specimens.

The West System epoxy resin system, which consisted of both a resin and hardener, was designed to have a mix ratio of 3:1 (i.e., 75% resin: 25% hardener). Taking the fiberglass cloth weight, W_{fiber} , and resin-to-fiber ratio into account, the weight of the West System *105 Epoxy Resin* was calculated using Eqn. 3.1:

$$W_{resin} = 0.75 * \left[\frac{3}{2}(W_{fiber}) \right] \quad (3.1)$$

Similarly, the weight of the West System *206 Slow Hardener* was calculated using Eqn. 3.2:

$$W_{hardener} = 0.25 * \left[\frac{3}{2}(W_{fiber}) \right] \quad (3.2)$$

The *Aeropoxy* epoxy resin system was designed to have a mix ratio of 100:27 (i.e., 78.7% resin:21.3% hardener). Taking the fiberglass cloth weight, W_{fiber} , and resin-to-fiber ratio into account, the weight of the *Aeropoxy PR2032* resin was calculated using Eqn. 3.3:

$$W_{resin} = 0.787 * \left[\frac{3}{2}(W_{fiber}) \right] \quad (3.3)$$

Similarly, the weight of the *Aeropoxy PH3660* hardener was calculated using Eqn. 3.4:

$$W_{hardener} = 0.213 * \left[\frac{3}{2}(W_{fiber}) \right] \quad (3.4)$$

Once the ideal fiber, resin, and hardener weights were known for each specimen, it was possible to determine the corresponding filler weights, W_{filler} , from Eqn. 3.5:

$$W_{filler} = x * [W_{fiber} + W_{resin} + W_{hardener}] \quad (3.5)$$

where x represents the percent of filler (15%, 20%, or 25%), by weight, based on the sum of the ideal fiber, resin, and hardener weights.

Table 3.4 provides a summary of the raw material weights determined for each of the 2-ply specimens made with West System's *105 Epoxy Resin* and *206 Slow Hardener*.

Table 3.3: 2-Ply Specimens with West System Epoxy Resin System

Specimen Name	W₂^{15HD}	W₂^{20HD}	W₂^{25HD}	W₂^{15L}	W₂^{20L}	W₂^{25L}
Epoxy Resin System	West System	West System	West System	West System	West System	West System
Plies	2	2	2	2	2	2
% Filler	15	20	25	15	20	25
Filler Type	<i>404 High Density</i>	<i>404 High Density</i>	<i>404 High Density</i>	Limestone	Limestone	Limestone
Resin Weight (g)	36.9	36.9	36.9	39.4	39.4	39.5
Hardener Weight (g)	12.3	12.3	12.3	13.1	13.1	13.2
Filler Weight (g)	12.3	16.4	20.5	13.1	17.5	21.9
Matrix Weight (g)	61.5	65.6	69.7	65.6	70.0	74.6
Fiber Weight (g)	32.8	32.8	32.8	35.0	35.0	35.1
Total Weight (g)	94.3	98.4	102.5	100.6	105.0	109.7

The specimen naming convention was selected to organize the materials used to fabricate each laminate. For example, the “W” in W₂^{15HD} indicates that West System’s epoxy resin system was used. The subscript “2” indicates that the laminate was made with 2-ply. The superscript “15HD” indicates that 15% West System *404 High-Density Adhesive Filler*, by weight, was added during the resin mixing process. Similarly, a superscript “15L” indicates that 15% Limestone filler, by weight, was added during the resin mixing process.

As previously mentioned, two different epoxy resin systems were chosen to fabricate the 2-ply fiberglass laminates. Table 3.4 provides a

summary of the raw material weights calculated for the 2-ply specimens made with *Aeropoxy PR2032* resin and *Aeropoxy PH3660* hardener:

Table 3.4: 2-Ply Specimens with Aeropoxy Epoxy Resin System

Specimen Name	A ₂ ^{15HD}	A ₂ ^{20HD}	A ₂ ^{25HD}	A ₂ ^{15L}	A ₂ ^{20L}	A ₂ ^{25L}
Epoxy Resin System	<i>Aeropoxy</i>	<i>Aeropoxy</i>	<i>Aeropoxy</i>	<i>Aeropoxy</i>	<i>Aeropoxy</i>	<i>Aeropoxy</i>
Plies	2	2	2	2	2	2
% Filler	15	20	25	15	20	25
Filler Type	<i>404 High Density</i>	<i>404 High Density</i>	<i>404 High Density</i>	Limestone	Limestone	Limestone
Resin Weight (g)	38.9	39.0	39.0	41.5	39.1	39.0
Hardener Weight (g)	10.5	10.5	10.5	11.2	10.6	10.5
Filler Weight (g)	12.3	16.5	20.6	13.2	16.6	20.6
Matrix Weight (g)	61.7	66.0	70.1	65.8	66.2	70.1
Fiber Weight (g)	32.9	33.0	33.0	35.1	33.1	33.0
Total Weight (g)	94.6	99.0	103.1	100.9	99.3	103.1

The only notable difference in the specimen name for these laminates is marked by the use of an “A” instead of a “W”. The “A” indicates that the *Aeropoxy* epoxy resin system was used instead of West System’s.

The mechanical properties and natural frequency responses of the 2-ply laminates were determined from the initial tensile and modal tests (Note: a detailed review of the laminate test results can be found in the “*Analysis of Experimental Results*” section, below). Those results were analyzed to determine which epoxy resin system to use for the fabrication of the 10-ply S-

glass composite specimens. Consequently, the *Aeropoxy* resin system was selected. Table 3.5 provides a summary of the raw material weights calculated for the 10-ply specimens made with *Aeropoxy PR2032* resin and *Aeropoxy PH3660* hardener:

Table 3.5: 10-Ply Specimens with Aeropoxy Epoxy Resin System

Specimen Name	A ₁₀ ^{15HD}	A ₁₀ ^{20HD}	A ₁₀ ^{25HD}	A ₁₀ ^{15L}	A ₁₀ ^{20L}	A ₁₀ ^{25L}
Epoxy Resin System	<i>Aeropoxy</i>	<i>Aeropoxy</i>	<i>Aeropoxy</i>	<i>Aeropoxy</i>	<i>Aeropoxy</i>	<i>Aeropoxy</i>
Plies	10	10	10	10	10	10
% Filler	15	20	25	15	20	25
Filler Type	<i>404 High Density</i>	<i>404 High Density</i>	<i>404 High Density</i>	Limestone	Limestone	Limestone
Resin Weight (g)	195.0	196.9	193.8	196.3	197.4	197.5
Hardener Weight (g)	52.7	53.2	52.3	53.0	53.3	53.3
Filler Weight (g)	61.9	83.4	102.6	62.3	83.6	104.5
Matrix Weight (g)	309.6	333.4	348.7	311.6	334.2	355.3
Fiber Weight (g)	165.1	166.7	164.1	166.2	167.1	167.2
Total Weight (g)	474.7	500.1	512.8	477.8	501.3	522.5

The same naming convention was adhered to for the 10-ply laminates. The only notable difference to the specimen name for these laminates is marked by the use of a subscript “10” instead of a “2”. This denotes that the specimens were laid up with ten plies instead of two.

3.3.3 *Mixing and Application of Epoxy Resin System*

Three separate containers were used to pre-weigh the proper amounts of resin, hardener, and filler for each specimen. First, the resin and hardener were combined in a mixing cup. The consistency of the resin-hardener mixture was similar to maple syrup and it dripped off of vertical surfaces. Next, filler was added to modify the properties of the resin system. The consistency of the resin system with 15% filler was similar to ketchup and it sagged down vertical surfaces. The consistency of the resin system with 20% filler was similar to mayonnaise; it clung to vertical surfaces and peaks fell over. The consistency of the final resin system with 25% filler was similar to peanut butter; it clung to vertical surfaces and peaks did not fall over.

It was critical to ensure that the exact quantities of resin, hardener, and filler were used and that they were mixed thoroughly. Care was also taken to minimize the amount of air trapped during the mixing process because air bubbles can lead to defects in the final composite [4]. These steps were essential for a proper cure for experimental analysis purposes. The resin system for each laminate was mixed separately in order to maximize the pot life of the epoxy. It is usually best to avoid mixing large quantities of epoxy because the resin system heats up more rapidly. Fig. 3.13 shows the epoxy resin system being mixed for one of the 2-ply specimens:

Figure 3.13: Mixing Epoxy, Hardener, and Filler

The application of the epoxy to the fiberglass cloth was done over a table which was covered with plastic sheets. The plastic prevented the epoxy from damaging the table surface and limited the potential of the fiberglass cloth from changing orientation as it was laid-up. A picture of the layup tools and table can be seen in Fig. 3.14.

Figure 3.14: Tools Used for Specimen Layup

A thin coat of epoxy was initially applied to the plastic sheet on the table. A layer of fiberglass was then laid on top of the resin, and then more resin was applied to the top surface of the fiberglass using a wood stirring utensil. The epoxy was then spread evenly across the S-glass by using a flat spatula applicator, as shown in Fig. 3.15:

Figure 3.15: Application of Epoxy Resin and Filler to Fiberglass Plies

This process was repeated for each pre-cut piece of woven roving fiberglass in order to completely wet out each layer of fabric without retaining extra resin.

Depending on the specimen fabricated, either two or ten plies were then stacked on top of one another with the fiber orientation running in the same direction. That is to say, the specimens were laid up with a ply orientation of either $[0_2]$ or $[0_{10}]$ to create balanced laminates which should exhibit in-plane orthotropic behavior. Each laminate was considered balanced since its plies were symmetric about the mid-plane and were all

oriented at 0° , with equal thickness and the same material properties throughout.

For balanced laminates, an in-plane normal load should only induce mid-plane normal strains and should not induce any mid-plane shear strains. Also, an applied shear load should only induce a mid-plane shear strain with no accompanying normal strain. Therefore, there is no coupling between extension loads and shear strain. Also, since all of the plies are oriented at 0 degrees, the corresponding coupling and bending stiffness coefficients of the laminate are zero [4]. This infers that there should be little to no bending or twisting once the laminates are cured.

A rolling pin was then used on the stack of fiberglass plies so that the epoxy would evenly disperse throughout the specimen. The rolling pin was also used to apply pressure to reduce the likelihood of voids and defects between the layers. Fig. 3.16 shows rolling a 10-ply specimen after the layers had been stacked symmetrically.

Figure 3.16: Spreading Epoxy Resin and Filler with Rolling Pin

3.3.4 Vacuum Bagging

Once the plies were wetted out, each stack was carefully transferred to the vacuum bagging fixture. A non-porous polyethylene release film was placed between the plies and the bottom plate of the aluminum bagging fixture to provide a smooth surface finish on the underside of the composite and to prevent epoxy from clogging the fixture's vacuum vent holes. A perforated polyethylene release film was placed on the top surface of the composite to provide a smooth surface finish and to allow excess resin to be squeezed out of the laminate during the vacuum process. Breather/ bleeder cloth was placed over the perforated release film to allow the vacuum to actively pull air from the system and to absorb excess resin removed from the laminate. A *Teflon* non-porous release film was then put on top of the breather/bleeder cloth to prevent the cloth from sticking to the final layer of vacuum bagging film and the top aluminum frame of the bagging fixture. A schematic of the vacuum bag stacking sequence is shown in Fig. 3.17.

Figure 3.17: Vacuum Bag Stacking Sequence

As previously mentioned, the vacuum bagging fixture was 24 inches square (i.e., 24 inches wide by 24 inches long). The internal dimensions of the fixture were slightly smaller, being approximately 20 inches square. Since each fiberglass specimen was 6 inches wide by 14 inches long, only three could be placed in the vacuum bagging fixture at a time. The bagging fixture was closed and the lid was secured once 3 laminate specimens were placed inside. The vacuum pump was then attached to the fixture via a high pressure (HP) quick-disconnect valve. The vacuum was turned on and the laminates were allowed to cure at room temperature for 10 hours. The average curing temperature for the specimens was 78°F, which is above both epoxy manufactures' suggested minimum curing temperature [39]. Fig. 3.18 shows a wetted out 10-ply specimen placed in the vacuum bagging fixture, as well as a picture of the closed fixture with the vacuum pump attached to the HP quick-disconnect valve.

Figure 3.18: Vacuum Bagging Fixture with Wetted Out Specimen (Left) and Vacuum Bagging Fixture with Vacuum Applied (Right)

3.3.5 *Post-Cure*

Even though both manufacturers indicate that a room temperature cure (RTC) is adequate for most applications, a post-cure is still recommended. Post-cures are done subsequent to the RTC and require that external heat be applied to the specimen for an extended period of time. The additional heat increases the molecular flow of the epoxy and allows the resin and hardener molecules to continue cross-linking. The continuation of the curing process at elevated temperatures results in composites that are less brittle than those only cured at room temperature [7]. The additional heat also helps improve the physical characteristics such as the specimen's hardness, tensile modulus and strength, flexural modulus and strength, compression yield strength, and glass transition temperature (T_g). T_g is the temperature at which the cured epoxy becomes molecularly active again. Subjecting a composite structure to temperatures beyond its glass transition temperature can make it more susceptible to damage; therefore, it is important to obtain a T_g higher than the intended service temperature of the composite.

All test specimens were subjected to a post-cure to ensure that the optimum mechanical properties were obtained. The post-cure heat cycle was carried out at atmospheric pressure using an industrial oven located in the Cal Poly Aerospace hangar. The specimens were placed in the oven at room temperature and then temperature was increased at a rate of 4°F per minute. It took approximately twenty-four minutes to reach the operating temperature

of 120°F, at which point the temperature was held constant for four hours. The temperature was then decreased at approximately the same rate (4°F/min) for twenty-one minutes until the oven reached an operating temperature of 85°F. The oven was run for an additional eight hours at this temperature until it was shutoff. A plot of the post-cure heat cycle can be seen in Fig. 3.19.

Figure 3.19: Post-Cure Heat Cycle

Unfortunately, the rate of temperature increase and decrease was not always consistent. It was necessary to manually adjust the oven's temperature dial throughout the ramp-up and ramp-down stages of the heat cycle in order to obtain a rate as close as possible to 4°F/min. Caution was exercised to ensure that the laminates did not heat up too quickly. Doing so

could over-excite the molecules, causing them to become entrapped and to plasticize before cross-linking, which would prevent the specimens from obtaining their optimum mechanical properties [33]. A sample of the untrimmed post-cured laminates is shown in Fig. 3.20.

Figure 3.20: Cured 2-Ply Laminates

The specimens shown above are 2-ply laminates which were laid-up with the *Aeropoxy* resin system and high-density filler. To the naked eye, there was no visible difference between the laminates made with the *Aeropoxy* or West System resin products. However, there was a noticeable difference between the specimens made with high-density and limestone filler. The specimens made with limestone filler appeared green in color, whereas the ones made with high-density filler appeared white. This can be seen in Fig. 3.21:

Figure 3.21: Post-Cured and Trimmed Laminates

The eighteen laminates were approximately 6 inches wide and 14 inches long after curing. They were then trimmed with the tile saw to a final dimension of 4 inches by 12 inches, as shown in the figure above, to create orthogonal edges and to remove loose fibers and excess epoxy. These trimmed laminates were used for dynamic modal analysis prior to cutting them down for use as tensile and low-velocity impact specimens.

4 EXPERIMENTAL EQUIPMENT AND SETUP

4.1 Weight Fraction Test

The weight fraction, which is also referred to as the mass fraction, is an experimental means to compare the respective fiber-to-resin ratio of a given test specimen. The results of a weight fraction test also provide a basis for substantiating similarities and/or differences between the mechanical properties of different specimens.

In order to carry out the test, a one-inch by one-inch square was cut off of each of the eighteen laminates. The dimensions of each 1-inch square were then recorded to determine their approximate volume. The square specimens were then weighed on a digital scale and their pre-test weights were noted. Next, the specimens were “cooked” one at a time in a *Thermolyne 47900* furnace which was preheated to 750°F. The furnace is shown in Fig. 4.1.

Figure 4.1: Thermolyne 47900 Furnace

Each specimen was placed on a steel plate during the “cooking” process to ensure that the post-test specimens could be removed easily and weighed accurately. The 2-ply and 10-ply square laminates were left in the furnace for approximately 25 and 85 minutes, respectively, until the resin melted and the fiberglass plies had separated. The post-test specimen weights were then recorded. The results of the fiber weight fraction test are documented in section 5.1.1.

4.2 Static Test Equipment

Tensile and compressive tests are the most common methods for obtaining a material’s basic mechanical properties. Depending on the type of analysis and the intended use for the data, it is not always necessary to conduct both types of tests. The primary objectives for the following static tests were to obtain each laminate’s tensile modulus of elasticity and to better understand the effects of filler material on a composite’s stiffness and strain-to-failure. The simplest method of experimentally calculating the elastic tensile modulus of a composite is by conducting a tensile test. Tensile test equipment typically consists of a load frame with either mechanical or hydraulic grips, a load cell, an extensometer, and a computer to record and analyze the data.

The tensile strength tests were conducted per American Society for Testing and Materials (ASTM) specification D-638 with the exception of the specimens not being machined to the specified “dog bone” shape. Rather,

the test specimens were cut with the tile saw in a rectangular shape which did not have a rounded transition from a wide loading region to a narrow loading region. The “dog bone” shape is ideal since it generally limits the specimen’s ultimate failure to the narrow loading region. However, machining equipment was not available for use and attempting to shape the specimens with a tile saw would likely introduce unwanted stress concentrations. Metal tabs were not bonded to the tensile specimens since the load frame had an adjustable-pressure hydraulic grip with surfalloy-surfaced grips, which are shown in Fig. 4.2. Surfalloy grips are designed to be directly clamped to tensile test specimens without bonded tabs. The unique surface texture is intended to prevent damage which is typically caused by grips with “teeth”.

Figure 4.2: Surfalloy-Surfaced Grips

The width and thickness of each tensile test specimen was recorded prior to conducting the static tests to determine their undeformed cross-sectional area. A dimensional summary of the specimens is provided in the experimental results section.

4.2.1 Tensile Test Load Frame

The tensile tests for the 2-ply specimens were conducted at room temperature on a 5-kip MTS *Sintec Load Frame* which was equipped with a load cell to measure the applied tensile force. The load frame is shown in Fig. 4.3.

Figure 4.3: 5-kip MTS Sintec Load Frame

The tensile tests for the 10-ply specimens were conducted at room temperature on a 10-kip MTS *Sintec Load Frame* since the maximum tensile loads were expected to exceed the capabilities of the 5-kip machine. The 10-

kip load frame was also equipped with a load cell to measure the applied tensile force. The load frame is shown in Fig. 4.4.

Figure 4.4: 10-kip MTS Sintec Load Frame

Each of the 2- and 10-ply laminates were aligned in the respective MTS tensile machine, clamped with the hydraulic-pressure grips at 1-inch from each end, and loaded by the crosshead at a ramp rate of 0.050 inches per minute until the specimens ultimate failure occurred.

4.2.2 Tensile Test Extensometer

The tensile strain was measured with an MTS *Model 632.11B-20* extensometer which had a total gage length of 1.00-inch. The extensometer, which is shown in Fig. 4.5, calculates the axial strain for each specimen by

measuring the percent elongation of the composite over the total gauge length.

Figure 4.5: MTS Extensometer

The extensometer was attached using metal clips which applied pressure to each side of the specimen to prevent the device from sliding during each static test. Fig. 4.6 shows a 10-ply S-glass laminate aligned in the hydraulic-pressure grips with the MTS extensometer applied.

Figure 4.6: MTS Extensometer Attached to 10-Ply Static Test Specimen

4.2.3 Tensile Test Data Acquisition

The tensile load frame, load cell, and extensometer were connected to a desktop computer equipped with MTS *TestWorks 4* data acquisition software. Using the undeformed cross-sectional area of each laminate and the transient uniaxial tensile force recorded by the load cell, the MTS software calculated the resultant stress history. The software concurrently recorded the longitudinal strain measured by the extensometer. The program then output the resulting tensile stress-strain curve for each static test specimen. A screen-shot of the MTS *TestWorks 4* software used for experimental testing is shown in Fig. 4.7.

Figure 4.7: Stress-Strain Plot Generated by MTS TestWorks 4 Software

4.3 Dynamic Test Equipment

The main objective of the dynamic tests was to examine matrix composition and thickness effects of the laminated woven roving S-glass epoxy composite plates, which were subjected to vibrational and low-velocity impact loads.

4.3.1 Modal Analysis Test Equipment

The 2- and 10-ply laminates used for dynamic modal analysis had an average thickness of 0.030 and 0.155 inches, respectively, and were approximately 4 inches wide and 12 inches long (These specimens were later cut down for use as tensile and low-velocity impact specimens). The modal analysis for each of the 2- and 10-ply specimens was conducted at room temperature on an MB Electronics magnetic shake table which had a single degree of freedom. The shake table is shown in Fig. 4.8:

Figure 4.8: MB Electronics Magnetic Shake Table

The shake table's oscillatory platform was equipped with an Aluminum 2024 clamp fixture which was approximately 1-inch wide and 6-inches in length. The test specimens were centered in the clamp fixture, width-wise, with one end positioned flush with the rear of the aluminum fixture. The clamp was then tightened using two nuts and bolts, effectively creating a cantilever plate for vibrational testing. The magnetic shake table with a 2-ply S-glass specimen loaded in the clamp fixture can be seen in Fig. 4.9.

Figure 4.9: Shake Table with Specimen Loaded in Clamp Fixture

The rotational shake table was then fed an electronic sinusoidal signal with a frequency range of 0 to 1,000 Hertz, which was produced by an analog Hewlett Packard function generator. Before entering the shake table, the signal from the function generator was passed through a power amplifier to increase the voltage, as needed, to operate the shake table. A piezoelectric

accelerometer, shown in the figure above, was initially connected to a National Instruments *SCB-100* electronic module which interfaces with a desktop computer equipped with *LabVIEW* software. The module and software act as a spectrum analyzer to control the sweep speed and frequency range of the shake table, while the computer records the signal amplitudes and frequencies. The system is also capable of determining the modes of the natural frequencies and plotting the transient signal amplitude.

Unfortunately, the *SCB-100* electronic module was malfunctioning, so the piezoelectric accelerometer and *LabVIEW* software could not be used. Therefore, the natural frequencies and corresponding mode shapes had to be determined using a more rudimentary approach. Similar to the previous experimental setup, the output signal was produced with the analog Hewlett Packard frequency generator and had a frequency range of 0 to 1,000 Hertz. Before entering the shake table, the signal was passed through a power amplifier to increase the voltage, as needed, to operate the shake table and then through a digital frequency meter. The frequency generator, power amplifier, and digital frequency meter are shown below in Fig. 4.10.

Figure 4.10: Function Generator (Top-Left), Signal Amplifier (Top-Right), and Digital Frequency Meter (Bottom)

The natural frequencies and mode shapes were determined by attaching each composite test specimen to the magnetic shake table one at a time and manually adjusting the frequency and amplitude inputs. The first mode shape and frequency were found when the plate yielded a maximum deflection at the tip. The successive frequencies were found by sprinkling salt or coffee grounds across the surface and determining the frequency at which the granules aligned at the nodes.

4.3.2 Impact Test Equipment

The dynamic impact tests were conducted at room temperature with an Instron *Dynatup 9250HV* transverse drop-weight machine at increasing impact energies of 50, 55, and 60 inch-lb_f and a constant impactor mass of

12.57 pounds. Impacts tests were only carried out on the 10-ply specimens because the minimum impactor mass of the machine exceeded the penetration threshold of the 2-ply laminates. A piezoelectric force transducer affixed to the drop-weight device, localized in the 5/8-inch hemispherical impactor nose, yielded the complete force versus time history of each impact event. The contact force between the impactor and the composite plate, as well as the energy absorbed during impact, were captured as functions of time. The *Dynatup 9250HV* shown in Fig. 4.11 was equipped with a pneumatic rebound brake to prevent the impactor from striking a specimen more than once per impact test.

Figure 4.11: Instron Dynatup 9250HV Impact Machine and Controls

The impact tests followed the applicable standards in ASTM D-5628 with the exception of how the laminates were attached to the test fixture. The standard requires the test specimen to be clamped along a circumference; however, a device with this geometry was not available for use. Consequently, the 3-inch square composite impact coupons were placed in the center of a 6-inch by 12-inch steel test fixture which had a 1.50-inch diameter hole in the center. The specimens were centered on the fixture, over the hole, and then clamped on all four sides using 0.25-inch wide aluminum strips and locking c-clamp vise grips. The protective clear acrylic enclosure was then sealed and the impact tests were conducted. The impact test fixture is shown in Fig. 4.12.

Figure 4.12: Instron Dynatup 9250HV and Impact Test Fixture

The force transducer, impact machine, and associated controls were connected to a desktop computer equipped with Instron *Impulse* software. The system was equipped with an impulse signal conditioning unit and impulse data acquisition software to record the transient impact force, energy, and velocity. The impact machine also used a velocity detector to integrate the displacement-time trace from the recorded force-time data. Subsequent to the tests, the *Impulse* software plotted the force and energy curves as functions of time. A screen-shot of the Instron *Impulse* software after running a low-velocity impact test is shown in Fig. 4.13.

Figure 4.13: Transient Force and Energy Plots Generated by Instron Impulse Software

The maximum indentation depth of each low velocity impact was measured with a Mitutoyo *ABSOLUTE Digimatic 547 Series* depth gauge subsequent to the dynamic impact testing. The gauge, which is shown in Fig. 4.14, has a resolution of 0.0005-inch and an accuracy of 0.001-inch [3].

Figure 4.14: Mitutoyo ABSOLUTE Digimatic Depth Gauge

5 ANALYSIS OF EXPERIMENTAL RESULTS

5.1 Weight and Volume Fraction Results

5.1.1 Weight Fraction Calculations

The fiber weight fraction of a cured laminate can be approximated using Eqn. 5.1 by determining the total composite weight, w_c , and the constituent fiber weight, w_f .

$$\text{Fiber Weight \%} = \frac{w_f}{w_c} * 100 \quad (5.1)$$

As previously mentioned, the pre-test volume and weight of the eighteen 1-inch square test specimens were recorded. The 2-ply and 10-ply test coupons were then cooked in a furnace for approximately 25 and 85 minutes, respectively, until the resin melted and the fiberglass plies had separated. The remaining fiberglass plies were then weighed to determine each specimen's constituent fiber weight. Eqn. 5.1 was then used to determine the fiber weight as a percentage of the original coupon weight. The results of the weight fraction test for the 2-ply specimens are shown in Table 5.1:

Table 5.1: Fiber Weight Fractions for 2-Ply Laminates

Specimen	Laminate Volume (in ³)	Laminate Mass (g)	Fiber Mass (g)	Matrix Mass (g)	Fiber Weight Fraction (%)
W ₂ ^{15HD}	0.028	0.75	0.51	0.24	68.0
W ₂ ^{20HD}	0.027	0.74	0.47	0.27	63.5
W ₂ ^{25HD}	0.028	0.78	0.46	0.32	59.0
A ₂ ^{15HD}	0.028	0.76	0.50	0.26	65.8
A ₂ ^{20HD}	0.030	0.83	0.52	0.31	62.7
A ₂ ^{25HD}	0.029	0.81	0.49	0.32	60.5
W ₂ ^{15L}	0.030	0.76	0.54	0.22	71.1
W ₂ ^{20L}	0.028	0.73	0.48	0.25	65.8
W ₂ ^{25L}	0.029	0.78	0.48	0.30	61.5
A ₂ ^{15L}	0.029	0.77	0.52	0.25	67.5
A ₂ ^{20L}	0.030	0.81	0.50	0.31	61.7
A ₂ ^{25L}	0.028	0.78	0.48	0.30	61.5
Mean	0.029	0.78	0.50	0.28	64.0

The fiber weight fractions for the 2-ply laminates with high-density filler ranged from 59.0% to 68.0%, with an average of 63.3%. Similarly, the weight fraction for the laminates with limestone filler ranged from 61.5% to 71.1%, with an average of 64.9%. The average fiber weight fraction for all of the 2-ply specimens was 64.0%, which was within $\pm 1\%$ of the averages for the laminates with high-density and limestone filler. Therefore, it was assumed that the differences in the weight fractions were negligible and that the differences in mechanical properties for each 2-ply specimen could be attributed to the constituent epoxy resin and filler materials. It can also be noted that the fiber weight fraction tended to decrease as the quantity of filler increased. This could be a result of the filler material increasing the viscosity

of the resin system, which could have led to the fiberglass not being wetted-out properly.

The same weight fraction test procedures were used to determine the fiber weight percentage for each of the 10-ply specimens. The results of the test and the calculated fiber weight percentages are shown in Table 5.2:

Table 5.2: Fiber Weight Fractions for 10-Ply Laminates

Specimen	Laminate Volume (in ³)	Laminate Mass (g)	Fiber Mass (g)	Matrix Mass (g)	Fiber Weight Fraction (%)
A ₁₀ ^{15HD}	0.152	4.12	2.66	1.46	64.6
A ₁₀ ^{20HD}	0.149	4.15	2.54	1.61	61.2
A ₁₀ ^{25HD}	0.144	4.05	2.59	1.46	64.0
A ₁₀ ^{15L}	0.155	4.08	2.51	1.57	61.5
A ₁₀ ^{20L}	0.158	4.23	2.77	1.46	65.5
A ₁₀ ^{25L}	0.152	4.19	2.61	1.58	62.3
Mean	0.152	4.14	2.61	1.52	63.2

The fiber weight fraction for the 10-ply laminates with high-density filler ranged from 61.2% to 64.6%, with an average of 63.3%. Similarly, the weight fraction for the laminates with limestone filler ranged from 61.5% to 65.5%, with an average of 63.1%. The average fiber weight fraction for all of the 10-ply specimens was 63.2%, which was within $\pm 0.1\%$ of the averages for the laminates with high-density and limestone filler. Therefore, it was assumed that the differences in the weight fractions were negligible and that the differences in mechanical properties for each 10-ply specimen could be attributed to the constituent epoxy resin and filler materials. Unlike the 2-ply specimens, the fiber weight fractions for the 10-ply laminates did not tend to

decrease as the quantity of filler increased. This is indicative of the fiberglass being wetted-out properly for the 10-ply laminates with higher quantities of filler.

5.1.2 Volume Fraction Calculations

The volume fraction of a composite is similar to the weight fraction in the sense that it is used to determine the relative proportions of the resin and reinforcing fiber materials. However, the fiber volume fraction, V_f , is only used for theoretical analysis and is primarily employed during the design phase to approximate the properties of a composite material.

V_f of a fiber-reinforced laminate is maximized when the fabric plies are stacked such that the individual strands are hexagonally close packed. Hexagonally close packed means that if the cross-section of a composite were to be examined, one would note that the plies are stacked in a manner to minimize the gap sizes between the fibers. As a result of this stacking technique, the required resin quantity is reduced and the surface-area contact between plies is increased. This generally maximizes the strength-to-weight ratio of the composite and optimizes its mechanical properties.

A more common fiber stacking technique is known as the rectangular array. If a composite cross-section with rectangular array packed fibers were to be examined, the fibers of each ply would be stacked precisely on top of each other. This is one of the most simple and least labor-intensive methods

of stacking plies; however, it usually results in a less than optimal strength-to-weight ratio.

The volume fractions of a composite can be expressed as functions of the densities and weight fractions of the constituent materials (e.g. fiber and matrix). For example, the fiber volume fraction of a laminate can be determined using Eqn. 5.2, where W_f is the fiber weight fraction and ρ_f and ρ_m are the fiber and matrix densities, respectively.

$$V_f = \frac{\frac{W_f}{\rho_f}}{\frac{W_f}{\rho_f} + \frac{1-W_f}{\rho_m}} \quad (5.2)$$

The fiber and matrix densities are typically provided by the material manufacturers. However, the resin system for each test specimen was modified with different quantities and types of filler material, so the matrix densities (ρ_m) supplied by the manufacturers could not be used. Instead, the density of each composite specimen was approximated using the volume and mass measurements recorded from the weight fraction test. The calculated composite densities for the 2-ply laminates are shown in Table 5.3:

Table 5.3: Calculated Densities for 2-Ply Laminates

Specimen	Laminate Mass (g)	Laminate Volume (in ³)	Laminate Density (g/in ³)
W ₂ ^{15HD}	0.75	0.028	26.79
W ₂ ^{20HD}	0.74	0.027	27.41
W ₂ ^{25HD}	0.78	0.028	27.86
A ₂ ^{15HD}	0.76	0.028	27.14
A ₂ ^{20HD}	0.83	0.030	27.67
A ₂ ^{25HD}	0.81	0.029	27.93
W ₂ ^{15L}	0.76	0.030	25.33
W ₂ ^{20L}	0.73	0.028	26.07
W ₂ ^{25L}	0.78	0.029	26.90
A ₂ ^{15L}	0.77	0.029	26.55
A ₂ ^{20L}	0.81	0.030	27.00
A ₂ ^{25L}	0.78	0.028	27.86
Mean	0.78	0.029	27.04

The laminate densities for the 2-ply specimens ranged from 25.33 to 27.93 g/in³, with an average density of 27.04 g/in³. The densities of the laminates generally increased with the addition of filler material, which was expected. For the most part, specimens with the same quantity of filler material tended to have a higher density if they were laid-up with the *Aeropoxy* resin system as opposed to West Systems.

The composite densities were then calculated in a similar fashion for the 10-ply laminates. The results can be seen in Table 5.4, below.

Table 5.4: Calculated Densities for 10-Ply Laminates

Specimen	Laminate Mass (g)	Laminate Volume (in ³)	Laminate Density (g/in ³)
A ₁₀ ^{15HD}	4.12	0.152	27.11
A ₁₀ ^{20HD}	4.15	0.149	27.85
A ₁₀ ^{25HD}	4.05	0.144	28.13
A ₁₀ ^{15L}	4.08	0.155	26.32
A ₁₀ ^{20L}	4.23	0.158	26.77
A ₁₀ ^{25L}	4.19	0.152	27.57
Mean	4.14	0.152	27.29

The laminate densities for the 10-ply specimens ranged from 26.32 to 28.13 g/in³, with an average density of 27.29 g/in³. Again, the densities of the laminates increased with the addition of filler material.

Similar to a composite's volume fraction, the density of a laminate is a direct result of its constituents. As such, the composite density, ρ_c , can be expressed as a function of the fiber density, matrix density, and the respective fiber and matrix weight fractions, as shown in Eqn. 5.3 [5]:

$$\rho_c = \frac{1}{\frac{W_f}{\rho_f} + \frac{W_m}{\rho_m}} \quad (5.3)$$

By manipulating Eqn. 5.3, the matrix density (ρ_m) can then be written as a function of the fiber density (ρ_f), composite density (ρ_c), and the fiber and matrix weight fractions (W_f and W_m , respectively). The equation for fiber volume fraction, V_f , can then be reduced to Eqn. 5.4 by substituting in the aforementioned expression for the matrix density:

$$V_f = \frac{\rho_c}{\rho_f} * W_f \quad (5.4)$$

Eqn. 5.4 was then used to determine the respective fiber volume fraction for each of the 2-ply laminates. A summary of the results is shown in Table 5.5:

Table 5.5: Fiber Volume Fractions for 2-Ply Laminates

Specimen	Laminate Density (g/in ³)	Fiber Density (g/in ³)	Weight Fraction (%)	Fiber Volume Fraction (%)
W₂^{15HD}	26.79	37.69	68.0	48.3
W₂^{20HD}	27.41	37.69	63.5	46.2
W₂^{25HD}	27.86	37.69	59.0	43.6
A₂^{15HD}	27.14	37.69	65.8	47.4
A₂^{20HD}	27.67	37.69	62.7	46.0
A₂^{25HD}	27.93	37.69	60.5	44.8
W₂^{15L}	25.33	37.69	71.1	47.8
W₂^{20L}	26.07	37.69	65.8	45.5
W₂^{25L}	26.90	37.69	61.5	43.9
A₂^{15L}	26.55	37.69	67.5	47.6
A₂^{20L}	27.00	37.69	61.7	44.2
A₂^{25L}	27.86	37.69	61.5	45.5
Mean	27.04	37.69	64.0	45.9

Theoretically, unidirectional composites can have a fiber volume fraction as high as 90% with hexagonally close packed fibers, and as high as 75% with rectangular array packed fibers. However, the use of woven roving fabric in a composite will decrease the maximum obtainable fiber volume fraction. Furthermore, composites fabricated with hand-layup techniques, especially those that do not apply external pressure during the cure cycle, can result in a “resin-rich” laminate. Consequently, fiberglass composites with woven roving fiber typically have a V_f between 40% and 60% [47].

The fiber volume fraction for the 2-ply laminates with high-density filler ranged from 43.6% to 48.3%, with an average of 46.1%. The fiber volume

fraction for the laminates with limestone filler ranged from 43.9% to 47.6%, with an average of 45.8%. The average fiber volume fraction for all of the 2-ply specimens was 45.9%, which indicates that the fibers were not hexagonally close packed. Also, as mentioned in the *Epoxy Resin System Preparation* section, the laminates were designed to have a fiber volume fraction of 50%. However, the volume fraction for each of the 2-ply specimens was slightly less than the design value, which means the laminates were “resin-rich”. The use of different epoxy resin systems did not appear to have a significant effect on the fiber volume fraction.

Eqn. 5.4 was also used to determine the fiber volume fraction for each of the 10-ply specimens. A summary of the results is shown in Table 5.6:

Table 5.6: Fiber Volume Fractions for 10-Ply Laminates

Specimen	Laminate Density (g/in ³)	Fiber Density (g/in ³)	Weight Fraction (%)	Fiber Volume Fraction (%)
A ₁₀ ^{15HD}	27.11	37.69	64.6	46.4
A ₁₀ ^{20HD}	27.85	37.69	61.2	45.2
A ₁₀ ^{25HD}	28.13	37.69	64.0	47.7
A ₁₀ ^{15L}	26.32	37.69	61.5	43.0
A ₁₀ ^{20L}	26.77	37.69	65.5	46.5
A ₁₀ ^{25L}	27.57	37.69	62.3	45.6
Mean	27.29	37.69	63.2	45.7

The fiber volume fraction for the 10-ply laminates with high-density filler ranged from 45.2% to 47.7%, with an average of 46.4%. The fiber volume fraction for the laminates with limestone filler ranged from 43.0% to 46.5%, with an average of 45.0%. The average fiber volume fraction for all of

the 10-ply specimens was 45.7%. Similar to the 2-ply specimens, the average fiber volume fraction for these laminates indicates that the fibers were not hexagonally close packed and that the specimens were slightly “resin-rich”.

The fibers for each laminate were likely arranged in a pattern similar to the rectangular array since the fiber volume fractions were all below 50%. It was assumed that the differences in V_f were negligible when comparing the material properties of each specimen since the fiber volume fractions were all within 7% of the design value.

5.2 Static Test Results

5.2.1 Tensile Test Theory and Calculations

The width and thickness of each tensile test specimen was recorded prior to conducting the tensile tests in order to determine the undeformed cross-sectional area of each laminate. A dimensional summary of the specimens is provided in the subsections below. The cross-sectional areas were then entered into the MTS *TestWorks 4* software to enable the program to calculate the resultant stress due to the applied tensile load. The uniaxial tensile loads for the 2-ply and 10-ply specimens were recorded by the load cells on the 5-kip and 10-kip MTS *Sintec Load Frames*, respectively. The tensile stress, σ , was then calculated as a function of the laminate cross-sectional area (A_c) and the applied tensile load (F) using Eqn. 5.5.

$$\sigma = \frac{F}{A_c} \quad (5.5)$$

The tensile strain, ϵ , was captured by the MTS *Model 632.11B-20* extensometer which had a gauge length of 1.00-inch. The extensometer calculates the strain by measuring the elongation of the material, ΔL , and dividing it by the gauge length, L , as shown in Eqn. 5.6:

$$\epsilon = \frac{\Delta L}{L} \quad (5.6)$$

The axial strain was recorded by the MTS *TestWorks 4* software in order to create a tensile stress-strain curve for each test specimen.

All of the laminates were assumed to be isotropic due to the use of fiberglass fabric with a bi-directional woven roving weave. Isotropic materials have stress-strain relationships that are independent of the orientation of the coordinate system for any given point. Since fiberglass is brittle, it generally does not exhibit much, if any plastic deformation before ultimate failure [30]. Therefore, it was also assumed that the tensile test specimens only experienced linear-elastic deformation before rupture. As a result, *Young's modulus*, E , was found by plotting the stress-strain curve, generating a linear trend-line, and then determining the slope of the line. The slope of the trend-line is a representation of the material's stiffness and can be expressed by Eqn. 5.7.

$$E = \frac{\sigma}{\epsilon} \quad (5.7)$$

The shear modulus, which is also known as the modulus of rigidity, is used to determine a material's response to shearing strains. It is difficult to directly measure the shear modulus, G , since it is a ratio of the shear stress to shear strain. A more common and practical method for approximating the shear modulus for isotropic laminates is by using the material's modulus of elasticity and its *Poisson's ratio*, as shown in Eqn. 5.8.

$$G = \frac{E}{2(1+\nu)} \quad (5.8)$$

Poisson's ratio, ν , is a ratio of the transverse strain to the axial strain as a material is subjected to an axial load. Only one extensometer was available for the tensile tests, so the strain in the transverse direction was not measured. As a result, *Poisson's ratio* for the S-glass fabric was assumed to be 0.22 [21].

5.2.2 Tensile Test Results for 2-Ply Specimens

The undeformed cross-sectional area of each 2-ply specimen was calculated prior to inserting the laminates into the 5-kip MTS *Sintec Load Frame*, one at a time. A dimensional summary is provided in Table 5.7.

Table 5.7: Dimensions of 2-Ply Tensile Test Specimens

Specimen	Width (in)	Thickness (in)	Cross-Sectional Area (in ²)
W_2^{15HD}	0.986	0.0285	0.0281
W_2^{20HD}	1.009	0.0261	0.0263
W_2^{25HD}	1.014	0.0266	0.0270
A_2^{15HD}	1.006	0.0282	0.0284
A_2^{20HD}	1.000	0.0310	0.0310
A_2^{25HD}	1.010	0.0322	0.0325
W_2^{15L}	1.009	0.0311	0.0314
W_2^{20L}	1.009	0.0318	0.0321
W_2^{25L}	0.995	0.0295	0.0294
A_2^{15L}	1.023	0.0316	0.0323
A_2^{20L}	1.002	0.0301	0.0302
A_2^{25L}	1.004	0.0280	0.0281
Mean	1.006	0.0296	0.0297
Std. Dev.	0.009	0.0021	0.0022

As mentioned previously, the tensile strength tests were conducted per ASTM D-638 with the exception that the specimens were cut into 1-inch by 4.5-inch rectangles which did not have a rounded transition from a wide loading region to a narrow loading region. Metal tabs were not bonded to the tensile specimens since the load frame had an adjustable-pressure hydraulic grip with surfalloy-surfaced grips.

The first 2-ply laminate, W_2^{15HD} , was aligned in the MTS tensile machine and then loaded at a ramp rate of 0.050 inches per minute until the specimen ruptured. The resultant stress-strain curve is shown in Fig. 5.1.

Figure 5.1: Tensile Strength for Laminate W_2^{15HD}

From the tensile strength results for laminate W_2^{15HD} it was concluded that the initial assumption of only linear-elastic deformation prior to rupture was valid. The S-glass fiber-reinforced laminate did not appear to undergo any plastic deformation as the applied stress and resulting strain increased with a linear relationship. As mentioned in the *Material Selection* section, this linear-elastic region is defined by *Hooke's Law* since the stress-to-strain ratio is constant. Using the least squares method, a linear regression was then developed to determine the average slope of the stress-strain curve. The value of the slope is significant because it represents the modulus of elasticity for the material, which was determined to be 2,172.9 ksi with an R-squared value of 0.9964. The R-squared value is worth noting since it is indication of how well the experimental results fit the linear trend line. A low R-squared value could imply that something went wrong during the static test, such as

the material slipping between the hydraulic grips. A high R-squared value likely indicates that the material experienced pure elastic deformation prior to ultimate failure. With an assumed *Poisson's ratio* of 0.22, the associated shear modulus determined for the laminate was 890.5 ksi. The maximum tensile load applied to laminate W_2^{15HD} was 1,296 lb_f, which resulted in a corresponding ultimate stress of 46.11 ksi and ultimate strain of 2.1%.

Fig. 5.2 shows laminate W_2^{15HD} after ultimate failure. The rupture occurred relatively close to the center of the specimen and the crack propagated in the latitudinal direction, which indicates that the laminate was uniformly loaded and aligned correctly in the load frame. Since the crack did not propagate on a diagonal, it also indicates that the fabric plies were aligned properly during the fabrication process. Laminate A_2^{25HD} experienced a similar failure mode. Refer to Appendix A for additional information regarding the tensile test mechanical behavior and failure mode of Laminate A_2^{25HD} .

Figure 5.2: Failure Mode for Laminate W_2^{15HD} Under Tensile Load

The second 2-ply tensile test specimen, W_2^{20HD} , was aligned and loaded in the tensile machine in a similar fashion as the first laminate. The resultant tensile strength results are shown in Fig. 5.3:

Figure 5.3: Tensile Strength for Laminate W_2^{20HD}

Laminate W_2^{20HD} did not appear to experience any plastic deformation prior to rupturing. The applied stress and resulting strain increased with a linear relationship until the laminate failed. The maximum tensile load applied to laminate W_2^{20HD} was 1,140 lb_f, which resulted in a corresponding ultimate stress of 43.28 ksi and strain-to-break of 1.8%. *Young's modulus* for the material was determined to be 2,370.1 ksi with an R-squared value of 0.9932. The modulus of rigidity determined for the laminate was 1,185.1 ksi.

Fig. 5.4 shows laminate W_2^{20HD} after rupturing due to applied loads from the static tensile test. The onset of damage to the composite began near the upper-left edge where the hydraulic grip was applying pressure,

which likely caused a stress concentration. The crack then propagated diagonally until the specimen experienced ultimate failure. Typically, the onset of damage to a tensile test specimen should occur near the center due to the load being uniform in the axial direction. The damage to this laminate likely propagated on an angle due to the specimen being misaligned in the MTS tensile machine and/or transverse shear loading. Laminates W_2^{15L} , W_2^{25L} , A_2^{15L} and A_2^{20L} experienced a similar failure mode. Refer to Appendix A for additional information regarding the tensile test mechanical behavior and failure modes of these specimens.

Figure 5.4: Failure Mode for Laminate W_2^{20HD} Under Tensile Load

The third 2-ply tensile test specimen, W_2^{25HD} , was aligned and loaded in the tensile machine in a similar manner as the other laminates. The resultant stress-strain curve is shown in Fig. 5.5.

Figure 5.5: Tensile Strength for Laminate W_2^{25HD}

Laminate W_2^{25HD} did not appear to experience any plastic deformation prior to rupturing. The applied stress and resulting strain increased with a linear relationship until the laminate failed. The maximum tensile load applied to laminate W_2^{25HD} was 1,156 lb_f, which resulted in a corresponding ultimate stress of 42.85 ksi and ultimate strain of 1.4%. The elastic modulus for the material was determined to be 2,805.1 ksi with an R-squared value of 0.9961. The associated shear modulus for the laminate was 1,402.6 ksi.

Fig. 5.6 shows laminate W_2^{25HD} after ultimate failure. The initial failure occurred in the center of the specimen near the left edge, likely due to a stress concentration. The crack then propagated diagonally until the specimen experienced ultimate failure. The damage likely propagated on an angle due to the specimen being misaligned in the tensile load frame. It is possible that flaws introduced during the fabrication process also affected the

material's strength. Laminates A_2^{20HD} and A_2^{25L} experienced a similar failure mode. Refer to Appendix A for additional information regarding the tensile test mechanical behavior and failure modes of these specimens.

Figure 5.6: Failure Mode for Laminate W_2^{25HD} Under Tensile Load

The fourth 2-ply tensile test specimen, A_2^{15HD} , was aligned and loaded in the tensile machine in a similar manner as the other laminates. The resultant stress-strain curve is shown in Fig. 5.7:

Figure 5.7: Tensile Strength for Laminate A_2^{15HD}

Laminate A_2^{15HD} did not appear to experience any plastic deformation prior to rupturing; however, the specimen did slip in the hydraulic grips during the first-half of the test. As a result, the grip pressure had to be increased “on the fly” to prevent the laminate from coming loose. The applied stress and resulting strain increased with a relatively linear relationship until the laminate failed. The maximum tensile load applied to laminate A_2^{15HD} was 1,284 lb_f, which resulted in a corresponding ultimate stress of 45.27 ksi and strain-to-break of 2.2%. *Young’s modulus* for the material was determined to be 2,044.2 ksi with an R-squared value of 0.9727. The associated modulus of rigidity for the laminate was 1,022.1 ksi.

Fig. 5.8 shows laminate A_2^{15HD} after rupturing due to applied loads from the static tensile test. The onset of damage to the composite began near the lower-left edge where the hydraulic grip was applying pressure. The crack then propagated in the transverse direction until the specimen experienced ultimate failure. Typically, the onset of damage to a tensile test specimen should occur near the center due to the load being uniform in the axial direction. The damage to this laminate likely occurred near the hydraulic grip due to excessive clamping pressure applied during the second-half of the test. The white striations in the longitudinal direction are also indicative of brittle failure due to fiber pull-out. Laminate W_2^{20L} experienced a similar failure mode. Refer to Appendix A for additional information regarding the tensile test mechanical behavior and failure mode of Laminate W_2^{20L} .

Figure 5.8: Failure Mode for Laminate A_2^{15HD} Under Tensile Load

Fig. 5.9 shows a comparison of the stress-strain curves for each of the 2-ply laminates with high-density filler. The general trend of data implies that increasing the quantity of filler will result in a higher modulus of elasticity and a lower ultimate strain. When evaluating the specimens with the same percentage of filler, the majority of composites fabricated with West System epoxy had a higher *Young's modulus*. This indicates that the laminates fabricated with West System epoxy were stiffer than those made with *Aeropoxy* epoxy, but also means they were more brittle. The specimens laid-up with West System products were expected to exhibit a higher elastic modulus because the high-density filler was specifically designed for use with the *105 Epoxy Resin and 206 Slow Hardener* resin system. The laminates fabricated with the *Aeropoxy* resin system had higher strain-to-break values, which suggests that they were more capable of deforming before ultimate failure.

Figure 5.9: Tensile Strength for 2-Ply Laminates with High-Density Filler

Fig. 5.10 shows a comparison of the stress-strain curves for each of the 2-ply laminates with limestone filler. Similar to the previous plot, the general trend of data implies that increasing the quantity of filler will result in a higher modulus of elasticity and a lower ultimate strain. Converse to the specimens with high-density filler, the composites with the same percentage of limestone filler had a higher *Young's modulus* when fabricated with *Aeropoxy* epoxy. This indicates that the laminates made with *Aeropoxy* epoxy were stiffer than those made with West System epoxy, but also means they were more brittle. The laminates fabricated with the West System resin system had higher strain-to-break values, which suggests that they were more capable of deforming before ultimate failure.

Figure 5.10: Tensile Strength for 2-Ply Laminates with Limestone Filler

Fig. 5.11 shows a comparison of the stress-strain curves for all of the 2-ply laminates. Independent of filler type (high-density or limestone), the data implies that increasing the quantity of filler will result in a higher modulus of elasticity and a lower strain-to-break. Therefore, increasing the quantity of filler also increases the brittleness of the material. Laminate W_2^{25HD} had a *Young's modulus* and shear modulus of 2,805.1 ksi and 1,402.6 ksi, respectively, which was the highest of all the specimens. Laminate W_2^{15L} had the lowest moduli of elasticity and rigidity, which were 1,916.2 ksi and 958.1 ksi, respectively.

Figure 5.11: Tensile Strength for All 2-Ply Laminates

The average E and strain-to-break values for the laminates fabricated with West System epoxy and high-density filler were 2,449.4 ksi and 1.8%, respectively; whereas the averages for the *Aeropoxy* specimens were 2,120.0 ksi and 2.1%. The average elastic modulus and ultimate strain for the laminates fabricated with West System epoxy and limestone filler were 1,980.1 ksi and 2.4%, respectively; whereas the averages for the *Aeropoxy* specimens were 2,188.5 ksi and 2.3%.

Fig. 5.12 shows all of the 2-ply laminates after the tensile tests had been conducted. The onset of damage for nearly half of the specimens began due to stress concentrations near the hydraulic grip. The damage caused by excessive clamping pressure could have been prevented by using

bonded metal tabs on both ends of each specimen. The probability of the laminates fracturing near their center would have been increased by machining the specimens into a “dog bone” shape with a rounded transition from a wide loading region to a narrow loading region. Two of the tensile test specimens that incurred damage near the grips also exhibited signs of brittle failure due to fiber pull-out. This could have been caused by the use of filler material in the resin system which may have weakened the bonding strength and load-transfer mechanism between the matrix and fibers.

Figure 5.12: Failure Mode for All 2-Ply Laminates

The other half of the test specimens fractured near the center of the laminate and then the cracks either propagated diagonally or in the latitudinal direction. This damage may have propagated on an angle due to the specimen slipping in the hydraulic grips and becoming misaligned in the load frame. The direction of crack propagation could have also been impacted by flaws introduced during specimen fabrication. Since fibers oriented at $\pm 45^\circ$ typically carry the shear loads in a composite, and none of the woven roving

S-glass test specimens had angled plies, the strength of the laminates may have been reduced due to transverse shear loading.

Table 5.8 provides a summary of the tensile test results for all of the 2-ply laminates. The average E and G for all of the 2-ply laminates was 2,184.5 ksi and 1,075.9 ksi, respectively. The strain recorded at the maximum load (also referred to as the strain-to-peak) was equal to the strain-at-break for all of the 2-ply specimens due to the brittleness of the glass fiber-reinforced composites.

Table 5.8: Mechanical Behavior of Tensile Test for All 2-Ply Specimens

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
W ₂ ^{15HD}	1,296	46.11	2.1	2,172.9	890.5
W ₂ ^{20HD}	1,140	43.28	1.8	2,370.1	1,185.1
W ₂ ^{25HD}	1,156	42.85	1.4	2,805.1	1,402.6
A ₂ ^{15HD}	1,284	45.27	2.2	2,044.2	1,022.1
A ₂ ^{20HD}	1,368	44.11	2.0	2,126.2	1,063.1
A ₂ ^{25HD}	1,546	47.55	2.1	2,189.6	1,094.8
W ₂ ^{15L}	1,443	46.00	2.4	1,916.2	958.1
W ₂ ^{20L}	1,534	47.79	2.4	1,972.8	986.4
W ₂ ^{25L}	1,477	50.30	2.4	2,051.2	1,025.6
A ₂ ^{15L}	1,607	49.71	2.4	2,004.4	1,002.2
A ₂ ^{20L}	1,457	48.32	2.2	2,140.7	1,070.4
A ₂ ^{25L}	1,505	53.55	2.2	2,420.3	1,210.2
Mean	1,401	47.07	2.1	2,184.5	1,075.9
Std. Dev.	153	3.13	0.3	136.4	146.8

On average, the 2-ply laminates laid-up with West System epoxy were more brittle than those made with *Aeropoxy*. Brittle materials are more likely

to experience total failure after being subjected to a low velocity impact when compared to ductile materials impacted at the same incident impact energy [6]. Ductile materials deflect more than stiff materials when subjected to loading, which allows the absorption of more impact energy without causing catastrophic damage. This is significant since the 10-ply laminates, which had not been fabricated yet, were primarily being made for analyzing the effect of impact performance as a result of filler type. Consequently, the 10-ply specimens were laid-up with the *Aeropoxy* resin system since it resulted in less brittle laminates and because it was less expensive than the West System epoxy.

5.2.3 Tensile Test Results for 10-Ply Specimens

The undeformed cross-sectional area of each 10-ply specimen was calculated prior to inserting the laminates into the 10-kip MTS *Sintec Load Frame*, one at a time. A dimensional summary is provided in Table 5.9.

Table 5.9: Dimensions of 10-Ply Tensile Test Specimens

Specimen	Width (in)	Thickness (in)	Cross-Sectional Area (in ²)
A₁₀^{15HD}	1.009	0.1579	0.1593
A₁₀^{20HD}	1.008	0.1510	0.1522
A₁₀^{25HD}	1.014	0.1420	0.1440
A₁₀^{15L}	1.002	0.1633	0.1636
A₁₀^{20L}	1.018	0.1561	0.1589
A₁₀^{25L}	0.964	0.1588	0.1531
Mean	1.003	0.1548	0.1552
Std. Dev.	0.020	0.0075	0.0069

Similar to tests for the 2-ply laminates, the 10-ply tensile strength tests were conducted per ASTM D-638 with the exception that the specimens were not machined to the specified “dog bone” shape. The first 10-ply laminate, A_{10}^{15HD} , was aligned in the MTS tensile machine and then loaded at a ramp rate of 0.050 inches per minute until the specimen ruptured. The resultant stress-strain curve is shown in Fig. 5.13:

Figure 5.13: Tensile Strength for Laminate A_{10}^{15HD}

Laminate A_{10}^{15HD} did not appear to experience any plastic deformation prior to rupturing; however, the specimen did slip in the hydraulic grips during the first-half of the test. As a result, the grip pressure had to be increased “on the fly” to prevent the laminate from coming loose. The applied stress and resulting strain increased with a relatively linear relationship until the laminate failed. The maximum tensile load applied to laminate A_{10}^{15HD} was 5,308 lb_f, which resulted in a corresponding ultimate stress of 33.3 ksi and strain-to-break of 1.37%. The elastic modulus for the material was determined to be

23.047 ksi with an R-squared value of 0.9861. The associated shear modulus for the laminate was 9.445 ksi.

Fig. 5.14 shows laminate A_{10}^{15HD} after rupturing due to applied loads from the static tensile test. The onset of damage to the composite began near the upper-right edge where the hydraulic grip was applying pressure. The crack then propagated in the latitudinal direction until the specimen experienced ultimate failure. Typically, the onset of damage to a tensile test specimen should occur near the center due to the load being uniform in the axial direction. The damage to this laminate likely occurred near the hydraulic grip due to excessive clamping pressure applied during the second-half of the test, which caused a stress concentration. Laminates A_{10}^{25HD} , A_{10}^{15L} , A_{10}^{20L} and A_{10}^{25L} experienced a similar failure mode. Refer to Appendix A for additional information regarding the tensile test mechanical behavior and failure modes of these specimens.

Figure 5.14: Failure Mode for Laminate A_{10}^{15HD} Under Tensile Load

The second 10-ply tensile test specimen, A_{10}^{20HD} , was aligned and loaded in the tensile machine in a similar fashion as the first laminate. The resultant tensile strength results are shown in Fig. 5.15:

Figure 5.15: Tensile Strength for Laminate A_{10}^{20HD}

Laminate A_{10}^{20HD} did not appear to experience any plastic deformation prior to rupturing. The applied stress and resulting strain increased with a linear relationship until the laminate failed. The maximum tensile load applied to laminate A_{10}^{20HD} was 6,135 lb_f , which resulted in a corresponding ultimate stress of 40.3 ksi and ultimate strain of 1.69%. *Young's modulus* for the material was determined to be 23.396 ksi with an R-squared value of 0.9959. The associated modulus of rigidity for the laminate was 11.698 ksi.

Fig. 5.16 shows laminate A_{10}^{20HD} after rupturing due to applied loads from the static tensile test. The onset of damage to the composite began near the lower-right edge where the hydraulic grip was applying pressure.

The crack then propagated in the latitudinal direction until the specimen experienced ultimate failure. Typically, the onset of damage to a tensile test specimen should occur near the center due to the load being uniform in the axial direction. The damage to this laminate likely occurred near the hydraulic grip due to excessive clamping pressure which caused a stress concentration.

Figure 5.16: Failure Mode for Laminate A_{10}^{20HD} Under Tensile Load

Fig. 5.17 shows a comparison of the stress-strain curves for each of the 10-ply laminates with high-density filler. The strain-to-break for laminate A_{10}^{15HD} was less than the ultimate strain for laminate A_{10}^{20HD} , but it was assumed that laminate A_{10}^{15HD} prematurely failed due to excess grip pressure applied to the specimen as it started to slip. As such, the general trend of data was similar to the 2-ply laminates with high-density filler since increasing the quantity of filler resulted in a higher modulus of elasticity and a lower

ultimate strain. Again, increasing the percentage of filler made the material more brittle and decreased the percentage of elongation prior to ultimate failure.

Figure 5.17: Tensile Strength for 10-Ply Laminates with High-Density Filler

Fig. 5.18 shows a comparison of the stress-strain curves for each of the 10-ply laminates with limestone filler. The general trend of data was similar to that of the 2-ply laminates with limestone filler since an increase in the percentage of inorganic filler resulted in a higher modulus of elasticity and a lower strain-to-break. For example, Laminate A_{10}^{25L} had a higher percentage of filler than laminate A_{10}^{15L} , which resulted in it being stiffer and

more brittle. However, laminate A_{10}^{15L} had a higher maximum percent of elongation (ultimate strain) prior to rupturing.

Figure 5.18: Tensile Strength for 10-Ply Laminates with Limestone Filler

Fig. 5.19 shows a comparison of the stress-strain curves for all of the 10-ply laminates. Laminate A_{10}^{25HD} had the highest stiffness and rigidity of all the specimens. On the contrary, laminate A_{10}^{15L} had the lowest *Young's modulus* and shear modulus, but had the highest ultimate strain. Laminate A_{10}^{25L} had the lowest ultimate strain before rupturing likely due to it having the largest percentage of filler by weight. Regardless of filler type (high-density or limestone), the data implies that increasing the quantity of filler will result in a higher modulus of elasticity and a lower strain-to-break. Therefore,

increasing the quantity of filler will result in a stiffer, more brittle material with a lower threshold of tensile deformation prior to ultimate failure.

Figure 5.19: Tensile Strength for All 10-Ply Laminates

The average E and strain-to-break values for the laminates fabricated with the *Aeropoxy* resin system and high-density filler were 24.763 ksi and 1.46%, respectively; whereas the averages for the specimens were limestone filler were 22.643 ksi and 1.52%.

Fig. 5.20 shows all of the 10-ply laminates after the tensile tests had been conducted. The onset of damage for nearly all of the specimens began near the hydraulic grip, which was likely due to excessive clamping pressure that caused stress concentrations. Those stress concentrations could have been prevented by using bonded metal tabs on both ends of each specimen.

None of the tensile test specimens showed signs of brittle failure due to fiber pull-out. The damage created by the hydraulic grip propagated through one test specimen on a diagonal. This is likely due to the specimen not being properly aligned in the load frame or due to flaws introduced during specimen fabrication. The probability of the laminates fracturing near their center would have been increased by machining the specimens into a “dog bone” shape with a rounded transition from a wide loading region to a narrow loading region.

Figure 5.20: Failure Mode for All 10-Ply Laminates

Table 5.10 provides a summary of the tensile test results for all of the 10-ply laminates. The experimental elastic moduli shown below were used for the numerical analysis, which will be discussed later on. The average E and G for all of the 10-ply laminates was 23.703 ksi and 11.505 ksi, respectively. The strain recorded at the maximum load (strain-to-peak) was equal to the strain-at-break for all of the 10-ply specimens due to the brittleness of the glass fiber-reinforced composites.

Table 5.10: Mechanical Behavior of Tensile Test for All 10-Ply Specimens

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A ₁₀ ^{15HD}	5,308	33.3	1.37	23.047	9.445
A ₁₀ ^{20HD}	6,135	40.3	1.69	23.396	11.698
A ₁₀ ^{25HD}	5,356	37.2	1.31	27.847	13.924
A ₁₀ ^{15L}	6,377	39.0	1.74	21.421	10.711
A ₁₀ ^{20L}	5,928	37.3	1.60	22.106	11.053
A ₁₀ ^{25L}	4,551	29.7	1.21	24.401	12.201
Mean	5,609	36.1	1.49	23.703	11.505
Std. Dev.	670	3.9	0.22	1.324	0.958

When comparing the 10-ply laminates with the same percentage of filler material by weight, the specimens with limestone were less stiff than those fabricated with high-density filler. Since a material's modulus of rigidity is affected by its stiffness, the laminates with high density filler also had a larger shear modulus.

The average maximum tensile force for the 2- and 10-ply specimens was 1,401 lb_f and 5,609 lb_f, respectively. The average ultimate tensile stress for the 10-ply laminates was 23.3% lower than for the 2-ply specimens even though the average cross-sectional area of 10-ply specimens was more than 5-times the average of the 2-ply laminates. Similarly, the average strain-to-break for the 10-ply laminates was 30.1% lower than for the 2-ply specimens. Taking this into consideration when comparing the transient stress-strain plots

for all test laminates, one can deduce that increasing the laminate thickness resulted in a lower average elastic modulus and modulus of rigidity.

5.3 Dynamic Test Results

5.3.1 Modal Analysis in General

Resonant vibration, which is caused by an interaction between the inertial and elastic properties of a structure's materials, is a contributing factor to many vibrational related problems which occur with composite fabricated designs. These vibrational issues can lead to noisy operation, uncontrollability, failure to maintain tolerances, premature fatigue, material failure, and shortened product life [40]. Consequently, it is useful to characterize the resonances of a structure in order to predict, and therefore prevent, any vibrational issues.

All structures readily absorb energy at their resonant frequencies and retain the energy in the form of a deformation wave. Since modes are directly associated with these structural resonances, a typical and relatively simple method to characterize a laminate's resonances is to define its modes of vibration. Each mode is defined by a discrete natural frequency, modal dampening, and a mode shape. Modes are inherent properties of a structure that do not depend on the forces or loads acting on the structure [43]. However, modes will change if the boundary conditions and/or material properties, such as the mass, stiffness, or damping, are modified. On the

contrary, Operating Deflection Shapes (ODS) are dependent on the forces applied to a structure. ODSs are defined as the deflection of a structure at a specific frequency and can be obtained from impulsive or sinusoidal time domain responses. They are generally used to determine how much a structure will move when subjected to a certain frequency.

5.3.2 Modal Analysis for 2-Ply Specimens

All vibrations are caused by a combination of both forced and resonant excitation. In the case of the 2-ply modal analysis specimens, the forced vibration was generated with an amplified sinusoidal signal connected to the magnetic, electro-dynamic shake table. Sine tests were conducted in lieu of random vibration since they are simple to perform and because they are commonly used to survey the dynamic response of test structures [46]. The laminates were attached to the shake table using an aluminum clamp, which inherently acted as a dampener to dissipate some of the system's energy. The resonances of the dynamic specimens were excited across a frequency range of 0 to 1,000 Hertz to determine the mode shapes and corresponding natural frequencies.

Vibrations can induce bending-extension coupling in unsymmetrical laminates, however, coupling is generally not present in symmetrically laminated composites [25]. This infers that the effects of rotational inertia are negligible for symmetric laminates subjected to vibration. Since each dynamic test specimen was symmetric about its mid-plane and fabricated with

all of its bi-direction (0-90) plies oriented at 0° degrees, the presence of torsion was not anticipated at the first natural frequency. Rather, the first mode shape was expected to be similar to that of a homogeneous cantilever plate, with pure bending and one node located near the clamped boundary. An example of this can be seen in Fig. 5.21.

Figure 5.21: First Bending Mode of a Cantilever Plate

Consequently, the first mode shape and natural frequency for each 4-inch by 12-inch specimen were found by starting at zero and adjusting the frequency and amplitude of the input signal until the fiberglass cantilever plates yielded a maximum deflection at the tip. The successive natural frequencies and mode shapes were found by evenly distributing salt granules or coffee grounds across the upper surface of each specimen. The frequency and amplitude inputs were then manually increased until the granules aligned to define the node locations for each mode. Once the node locations were known, the corresponding natural frequency for the mode shape was recorded.

The first fiberglass plate dynamically tested was specimen W_2^{15HD} . Its first mode, which is shown in the top-left of Fig. 5.22, had a corresponding

natural frequency of 4 Hertz. As expected, the coffee grounds aligned to only one node, adjacent to the clamp fixture.

Figure 5.22: First 8 Mode Shapes for Laminate W_2^{15HD}

In total, eight resonant frequencies were found for laminate W_2^{15HD} between the 0 to 1,000 Hertz frequency range. Their respective modes are shown above in sequential order. The nodes for the first four modes were all parallel to the clamp fixture, which indicates that the cantilever specimen experienced pure bending. However, the subsequent modes at elevated frequencies all exhibited signs of torsional effects. This issue was exemplified by the curvature of the nodes, which indicated that an increase in the frequency of the forcing function caused the plates to twist. This could also be attributed to

fabrication issues, such as laminate plies being misaligned during the hand layup process.

The five remaining 2-ply specimens made with high-density filler were tested using the same techniques as for laminate W_2^{15HD} . All six of the laminates demonstrated similar behavior during modal analysis. Consequently, the mode shapes for specimens W_2^{20HD} , W_2^{25HD} , A_2^{15HD} , A_2^{20HD} and A_2^{25HD} are shown in Appendix B since they do not appreciably contribute to this discussion. The natural frequency for the first eight bending modes of each laminate made with West System epoxy and *Aeropoxy* epoxy are shown in Tables 5.11 and 5.12, respectively.

Table 5.11: Natural Frequency Response for 2-Ply Laminates with West System Epoxy Resin System and High-Density Filler

Bending Mode	W_2^{15HD}	W_2^{20HD}	W_2^{25HD}	Mean
Frequency (Hz)				
1	4	5	5	5
2	30	33	32	32
3	66	82	87	78
4	161	171	200	177
5	240	279	284	268
6	360	420	439	406
7	577	598	604	593
8	609	774	758	714

When comparing the specimens made with West System epoxy, laminate W_2^{15HD} had the lowest natural frequency for each bending mode. On the contrary, vibrational specimen W_2^{25HD} had the highest natural frequency for the majority of the modes. This quantitative trend indicates that an increase in the percentage of high-density filler will result in higher resonant

frequencies for a given material. This corresponds with the basic theories of oscillatory behavior, which state that an increase in a material's stiffness will result in higher natural frequencies [31].

Similarly, when comparing the specimens made with *Aeropoxy* epoxy, the laminate with the smallest percentage of high-density filler, A_2^{15HD} , had the lowest natural frequency for each bending mode. On the contrary, the laminate with the largest quantity of filler, A_2^{25HD} , had the highest natural frequency for all modes (except the third). This experimental trend also indicates that an increase in the percentage of high-density filler material, and therefore elastic modulus, will result in higher resonant frequencies for each of the respective modes.

Table 5.12: Natural Frequency Response for 2-Ply Laminates with *Aeropoxy* Epoxy Resin System and High-Density Filler

Bending Mode	A_2^{15HD}	A_2^{20HD}	A_2^{25HD}	Mean
	Frequency (Hz)			
1	5	5	6	5
2	31	32	34	32
3	90	96	92	93
4	172	181	192	182
5	286	291	319	299
6	412	427	434	424
7	602	618	648	623
8	803	879	925	869

The West System and *Aeropoxy* specimens with high-density filler had equivalent mean resonant frequencies for the first two modes. However, the *Aeropoxy* laminates had higher natural frequencies for modes three through eight. Therefore, the modal analysis results for these specimens agree with

the tensile test results which indicated the *Aeropoxy* laminates were stiffer than those fabricated with West System epoxy.

The next set of fiber-reinforced composite plates to undergo dynamic testing were the 2-ply specimens made with limestone filler. Of those, laminate W_2^{15L} was the first to be dynamically tested. Its first eight modes are shown in Fig. 5.23, below:

Figure 5.23: First 8 Mode Shapes for Laminate W_2^{15L}

Similar to the specimens with high-density filler, eight resonant frequencies were found for all of the 2-ply laminates with limestone filler between the input signal range of 0 to 1,000 Hertz. All six of the laminates demonstrated similar behavior during modal analysis. Consequently, the mode shapes for

specimens W_2^{20L} , W_2^{25L} , A_2^{15L} , A_2^{20L} and A_2^{25L} are shown in Appendix B since they do not appreciably contribute to this discussion.

Similar to the prior case, the nodes for the first four modes of each laminate were all parallel to the clamp fixture, which indicates that the cantilever specimens experienced pure bending. However, the subsequent modes at elevated frequencies all exhibited signs of torsional effects. This was exemplified by the curvature of the nodes, which showed that increasing the frequency of the forcing function caused the plates to twist. This could also be attributed to fabrication issues, such as laminate plies being misaligned during the hand layup process.

The natural frequency for the first eight bending modes of each laminate made with West System epoxy and *Aeropoxy* epoxy are shown in Tables 5.13 and 5.14, respectively.

Table 5.13: Natural Frequency Response for 2-Ply Laminates with West System Epoxy Resin System and Limestone Filler

Bending Mode	W_2^{15L}	W_2^{20L}	W_2^{25L}	Mean
	Frequency (Hz)			
1	5	5	5	5
2	27	27	29	28
3	76	80	82	79
4	161	166	173	167
5	267	284	286	279
6	413	425	444	427
7	496	551	625	557
8	742	765	786	764

When comparing the specimens made with West System epoxy, laminate W_2^{15L} had the lowest natural frequency for each bending mode. On the contrary, dynamic specimen W_2^{25L} had the highest natural frequency for the majority of the modes. This quantitative trend indicates that an increase in the percentage of limestone filler will also result in higher resonant frequencies for a given material. Similar to the laminates with high-density filler, this trend corresponds with the basic theories of oscillatory behavior which state that an increase in a material's stiffness will result in higher natural frequencies.

When comparing the specimens made with *Aeropoxy* epoxy, the laminate with the smallest percentage of high-density filler, A_2^{15L} , had the lowest natural frequency for every bending mode except for the second. Based on the previous experimental data, the laminate with the least amount of filler was expected to have the lowest resonant frequency for every mode. This discrepancy could have been caused by poor fabrication techniques used during the layup process or inaccurate measurements with the digital frequency meter. The laminate with the largest quantity of filler, A_2^{25L} , had the highest natural frequency for all modes (except the fifth). This experimental trend also indicates that an increase in the percentage of limestone filler material, and therefore modulus of elasticity, will result in higher resonant frequencies for each of the respective modes.

Table 5.14: Natural Frequency Response for 2-Ply Laminates with Aeropoxy Epoxy Resin System and Limestone Filler

Bending Mode	A ₂ ^{15L}	A ₂ ^{20L}	A ₂ ^{25L}	Mean
	Frequency (Hz)			
1	4	5	5	5
2	28	26	29	28
3	70	78	86	78
4	166	179	184	176
5	230	288	264	261
6	347	387	407	380
7	491	539	582	537
8	668	722	771	720

The West System and *Aeropoxy* specimens with limestone filler had similar mean resonant frequencies for the first four modes. However, the West System laminates had higher natural frequencies for modes five through eight. This is inconsistent with the first batch of specimens where the *Aeropoxy* laminates had higher natural frequencies for modes three through eight. This discrepancy is further indicative of specimen preparation and test equipment issues that consequently skewed the experimental results. The fabrication issues may have been prevented by preparing the laminates in a controlled environment with fewer variables. In addition, the accuracy of the resonant frequency readings would have been increased if the piezoelectric accelerometer and spectrum analyzer were functional and available for the modal analysis.

When comparing the 2-ply *Aeropoxy* and West System specimens with high-density filler, the *Aeropoxy* laminates had higher resonant frequencies. Relating back to the mechanical properties calculated during the static

testing, this indicates that the specimens with a higher *Young's modulus* had higher natural frequencies for their respective bending modes. A similar, yet less distinct, trend was noted with the 2-ply laminates with limestone filler material.

5.3.3 Modal Analysis for 10-Ply Specimens

The modal testing for the 10-ply laminates was executed in the same fashion as the twelve 2-ply specimens. The initial 10-ply S-glass plate dynamically tested was specimen A_{10}^{15HD} . Its first mode, which is shown on the far left side of Fig. 5.24, had a corresponding natural frequency of 24 Hertz. This was approximately five times greater than the first natural frequency of the equivalent 2-ply laminate. The higher mode frequency is attributed to the viscous damping effects of the thicker laminate.

Figure 5.24: First 4 Mode Shapes for Laminate A_{10}^{15HD}

Similar to the 2-ply tests, the salt granules for the first bending mode of laminate A_{10}^{15HD} aligned to one node; however, the node was approximately 2 inches away from the clamp instead of being against it. The node was

expected to be closer or adjacent to the clamp fixture. The 2-inch distance from the clamp was likely due to an insufficient input signal amplitude, which limited the specimen's wave energy and prevented the salt from migrating to the exact node location.

Laminate A_{10}^{15HD} displayed four discrete bending modes up to the maximum sinusoidal test frequency of 1,000 Hertz, which were four less modes than any of the 2-ply laminates exhibited. The nodes for each mode were all relatively parallel to the clamp fixture, which indicates that the cantilever specimen would have experienced pure bending if the laminates had been fabricated with their plies properly aligned during the hand layup process.

The five remaining 10-ply specimens were also made with the *Aeropoxy* resin system, which was mixed with either high-density or limestone filler. All six of the laminates demonstrated similar behavior during modal analysis. Consequently, the mode shapes for specimens A_{10}^{20HD} , A_{10}^{25HD} , A_{10}^{15L} , A_{10}^{20L} and A_{10}^{25L} are shown in Appendix B since they do not significantly contribute to this discussion. The natural frequency for the first four bending modes of each laminate made with high-density and limestone filler are shown in Tables 5.15 and 5.16, respectively.

Table 5.15: Natural Frequency Response for 10-Ply Laminates with Aeropoxy Epoxy Resin System and High-Density Filler

Bending Mode	A ₁₀ ^{15HD}	A ₁₀ ^{20HD}	A ₁₀ ^{25HD}	Mean
	Frequency (Hz)			
1	24	25	27	25
2	160	178	183	174
3	452	480	477	470
4	892	933	916	914

When comparing the specimens made with the inorganic high-density filler, laminate A₁₀^{15HD} had the lowest natural frequency for each bending mode. Specimen A₁₀^{25HD} had the highest natural frequency for modes one and two, and specimen A₁₀^{20HD} had the largest for modes three and four. For any given mode, the standard deviation between the resonant frequencies was substantially smaller for the 10-ply specimens as compared to the 2-ply specimens. This made it difficult to clearly delineate a quantitative trend with respect to the amount of filler used. In general, it appeared that an increase in the percentage of high-density filler resulted in higher resonant frequencies. This corresponds with the basic theories of oscillatory behavior, which state that an increase in a material's stiffness will result in higher natural frequencies.

When comparing the specimens made with limestone filler, laminate A₁₀^{15L} had the lowest natural frequency for each bending mode except the fourth. Although laminate A₁₀^{20L} did not have the largest quantity of filler, it did have the highest resonant frequency for all of the recorded modes. Based on the previous experimental data, the laminate with the least amount of filler

was expected to have the lowest resonant frequency for every mode, and vice-versa. These discrepancies could have been caused by poor fabrication techniques used during the layup process or inaccurate measurements with the digital frequency meter.

Table 5.16: Natural Frequency Response for 10-Ply Laminates with Aeropoxy Epoxy Resin System and Limestone Filler

Bending Mode	A ₁₀ ^{15L}	A ₁₀ ^{20L}	A ₁₀ ^{25L}	Mean
	Frequency (Hz)			
1	22	25	24	24
2	149	171	169	163
3	431	481	453	455
4	837	917	825	860

The 10-ply specimens made with high-density filler had higher resonant frequencies for each bending mode when compared to those made with limestone filler. The 10-ply specimens also required a larger signal amplitude than the 2-ply laminates in order for the salt granules to align to the modes, which indicates that thicker laminates are more effective at damping energy in the form of deformation waves.

The presence of torsion was evident in the higher modes (5 through 8) of the 2-ply specimens. Torsional effects were not as discernible in the modes of the 10-ply specimens, but they may have been encountered if the sinusoidal input frequency range had been expanded. In general, the stiffer specimens had a higher natural frequency at each bending mode. When the specimens were excited near one of their natural frequencies, the response of the laminate was quite large when compared to the input force. On the

contrary, when the laminate was excited near one of its anti-resonances, the response of the structure was insignificant relative to the input force.

In conclusion, the resonances of a structure can be modified by altering the quantity of filler material mixed in the resin system. For example, increasing the amount of inorganic filler, which improves the elastic modulus of the material, will result in a higher resonant frequency for each mode. The effects of laminate thickness with respect to modal frequency suggest that thicker materials are less susceptible to low magnitude vibrational issues than thin laminates. Damping the system, by use of a boundary condition (clamp) or otherwise, will also reduce the magnitude of the vibration [46].

5.3.4 Low-Velocity Impact Testing

The Damage Threshold Load (DTL) for a material subjected to a low-velocity collision is defined as the impact force at which the incipient damage can lead to severe damage growth [29]. DTLs should be considered when designing composite structures because failure modes induced by impact forces equivalent to or greater than the DTL can greatly reduce a material's residual performance. When analyzing the transient impact force, the DTL is characterized by a sudden drop in the load displacement response. This abrupt change in impact force is a result of a critical instability created by excessive interlaminar shear stress, which can cause the elastic strain energy to be released in the form of delamination, matrix cracking and/or fiber breakage.

The total impact energy, which is the sum of the initiation and propagation energies, is another important factor to consider when analyzing the fracture mechanisms and impact behavior of composites. To better understand the correlation of these energies and the associated damage modes, three impact tests at different incident kinetic energies were executed for each type of laminate. The effects of the incident impact energy were then compared to the impact force at the onset of first failure, the energy at maximum applied load, and the total absorbed energy of the specimen.

Since advanced Non-Destructive Inspection (NDI) equipment was not available to examine the post-impact internal damage, and characteristic low-velocity impact damage does not generally include penetration of the composite [25], it was necessary to determine the approximate incident impact energy range between which Barely Visible Impact Damage (BVID) began and the penetration threshold was reached. This was done by conducting an impact survey on 3-inch square test specimens which were cut from the same laminates as all of the other coupons.

A quantitative, universally accepted definition for BVID does not yet exist [7], therefore, the onset of BVID for this experiment was classified as when the impact tup created an indentation on the surface of the composite between 0.001 and 0.002 inches deep. This was the smallest indentation size considered to be discernible to the naked eye and measurable with the Mitutoyo depth gauge. Incident impact energies between 15 and 90 in-lb_f

were surveyed. On average, BVID began at an incident impact energy of 30 in-lb_f. All the laminates exhibited signs of penetration at an incident impact energy of 80 in-lb_f. Therefore, three incident impact energies (50, 55, and 60 in-lb_f) were selected from the middle of the low-velocity impact damage range to conduct the experimental tests. The incident kinetic energy of the impactor, E_k , is a function of the mass (m) and velocity (v) of the machine's crosshead, as shown in Eqn. 5.9:

$$E_k = \frac{1}{2}mv^2 \quad (5.9)$$

Since the mass of the impactor was held constant, the incident velocity was adjusted, as needed, to achieve the desired impact energy.

It was also necessary to define the internal and external energies of the system in order to understand the balance of energy throughout the impact event. To do so, the impact tup was assumed to be a rigid body so that its elastic energy could be fixed to zero. In addition, the mass of the specimen was considered negligible with respect to the mass of the impactor, which allowed the gravitational and kinetic energy variation to be considered negligible [11]. The balance of energy could then be expressed as shown in Eqn. 5.10:

$$E_{tot} = E_i + E_{cb} + E_{cd} \quad (5.10)$$

Where E_{tot} is the total energy of the system at any point during the impact event, E_i is the instantaneous energy of the impactor, E_{cb} is the instantaneous

elastic energy of the composite due to bending, and E_{cd} is the energy dissipated due to composite damage, friction, etc. With the aforementioned assumptions, this equation implies the total energy of the system at any point during the impact event will be equivalent to the incident kinetic energy of the impactor, E_k . Conceptually, this means that the initial impact energy will be transferred from the impactor to the composite (in the form of bending and damage), then some of the elastic energy (which could not be dissipated by the specimen) will be transferred back to the impactor.

5.3.5 Impact Test Results

The thickness of each 3-inch square laminate was measured with a micrometer prior to impact testing. The laminate thicknesses of the 10-ply specimens ranged between 0.1519 and 0.1601 inches, with a mean of 0.1554 inches. A summary of the specimen thicknesses is provided in Table 5.17.

Table 5.17: Thickness of 10-Ply Impact Test Specimens

Specimen	Average Laminate Thickness (in)
A_{10}^{15HD}	0.1552
A_{10}^{20HD}	0.1519
A_{10}^{25HD}	0.1507
A_{10}^{15L}	0.1601
A_{10}^{20L}	0.1567
A_{10}^{25L}	0.1580
Mean	0.1554

As mentioned previously, the impact tests followed the applicable standards in ASTM D-5628 with the exception of how the laminates were attached to the test fixture. All of the impact tests were conducted with a constant impactor mass of 12.57 pounds, which was the smallest drop-weight available for use. Three impact test coupons were prepared from each of the original 10-ply laminates. Each coupon was impacted once and then a new specimen was loaded in the drop-weight machine. This process was continued until each type of specimen had been impacted at the three predetermined incident energies. The Instron *Impulse* data acquisition system was equipped with a signal conditioning unit, which was assumed to minimize excessive noise produced by ringing in the impact test frame. In addition, the compressive wave oscillations produced by the impact event were assumed to be negligible since their magnitude is insignificant for low speed collisions [23].

The first coupon, A_{10}^{15HD} , was centered on the test fixture over the 1.5 inch diameter hole and then clamped on all four sides. The position of the impactor crosshead was then calibrated by gently placing the hemispherical tup against the surface of the laminate and setting the *Impulse* program to recognize its relative vertical position as zero displacement. The impact tower was then closed and the program was used to calculate the crosshead height necessary to achieve an incident energy of 50 in-lb_f. The impactor crosshead was then released using the *Dynatup 9250HV* control panel. The

actual kinetic energy and velocity of the impactor (50.05 in-lb_f and 4.62 ft/s, respectively) were recorded as the crosshead reached the preset tare location. The transient force and energy from the impact test are shown in Fig. 5.25:

Figure 5.25: Force-Time and Energy-Time Response for Laminate A_{10}^{15HD} at Incident Impact Energy of 50 in-lb_f

From the figure it can be seen that the force-time response for laminate A_{10}^{15HD} increased in a linear fashion until the Damage Threshold Load (DTL) was reached at approximately 552 lb_f. The abrupt drop in impact force just after the DTL is likely the release of elastic strain energy being in the form of delamination and matrix cracking caused by interlaminar stress. The post-DTL transient force was non-linear, which indicates that the force-time response after the initial onset of damage was governed by major failure modes as opposed to the elastic resistance witnessed prior to the DTL.

The laminate was subjected to a maximum impact load of 826 lb_f at approximately 3.09 ms, which corresponded to a deflection of 0.11 inches and maximum deformation energy of 52.46 in-lb_f. Since the maximum energy recorded by the *Impulse* data acquisition software during the impact event was greater than the incident kinetic energy, it was suspected that one or more of the system's sensors was not calibrated correctly. The impact energy, represented by the red line on the plot, had a distinct inflection point which corresponded to the maximum force achieved. This indicated the point at which the specimen reached its maximum deflection and the velocity of the impact tup reached zero. Using stored elastic energy, the laminate then rebounded and returned some of its energy to the impact tup.

The impact event was considered complete when the contact force between the impact tup and coupon reached zero. This occurred at approximately 6.26 ms for laminate A₁₀^{15HD}, at which point the specimen's total absorbed energy was determined to be 32.51 in-lb_f. Relating this back to Eqn. 5.10, this implies that the specimen dissipated approximately 65.0% of the incident kinetic energy, some of which was in the form of permanent damage.

The first test specimen was then removed from the transverse impact machine and a new A₁₀^{15HD} coupon was inserted so that it could be tested at an incident kinetic energy of 55 in-lb_f. The recorded incident energy and

velocity of the impactor were 55.49 in-lb_f and 4.87 ft/s, respectively. The results of the low-velocity impact test are shown in Fig. 5.26.

Figure 5.26: Force-Time and Energy-Time Response for Laminate A_{10}^{15HD} at Incident Impact Energy of 55 in-lb_f

The force and energy responses of laminate A_{10}^{15HD} at an incident energy of 55 in-lb_f were similar to the responses witnessed for the 50 in-lb_f impact case, which indicates that the basic damage modes for both coupons were similar. The transient force increased in a linear fashion until reaching the DTL of 643 lb_f. Again, the sudden drop in impact force just after the DTL is due to the initial onset of damage caused by elastic strain energy being released in the form of delamination and matrix cracking. The impact force after the DTL oscillated slightly more than in the 50 in-lb_f case, which is indicative of damage propagation [8]. The interlaminar damage likely

contributed to the continuation of the non-linear trend until the force went to zero.

The laminate was subjected to a maximum impact load of 870 lb_f at approximately 3.02 ms, which corresponded to a deflection of 0.12 inches and maximum deformation energy of 58.12 in-lb_f. Similar to the first test, the *Impulse* data acquisition software recorded a maximum energy greater than the incident kinetic energy. Again, the impact energy had a distinct inflection point which corresponded to the maximum force achieved. This correlated to the point at which the specimen reached its maximum deflection and the velocity of the impact tup reached zero. Using stored elastic energy, the laminate then rebounded and returned some of its energy to the impact tup.

The impact event was considered complete when the contact force between the impact tup and coupon reached zero. This occurred at approximately 6.25 ms for laminate A₁₀^{15HD}, at which point the specimen's total absorbed energy was determined to be 37.11 in-lb_f. This indicated that the specimen dissipated approximately 66.9% of the incident kinetic energy, some of which was in the form of permanent damage.

The second test specimen was then removed from the test fixture and the third and final A₁₀^{15HD} coupon was inserted so that it could be tested at an incident kinetic energy of 60 in-lb_f. The recorded impact energy and velocity of the impactor were 60.07 in-lb_f and 5.06 ft/s, respectively. The results of the low-velocity impact test are shown in Fig. 5.27:

Figure 5.27: Force-Time and Energy-Time Response for Laminate A_{10}^{15HD} at Incident Impact Energy of 60 in-lb_f

The force and energy responses of laminate A_{10}^{15HD} at an incident energy of 60 in-lb_f were similar to the responses witnessed for both the 50 and 55 in-lb_f impact cases. The transient force increased in a linear fashion until reaching the DTL of 631 lb_f. The laminate was subjected to a maximum impact load of 915 lb_f at approximately 2.96 ms, which corresponded to a deflection of 0.12 inches and maximum deformation energy of 63.00 in-lb_f. Similar to the first two tests, the *Impulse* data acquisition software recorded a maximum energy greater than the incident kinetic energy. Again, the impact energy had a distinct inflection point which corresponded to the maximum force achieved. This correlated to the point at which the specimen reached its maximum deflection and the velocity of the impact tup reached zero.

Using stored elastic energy, the laminate then rebounded and returned some of its energy to the impact tup.

The impact event was considered complete when the contact force between the impact tup and coupon reached zero. This occurred at approximately 6.22 ms for laminate A_{10}^{15HD} , at which point the specimen's total absorbed energy was determined to be 39.94 in-lb_f. This indicated that the specimen dissipated approximately 66.5% of the incident kinetic energy, some of which was in the form of permanent deformation.

Table 5.18 provides a summary of the impact test results for laminate A_{10}^{15HD} which had a fiber volume fraction of 46.4%.

Table 5.18: Mechanical Behavior of Impact Test for Laminate A_{10}^{15HD}

Specimen	Incident Impact Energy (in-lb _i)	Incident Impact Velocity (ft/sec)	Damage Threshold Load (lb _f)	Max Load (lb _f)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
A_{10}^{15HD}	50.05	4.62	552	826	52.46	32.51	0.11
	55.49	4.87	643	870	58.12	37.11	0.12
	60.07	5.06	631	915	63.00	39.94	0.12
Mean	55.20	4.85	609	870	57.86	36.52	0.12

The maximum load and deflection at maximum load increased as the incident impact velocity and energy was escalated. While the DTL did not consistently increase from one test to the next, the lowest incident impact energy (50.05 in-lb_i) did result in the smallest DTL (552 lb_f). Initially, it was suspected that the variation in the DTL could be attributed, in part, to the different incident velocities. However, findings by Briggs and Ramulu indicate that the DTL is highly insensitive to changes in the initial impact velocity [12]. Therefore, the

unexpectedly high DTL for the 55.49 in-lb_f case is assumed to be a result of fewer voids or stress concentrations in the specific test coupon, which allowed it to absorb more potential energy in the form of elastic strain prior to damage initiation and propagation. The total percentage of energy absorbed by each coupon, with respect to the kinetic incident energy, only varied by approximately 2 percent for all cases. This indicated that the total percentage of energy absorption of laminate A₁₀^{15HD} was not appreciably influenced by variations in the incident impact energy for the specific range (50-60 in-lb_f) selected.

Fig. 5.28 shows the damage incurred by laminate A₁₀^{15HD} as a result of the low-velocity impacts. The pictures are shown in sequential order, left to right, from lowest to highest incident impact energy.

Figure 5.28: Failure Mode for Laminate A₁₀^{15HD} Due to Impact Test at Incident Energies of 50, 55 and 60 in-lb_f

The indentation depths for the 50, 55 and 60 in-lb_f impacts were 0.0024, 0.0065 and 0.0055 inches, respectively. None of the coupons experienced fiber breakout or penetration. The specimen impacted at 50 in-lb_f had the smallest indentation of all three cases, which was expected since it had the

lowest dynamic loading and impact velocity, and it absorbed the smallest percentage of incident kinetic energy. On the contrary, the specimen impacted at 55 in-lb_f had the largest indentation, indicating that it likely absorbed the most energy out of all three specimens by the means of permanent deformation. This could explain why the 55 in-lb_f coupon absorbed the largest percentage of incident kinetic energy.

The five remaining 10-ply specimens were impact tested using the same techniques as for laminate A₁₀^{15HD}. Analysis of the experimental test data indicated that all six of the laminates demonstrated similar behavior with respect their transient force, displacement, and impact energy. In addition, none of the test coupons experienced fiber breakout or penetration. Consequently, the force-time and energy-time plots, as well as the corresponding pictures of impact damage, are shown in Appendix C for specimens A₁₀^{20HD}, A₁₀^{25HD}, A₁₀^{15L}, A₁₀^{20L} and A₁₀^{25L}. For discussion purposes, a summary of the tests results for incident impact energies of 50, 55 and 60 in-lb_f are shown in Tables 5.19, 5.20 and 5.21, respectively.

Table 5.19: Mechanical Behavior of Impact Test for 10-Ply Laminates at Incident Impact Energy of 50 in-lb_f

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Damage Threshold Load (lb _f)	Max Load (lb _f)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Kinetic Energy Absorbed (%)	Deflection at Max Load (in)
A ₁₀ ^{15HD}	50.05	4.62	552	826	52.46	32.51	65.0	0.11
A ₁₀ ^{20HD}	49.27	4.58	786	932	50.49	30.41	61.7	0.09
A ₁₀ ^{25HD}	49.48	4.59	736	859	52.31	35.48	71.7	0.10
A ₁₀ ^{15L}	49.06	4.57	787	860	51.42	35.07	71.5	0.10
A ₁₀ ^{20L}	49.41	4.59	802	925	51.17	32.35	65.5	0.09
A ₁₀ ^{25L}	49.29	4.59	704	886	51.34	32.93	66.8	0.10
Mean	49.43	4.59	728	882	51.53	33.13	67.0	0.10

For the 50 in-lb_f case, laminate A₁₀^{15HD} exhibited the lowest DTL (552 lb_f) and laminate A₁₀^{20L} had the highest DTL (802 lb_f) of all the specimens. The test coupons with 20% filler (A₁₀^{20HD} and A₁₀^{20L}), by weight, had the highest DTLs for their respective filler type. Since the specimens with 25% filler (A₁₀^{25HD} and A₁₀^{25L}) did not have the highest DTLs, it infers that the amount of filler material did not have a consistent effect on the DTL of the composites. Similar results were found for the maximum impact force, where laminate A₁₀^{15HD} had the smallest ultimate load (826 lb_f) and the test coupons with 20% filler (A₁₀^{20HD} and A₁₀^{20L}) had the highest maximum loads (932 lb_f and 925 lb_f, respectively) for their filler type.

A direct correlation for each specimen was witnessed between its respective DTL and maximum impact force. For example, an increase in the DTL generally resulted in a higher ultimate force. This indicates that if a material requires a higher impact force to initiate damage, less force will be

dissipated by the onset and propagation of damage *prior* to the material reaching its maximum deflection.

The specimens with the highest DTL and max load (A_{10}^{20HD} and A_{10}^{20L}) for each filler type also had the smallest deflection (0.09 inch). When analyzing the force-displacement relationship of impacted composites, research has shown that a laminate's flexural stiffness decreases after the onset of damage [12]. Therefore, the prolonged flexural stiffness prior to the DTL of laminates A_{10}^{20HD} and A_{10}^{20L} was believed to have limited their total deflection. It is also important to note that these specimens had the lowest percentage of energy absorption for their respective filler type.

Of all the specimens, laminate A_{10}^{25HD} absorbed the largest percentage (71.7%) of incident kinetic energy. Since the coupon did not encounter the largest deflection or surface indentation, it was assumed that the laminate absorbed more energy by the means of internal damage (such as delamination and matrix cracking) than the other specimens. The amount of absorbed energy did not increase in a linear fashion with respect to the amount of filler material used; however, the average percentage of energy absorption of the limestone specimens was higher than for the laminates made with high-density inorganic filler.

Table 5.20 below provides a summary of the tests results for the coupons impacted with an incident kinetic energy of 55 in-lb_f.

Table 5.20: Mechanical Behavior of Impact Test for 10-Ply Laminates at Incident Impact Energy of 55 in-lb_f

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Damage Threshold Load (lb _f)	Max Load (lb _f)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Kinetic Energy Absorbed (%)	Deflection at Max Load (in)
A ₁₀ ^{15HD}	55.49	4.87	643	870	58.12	37.11	66.9	0.12
A ₁₀ ^{20HD}	55.00	4.84	765	1,004	54.99	34.47	62.7	0.10
A ₁₀ ^{25HD}	55.45	4.86	628	884	57.07	38.76	69.9	0.11
A ₁₀ ^{15L}	54.77	4.83	703	921	55.21	38.12	69.6	0.10
A ₁₀ ^{20L}	54.95	4.84	768	979	55.69	36.01	65.5	0.10
A ₁₀ ^{25L}	54.80	4.83	641	947	56.61	36.05	65.8	0.10
Mean	55.08	4.85	691	934	56.28	36.75	66.7	0.11

Interestingly, the vast majority of the extreme (minimum and maximum) values identified from the experimental data for the 50 in-lb_f case corresponded to the same specimens for the 55 in-lb_f case. A description of the similarities and differences are provided below.

55 in-lb_f impact test results similar to the 50 in-lb_f case:

- Laminate A₁₀^{20L} had the highest DTL (768 lb_f) of all the specimens;
- The test coupons with 20% filler (A₁₀^{20HD} and A₁₀^{20L}), by weight, had the highest DTLs (765 lb_f and 768 lb_f, respectively) for their particular filler type;
- The test coupons with 20% filler (A₁₀^{20HD} and A₁₀^{20L}), by weight, had the highest ultimate loads (1,004 lb_f and 979 lb_f, respectively) for their particular filler type;
- Laminate A₁₀^{15HD} had the lowest ultimate load (870 lb_f) of all the specimens;

- The specimens with the highest DTL and max load (A_{10}^{20HD} and A_{10}^{20L}) for each filler type also had the smallest deflection (0.10 inch);
- Laminate A_{10}^{25HD} absorbed the largest percentage (69.9%) of incident kinetic energy of all the specimens; and
- The specimens with the lowest amount of filler (A_{10}^{15HD} and A_{10}^{15L}), by weight, had the largest deflections for their respective filler type.

55 in-lb_f impact test results different from the 50 in-lb_f case:

- Laminate A_{10}^{25HD} (instead of A_{10}^{15HD}) exhibited the lowest DTL (628 lb_f).

Table 5.21 below provides a summary of the tests results for the coupons impacted with an incident kinetic energy of 60 in-lb_f.

Table 5.21: Mechanical Behavior of Impact Test for 10-Ply Laminates at Incident Impact Energy of 60 in-lb_f

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Damage Threshold Load (lb _f)	Max Load (lb _f)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Kinetic Energy Absorbed (%)	Deflection at Max Load (in)
A_{10}^{15HD}	60.07	5.06	631	915	63.00	39.94	66.5	0.12
A_{10}^{20HD}	59.44	5.04	759	953	61.90	37.18	62.6	0.12
A_{10}^{25HD}	59.01	5.02	792	937	61.19	42.13	71.4	0.11
A_{10}^{15L}	59.28	5.03	800	962	59.96	42.26	71.3	0.10
A_{10}^{20L}	59.45	5.04	809	1,003	59.77	39.45	66.4	0.10
A_{10}^{25L}	59.41	5.03	699	967	59.04	40.33	67.9	0.10
Mean	59.44	5.04	748	956	60.81	40.22	67.7	0.11

Again, the majority of the extreme values identified from the experimental data for the 50 and 55 in-lb_f cases corresponded to the same specimens for

the 60 in-lb_f case. A description of the similarities and differences are provided below.

60 in-lb_f impact test results similar to the 50 and 55 in-lb_f cases:

- Laminate A_{10}^{20L} had the highest DTL (809 lb_f);
- The test coupons with 20% filler (A_{10}^{20HD} and A_{10}^{20L}), by weight, had the highest ultimate loads (953 lb_f and 1,003 lb_f, respectively) for their particular filler type;
- Laminate A_{10}^{15HD} had the lowest ultimate load (915 lb_f) of all the specimens;
- The specimen with limestone filler with the highest DTL and max load (A_{10}^{20L}) also had the smallest deflection (0.10 inch);
- Laminate A_{10}^{25HD} absorbed the largest percentage (71.4%) of incident kinetic energy of all the specimens; and
- The specimens with the lowest amount of filler (A_{10}^{15HD} and A_{10}^{15L}), by weight, had the largest deflections for their respective filler types.

60 in-lb_f impact test results similar to the 50 in-lb_f case, but different from the 55 in-lb_f case:

- Laminate A_{10}^{15HD} (instead of A_{10}^{25HD}) exhibited the lowest DTL (631 lb_f).

60 in-lb_f impact test results different from both the 50 and 55 in-lb_f cases:

- Test coupon A_{10}^{25HD} (instead of A_{10}^{20HD}) had the highest DTL (792 lb_f) of the specimens made with high-density filler.

For any of the given incident impact energies, the percentage of kinetic energy absorbed did not consistently increase or decrease as the *amount* of filler material was increased. However, there was a distinct trend in the DTL, maximum load, and energy absorbed for all of the low-velocity impact tests conducted on the specimens made with 20% filler. Specifically, laminates A_{10}^{20HD} and A_{10}^{20L} had the highest DTL and maximum load, as well as the lowest percentage of incident energy absorbed, for their respective filler type. The only exception was the 60 in-lb_f case, where specimen A_{10}^{20HD} had the second highest DTL for its filler type. The transient responses for these specimens were closely examined to better understand their unique impact behavior. At all three incident impact energies, the force-time response for both laminates increased in a linear fashion until the DTL, but unlike the other specimens, the impact force for A_{10}^{20HD} and A_{10}^{20L} only experienced a *very subtle* drop at the onset of damage. This indicated that the composites made with 20% filler transferred less elastic strain energy into delamination and matrix cracking prior to their maximum deflection. The dynamic response for these specimens also had a more even loading and unloading distribution, which implies that their post-DTL behavior was not as influenced by major failure modes when compared to the other test coupons. Consequently, the laminates with 20% filler absorbed the lowest percentage of incident impact energy for their respective filler type.

The trends between filler *type* for the batch of specimens impacted at 50 in-lb_f were consistent with that of the 55 and 60 in-lb_f cases. For example, all three impact test cases resulted in lower average deflections for the specimens made with limestone filler when compared to the laminates made with high-density filler. In addition, the average indentation depth and average percentage of incident kinetic energy absorbed were greater for the specimens made with limestone filler. Together, these results indicated that the coupons made with limestone filler were more susceptible, on average, to impact damage than the high-density filler specimens. This was not anticipated since the tensile moduli of elasticity for the limestone specimens were found to be lower than that of the high-density laminates. Thus, it was concluded that the impact performance of S-glass fiber-reinforced composites cannot be predicted solely on their relative brittleness or ductility. One must also account for the complex and non-linear response of the material after the onset of damage, which is largely influenced by the reduction in flexural stiffness and the propagation of impact damage.

Each of the test specimens exhibited slightly different damage initiation and propagation energies, even when subjected to the same incident impact energy. In general, the limestone filler specimens had large damage initiation energy and smaller propagation energy. Conversely, the high-density coupons had smaller damage initiation energy and larger propagation energy. Therefore, to determine which filler material and quantity is ideal for a specific

design, one must determine the importance of the structure's residual strength after impact. If a design was made with similar fiberglass laminates and subjected to continued loading after an impact event (with incident energy equivalent to or less than 60 in-lb_i), it would be preferable to build the composite structure using a laminate made with 20% high-density filler in lieu of limestone filler. This is due to the increased hardness (resistance to indentation) of the high-density filler laminates and their inherent ability to limit the propagation of damage.

On the contrary, if a design were intended to absorb as much energy as possible and its residual strength was unimportant, it would be best to build the composite structure using a laminate made with 15% limestone filler. A good application for laminates made with this type of filler material would be protective structures designed to prevent or limit damage to internal components or objects. Laminates made with limestone filler are more adept for these scenarios since they require higher impact forces for incipient damage to occur, but energy is more readily absorbed after the DTL due to damage propagation. Consequently, the use of limestone filler instead of high-density filler would reduce impact loads transferred to the structure's internal components after the damage threshold was reached.

6 NUMERICAL ANALYSIS

6.1 Finite Element Analysis

Finite Element Methods (FEMs) provide a computation means to validate the performance of both simple and complex structural designs by analyzing their stresses, displacements, vibration, and/or buckling characteristics under given loading and boundary conditions [7]. Finite Element Analysis (FEA), which is the most common FEM, can be applied at either a macroscopic or microscopic level. This allows designers to analyze the stiffness and strength of a structure or go as far as to examine the interface between its fiber and resin. Suffice to say, FEA models can help prevent design flaws and deficiencies when used properly.

FEA models generally start with either a 2-dimensional or 3-dimensional representation of the structure or specimen of interest. A series of points, which are referred to as nodes, are then created over the structure's geometry in order to create a mesh of individual elements. The mesh is then programmed with the material properties and boundary conditions which determine how the structure deforms under certain loading conditions. Depending on the structural performance aspects of interest and the required accuracy of the results, the nodes can be dispersed evenly throughout the material or concentrated in certain areas.

Most commercially available FEA programs allow users to input specific variables such as the mass, volume, temperature, stress, strain, force, displacement, velocity, and acceleration of the system. In addition, they typically have an element library or allow designers to create their own. More advanced FEA programs, such as *Abaqus* and *Nastran*, are capable of analyzing structures made from multiple materials. This is specifically helpful when examining composite designs that may be isotropic, orthotropic, or anisotropic.

6.2 Modal Finite Element Analysis

6.2.1 Numerical Formulation for Dynamic Vibration Model

The numerical models for the modal analysis were generated in *Abaqus/CAE, Version 6.10-3*, which is a product of Dassault Systems Simulia Corporation. The fiber-reinforced laminate plate models consisted of ten plies which were individually modeled with 3-dimensional shell elements and hourglass control. The use of deformable shell continuum elements simplified the vibration model since the elements are located in the plane of the laminae, limiting the variation of strain through the thickness to a linear distribution, which reduces the effects of more complex behavior [1]. The mesh of the numerical formulation included four-node, doubly-curved shells with SR4 elements. These elements are first order, reduced integration and linear-quadrilateral, which allowed the computational runtime to be minimized.

The dimensions of the simulated specimens (including their thicknesses) were based off of the measurements taken prior to the experimental modal analysis, but with one exception. The experimental laminates were approximately 12-inches long, but one inch of their length was clamped in the Aluminum 2024 test fixture. Therefore, the FEA models were reduced to 11-inches in length and the clamp was simulated by creating a fixed boundary condition on one end which constrained movement in all six degrees of freedom. This prevented displacement and rotation at the fixed end. The geometry and material properties used for each specimen are shown in Table 6.1.

***Table 6.1: Specimen Geometry and Properties
Used in Numerical Modal Analysis***

Specimen	Laminate Mass (g)	Laminate Volume (in³)	Measured Laminate Density (g/in³)	Converted Laminate Density (lb_r-s²/in⁴)	Young's Modulus (ksi)	Poisson's Ratio (-)
A₁₀^{15HD}	197.76	7.296	27.11	0.00253	23.047	0.22
A₁₀^{20HD}	199.20	7.152	27.85	0.00260	23.396	0.22
A₁₀^{25HD}	194.40	6.912	28.13	0.00262	27.847	0.22
A₁₀^{15L}	195.84	7.440	26.32	0.00245	21.421	0.22
A₁₀^{20L}	203.04	7.584	26.77	0.00250	22.106	0.22
A₁₀^{25L}	201.12	7.296	27.57	0.00257	24.401	0.22

The laminate densities (g/in³), shown above, were measured during the experimental fiber volume fraction calculations. Using the constant for gravitational acceleration, g (32.174 ft/s²), they were then converted to mass density with units of lb_r-s²/in⁴ so that they could be utilized in *Abaqus/CAE*. The elastic moduli determined from the experimental static tests were also

used. Again, *Poisson's ratio* (ν) was assumed to be 0.22 for all of the S-glass specimens [21]. The application of the aforementioned elements and material properties were based on the assumption of the bi-directional woven roving fiberglass being isotropic, with a uniform mass distribution and thickness. In addition, it assumed pure bending with plane cross-sections remaining plane throughout the deformation, and therefore, no membrane shear strain.

Since the quantity of nodes in the mesh directly affect the accuracy of the results, it was necessary to determine the global seed size based on a mesh-refinement convergence study. The trade study selected was based on a symmetric composite laminate with similar geometry (aspect ratio), boundary conditions, and degrees of freedom. The numerical model, which was subjected to vibration, also used 4-node quadrilateral elements. The specimen geometry and material properties were held constant while the mesh density was varied to determine its effects on the accuracy of the first ten resonant frequencies [45]. The research indicated that reducing the global seed size would produce a finer mesh with more quadrilateral elements, but also led to a higher distortion of the element shapes. In addition, the investigation showed that a seed size of 0.5 was sufficient for approximating the first five mode shapes and natural frequencies of the laminate. Therefore, it was selected and used in the modal analysis FEA models since only four mode shapes were expected in the test frequency range.

A linear steady-state vibration model with eigenvalue extraction was utilized in conjunction with the dynamic-linear perturbation method to determine the natural frequencies and mode shapes of each specimen in the frequency domain of 0 to 1,000 Hertz [25]. The eigenvalue extraction used in the numerical model is shown in Eqn. 6.1:

$$\Phi^N (K^{MN} - \omega^2 M^{MN}) = 0 \quad (6.1)$$

In this equation, Φ^N represents the mode of vibration, or eigenvector. M is the mass matrix of the material, ω is the oscillation frequency, K is the stiffness matrix, and the M and N superscripts represent the degrees of freedom of the system.

6.2.2 Numerical Results for Modal Analysis

The frequency extraction for each 10-ply specimen was conducted after the numerical models were established and the boundary conditions were defined. A deformation scale factor of 0.12 was used throughout all of the numerical runs in order to make the mode shapes discernible.

The first numerical modal analysis was simulated for laminate A₁₀^{15HD}. Its first mode, which is shown in Fig. 6.1, had a corresponding natural frequency of 26 Hertz. The first bending mode of the model was similar to the experimental vibration test, with one node located parallel and adjacent to the fixed end and the maximum deflection at the free end.

Figure 6.1: First Bending Mode of Laminate A_{10}^{15HD}

The magnitude of the tip deflection relative to the neutral axis was a direct result of the deformation scale factor, and could be increased or decreased based on the value selected. This can be equated to adjusting the supplied power by the amplifier during experimental testing.

In total, four resonant frequencies were numerically determined for laminate A_{10}^{15HD} between the 0 to 1,000 Hertz frequency range. Their respective mode shapes are shown in the figures below. Wire frame models were used to clearly define the shape of the dynamic model at each resonance and to locate the nodes relative to the length of the plate. The nodes for all four modes were parallel to the fixed end, indicating that the specimen did not experience torsion. This was expected since the numerical model was established on the principle of pure bending with plane cross-sections remaining plane throughout the deformation. The second mode shape, which had a resonant frequency of 166 Hertz, is shown in Fig. 6.2.

Figure 6.2: Second Bending Mode of Laminate A_{10}^{15HD}

The third mode shape for laminate A_{10}^{15HD} , which had a resonant frequency of 471 Hertz, is shown in Fig. 6.3:

Figure 6.3: Third Bending Mode of Laminate A_{10}^{15HD}

The fourth mode shape for laminate A_{10}^{15HD} , which had a resonant frequency of 943 Hertz, is shown in Fig. 6.4:

Figure 6.4: Fourth Bending Mode of Laminate A_{10}^{15HD}

The first four modes shapes for all six of the 10-ply laminates were similar to laminate A_{10}^{15HD} , however, they each had a discrete resonant frequency for each mode. The corresponding natural frequency for the first four bending modes of each laminate made with high-density and limestone filler are shown in Tables 6.2 and 6.3, respectively.

Table 6.2: Numerical Natural Frequency Response for 10-Ply Laminates with High-Density Filler

Bending Mode	A_{10}^{15HD}	A_{10}^{20HD}	A_{10}^{25HD}	Mean
	Frequency (Hz)			
1	26.46	24.77	23.24	24.82
2	166.09	163.14	159.64	162.96
3	471.73	462.35	458.81	464.30
4	943.92	923.88	909.49	925.76

When comparing the specimens made with inorganic high-density filler, laminate A_{10}^{15HD} had the highest natural frequency for each bending mode. On the contrary, specimen A_{10}^{25HD} had the lowest natural frequency for all four modes. Therefore, the numerical results for these specimens

indicate that an increase in the percentage of high-density filler will result in lower resonant frequencies. A similar trend can be seen in Table 6.3 for the laminates made with limestone filler:

Table 6.3: Numerical Natural Frequency Response for 10-Ply Laminates with Limestone Filler

Bending Mode	A_{10}^{15L}	A_{10}^{20L}	A_{10}^{25L}	Mean
	Frequency (Hz)			
1	28.61	27.71	25.23	27.18
2	173.42	168.33	164.00	168.58
3	482.89	475.26	466.05	474.73
4	952.22	936.04	923.64	937.30

Although the resonant frequencies for the numerical modal analysis are on the same order of magnitude as the experimental results, the effects of increasing the quantity of filler material were different. Specifically, the numerical results indicated that the specimens with higher stiffness would have *lower* resonant frequencies. The FEA models also indicated that the laminates made with limestone filler have *higher* natural frequencies for all bending modes when compared to the laminates with high-density filler. Again, this did not agree with the finding from the experimental tests. Further discussion regarding these discrepancies is provided in the section below.

6.2.3 Comparison of Experimental and Numerical Results

Table 6.4 provides a summary of the natural frequency response for each of the 10-ply laminates which were obtained from the experimental and numerical modal analyses.

Table 6.4: Comparison of Experimental and Numerical Results – Natural Frequency Response for All 10-Ply Laminates

Experimental Results						
Bending Mode	A_{10}^{15HD}	A_{10}^{20HD}	A_{10}^{25HD}	A_{10}^{15L}	A_{10}^{20L}	A_{10}^{25L}
	Frequency (Hz)					
1	24	25	27	22	25	24
2	160	178	183	149	171	169
3	452	480	477	431	481	453
4	892	933	916	837	917	825

Numerical Results						
Bending Mode	A_{10}^{15HD}	A_{10}^{20HD}	A_{10}^{25HD}	A_{10}^{15L}	A_{10}^{20L}	A_{10}^{25L}
	Frequency (Hz)					
1	26.46	24.77	23.24	28.61	27.71	25.23
2	166.09	163.14	159.64	173.42	168.33	164.00
3	471.73	462.35	458.81	482.89	475.26	466.05
4	943.92	923.88	909.49	952.22	936.04	923.64

Error						
Bending Mode	A_{10}^{15HD}	A_{10}^{20HD}	A_{10}^{25HD}	A_{10}^{15L}	A_{10}^{20L}	A_{10}^{25L}
	%					
1	10.3	0.9	13.9	30.0	10.8	5.1
2	3.8	8.3	12.8	16.4	1.6	3.0
3	4.4	3.7	3.8	12.0	1.2	2.9
4	5.8	1.0	0.7	13.8	2.1	12.0

Both the experimental and numerical data indicated that the resonances of a structure can be modified by altering the quantity and type of filler material mixed in the resin system. Although the mode shapes exhibited by the 10-ply specimens were similar between the experimental and numerical tests, opposing trends were decipherable with respect to the effects of filler type and quantity in relation to the resonant frequency:

- 1) Filler type: The experimental results showed that the specimens made with high-density filler had higher resonant frequencies for almost every bending mode when compared to those made with limestone.

On the contrary, the FEA results showed that the specimens with limestone filler had higher resonant frequencies.

- 2) Percentage of filler material: The experimental results indicated that increasing the amount of filler, and therefore elastic modulus of the laminate, would result in higher resonant frequencies. This was originally attributed to the damping effects of the laminate's increased stiffness. However, the FEA results showed that increasing the amount of filler would result in lower resonant frequencies.

A structure's resonant frequencies are directly related to its mass and stiffness. For example, increasing a material's stiffness will increase the corresponding natural frequency for each mode. This is a result of improved vibrational damping due to the higher elastic modulus. On the other hand, increasing a material's mass will decrease the corresponding natural frequency for each mode [31]. Since the numerical model indicated that the resonant frequency decreased as the percent filler increased, it implied that the change in mass of the specimen affected the resonance of the plates more than the relative increase in stiffness. Analogous results were found in similar studies when comparing the effects of inorganic filler on the frequency response of fiberglass laminates [32]. Furthermore, the numerical model was based on specimens with a uniform mass distribution. It is unlikely that the laminates used for experimental testing had a uniform mass distribution since they were hand fabricated. The experimental laminates may have also had

misaligned plies or other flaws which contributed to the discrepancy between results. In addition, error could have been introduced in the FEA model via inaccurate material properties, inadequate mesh density, etc.

6.3 Low-Velocity Impact Finite Element Analysis

6.3.1 Numerical Formulation for Low-Velocity Impact Model

A numerical evaluation of each impact test specimen was performed using *Abaqus/Explicit*, which is subset of the *Abaqus/CAE* software suite. The principles of the transient dynamic FEA code are based on the formula shown in Eqn. 6.2, where F represents the impact force, m is the mass of the body, and a is the acceleration of that body.

$$F = m * a \quad (6.2)$$

The FEA code calculates the acceleration for the body and then uses a step in time to translate the acceleration into displacement of the body. This displacement is then used to calculate the “responsive” force created by the composite laminate as it stretches. The responsive force is then used by the software to calculate the corresponding acceleration. Once this is complete, the process is repeated from the beginning. As long as the time-step is sufficiently small, the impact energy results can be relatively accurate [2].

Due to the relatively simple impact test setup and specimen geometry, it was possible to modify a pre-established FEA model from *Abaqus*’ tool library to simulate the experimental impact tests. The model consisted of 5

plies, with each laminae modeled from 3-dimensional, eight-node CD38R elements. Therefore, it was necessary to adjust the specimen thickness to 10 bi-directional (0-90) plies. The individual laminae were bound using a “sliding contact interface” in order to simulate delamination damage between the plies. The 3-D, eight-node CD38R elements were not modified since they are ideal for analyzing low-velocity impact behavior, especially when penetration of the composite is not expected [49].

The dimensions of the simulated specimens, including their thickness, were based off of the measurements taken prior to the experimental impact tests, with just one exception. The experimental laminates were approximately 3-inches square; however, 0.25-inch along each edge was clamped using aluminum strips and vise grips. Therefore, the FEA models were reduced to 2.75-inches square and the clamps were simulated by creating a fixed boundary condition along each edge. The lower surface boundary condition was set by supporting the underside of the entire specimen except for a 1.50-inch diameter circle in the center, to simulate the hole in the experimental test fixture. The geometry and material properties used for each specimen are shown in Table 6.5.

**Table 6.5: Specimen Geometry and Properties
Used in Numerical Low-Velocity Impact Analysis**

Specimen	Laminate Mass (g)	Laminate Thickness (in)	Laminate Volume (in ³)	Converted Laminate Density (lb _r -s ² /in ⁴)	Young's Modulus (ksi)	Poisson's Ratio (-)
A ₁₀ ^{15HD}	37.08	0.1552	1.368	0.00253	23.047	0.22
A ₁₀ ^{20HD}	37.35	0.1519	1.341	0.00260	23.396	0.22
A ₁₀ ^{25HD}	36.45	0.1507	1.296	0.00262	27.847	0.22
A ₁₀ ^{15L}	36.72	0.1601	1.395	0.00245	21.421	0.22
A ₁₀ ^{20L}	38.07	0.1567	1.422	0.00250	22.106	0.22
A ₁₀ ^{25L}	37.71	0.1580	1.368	0.00257	24.401	0.22

The laminate densities (g/in³), shown above, were measured during the experimental fiber volume fraction calculations. Using the constant for gravitational acceleration, g (32.174 ft/s²), they were then converted to mass density with units of lb_r-s²/in⁴ so that they could be utilized in *Abaqus/Explicit*. The elastic moduli determined from the experimental static tests were also used. The application of the aforementioned material properties was based on the assumption of the bi-directional woven roving fiberglass laminate being isotropic with a uniform mass distribution and thickness.

Once the specimen geometry was matched to the experimental case, the pre-establish mesh was replicated to the new geometry. This was accomplished by with *Abaqus*' 3-D auto-mesh feature for low-velocity impact modeling. The mesh was then refined using the "percent of automatic" function, which allows the operator to minimize the computational run-time without substantially affecting the accuracy of the results [2]. The mesh density was set to 85% and Griffith surface energy criterion was employed.

The utilization of this energy principle assumes that when the maximum surface energy exceeds the crack opening energy, the crack will initiate until failure of the element. In addition, the criterion applied in the numerical model assumed the following: internal damage consisted of delamination and transverse cracking; longitudinal cracking would occur in the direction of the fibers due to bending effects; and matrix cracking and delamination are connected failure mechanisms [49].

The pre-established impact model used a rigid-body spherical projectile as the impactor. Since the maximum incident kinetic energy numerically analyzed was not expected to penetrate the laminates, it was assumed that the geometry of the 5/8-inch diameter hemispherical impact tup could be simplified to a 5/8-inch diameter sphere. The impactor mass in the FEA model was also adjusted to 12.57 pounds, which was the same as the *Dynatup 9250HV* crosshead. The incident velocity and impact energy for each numerical simulation was matched to the recorded values taken by the *Impulse* software during the experimental tests.

6.3.2 Numerical Results for Low-Velocity Impact

It was not possible to determine the surface indentation after impact from the numerical model. Therefore, the FEA simulation was initially used to provide a *quantitative* comparison to the experimental deflection and energy absorbed at the minimum incident impact energy (30 in-lb_f) required to create BVID to laminate A₁₀^{15HD}. Fig. 6.5 shows the resulting deformation and

transient energy wave at the time (2.81 ms) of maximum deflection and ultimate impact force.

Figure 6.5: Low-Velocity Impact at Incident Energy Equivalent to the Barely Visible Impact Damage Threshold for Laminate A_{10}^{15HD}

The results of the model for laminate A_{10}^{15HD} indicated that the impact energy at the maximum load was 29.87 in-lb_f, which was equivalent to the input value for the incident kinetic energy. This was expected since the transient dynamic model was based off of the principles of energy conservation. The corresponding deflection at the maximum load was 0.034 inch, which was approximately 13.3% larger than the deflection recorded for the similar experimental case. In addition, the total absorbed energy (18.22 in-lb_f) of the specimen was determined to 4.7% larger for the FEA model. A comparison of the experimental and numerical test results for laminate A_{10}^{15HD} (at incident impact energy of 30 in-lb_f) is shown in Table 6.6.

Table 6.6: Comparison of Experimental and Numerical Results for Laminate A_{10}^{15HD} at Incident Impact Energy of 30 in-lb_f

Specimen A_{10}^{15HD}	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
Experimental	31.08	17.41	0.03
Numerical	29.87	18.22	0.034
Error	3.9%	4.7%	13.3%

An analogous case was also simulated at an incident kinetic energy of 90 in-lb_f, which was the approximate penetration threshold of laminate A_{10}^{15HD} . The numerical results for this run were only intended to provide a *qualitative* comparison to the experimental impact test since the FEA model was not developed to analyze the energy absorption characteristics of materials subjected to through-the-thickness penetration. Therefore, the simulation was used to validate the boundary conditions and the failure mode criterion applied. Fig. 6.6 shows the energy dissipation and resulting damage after complete penetration of laminate A_{10}^{15HD} .

Figure 6.6: Impact at Incident Energy Greater Than Penetration Threshold of Laminate A_{10}^{15HD}

As expected, the fixed boundary condition along the four edges of the plate created a damping effect which contributed to a portion of the total absorbed energy. The supported lower surface boundary condition prevented downward deflection of the specimen except where the test fixture's 1.50-inch diameter hole was simulated. The numerical simulation beyond the penetration threshold of the laminate indicated that the majority of incident kinetic energy was transferred into permanent damage by the means matrix cracking, delamination, and fiber breakout. This was expected since the flexural stiffness of glass fiber-reinforced laminates is rate-sensitive, which means their bending stiffness generally increases as the incident impact energy is elevated [12]. An increased flexural stiffness during the initial

stages of an impact event will limit the deflection of the specimen. Consequently, if the incident impact energy is beyond the absorption limitations of the material, more energy goes into breaking the laminate than bending it.

Once the BVID and penetration threshold cases had been executed to substantiate the basic numerical model, impact simulations were conducted on each of the 10-ply specimens at an incident impact energy of approximately 50 in-lb_f. Laminate A₁₀^{15HD} reached its maximum deflection at 2.96 ms after impact, as shown in Fig. 6.7:

Figure 6.7: Low-Velocity Impact at Incident Energy of 50 in-lb_f for Laminate A₁₀^{15HD}

The numerical simulations at an incident impact energy of 50 in-lb_f were similar for all of the 10-ply coupons, but they each had a discrete

maximum deflection and energy absorption. The transient energy responses for the laminates made with high-density filler are shown in Fig. 6.8.

Figure 6.8: Numerical Energy-Time Response for 10-Ply Laminates with High-Density Filler at Incident Impact Energy of 50 in-lb_f

The maximum impact energy achieved during each simulation was equivalent to the input value for the incident kinetic energy. Again, this was anticipated since the FEA model was based on the principles of energy conservation. Similar to the experimental tests, each impact energy response had a distinct inflection point which corresponded to the time at which the specimens reached their maximum deflection. The peak on each energy response curve also represents the point at which the velocity of the rigid-body sphere slowed to zero. Using stored elastic energy, the simulated

coupons then rebounded and returned some of their energy to the impacting sphere. A summary of the FEA results for the laminates made with high-density filler is shown in Table 6.7.

Table 6.7: Mechanical Behavior of Numerical 10-Ply Laminates with High-Density Filler at Incident Impact Energy of 50 in-lb_f

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
A ₁₀ ^{15HD}	50.05	4.62	50.05	33.69	0.121
A ₁₀ ^{20HD}	49.27	4.58	49.27	31.28	0.106
A ₁₀ ^{25HD}	49.48	4.59	49.48	28.89	0.087
Mean	49.60	4.60	49.60	31.29	0.105

The numerical analysis of the specimens made with high-density filler provided three significant and noteworthy trends. The first was with respect to the time required for each laminate to reach its maximum impact energy and total absorbed energy. Of the high-density filler laminates, A₁₀^{25HD} took the least amount of time to reach its maximum impact energy and to dissipate the impact force. On the contrary, laminate A₁₀^{15HD} took the longest to reach an energy of 50 in-lb_f and for the impact event to come to an end. This trend matched the experimental tests which indicated that the transient energy response of the composites was quicker as the percentage of filler material was increased.

The second trend was with respect to the total quantity of energy absorbed. The numerical results clearly indicated that the absorbed energy decreased as the percentage of filler material increased. This trend agreed

with the findings made by Beard and Chang, who showed that the energy absorption characteristics of a composite material can be altered by modifying its resin system [10]. Specifically, their research indicated that increasing the elastic modulus of a composite's resin system generally leads to a decrease in mechanical strength. The decrease in strength then results in a lower specific energy absorption.

The third trend was associated with the maximum deflection achieved for each specimen at their respective ultimate loading and impact energy. Similar to the experimental results, the numerical models showed that the maximum deflection decreased as the percentage of filler material increased. Therefore, increasing the material stiffness limited the elastic deformation and led to less impact energy being dissipated by the means of bending. Consequently, more energy went into permanently damaging the laminates as the percentage of inorganic filler material was increased.

The transverse drop-weight low-velocity impact tests for the laminates made with limestone filler were simulated in *Abaqus/Explicit* using the same techniques as those made with high-density filler. The transient energy responses for the laminates made with limestone filler are shown below in Fig. 6.9.

Figure 6.9: Numerical Energy-Time Response for 10-Ply Laminates with Limestone Filler at Incident Impact Energy of 50 in-lb_f

Again, each specimen had a discrete maximum deflection and energy absorption, and the maximum impact energy achieved during each simulation was equivalent to the incident kinetic energy at the onset of the impact event. Each transient energy response also had a distinct inflection point which corresponded to the time at which the specimens reached their maximum deflection. A summary of the FEA results for the laminates made with limestone filler is shown in Table 6.8.

Table 6.8: Mechanical Behavior of Numerical 10-Ply Laminates with Limestone Filler at Incident Impact Energy of 50 in-lb_i

Specimen	Incident Impact Energy (in-lb _i)	Incident Impact Velocity (ft/sec)	Energy to Max Load (in-lb _i)	Total Absorbed Energy (in-lb _i)	Deflection at Max Load (in)
A₁₀^{15L}	49.06	4.57	49.06	33.66	0.124
A₁₀^{20L}	49.41	4.59	49.41	31.30	0.111
A₁₀^{25L}	49.29	4.59	49.29	30.71	0.094
Mean	49.25	4.58	49.25	31.89	0.110

The numerical analysis of the specimens made with limestone filler provided the same trends as the specimens made with high-density filler:

- 1) The transient energy response was quicker as the percentage of filler material was increased;
- 2) The total absorbed energy decreased as the percentage of filler material increased; and
- 3) The maximum deflection decreased as the percentage of filler material increased.

Since the basic findings for each set of specimens were the same, it was prudent to compare their relative results. Therefore, each laminate's simulated dynamic energy response was plotted on the same graph, as shown in Fig. 6.10.

Figure 6.10: Numerical Energy-Time Response for All 10-Ply Laminates at Incident Impact Energy of 50 in-lb_f

From the figure, it can be seen that laminates A_{10}^{15HD} and A_{10}^{15L} absorbed the largest amounts of total energy (33.69 and 33.66 in-lb_f, respectively). After including the incident kinetic energy of the sphere projectile from each simulation, it was determined that laminate A_{10}^{15L} absorbed a slightly larger *percentage* of energy than laminate A_{10}^{15HD} (68.6% versus 67.3%), which agreed with the experimental results. Also, according to the numerical results, laminates A_{10}^{25HD} and A_{10}^{25L} absorbed the lowest quantities and percentages of impact energy (28.89 in-lb_f / 58.4% and 30.71 in-lb_f / 62.3%, respectively). The transient energy responses for the laminates

made with 20% filler, by weight, were hardly discernible, with the high-density filler specimen (A_{10}^{20HD}) absorbing only 0.2% more incident kinetic energy than the limestone filler specimen (A_{10}^{20L}). A comparison of the numerical results for all of the 10-ply laminates is shown in Table 6.9.

Table 6.9: Mechanical Behavior of All Numerical 10-Ply Laminates at Incident Impact Energy of 50 in-lb_f

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Kinetic Energy Absorbed (%)	Deflection at Max Load (in)
A_{10}^{15HD}	50.05	4.62	50.05	33.69	67.3	0.121
A_{10}^{20HD}	49.27	4.58	49.27	31.28	63.5	0.106
A_{10}^{25HD}	49.48	4.59	49.48	28.89	58.4	0.087
A_{10}^{15L}	49.06	4.57	49.06	33.66	68.6	0.124
A_{10}^{20L}	49.41	4.59	49.41	31.30	63.3	0.111
A_{10}^{25L}	49.29	4.59	49.29	30.71	62.3	0.094
Mean	49.43	4.59	49.43	31.59	63.9	0.107

Comparing the specimens with the same percentage of filler material, the laminates made with limestone had greater maximum deflections during the dynamic impact event, which likely contributed to them absorbing more incident kinetic energy than the high-density specimens. This trend differed from the experimental tests which showed that the coupons made with high-density filler deflected more, on average, than those made with limestone filler. Further discussion regarding the similarities and differences between the experimental and numerical results is provided in the proceeding section.

6.3.3 Comparison of Experimental and Numerical Results

Table 6.10 provides a summary of the energy to maximum load, total energy absorbed, and maximum deflection for each of the 10-ply laminates which were determined from the experimental and numerical low-velocity impact tests at incident energy of approximately 50 in-lb_f.

Table 6.10: Comparison of Experimental and Numerical Results – All 10-Ply Laminates at Incident Impact Energy of 50 in-lb_f

Experimental Results for Incident Impact Energy of 50 in-lb _f			
Specimen	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
A ₁₀ ^{15HD}	52.46	32.51	0.11
A ₁₀ ^{20HD}	50.49	30.41	0.09
A ₁₀ ^{25HD}	52.31	35.48	0.10
A ₁₀ ^{15L}	51.42	35.07	0.10
A ₁₀ ^{20L}	51.17	32.35	0.09
A ₁₀ ^{25L}	51.34	32.93	0.10

Numerical Results for Incident Impact Energy of 50 in-lb _f			
Specimen	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
A ₁₀ ^{15HD}	50.05	33.69	0.121
A ₁₀ ^{20HD}	49.27	31.28	0.106
A ₁₀ ^{25HD}	49.48	28.89	0.087
A ₁₀ ^{15L}	49.06	33.66	0.124
A ₁₀ ^{20L}	49.41	31.30	0.111
A ₁₀ ^{25L}	49.29	30.71	0.094

Table 6.10 (Continued):

Specimen	Error		
	Energy to Max Load (%)	Total Absorbed Energy (%)	Deflection at Max Load (%)
A_{10}^{15HD}	4.6	3.6	10.0
A_{10}^{20HD}	2.4	2.9	17.8
A_{10}^{25HD}	5.4	18.6	13.0
A_{10}^{15L}	4.6	4.0	24.0
A_{10}^{20L}	3.4	3.2	23.3
A_{10}^{25L}	4.0	6.7	6.0

The energy to maximum load was slightly higher than the corresponding incident kinetic energy for each of the experimental tests. On the contrary, the impact energy at the maximum load was equivalent to the incident kinetic energy for all of the numerical tests. Since the basic theory of energy conservation states that energy cannot be created or destroyed, the slightly skewed experimental results and associated error were attributed to an incorrectly calibrated sensor in the *Impulse* data acquisition system.

Both the experimental and numerical data indicated that the impact performance of S-glass fiber-reinforced composites can be modified by altering the quantity and type of filler material mixed in the resin system. Specifically, the FEA results showed that the absorbed energy for each set of specimens decreased as the amount of filler material was increased. The experimental results were not as conclusive because the specimens made with 25% filler, by weight, absorbed the largest percentages of incident kinetic energy. The same can be said with respect to experimental and numerical

results for maximum deflection. The FEA models indicated that the deflection at maximum load decreased as the amount of filler material increased. However, the experimental tests showed that the laminates with 20% filler, by weight, deflected the least. These discrepancies are partially attributed to the numerical models not accounting for the reduction in the bond strength between the resin system and fibers as the amount of filler material was modified. Similar research has shown that there is a critical limit of filler material that can be used to modify the mechanical properties of a composite's resin system, beyond which the resin-to-fiber bond strength begins to significantly depreciate [44]. In addition, the error between the experimental and numerical deflections was partially attributed to the low granularity of the *Impulse* data acquisition system.

Laminate A₁₀^{25HD} had the largest percentage of error (18.6%) of all the specimens with respect to the total absorbed energy. This is believed to be a result of the experimental specimen absorbing more energy by the means of permanent damage than the other test specimens. Excessive delamination or matrix cracking, such as that exhibited by laminate A₁₀^{25HD}, could be a result of improper wet-out during the fabrication process. The experimental laminates may have also had misaligned plies or other flaws which contributed to the discrepancy between results. In addition, error could have been introduced in the FEA model via inaccurate material properties, inadequate mesh density, etc.

7 CONCLUSION

This thesis primarily focused on the effects of different matrix and filler composition of laminated woven roving S-glass epoxy composite plates which were subjected to static test, frequency resonance, and low-velocity impact. The tensile tests were used to obtain each laminate's tensile modulus of elasticity and to understand the effects of filler material on a composite's stiffness and strain-to-failure. The dynamic tests characterized several mode shapes and natural frequencies for each specimen, and determined the damping effects of the constituent filler material and laminate thickness. The impact testing was conducted with a transverse drop-weight machine with increasing impact energies and a constant impactor mass. Each laminate's Damage Threshold Load (DTL) was examined at three incident impact energies to determine the respective matrix composition influences. In addition, a numerical evaluation of the specimens was executed using *Abaqus/Explicit* to substantiate the experimental results.

All of the 2- and 10-ply static tensile tests showed that increasing the quantity of either high-density or limestone filler material resulted in a higher modulus of elasticity and shear modulus. However, the increased quantity of filler material resulted in a lower strain-to-break, producing a stiffer, more brittle material with a lower threshold of tensile deformation prior to ultimate failure. The average ultimate tensile stress and strain-to-break for the 10-ply

laminates was 23.3% and 30.1% lower, respectively, than for the 2-ply specimens. Therefore, increasing the laminate thickness resulted in a lower average elastic modulus and modulus of rigidity.

The dynamic modal analysis conducted on the magnetic shake table showed that the specimens made with high-density filler had higher resonant frequencies for each bending mode when compared to those made with limestone filler. Increasing the amount of inorganic filler material resulted in a higher resonant frequency for each mode. The 10-ply specimens required larger signal amplitudes than the 2-ply laminates to define the mode shapes, indicating that thicker laminates were more effective at damping energy in the form of deformation waves. Similar to the experimental results, the dynamic FEA model showed that the resonances of the laminates were modified by altering the quantity and type of filler material mixed in the resin system.

The experimental and numerical impact test data indicated that the impact performance of S-glass fiber-reinforced composites can be modified by altering the quantity and type of filler material mixed in the resin system. The transient impact force increased in a linear fashion in each experimental test until incipient damage was incurred at the DTL. The linear pre-DTL loading was attributed to each laminate having a constant flexural stiffness before the onset of damage. The majority of specimens experienced an abrupt drop in impact force just after the DTL due to elastic strain energy being released in the form of delamination and matrix cracking caused by

transverse and interlaminar stress. The post-DTL transient force was non-linear, which indicated that the force-time response after the initial onset of damage was governed by major failure modes, as opposed to the elastic resistance witnessed prior to the DTL.

The laminates made with 20% filler, by weight, had the highest DTL and maximum load, as well as the lowest percentage of incident energy absorbed, for their respective filler type. The composites fabricated with 20% filler also released the least elastic strain energy in the form of delamination and matrix cracking prior to maximum deflection. The post-DTL behavior for these specimens was not as influenced by major failure modes when compared to the test coupons made with 15% and 25% filler material.

The laminates fabricated with limestone filler had lower average deflections than the high-density filler specimens and were more susceptible to impact damage. The average indentation depth and percentage of incident kinetic energy absorbed were also greater for the laminates made with limestone filler. Regardless of filler type, the FEA results showed that the absorbed energy decreased as the amount of filler material increased. The FEA model also showed that the deflection at maximum load decreased as the amount of filler material increased.

The impact performance of S-glass fiber-reinforced composites cannot be predicted solely on their relative brittleness or ductility. One must also account for the complex and non-linear response of the material after the

onset of damage, which is largely influenced by the reduction in flexural stiffness and the propagation of impact damage. To determine which filler material is ideal for a specific application, one must determine the importance of the composite's residual strength after impact. If a design were to be subjected to a continued loading after an impact event, it would be preferable to build the composite structure using a laminate made with high-density filler in lieu of limestone filler. This is due to the increased modulus of elasticity, resistance to indentation, and inherent ability to limit the propagation of damage. On the contrary, if a design was intended to absorb as much energy as possible and the structure's residual strength was inconsequential, it would be best to fabricate the composite using a laminate made with limestone filler. The specimens with limestone filler required higher impact forces for incipient damage to occur, but energy was more readily absorbed after the DTL due to damage propagation. Consequently, the use of limestone filler reduced the impact load and energy transferred to the surrounding system after the damage threshold of the material was reached.

8 FUTURE WORK

Due to the limited availability of experimental test equipment, the tensile tests and low-velocity impact tests were not conducted consistent with the applicable ASTM specifications. In the future, it would be recommended to machine the tensile test specimens to the ASTM D-638 standard “dog bone” shape. Doing so would result in a uniform loading distribution and limit the specimen’s ultimate failure to the narrow loading region. This would result in more accurate calculations for the elastic and shear moduli, as well as strain for given loading conditions. It is also recommended that future impact tests follow the ASTM D-5628 standard with respect to the test fixture used. Specifically, the test specimens should be clamped along a circumference when using a point-load impact device.

It is advisable to reduce the number of variables when fabricating the test specimens so that the effects of constituent filler material can be better isolated. This study introduced multiple epoxy resin systems, laminate thicknesses, filler types and quantities, etc. Consequently, it was difficult to decipher obvious trends produced from the use of different types or amounts of inorganic filler material.

Different types of impact test methods could be conducted to verify the transient impact force, energy absorption, failure mechanisms, etc., of the S-glass fiber-reinforced epoxy laminates with inorganic filler material. Such tests could include Charpy, Izod, and other drop weight methods (e.g. ASTM

D-7136). If available, non-destructive inspection equipment such as ultrasonic or C-scanning could be used to determine the BVID threshold of the specimens and to examine their interlaminar impact damage. Tensile and compressive tests could also be conducted subsequent to impact testing in order to determine each material's specific residual strength.

In-depth research of the failure mechanisms and mechanics of laminated composites led to the deduction that prevailing analytical formulations do not accurately predict low-velocity impact behavior such as energy absorption, transient force, or deflection [8-16, 18, 23-24, 26, 36, 47-49]. Similar findings were made by Choi, Wu and Chang, who concluded that existing models are erroneous and cannot correctly predict impact damage or its residual effects [16]. Therefore, it would be beneficial to develop analytical formulations capable of determining critical factors including the damage threshold load, ultimate deflection, and percent incident kinetic energy absorbed. This would allow designers to better understand and predict the impact behavior of certain fiberglass epoxy composite laminates, especially those with inorganic filler material.

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10 APPENDICES

Appendix A: Static Tensile Test Data

Tensile Test Data for Laminate W_2^{15HD}

Tensile Strength for Laminate W_2^{15HD}

Failure Mode for Laminate W_2^{15HD} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate W_2^{15HD}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
W_2^{15HD}	1,296	46.11	2.1	2,172.9	890.5

Tensile Test Data for Laminate W_2^{20HD}

Tensile Strength for Laminate W_2^{20HD}

Failure Mode for Laminate W_2^{20HD} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate W_2^{20HD}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
W_2^{20HD}	1,140	43.28	1.8	2,370.1	1,185.1

Tensile Test Data for Laminate W_2^{25HD}

Tensile Strength for Laminate W_2^{25HD}

Failure Mode for Laminate W_2^{25HD} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate W_2^{25HD}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
W_2^{25HD}	1,156	42.85	1.4	2,805.1	1,402.6

Tensile Test Data for Laminate A_2^{15HD}

Tensile Strength for Laminate A_2^{15HD}

Failure Mode for Laminate A_2^{15HD} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_2^{15HD}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_2^{15HD}	1,284	45.27	2.2	2,044.2	1,022.1

Tensile Test Data for Laminate A_2^{20HD}

Tensile Strength for Laminate A_2^{20HD}

Failure Due to Stress Concentration

Failure Mode for Laminate A_2^{20HD} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_2^{20HD}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_2^{20HD}	1,368	44.11	2.0	2,126.2	1,063.1

Tensile Test Data for Laminate A_2^{25HD}

Tensile Strength for Laminate A_2^{25HD}

Failure Due to Stress Concentration

Failure Mode for Laminate A_2^{25HD} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_2^{25HD}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_2^{25HD}	1,546	47.55	2.1	2,189.6	1,094.8

Tensile Test Data for Laminate W_2^{15L}

Tensile Strength for Laminate W_2^{15L}

Failure Mode for Laminate W_2^{15L} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate W_2^{15L}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
W_2^{15L}	1,443	46.00	2.4	1,916.2	958.1

Tensile Test Data for Laminate W_2^{20L}

Tensile Strength for Laminate W_2^{20L}

Failure Mode for Laminate W_2^{20L} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate W_2^{20L}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
W_2^{20L}	1,534	47.79	2.4	1,972.8	986.4

Tensile Test Data for Laminate W_2^{25L}

Tensile Strength for Laminate W_2^{25L}

Failure Due to Stress Concentration

Failure Mode for Laminate W_2^{25L} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate W_2^{25L}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
W_2^{25L}	1,477	50.30	2.4	2,051.2	1,025.6

Tensile Test Data for Laminate A_2^{15L}

Tensile Strength for Laminate A_2^{15L}

Failure Mode for Laminate A_2^{15L} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_2^{15L}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_2^{15L}	1,607	49.71	2.4	2,004.4	1,002.2

Tensile Test Data for Laminate A_2^{20L}

Tensile Strength for Laminate A_2^{20L}

Failure Mode for Laminate A_2^{20L} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_2^{20L}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_2^{20L}	1,457	48.32	2.2	2,140.7	1,070.4

Tensile Test Data for Laminate A_2^{25L}

Tensile Strength for Laminate A_2^{25L}

**Failure Due to
Stress Concentration**

Failure Mode for Laminate A_2^{25L} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_2^{25L}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_2^{25L}	1,505	53.55	2.2	2,420.3	1,210.2

Tensile Test Data for Laminate A_{10}^{15HD}

Tensile Strength for Laminate A_{10}^{15HD}

Failure Due to Stress Concentration

Failure Mode for Laminate A_{10}^{15HD} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_{10}^{15HD}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_{10}^{15HD}	5,308	33.3	1.37	23.047	9.445

Tensile Test Data for Laminate A_{10}^{20HD}

Tensile Strength for Laminate A_{10}^{20HD}

Failure Mode for Laminate A_{10}^{20HD} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_{10}^{20HD}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_{10}^{20HD}	6,135	40.3	1.69	23.396	11.698

Tensile Test Data for Laminate A_{10}^{25HD}

Tensile Strength for Laminate A_{10}^{25HD}

Failure Due to Stress Concentration

Failure Mode for Laminate A_{10}^{25HD} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_{10}^{25HD}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_{10}^{25HD}	5,356	37.2	1.31	27.847	13.924

Tensile Test Data for Laminate A_{10}^{15L}

Tensile Strength for Laminate A_{10}^{15L}

Failure Due to Stress Concentration

Failure Mode for Laminate A_{10}^{15L} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_{10}^{15L}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_{10}^{15L}	6,377	39.0	1.74	21.421	10.711

Tensile Test Data for Laminate A_{10}^{20L}

Tensile Strength for Laminate A_{10}^{20L}

Failure Mode for Laminate A_{10}^{20L} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_{10}^{20L}

Specimen	Max. Load (lb _f)	Ultimate Stress (ksi)	Ultimate Strain (%)	Young's Modulus (ksi)	Shear Modulus (ksi)
A_{10}^{20L}	5,928	37.3	1.60	22.106	11.053

Tensile Test Data for Laminate A_{10}^{25L}

Tensile Strength for Laminate A_{10}^{25L}

Failure Due to Stress Concentration

Failure Mode for Laminate A_{10}^{25L} Under Tensile Load

Mechanical Behavior of Tensile Test for Laminate A_{10}^{25L}

Specimen	Max. Load (lb_f)	Ultimate Stress (ksi)	Ultimate Strain (%)	<i>Young's Modulus</i> (ksi)	Shear Modulus (ksi)
A_{10}^{25L}	4,551	29.7	1.21	24.401	12.201

Appendix B: Dynamic Modal Analysis Pictures

First 8 Mode Shapes for Laminate W_2^{15HD}

First 8 Mode Shapes for Laminate W_2^{20HD}

First 8 Mode Shapes for Laminate W_2^{25HD}

First 8 Mode Shapes for Laminate A_2^{15HD}

First 8 Mode Shapes for Laminate A_2^{20HD}

First 8 Mode Shapes for Laminate A_2^{25HD}

First 8 Mode Shapes for Laminate W_2^{15L}

First 8 Mode Shapes for Laminate W_2^{20L}

First 8 Mode Shapes for Laminate W_2^{25L}

First 8 Mode Shapes for Laminate A_2^{15L}

First 8 Mode Shapes for Laminate A_2^{20L}

First 8 Mode Shapes for Laminate A_2^{25L}

First 4 Mode Shapes for Laminate A_{10}^{15HD}

First 4 Mode Shapes for Laminate A_{10}^{20HD}

First 4 Mode Shapes for Laminate A_{10}^{25HD}

First 4 Mode Shapes for Laminate A_{10}^{15L}

First 4 Mode Shapes for Laminate A_{10}^{20L}

First 4 Mode Shapes for Laminate A_{10}^{25L}

Appendix C: Low-Velocity Impact Test Data

Impact Test Data for Laminate A_{10}^{15HD}

Force-Time and Energy-Time Response for Laminate A_{10}^{15HD} at Incident Impact Energy of 50 in-lb_f

Force-Time and Energy-Time Response for Laminate A_{10}^{15HD} at Incident Impact Energy of 55 in-lb_f

Force-Time and Energy-Time Response for Laminate A_{10}^{15HD} at Incident Impact Energy of 60 in-lb_f

Failure Mode for Laminate A_{10}^{15HD} Due to Impact Test at Incident Energies of 50, 55 and 60 in-lb_f

Mechanical Behavior of Impact Test for Laminate A_{10}^{15HD}

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Damage Threshold Load (lb _f)	Max Load (lb _f)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
A_{10}^{15HD}	50.05	4.62	552	826	52.46	32.51	0.11
	55.49	4.87	643	870	58.12	37.11	0.12
	60.07	5.06	631	915	63.00	39.94	0.12
Mean	55.20	4.85	609	870	57.86	36.52	0.12

Impact Test Data for Laminate A₁₀^{20HD}

Force-Time and Energy-Time Response for Laminate A₁₀^{20HD} at Incident Impact Energy of 50 in-lb_f

Force-Time and Energy-Time Response for Laminate A₁₀^{20HD} at Incident Impact Energy of 55 in-lb_f

Force-Time and Energy-Time Response for Laminate A_{10}^{20HD} at Incident Impact Energy of 60 in-lb_f

Failure Mode for Laminate A_{10}^{20HD} Due to Impact Test at Incident Energies of 50, 55 and 60 in-lb_f

Mechanical Behavior of Impact Test for Laminate A_{10}^{20HD}

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Damage Threshold Load (lb _f)	Max Load (lb _f)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
A_{10}^{20HD}	49.27	4.58	786	932	50.49	30.41	0.09
	55.00	4.84	765	1,004	54.99	34.47	0.10
	59.44	5.04	759	953	61.90	37.18	0.12
Mean	54.57	4.82	770	963	55.79	34.02	0.10

Impact Test Data for Laminate A₁₀^{25HD}

Force-Time and Energy-Time Response for Laminate A₁₀^{25HD} at Incident Impact Energy of 50 in-lb_f

Force-Time and Energy-Time Response for Laminate A₁₀^{25HD} at Incident Impact Energy of 55 in-lb_f

Force-Time and Energy-Time Response for Laminate A_{10}^{25HD} at Incident Impact Energy of 60 in-lb_f

Failure Mode for Laminate A_{10}^{25HD} Due to Impact Test at Incident Energies of 50, 55 and 60 in-lb_f

Mechanical Behavior of Impact Test for Laminate A_{10}^{25HD}

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Damage Threshold Load (lb _f)	Max Load (lb _f)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
A_{10}^{25HD}	49.48	4.59	736	859	52.31	35.48	0.10
	55.45	4.86	628	884	57.07	38.76	0.11
	59.01	5.02	792	937	61.19	42.13	0.11
Mean	54.65	4.83	719	893	56.86	38.79	0.11

Impact Test Data for Laminate A₁₀^{15L}

Force-Time and Energy-Time Response for Laminate A₁₀^{15L} at Incident Impact Energy of 50 in-lb_f

Force-Time and Energy-Time Response for Laminate A₁₀^{15L} at Incident Impact Energy of 55 in-lb_f

Force-Time and Energy-Time Response for Laminate A_{10}^{15L} at Incident Impact Energy of 60 in-lb_f

Failure Mode for Laminate A_{10}^{15L} Due to Impact Test at Incident Energies of 50, 55 and 60 in-lb_f

Mechanical Behavior of Impact Test for Laminate A_{10}^{15L}

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Damage Threshold Load (lb _f)	Max Load (lb _f)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
A_{10}^{15L}	49.06	4.57	787	860	51.42	35.07	0.10
	54.77	4.83	703	921	55.21	38.12	0.10
	59.28	5.03	800	962	59.96	42.26	0.10
Mean	54.37	4.81	763	914	55.53	38.48	0.10

Impact Test Data for Laminate A₁₀^{20L}

Force-Time and Energy-Time Response for Laminate A₁₀^{20L} at Incident Impact Energy of 50 in-lb_f

Force-Time and Energy-Time Response for Laminate A₁₀^{20L} at Incident Impact Energy of 55 in-lb_f

Force-Time and Energy-Time Response for Laminate A_{10}^{20L} at Incident Impact Energy of 60 in-lb_f

Failure Mode for Laminate A_{10}^{20L} Due to Impact Test at Incident Energies of 50, 55 and 60 in-lb_f

Mechanical Behavior of Impact Test for Laminate A_{10}^{20L}

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Damage Threshold Load (lb _f)	Max Load (lb _f)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
A_{10}^{20L}	49.41	4.59	802	925	51.17	32.35	0.09
	54.95	4.84	768	979	55.69	36.01	0.10
	59.45	5.04	809	1,003	59.77	39.45	0.10
Mean	54.60	4.82	793	969	55.54	35.94	0.10

Impact Test Data for Laminate A₁₀^{25L}

Force-Time and Energy-Time Response for Laminate A₁₀^{25L} at Incident Impact Energy of 50 in-lb_f

Force-Time and Energy-Time Response for Laminate A₁₀^{25L} at Incident Impact Energy of 55 in-lb_f

Force-Time and Energy-Time Response for Laminate A_{10}^{25L} at Incident Impact Energy of 60 in-lb_f

Failure Mode for Laminate A_{10}^{25L} Due to Impact Test at Incident Energies of 50, 55 and 60 in-lb_f

Mechanical Behavior of Impact Test for Laminate A_{10}^{25L}

Specimen	Incident Impact Energy (in-lb _f)	Incident Impact Velocity (ft/sec)	Damage Threshold Load (lb _f)	Max Load (lb _f)	Energy to Max Load (in-lb _f)	Total Absorbed Energy (in-lb _f)	Deflection at Max Load (in)
A_{10}^{25L}	49.29	4.59	704	886	51.34	32.93	0.10
	54.80	4.83	641	947	56.61	36.05	0.10
	59.41	5.03	699	967	59.04	40.33	0.10
Mean	54.50	4.82	681	934	55.66	36.44	0.10