THE EFFECT OF A LOW-VELOCITY IMPACT ON THE FLEXURAL STRENGTH AND DYNAMIC
RESPONSE OF COMPOSITE SANDWICHES WITH DAMAGE ARRESTMENT DEVICES

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TITLE: The Effect of a Low-Velocity Impact on the Flexural Strength and Dynamic Response of Composite Sandwiches with Damage Arrestment Devices

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Abstract

The Effect of a Low-Velocity Impact on the Flexural Strength and Dynamic Response of Composite Sandwiches with Damage Arrestment Devices

By: Kodi A. Rider

Impact strength is one of the most important structural properties for a designer to consider, but is often the most difficult to quantify or measure. A constant concern in the field of composites is the effect of foreign object impact damage because it is often undetectable by visual inspection. An impact can create interlaminar damage that often results in severe reductions in strength and instability of the structure. The main objective of this study is to determine the effectiveness of a damage arrestment device (DAD) on the mechanical behavior of composite sandwiches, following a low-velocity impact. A 7.56-lb_f crosshead dropped from a height of 37.5-inches was considered for the low-velocity impact testing. In this study, the experimental and numerical analysis of composite sandwiches were investigated, which included static 4-point bend and vibration testing. Composite sandwiches were constructed utilizing four-ply of Advanced Composites Group LTM45EL/CF1803 bi-directional woven carbon fiber face sheets with a General Plastics Last-A-Foam FR-6710 rigid polyurethane core. Specimens were cured in an autoclave, using the manufacturer's specified curing cycle.

In addition to the experimental and numerical analysis of composite sandwiches, developing and building a data acquisition (DAQ) system for the Dynatup 8250 drop weight impact tester was accomplished. Utilizing National Instruments signal conditioning hardware, in conjunction with LabView and MATLAB, complete testing software was developed and built to provide full data acquisition for an impact test. The testing hardware and software provide complete force vs. time history and crosshead acceleration of the impact event, as well as provide instantaneous impact velocity of the projectile. The testing hardware, software, and procedures were developed and built in the Aerospace Structures/Composites laboratory at Cal Poly for approximately 15% of the cost from the manufacturer.

In the first study, static 4-point bend testing was investigated to determine the residual flexural strength of composite sandwich beams following a low-velocity impact. Four different specimen cases were investigated in the 4-point bend test, with and without being impacted: first a control beam with no

delamination or DAD, second a control beam with a centrally located 1-inch long initial delamination, third a DAD key beam with two transverse DADs centrally located 1-inch apart, and finally a DAD key beam with a centrally located initial delamination between two transverse DADs. The specimens used followed the ASTM D6272 standard test method. The specimens were 1-inch wide by 11-inch long beams. The experimental results showed that the presence of DAD keys significantly improved both the residual stiffness and ultimate strength of a composite sandwich structure that had been damaged under low-velocity impact loading, even with the presence of an initial face-core delamination.

In the second study, vibration testing was investigated as a means to detect a delamination in the structure and the effect of impact damage on the vibrational characteristics, such as damping, on composite sandwich plates. Four different specimen cases were investigated in the vibration test, both with and without being impacted: first a control plate with no delamination or DAD, second three control plates with varying 1-inch initial delamination locations at the 1st, 2nd, and 3rd bending-mode nodes, third a DAD key plate with one DAD running the entire length longitudinally along the center of the plate, and finally three DAD key plates with one DAD running the entire length longitudinally along the center of the plate and varying 1-inch delamination locations at the 1st, 2nd, and 3rd bending mode-nodes. The response accelerometer location was varied at 1-inch increments along the length of the plate. From the experimental results, it was determined that varying the location of the accelerometer had a significant effect on the detection of face-core delamination in a composite sandwich structure. Additionally, it was shown that damping characteristics significantly degraded in control case plates after a low-velocity impact, but they were better retained when a DAD key was added to the structure.

Numerical analysis utilizing the finite element method (FEM) was employed to validate experimental testing, as well as provide a means to examine the stress distribution and impact absorption of the structure. The impact event was modeled utilizing the LS-Dyna explicit FE solver, which generated complete force vs. time history of the impact event. Static 4-point bending and vibration analysis were solved utilizing the LS-Dyna implicit solver. Finally a damaged mesh was obtained from the explicit impact solution and subjected to subsequent static 4-point bending and vibration analysis to numerically determine the residual mechanical behavior after impact. All cases showed good agreement between the numerical, analytical, and experimental results.

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Nomenclature

	<u>Units</u>
D – flexural rigidity	lb _f *in ²
E – elastic modulus	psi
F – force	lb _f
G – shear modulus	psi
I – area moment of inertia	in ⁴
K – stiffness	lb _f /in
L – length	in
M – moment	lb _f *in
P – load	lb _f
R – crosshead loading rate	in/min
V – volume fraction	%
W – weight fraction	%
X – longitudinal direction	
Y – transverse direction	
Z – minimum outer fiber straining rate	in/in*min
a – acceleration	ft/s ²
c – loading width	in
b – width	in
d – depth	in
f – frequency	Hz
l – longitudinal	
m – mass	lb _m
n – slope of the tangent to the initial straight line	
t – time	s
t – face thickness	in
u – time domain amplitude	in
w – deflection	in
x – location along the length	
α – shear stress nonlinear term after yielding has occurred	
β – weighing factor for shear term in tensile fiber mode	
δ – displacement	in
ε – strain	in/in
ζ – damping ratio	
ν – Poisson’s ratio	
ρ – density	lb _f /in ³
σ – stress	psi
φ – constant dependent on the boundary conditions	
ω – circular frequency	rad/s
FBRT – softening factor for fiber tensile strength after matrix failure	
SOFT – crush-front strength reducing parameter	
YCFAC – softening factor for fiber compressive strength after matrix failure	

SUBSCRIPTS

B – bending
C – compressive
T – tensile

a – left of resonant peak
b – right of resonant peak
c – core
e – equivalent
f – face
m – matrix
n – natural
t – transverse

FAIL – failure
FAILC – compressive failure
FAILM – matrix failure
FAILT – tensile failure
max – maximum

1 – first mode
2 – second mode

Chapter 1. Introduction

The following sections provide a brief overview of composites in general, and more specifically sandwich composites. The impact behavior of composites and the effect of applications are discussed. Finally previous research, including previous research efforts in the Aerospace Structures/Composites laboratory at Cal Poly, are examined, and the objective and scope of this research are addressed.

1.1 Overview of Composites

In the aerospace industry, composites have become the new material norm in manufacturing small components up to entire systems. They have replaced traditionally used high performance alloys, such as aluminum and titanium, in many applications and continue to become more prevalent every year. A composite is a combination of two or more different materials which when combined, exhibit certain properties of their constituent parts. In general, there are four types of composites: fibrous, laminated, particulate, and any combination of the preceding three [1]. Commonly, composites are made up of primary load bearing fibers which are reinforced and secured by a relatively weaker matrix. Matrix materials provide the general shape of the finished product and dictate the parameters of the manufacturing process. The stiffness of the matrix should correspond to the stiffness of the fibers and be sufficient to provide uniform loading of the fibers. High adhesion between load bearing fibers and the encasing matrix is necessary for high performance composites [2]. More often, composites are used because they generally exhibit improved stiffness, corrosion and wear resistance, thermal insulation and conductivity, and fatigue life compared to traditional metals and alloys.

Sandwich composites are a certain type of laminated composite consisting of a combination of different materials that utilize the properties of each component for the structural advantage of the whole assembly. Often, high stiffness, thin face sheets (carbon fiber, fiberglass, or aramid laminates) are used to resist in-plane loads while thick, lightweight cores (balsa wood, foam, or honeycomb) are used to resist shear loads. The use of a thick core increases the area moment of inertia, resulting in higher in-plane and flexural stiffness. In general, composite sandwich structures have high specific stiffness and strength, noise reduction,

thermal insulation, and impact energy absorption characteristics [3]. With these features, composite sandwich structures have become popular for many applications including boat hulls, primary structure spacecraft panels, aircraft flooring, and automotive bumpers and panels. The primary failure modes of composite sandwich structures under

Figure 1.1. A schematic of a typical sandwich composite plate [8].

static and dynamic loading include face-core delamination, face wrinkling and indentation failure, compressive failure, and core failure.

1.2 Impact Behavior of Composites

Impact to composite structures has recently come to the forefront of material research and testing. There are three main types of impact: high-mass low-velocity, low-mass high-velocity, and high-mass high-velocity impact events. During the lifetime of an aircraft, the structure experiences all of these impact events while some have a higher frequency of occurrence than others. An example of a high-mass low-velocity impact would be if a mechanic were to drop a wrench onto a composite wing or panel during assembly or even routine maintenance. Low-mass high-velocity impacts often occur during aircraft takeoff and landing when small particles such as rocks kick up from the wheels onto the primary structure. High-mass high-velocity impact is the least frequent of the three, and is often the most catastrophic

Figure 1.2. High-mass high-velocity impacts, such as bird strikes, often cause catastrophic damage as shown on this F-111 [4].

when it occurs, such as aircraft bird-strike or aircraft-aircraft collision mid-flight.

Impact strength is a structure's ability to resist high-rate loading. This is one of the most important structural properties for a designer to consider, but is often the most difficult to quantify or measure. A constant concern in the field of composites is the effect of foreign object impact damage because it is often undetectable by visual inspection. An impact can create interlaminar damage that often results in severe reductions in strength and instability of the structure. Different experimental tests are used to simulate various different types of impact. Drop weight testers are used to simulate low-velocity impacts typical of a tool-drop, while air-gun systems are used to simulate the type of impacts encountered during aircraft takeoffs and landings [5]. Understanding the impact behavior of composites is critical to many applications including ships, which are often constructed from fiberglass and are susceptible to sinking when the hulls are adversely impacted. Also, aircraft are regularly subjected to numerous impact events including bird-strikes, tool drops during manufacture and scheduled maintenance, and gravel strikes due to landing and takeoff.

1.3 Previous Research on Impact Behavior of Composites

Extensive research has been done in field of composite impact behavior with a focus on low-velocity impact. Gdoutos et al., [6] and [7], examined the failure mode of composite sandwich structures under various loading conditions and determined that the initiation of various failure modes depends on the various properties of the constituents, geometric dimensions, and the type of loading. Lim et al. [3] investigated the static load capabilities and failure modes of foam core composite sandwich beams by both experimental and simple analysis means. In addition, the researchers investigated impact loading both experimentally and numerically, and were able generate an impact failure mode map from test results and finite element analysis (FEA). It was determined that the impact energy absorption capability correlated strongly with the observed failure mode, and that sandwich beams should be designed to fail in the face-failure mode to maximize impact energy absorption.

In addition to experimental investigation, much research has been concentrated towards numerical analysis and developing finite element models that closely correlate with experimentally determined trends. Klaus et al. [9] determined the impact behavior of sandwich panels with different core materials and their residual strength after impact. The study developed a method to simulate the impact and perform numerical residual strength simulations with pre-damaged meshes, in which the numerical FEA results showed very

close correlation with experimental test results. Heimbs et al. [10] studied the influence of a compressive preload on the low-velocity impact behavior of a carbon fiber composite plates both experimentally and numerically (utilizing the LS-Dyna FE solver). The results of the study showed good agreement between experimental and numerical results in terms of impact force vs. time plots, kinetic energy time plots, and interlaminar damage of the plate. The numerical investigation showed that results are largely influenced by simulation parameters including element size, the number of shell element layers, and contact stiffness scale factors. Feraboli et al. [11] developed a methodology utilizing a building block approach to determine the response of a structure through numerical analysis supported by test evidence. With this approach, tests were done at the coupon level and were modeled in the FEA program to calibrate the analysis. Once each of the constituents was tested, analyzed, and calibrated, a model of the entire system was developed and analyzed. Numerical results showed good agreement with experimental test of the entire system, proving that the building block approach is a valid means for developing accurate numerical models.

1.4 Previous and Current Research Efforts at Cal Poly

This research is an extension of a project of the Aerospace Structures/Composites laboratory at Cal Poly funded by the C³RP (California Central Coast Research Partnership) Program. Many of the current test specimens manufactured for this study were based from previous theses which developed a methodology for the test specimen manufacture and experimental testing. Surano et al. [12] investigated the effect of heat on composite sandwich plates with center holes of varying diameters, involving conventional notched and notched specimens with shear keys subjected to in-plane monotonic compression loading. The study involved circular shear keys oriented around the center hole and it was found that the largest diameter shear keys with the smallest central holes were the strongest specimens. Eswonia [13] examined the effect of shear keys and delamination in composite sandwich structures under monotonic and fatigue loading. Results showed that sandwich structures with an initial delamination and/or shear key in the foam core experienced a 70% reduction in ultimate strength when subjected to monotonic loading. Additionally, sandwich structures with a shear key in the foam core had a fatigue life reduction of approximately 33%. Orientation of the shear key was then changed from 0° to 90° and initial tests showed a 30% increase in ultimate strength under monotonic testing. Tran [14] investigated initially delaminated composite sandwich structures with a

delamination arrest mechanism under buckling loading. A continuous damage arrestment key was imbedded into the sandwich structure parallel to the in-plane loading and provided significant increase in buckling strength. The shear key increased the ultimate strength by 126% for specimens with a 1-inch delamination, and decreased by 11% for specimens with no delaminated region. All of the previously mentioned work was accomplished using fiberglass face sheets cured utilizing a vacuum resin infusion (VRI) process.

Balatbat [15] investigated damage arrestment devices in a specific application with fastener/hole interactions under monotonic and fatigue loading. The damage arrestment devices used were made of multiple layers of composite strips placed beneath the face sheet to increase the overall strength of the structure and prevent failure propagation along the hole. Results showed an optimal damage arrestment thickness of 0.065 inches which correlated to a 109% increase in ultimate strength under monotonic loading. Experimental results also indicated that both the control and damage arrestment cases showed similar fatigue trends. Surano [16] studied the same damage arrestment application as Balatbat [15], but under various environmental temperatures. The test specimens were subjected to both monotonic compression and compression-compression fatigue testing under temperatures of 75, 100, 125, 150, 175, and 200 degrees Fahrenheit. While fatigue trends showed no differences between cases, monotonic testing showed an increase of 97, 87, 100, 131, 96, and 119% in failure strength under increased temperatures with the use of damage arrestment devices. Finally, Davis [17] investigated the effects of a damage arrestment device on the mechanical behavior of sandwich composite beams under 4-point bending. In total, six test specimen cases were investigated including: a control beam with no delamination, a control beam with 1-inch long delamination, a beam with two transverse DAD keys, a beam with two transverse DAD keys and a 1-inch delamination between them, a beam with one longitudinal DAD key, and finally a beam with one longitudinal DAD key and a 1-inch delamination. The research concluded that the addition of DAD keys significantly increased the structural integrity of the beam for both the initially delaminated and non-delaminated cases. In all studies [15], [16], and [17] bi-directional pre-impregnated carbon fiber face sheets with a rigid polyurethane foam core composite sandwiches was used and cured utilizing a composite press plate. Current research efforts in our lab include the work of Thomas Woo who is studying effects of seawater on the mechanical behavior of sandwich composite panels under monotonic shear loading, Yvette Wood who is studying the effect of a low-velocity impact on composite sandwiches with damage arrestment devices under

fatigue loading, and Gabriel Sanchez who investigated damage arrestment devices on carbon fiber sandwich specimens under dynamic loading.

1.5 Objective of the Study

The objective of this study was to determine the effectiveness of damage arrestment devices (DADs) placed in sandwich composite structures under both dynamic and static loading. Static 4-point bend testing was implemented in order to determine if the DAD keys increased flexural strength with the presence of an initial face-core delamination in the sandwich composite. Dynamic vibration testing was implemented in order to determine if the presence of DAD keys improved the vibrational damping characteristics of the structure and increased vibrational performance in the presence of a face-core delamination in the sandwich composite. In addition, the accelerometer location was varied to detect the effect of a delamination or impact damage and effect of the accelerometer inertia on test results.

Sandwiches were subjected to drop weight impact events to determine if DAD keys improved the impact characteristics by reducing face sheet impact indentation when the sandwich was impacted directly on the DAD key, and by reducing face-core delamination propagation when impacted between two DAD keys. In addition, the effects of an initial face-core delamination were investigated under impact to determine if the damage and propagation increased with the presence of an initial delamination.

Subsequent static 4-point bending and dynamic vibration tests were investigated on specimens initially impacted in order to determine the residual flexural strength properties and vibrational damping characteristics. Static 4-point bend testing was compared without impact and after impact to determine the effect of DAD keys on the residual flexural stiffness of the structure as well as the retention of flexural strength following a high-mass low-velocity impact event. Additionally dynamic vibration testing was compared both before and after impact to investigate the detection of a delamination in the structure and the effect of impact damage on the vibrational characteristics, such as damping, after an impact event.

1.6 Scope of the Study

The remainder of this study is organized in chronological order, detailing the experimental, numerical, and analytical methodologies and results. Chapter 2 introduces the method of manufacture adopted for all specimens utilized and tested throughout the experimental phase. This section also discusses

the tests conducted in order to determine the relevant mechanical characteristics of the constituent materials (face sheet, core, and DAD key) needed for numerical analysis and experimental verification of the entire composite sandwich. Chapter 3 discusses the methods used for test specimen preparation and manufacture of the beams subjected to impact loading and static 4-point bending and the plates subjected to impact loading and forced vibration. The manufacture and integration of the DAD keys is discussed in detail, as well as the methodology for forcing an initial delamination into the structure and its initial location. Chapter 4 presents an overview of the experimental methodology and procedures performed for impact of the test specimen beams and plates, static 4-point bend testing of the beams, and vibration testing of the plates. In addition, design of the Dynatup 8250 data acquisition and testing system is discussed in detail including the testing measurement and data acquisition hardware used, and the development and design of the testing software written. Chapter 5 discusses the results of the experimentally investigated impact and static 4-point bending of the test specimen beams, and impact and vibration of the test specimen plates. Failure modes are examined and discussed in detail for the test specimens subjected to impact loading and static 4-point bending. Time domain analysis and damping ratios were determined for the test specimen plates at nine locations along the length and compared both before and after impact. Chapter 6 discusses the methodology and approach to modeling and analyzing the experimentally investigated tests utilizing numerical methods. Chapter 7 discusses the methodology and approach in developing analytic results for the static 4-point bend and dynamic vibration test cases as a means of validation of both the experimental and numerical models and results. Chapter 8 discusses and compares the results of both the experimentally investigated and numerically analyzed impact of the test specimen beams, static 4-point bending of the test specimen beams, impact to the test specimen plates, and vibration of test specimen plates. Experimentally and numerically obtained force vs. time history curves are compared. Finally, chapter 9 addresses the conclusions of this research and presents the results of all analysis and apparent trends.

Chapter 2. Manufacturing Process and Mechanical Characteristics of Constituent Test Coupons

This section introduces the method of manufacture adopted for all specimens utilized and tested throughout the experimental phase. This section also discusses the tests conducted in order to determine the relevant mechanical characteristics of the constituent materials (face sheet, core, and DAD key) needed for numerical analysis and experimental verification of the entire composite sandwich. The mechanical characteristics of the carbon fiber face sheets determined through experimental tests include: tensile modulus, maximum tensile strength, maximum compressive strength, and Poisson's ratio. In addition the compressive moduli (parallel-to-rise and perpendicular-to-rise) were determined for the rigid polyurethane foam core, and the tensile moduli (longitudinal and transverse directions) were determined for the fiberglass damage arrestment devices.

2.1 Carbon Fiber Face Sheets (ACG LTM45EL/CF1803)

Advanced Composites Group (ACG) pre-impregnated LTM45EL matrix with CF1803 bidirectional woven carbon fiber was utilized as the face sheet material in the composite sandwich beams and plates. Because the fibers are pre-impregnated with matrix, a heated curing cycle is required to fully harden the matrix. Curing the pre-impregnated carbon fiber was accomplished using the American Autoclave Co. autoclave in the Cal Poly Aerospace Structures/Composites laboratory. The autoclave curing chamber measures 2-feet in diameter and 4-feet in length. Its pressurized and enclosed environment makes the highest quality material, ensuring minimal manufacturing voids and inconsistencies. The curing cycle employed for the pre impregnated test coupon plates and composite sandwich test specimens included a dwell period of 16 hours at 140°F and 70 psi, as shown in fig. 2.1.

Figure 2.1. Autoclave cure cycle utilized for the manufacture of composite sandwiches and tensile coupons.

In order to accurately simulate the face sheets used for the composite sandwich test specimens, 12-inch by 12-inch four-ply carbon plates were manufactured for testing to determine the mechanical characteristics of the ACG LTM45EL/CF1803 carbon fiber. The plates were cured on a vacuum-ported aluminum plate designated for use in the autoclave. Porous release media was applied to either side of the part to reduce surface build-up of excess resin and a vacuum breather was applied over the top of the part to allow for ideal airflow and vacuum pressure. The aluminum plate was then prepped with high-temperature mold release wax for easier part and excess resin removal, post cure. The test coupon plate was then placed on the aluminum plate and a high temperature vacuum bag was applied over the part and sealed with a General Sealants synthetic rubber vacuum bag sealant in tape form. In addition, a vacuum port was applied through the vacuum bag. Figure 2.2 shows a schematic including a laminate, prepping agents, and curing agents used in the manufacture of the test coupon plates and composite sandwich test specimens.

Figure 2.2. Schematic of prepping agents used to cure face sheets and sandwiches.

Prior to initiating the autoclave cure cycle, the aluminum plate with sealed laminate was placed into the curing chamber and put under vacuum for approximately one hour. This was done for a number of reasons. First, the atmospheric pressure applied to the part as a result of the vacuum reduces interlaminar voids and excess resin content within the part. Second, the amount of pressure applied by the vacuum indicated the seal quality of the vacuum bag. The vacuum port on the aluminum plate was connected to a pressure gage in order measure the pressure applied by the vacuum and the overall all effectiveness of the

vacuum seal. Specimens that were cured with bad seals resulted in a fibrous finish with most of the impregnated resin burned out of the structure. This resulted in a part that had very low bending stiffness and insufficient bonding with a core when cured as a composite sandwich. After numerous test cures at different initial vacuum pressures, it was determined that the minimum required vacuum pressure of -20-inches of Mercury

Figure 2.3. Test specimen in the autoclave prior with applied vacuum pressure prior to curing.

(in. Hg) was required in order to obtain a part with optimized fiber/resin content. Figure 2.3 shows a specimen in the autoclave curing chamber prior to curing.

The tensile properties of the ACG LTM45EL/CF1803 face sheets were determined utilizing the ASTM D3039 standard test – “*Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*” [18]. Test coupons were cut to overall dimensions of 11-inches in length and 1-inch in width using a wet tile saw. Prior to cutting, it was ensured that each cut followed a single fiber to negate adverse effects of off-angle fiber alignment and orientation. The standard calls for a 1% tolerance in coupon width variation and 4% tolerance in coupon thickness variation, so any coupons not fitting into the tolerance were not tested. In total, twenty coupons were tested from three separate cure cycles to ensure there was no deviation or effect on the mechanical properties due to coupon curing in the autoclave.

Tensile tests were performed using the Instron 8801 Servohydraulic Fatigue Testing System in the Cal Poly Aerospace Structures/Composites laboratory. The test fixture applies pressure to the coupon using wedge grips that provide a shear contacting force. Because carbon fiber has low crushing resistance, the gripping force applied by the wedge grips was set to 8500 lb_f which was approximately 10% higher than the expected ultimate load, a reference recommended by the Instron user’s manual [19]. The test was performed using a constant crosshead speed of 0.05-inches/minute as per the standard and testing ended when a 40% drop in applied load occurred.

Upon initial testing, it was determined that the coupons were slipping within the grips and yielding a tensile modulus that was much lower than expected. To alleviate the problem, 1-inch lengths of emery cloth were applied to each end of the coupon. The emery cloth increased the friction between the grips and test coupon, and also saved manufacturing time over using traditional steel or S-glass tabs. Figure 2.4 below shows the testing of the carbon face sheets under ASTM D3039 test standards, and the emery cloth used to increase friction between the test coupon and wedge grips.

Figure 2.4. Tensile test of face sheets under ASTM D3039 standard test (left) and the emery cloth used to increase friction between test coupon and wedge grips (right).

Once testing was completed, each coupon was examined to ensure that proper failure occurred. Any coupons that experienced fracture within the grips or less than the coupon width (1-inch) away from the grips were determined to have an unacceptable failure specified by testing standard and were not included in further analysis or results. Figure 2.5 below shows the failure modes of each coupon immediately after tensile loading, some coupons have failures only originating near or within the wedge grips.

Figure 2.5. Failure modes of tested tensile coupons immediately after testing.

In total, sixteen coupon load-extension curves were obtained from the testing software, and subsequent stress-strain curves were determined utilizing the measured test coupon dimensions. Stress was determined by dividing the measured load throughout the test by the by the measured cross sectional area of each coupon, and strain was determined by dividing the measured extension throughout the test by the length of coupon between the grips (9-inches). After obtaining stress-strain curves for the sixteen coupons that met the testing standard requirements, elastic tensile modulus and maximum tensile strength were determined for each coupon. The elastic modulus was determined finding the slope of the linear region of stress-strain curve and maximum tensile strength was determined by the maximum stress prior to failure. The average elastic modulus determined was 6.65×10^6 -psi with a standard deviation of 3.49% and the average maximum tensile strength was 97,873-psi with a standard deviation of 6.36%. The subsequent stress-strain curves for each tested coupon are shown in fig. 2.6.

Figure 2.6. Experimentally obtained tensile stress-strain curves for face sheets.

The Poisson's ratio of the ACG LTM45EL/CF1803 face sheets was determined utilizing the ASTM E132 standard test – "*Standard Test Method for Poisson's Ratio at Room Temperature*" [20]. This test follows the same coupon dimensions and tolerances specified in the ASTM D3039 test standard, and also the same constant crosshead rate of 0.05 inches/minute. The test differs in that a strain gage is mounted to the coupon

in the transverse direction in order to measure the change in width as the coupon is loaded, and ensure that the maximum applied load does not take the coupon to failure.

Strain gages were applied to coupons from each of the three cure cycles investigated in the tensile test. Vishay Micro-Measurements EA-13-125AD-120 strain gages were applied to the coupons using the recommended process specified by Vishay [21]. Once the strain gages were mounted and ample time was allowed for the bonding agent to dry, 1-inch lengths of emery cloth were applied to either end of the test coupons exactly as was done in the tensile test. Figure 2.7 shows a strain gage mounted in the transverse direction on a test coupon.

Figure 2.7. Transversely mounted Vishay strain gage on a test coupon.

Testing was executed using the same wedge grips and Instron testing system as the tensile test. In addition an extensometer was mounted to the coupon to measure longitudinal extension under loading. This served as an effective means for validating the crosshead displacement of the machine and additionally provided a means for measuring any slipping that might occur within the grips. The strain gage was then connected to a Wheatstone bridge strain indicator box, which was connected to a National Instruments BNC-2111. This was done so that the output from the strain gage could be directly measured and read by the testing software using the versa channel option in Bluehill 2. Instructions on how to use the versa channel option were followed from Amini's master's thesis [28]. The test was run on four coupons, which were loaded to a maximum of 3000-lb_f to avoid failure. Figure 2.8 shows a test in progress with applied transverse strain gage and longitudinal extensometer.

Figure 2.8. Poisson's ratio test in progress with applied transverse strain gage and longitudinal extensometer.

Upon completion of tests, four average-strain vs. applied-load curves were obtained from the testing software. One can see from fig. 2.9 that there are two distinct groups of strain-load curves. The group with the steeper slope is the longitudinal strain, while the group with shallower slope is the transverse strain.

Figure 2.9. Experimentally obtained strain-load curves for face sheets used to determine Poisson's ratio.

Poisson's ratio was calculated utilizing eqn. 2.1 below by determining the slopes of longitudinal and transverse strain vs. applied load.

$$\nu = \frac{\partial \varepsilon_t / \partial P}{\partial \varepsilon_l / \partial P} \quad (2.1)$$

The measured Poisson's ratio was determined to be 0.098 with a standard deviation of 13.54%. This Poisson's correlated closely to what was expected for a bidirectional weave which is often assumed to be between 0.9 and 0.11 [22].

The maximum compressive strength of the ACG LTM45EL/CF1803 face sheets was determined from the ASTM D3410 standard test – “Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading” [23]. Test coupons were cut to overall dimensions of 5.5-inches in length and 1-inch in width. The standard calls for a 1% tolerance in coupon width

variation and 2% tolerance in coupon thickness variation, so any coupons not fitting the tolerance were not tested. In total, twelve coupons cut from one 12-inch by 12-inch plate were tested.

Compression tests were carried out using the same wedge grips with the Instron testing system utilized for the tensile and Poisson's ratio tests. Instead of using emery cloth as a means to increase friction between the grip and test coupon, the standard called for the use of 1-inch wide by 2.5-inch long aluminum tabs. The 0.060-inch thick aluminum tabs were cut to size using a shear press, then the coupon contacting sides were scored to increase bonding strength. A 2-part 3M epoxy adhesive was used to bond tabs

Figure 2.10. Compression test coupons with mounted aluminum tabs prior to testing.

to both ends of the test coupon. Figure 2.10 shows the coupons prior to testing with bonded aluminum tabs. Once the epoxy was fully cured with the tabs bonded to the test coupons, each coupon was tested under compression using the same constant crosshead speed of 0.05 inches/minute as was done in the tensile and Poisson's ratio tests. The test was stopped once a 20% drop in applied compressive load occurred. A coupon undergoing the ASTM D3410 compression test is shown below in fig. 2.11.

Figure 2.11. Coupon undergoing compression testing following the ASTM D3410 standard test.

Once testing was completed, each coupon was examined for proper failure specified by the standard. Unacceptable failure modes involved coupon failure within the tabs or tab de-bonding. All of the coupons tested failed under acceptable conditions; a typical failure observed during testing is shown in fig. 2.12. Resulting compressive load vs. compressive extension curves were obtained from the testing software and subsequent stress-strain curves were determined utilizing the measured test coupon dimensions. Compressive stress again was calculated by dividing the measured compressive load throughout the test by the cross sectional area, and compressive strain was determined by dividing the measured compressive

Figure 2.12. Typical failure mode observed during compression testing of the face sheets.

extension by the length of coupon between the tabs, which was 0.5-inches for all of the test coupons. The maximum compressive strength was then determined by the maximum compressive stress the coupon experienced prior to failure. The average compressive strength of the tested face sheets was 40,833 psi with a standard deviation of 10.36%. Figure 2.13 shows the resulting stress-strain curves for each tested coupon under the ASTM D3410 compression test. One can see in fig. 2.13 that substantial variation in the compressive modulus, as well as the ultimate compressive strength, existed between all of the tested coupons. A significant contributor to this error was the length of the aluminum tabs. As shown in fig. 2.12, the tabs were too long to fit within the wedge grips on the testing fixture, so approximately 0.5-inches of tab was left unclamped by both upper and lower wedge grips. While specimen failure was deemed acceptable as defined in the standard, the aluminum tab length greatly affected the compressive response of the tested coupons.

Figure 2.13. Experimentally obtained compressive stress-strain curves for the face sheets.

Fiber volume fraction was measured in order to determine the density of the ACG LTM45EL/CF1803 face sheets as well as verify that the appropriate amount of resin remained in the composite after curing. The density of the face sheet was vital for the numerical analysis in order to obtain mass properties for dynamic analysis. In total, eight coupons approximately 2-inches in length and 1-inch in width were measured in order to obtain specimen volume. The weight of each coupon was then measured to obtain an approximate density of the face sheet. The fiber volume fraction was then determined through a burn test. The test involved placing each measured coupon in an oven at approximately 975°F for 20 minutes to burn the resin out of the composite. Upon removal from the oven, the remaining coupon fiber weight was measured. Figure 2.14 shows the burned samples with only the remaining fibers.

Figure 2.14. coupons after burn test (only fibers remain).

Once the fiber weight and composite density were determined, the fiber volume fraction was calculated using eqn. 2.2.

$$V_f = \frac{\frac{W_f}{\rho_f}}{\frac{W_f}{\rho_f} + \frac{1 - W_f}{\rho_m}} \quad (2.2)$$

Where the ρ_f was the final fiber weight divided by the original composite coupon volume and ρ_m was given to be 1.2 g/cm³ from the manufacturer's technical data sheet [24]. The fiber volume fraction was determined to be 72.6% with a standard deviation of 5.82%, correlating closely with standard values of pre-impregnated composites which can reach fiber volume ratios as high as 80% [25].

2.2 Foam Core (GP Last-A-Foam FR-6710)

General Plastics Last-A-Foam FR-6710 rigid polyurethane foam was utilized as the core material in the sandwich composite test specimens. The compressive properties of the Last-A-Foam FR-6710 were determined utilizing the ASTM D1621 standard test, "Standard Test Method for Compressive Properties of Rigid Cellular Plastics" [26]. The test procedure calls for a minimum coupon cross sectional area of 4-in² and a minimum height of 1-inch. The foam core available to this research only came in 0.5-inch thick boards, so coupons were taped together prior to testing. In total, eleven

Figure 2.15. Foam core compression test coupons: perpendicular-to-rise (left) and parallel-to-rise (right).

coupons were tested in two different orientations: 6 tested parallel-to-rise and five tested perpendicular-to-rise as shown in fig. 2.15. 2-inch by 2-inch sections of the rigid foam core were stacked on top of each other for the parallel-to-rise test while 1-inch by 2-inch sections of the rigid foam core were placed side by side for the perpendicular-to-rise test. Each coupon was tested using the Instron servohydraulic fatigue testing

system under compression with a constant crosshead motion of 0.1-inches per minute. The test ended when the coupon had been compressed by approximately 13% of its thickness. Figure 2.16 below shows the testing of a foam core coupon under ASTM D1621 standard test.

Figure 2.16. Foam core coupon undergoing compression test (parallel-to-rise test).

Once testing was completed, compressive stress-strain curves were generated for each coupon. Figure 2.17 and 2.18 below show the resulting stress-strain curves for each coupon of the parallel-to-rise and perpendicular-to-rise tests, respectively.

Figure 2.17. Experimentally obtained compressive stress-strain curves for rigid foam core parallel-to-rise.

Figure 2.18. Experimentally obtained compressive stress-strain curves for rigid foam core perpendicular-to-rise.

The compressive modulus determined was 6129-psi with a maximum compressive strength of 272.71-psi parallel-to-rise, and was 4454-psi with a maximum compressive strength of 275.23-psi perpendicular-to-rise. The obtained experimental characteristics differ by nearly 50% from the given manufacturer's data sheet [27]. One can see from the figure that the large variations existed between coupons in the parallel-to-rise test. This indicates that decoupling and motion between the sections occurred, yielding significant error. Another source of error, between the experimentally determined and manufacturer's properties, includes the foam degradation due to environment storing and age.

2.3 Damage Arrestment Device

In order to determine the mechanical characteristics of the damage arrestment device, unidirectional fiberglass plates were manufactured utilizing a wet layup technique. First, Jamestown Distributors FIB-947 woven-roving fiberglass strands were cut down to approximately 15-inch lengths and secured one next to the other using General Sealants synthetic rubber vacuum bag sealant. The strands were lined together until a width of approximately 12-inches was obtained. Figure 2.19 shows the secured unidirectional dry fiberglass fibers prior to layup.

Once the fibers were aligned in a unidirectional orientation, Aeropoxy PH3660-hardener/PR2023-resin epoxy resin system was used to wet the fibers. During the layup process, extra caution was ensured in order to guarantee that the fibers remained in their proper orientation. After wetting the fibers, porous release media was applied to either side of the plate, and non-porous release media was applied over that. Finally, the part

Figure 2.19. Secured unidirectional fibers prior to wet layup.

and release media were placed in the tetrahedron composite press, shown in fig. 2.20, and 1000-lb_f was applied to the composite plate by the machine. The plate was cured at room temperature for 24-hours and was cut down to 12-inches by 12-inches utilizing a wet tile saw. In total, two plates were manufactured in order to test the tensile properties in both the longitudinal and transverse directions.

Figure 2.20. Tetrahedron press utilized to cure the unidirectional fiberglass plate.

The tensile properties of the damage arrestment device were determined utilizing ASTM D3039 standard, as was done to determine the tensile properties of the ACG LTM45EL/CF1803 face sheets. Test coupons were cut to overall dimensions of 11-inches in length and 1-inch in width using a wet tile saw. Prior to cutting, it was ensured that each cut followed a single fiber to negate adverse effects of off-angle fiber alignment and orientation. In total, sixteen coupons were tested.

Tensile tests were performed utilizing the Instron 8801 Servohydraulic Fatigue Testing System in the Cal Poly Aerospace Structures/Composites laboratory. The test fixture applied pressure to the coupons using wedge grips that provided a shear contacting force. The test was performed with same crosshead speed and failure criterion utilized in the carbon fiber face sheet tensile test. 1-inch lengths of emery cloth were applied to each end of the coupon. Figure 2.21 below shows the testing of the unidirectional damage arrestment

device fiberglass tensile coupons under ASTM D3039 test standards, with the fibers both longitudinally (parallel to loading) and transversely (perpendicular to loading) oriented with respect to the length of the test coupon.

Figure 2.21. Tensile test of unidirectional fiberglass transverse (left) and longitudinal (right).

Once testing was completed, each coupon was examined to ensure that proper failure occurred. Figure 2.22 below shows the failure modes of each coupon immediately after tensile loading. One can see from the figure that the transversely oriented fiber coupons (Group 1) failed along the width due to matrix failure while the longitudinally oriented fiber coupons (Group 2) failed due to fiber fracture along the length.

Figure 2.22. Failure modes of unidirectional fiberglass coupons: longitudinal (left) and transverse (right).

In total, thirteen coupon load-extension curves were obtained from the testing software, and subsequent stress-strain curves were determined utilizing the test coupon dimensions. Stress was determined by dividing the measured load throughout the test by the by the measured cross sectional area of each coupon, and strain was determined by dividing the measured extension throughout the test by the length of coupon between the grips (9-inches). After obtaining stress-strain curves for the thirteen coupons that met the testing standard requirements, elastic tensile modulus and maximum tensile strength were determined for each coupon. The elastic modulus was by determined finding the slope of the linear region of stress-strain curve and maximum tensile strength was determined from the maximum stress prior to failure.

Figure 2.23. Experimentally obtained tensile stress strain curves for unidirectional fiberglass longitudinal test coupons.

The average elastic modulus determined was 3.30×10^6 -psi with a standard deviation of 17.2% and the average maximum tensile strength was 11,985-psi with a standard deviation of 14.0% when the fibers ran longitudinally along the length of the test coupon. The average elastic modulus was determined 6.24×10^5 -psi with a standard deviation of 13.1% and the average maximum tensile strength was 1,522-psi with a standard deviation of 14.0% when the fibers ran transversely along the coupon. The subsequent tensile stress vs. strain curves for each tested coupon are shown in figs. 2.23 and 2.24.

Figure 2.24. Experimentally obtained tensile stress strain curves for unidirectional fiberglass transverse test coupons.

Chapter 3. Manufacture of Composite Sandwich Test Specimens

This section discusses the methods used for test specimen preparation and manufacture of the beams subjected to impact loading and static 4-point bending and the plates subjected to impact loading and forced vibration. The curing cycle and method of manufacture for the composite sandwich test specimens follow what was previously discussed in section 2.1. All of the specimens manufactured consisted of two face sheets, each with four plies of ACG LTM45EL/CF1803 pre-impregnated carbon fiber and 0.5-inch thick GP Last-A-Foam Fr-6710 rigid polyurethane foam core. The manufacture and integration of the DAD keys are discussed in detail, as well as the methodology for forcing an initial delamination into the structure and its initial location.

3.1 Beams for Impact and Static 4-Point Bending Tests

Four cases were investigated for the beams subjected to the static 4-point bending test. The first case was a control beam with no DAD keys or an initial delamination. Two 12-inch by 12-inch composite sandwich plates were manufactured and cured in the autoclave following the method discussed in section 2.1. Test specimen beams were cut to size from the plate using a wet tile saw. In total, twenty test specimen beams were manufactured for this case. Figure 3.1 shows a drawing with dimensions of the control case beam with no DAD keys or initial delamination.

Figure 3.1. Drawing of a control case beam with no DAD keys or initial delamination (dimensions were kept constant for all beam test specimen cases).

The second case investigated was a control beam with no DAD keys present, but with a 1-inch long initial delamination centrally located along the length of the beam. The delamination was forced using non-

porous release media, which allowed no resin flow between the face sheet and core. A 1-inch wide by 12-inch long strip was placed between the upper face sheet and foam core prior to the lay-up of the composite sandwich plate. Test specimen beams were again cut to down to size using a wet tile saw. Twenty test specimen beams were manufactured for this test case as well. Figure 3.2 below shows an exploded view drawing and test specimen dimensions of the control case beam with a centrally located delamination.

Figure 3.2. Exploded view drawing and specimen dimensions of a control case beam with a centrally located initial delamination.

After manufacturing both the control case beams with no DAD keys, the DAD key case beam with no initial delamination was manufactured. The DAD keys were first manufactured using a similar method as was used to manufacture the damage arrestment device tensile coupons described in detail in section 2.3. The difference in manufacturing from tensile coupons was that damage arrestment devices were a half cylinder in shape and required the use of an aluminum mold to form. The mold contained twenty-two half-cylinders 0.25-inches in diameter and 12-inches in length. The DAD keys were manufactured according to the proceeding wet lay-up process described in section 2.3.

Jamestown Distributors FIB-947 woven, roving 18 oz. fiberglass was used as the fiber material of the DAD key. First, a 15-inch by 15-inch square was cut from the roll and individual fibers were extracted. Next, fifteen 15-inch long unidirectional fiberglass fibers were tied to together at either end with a rubber band to make up one DAD key, as shown in fig. 3.3. The

Figure 3.3. Tied dry shear key fibers (left) and aluminum mold (bottom right).

process was repeated several times so that multiple DADs were manufactured in one cure. The mold was then prepped with mold-release wax to minimize any bonding between the curing fiberglass and the mold. Once the mold was prepped, Aeropoxy PH3660/PR2023 two-part epoxy resin was mixed and applied the strands of dry fibers tied together. Excess resin was applied to ensure full wetting of the fibers, and was forced through fiber bundle using a sweep. Once the fibers were wet, the strands were twisted from either end and placed into one of the semicircles in the mold shown in fig. 3.3. The twisting was done to ensure that all of the fibers remained in the secured mold and did not unravel. Once the mold was filled, non-porous release was applied over the DAD key specimens and plate was placed over the non-porous release media. The two plates (mold and top-plate) were then placed in the tetrahedron composite press, shown in fig. 2.19, and the machine applied 1000-lb_f was applied for 24-hours.

After curing, the DAD keys were removed as one plate from the mold and cut using a wet tile saw, as shown in fig. 3.4, and then sanded down to size. In order for the foam core to accept the DAD keys, 0.25-inch diameter half cylinder slots in the foam were milled using the CNC end mill located in the Cal Poly Aerospace Engineering Machine Shop. Machining was accomplished using 0.25-inch round bit with

Figure 3.4. Cutting the DAD keys using a wet tile saw before sanding down to size.

extra caution to keep tolerances and gaps minimal. The slots were milled so that with a 1-inch gap existed between them. Once the DAD keys were cured and cut, and the foam core slots were machined, two 12-inch by 12-inch test specimen plates were manufactured. Once the plates cured, the test specimen beams were cut to size from the plates using the same wet tile saw shown in fig. 3.4. In total, twenty test specimen beams were manufactured. Figure 3.5 below shows a schematic of the DAD key case beam with no initial delamination added.

Figure 3.5. Exploded view drawing of a DAD key case beam with no initial delamination.

Finally, a DAD key case beam with a 1-inch long initial delamination was manufactured. This followed the process used to manufacture the DAD key case with no initial delamination, except a 12-inch long by 1-inch wide strip of non-porous release media was added between the DAD key slots in the foam and between the foam and face sheet prior to curing. Two 12-inch by 12-inch test specimen plates were cured in autoclave. Once cured, test specimen beams were cut to size using the wet tile saw. In total, twenty test specimen beams were manufactured. Figure 3.6 below shows a schematic of the DAD key with an initial delamination centrally located between the keys.

Figure 3.6. Exploded view drawing of a DAD key case beam with a centrally located initial delamination.

3.2 Plates for Impact and Vibration Tests

Eight test specimen plate cases were investigated for vibration testing. This consisted of four control cases and four cases with DAD keys. The control cases consisted of a specimen with no delamination, a 1-inch long initial delamination at the 1st bending mode-node, a 1-inch long initial delamination at the 2nd bending mode-node, and two 1-inch long initial delamination locations at the 3rd bending mode-nodes. The DAD key cases consisted of one DAD that was oriented longitudinally and ran along the entire length of the plate. Four

cases were investigated which included a specimen with no delamination, and three with varying 1-inch long initial delamination locations at the 1st, 2nd, and 3rd bending mode-nodes.

The first specimen manufactured for vibration testing was a control plate with no DAD key or initial delamination. One 12-inch by 12-inch composite sandwich plate was manufactured and cured in the autoclave following the method discussed in section 2.1. A test specimen plate was cut to size from the cured plate using a wet tile saw. Figure 3.7 shows a drawing with dimensions of the control plate with no DAD key or initial delamination.

Figure 3.7. Drawing of a control case plate with no DAD key or initial delamination (dimensions were kept constant for all plate test specimen cases).

In order to determine the location of the bending mode-nodes, a rudimentary approach was investigated utilizing sugar and placing it on the composite sandwich test specimen plate during a vertical vibration test. The MB electronics magnetic vertical shake table in the Cal Poly Aerospace Structures/Composites laboratory was used for the dynamic test. 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 control case plate with no DAD key or initial delamination was centered in the clamp fixture, width-wise, with one end positioned flush with the rear of the aluminum fixture. The clamp was then tightened effectively creating a cantilever beam for vibrational testing, as shown in fig. 3.8.

Figure 3.8. Vibration testing to determine the bending mode-node locations of the control plate specimen with no DAD key or initial delamination.

The 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 the signal entered the shake table, it was passed through a power amplifier to increase the voltage to operate the shake table. In addition the signal was also fed to a digital frequency meter so that the frequency could be easily read during testing. Figure 3.9 below shows the digital frequency meter (left), power amplifier (lower right), and function generator (upper right) used to generate and read the signal fed to the MB electronics vertical shaker table.

Figure 3.9. Devices used to generate and read the signal fed to the MB electronics vertical shaker table.

The bending mode-node locations were determined using a rudimentary approach in which sugar was placed on the surface of the control plate, with no DAD key or initial delamination, during a sinusoidal vibration test. Frequency was slowly increased using the Hewlett Packard function generator, and the sugar would align itself at the node(s) when a natural frequency was reached. At higher frequencies, torsional effects were present and could be seen with a curvature in the sugar aligned at a node. Once a pure bending mode natural frequency was obtained, the function generator was left constant and the node location was measured along the length of the plate from the support clamp base. Figure 3.10 shows the corresponding 1st, 2nd, and 3rd pure bending mode nodal locations indicated by the sugar alignment. These node locations followed initial analytical solutions of the locations prior to testing. The 1st bending mode-node aligned itself at base, indicating maximum deflection at the tip. The 2nd bending modes were aligned at the base and 7.1-inches from the base. The 3rd bending modes were aligned at the base, 3.8-inches from the base, and 8.8-inches from the base.

Figure 3.10. The 1st (left), 2nd (middle), and 3rd (right) pure bending modes determined using a rudimentary approach.

After determining the bending mode nodal locations, three control plates with varying initial delamination locations were manufactured. As was done with the test specimen beams for the static 4-point bend testing, a 1-inch wide by 12-inch long strip of non-porous release media was applied between the foam core and face sheet. The 1st bending mode-node initial delamination was placed so it began 1-inch from the base of the test specimen plate, and is illustrated below in fig. 3.11.

Figure 3.11. Exploded view drawing of a control case plate with an initial delamination located at the 1st bending mode-node. The 2nd bending mode initial delamination was placed 6.6-inches from the base of the test specimen plate so that the 1-inch delamination was centered at the node, as shown below in fig. 3.12.

Figure 3.12. Exploded view drawing of a control case plate with an initial delamination located at the 2nd bending mode-node.

The 3rd bending mode initial delamination locations were placed 3.3-inches and 8.8-inches from the base of the test specimen plate so that the 1-inch delamination locations were centered at the nodes, and is shown below in fig. 3.13.

Figure 3.13. Exploded view drawing of a control case plate with an initial delamination located at the 3rd bending mode-nodes.

After manufacturing the four control case test specimen plates, the DAD key case plate with no initial delamination was manufactured. The methodology adopted for manufacture of the plate followed that of the test specimen beams with DAD keys described in section 3.1, except that only one DAD key was inserted into the structure and the orientation differed. Rather than running transversely along the width of the specimen, as with the beam case, the DAD key ran longitudinally along the length of the plate. This was done for a number of reasons. Due to the vibration test set-up, the shear key was chosen to run longitudinally along the length of the plate to determine whether there was added stiffness to the structure and also if vibrational damping was affected. It was determined that orienting the shear key transversely along the width of the plate would not affect the stiffness of the specimen and only add a concentrated mass wherever it was located. In addition, the DAD key orientation and location was chosen so that when impacted, the vibrational characteristics could be studied at multiple points along the length of the plate and the DAD key. The damage arrestment device was centrally located across the width and ran the entire length of test specimen plate. Figure 3.14 shows a drawing of the test specimen plate with a DAD key and no initial delamination used for vibration testing.

Figure 3.14. Exploded drawing of a test specimen plate with a DAD key and no initial delamination.

Next, the DAD key case test specimens with delamination locations at the 1st, 2nd, and 3rd bending mode-nodes were manufactured. The test specimen plates were all manufactured using the rudimentary previously discussed. As with the control case beams with varying delamination locations, 1-inch long by 12-inch wide strips of non-porous release media were inserted between the face sheet and foam core. In addition, the delamination was also inserted between the face sheet and DAD key as shown in the DAD key case with 1st bending mode-node initial delamination in fig. 3.15.

Figure 3.15. Exploded drawing of a test specimen plate with a DAD key and an initial delamination located at the 1st bending mode-node.

The 2nd bending mode-node initial delamination was placed 6.6-inches from the base of the test specimen plate so that the 1-inch delamination was centered at the node, and is shown below in fig. 3.16.

Figure 3.16. Exploded drawing of a test specimen plate with a DAD key and an initial delamination located at the 2nd bending mode-node.

Finally, the 3rd bending mode initial delamination locations were placed 3.3-inches and 8.8-inches from the base of the test specimen plate so that the 1-inch delamination locations were centered at the nodes, as shown below in fig. 3.17.

Figure 3.17. Exploded drawing of a test specimen plate with a DAD key and an initial delamination located at the 3rd bending mode-nodes.

Chapter 4. Experimental Design Methodology

This section presents an overview of the experimental methodology and procedures performed for evaluating impact behavior of the test specimen beams and plates, static 4-point bend testing of the beams, and vibration testing of the plates. An overview and methodology for the applicable ASTM testing standards are discussed for the drop-weight impact tests and static 4-point bending tests. In addition, design of the Dynatup 8250 data acquisition and testing system are discussed in detail including the testing measurement and data acquisition hardware used, and the development and design of the testing software written.

4.1 Impact Test

4.1.1 Design and Development of Data Acquisition System

A key objective within this research was the design, development, and assembly of a full data acquisition system for the Dynatup 8250 drop weight impact machine located in the Cal Poly Aerospace Structures/Composites laboratory. Since being purchased and installed in 2003, the machine has sat idly in the laboratory with no data acquisition or means for specimen testing. With insufficient funding to purchase the data acquisition system from the manufacturer, the entire system had to be designed in-house at a fraction of the cost. Key requirements of the testing system were: test specimen must be properly secured in the machine, instantaneous velocity of the impactor at the time of impact must be known, an entire force vs. time history of the impact event must be attained, and acceleration vs. time history of the impacting crosshead throughout the impact event must also be attained.

The Dynatup 8250 drop weight impact machine consists of the frame, two guide rails, hoist motor, drop-weight mechanism, and crosshead. Secured to the lower end of the crosshead is the impactor, or tup, which directly impacts the test specimen. The crosshead is capable of accepting different weights so that a wide range of impact energies can be obtained. In addition, the crosshead can be supplied with pneumatic assist for higher impact velocity tests. Figure 4.1

Figure 4.1. Dynatup drop weight impact machine used for experimental testing.

shows the Dynatup 8250 drop weight tester in the Cal Poly Aerospace Structures/Composites Lab used for impact testing.

In order to determine the instantaneous velocity at impact, a Thor Labs DET10A high speed Si-biased detector and laser module system was used in conjunction with a double edged flag. The flag was located on the edge of the falling crosshead of the drop weight machine, as shown in fig. 4.2 The Si-detector and laser module were oriented so that they were facing each other on either side of a double-edged flag. The Si-biased detector operates by obtaining light and converting it to differential voltage based on the wavelength of the light received. The detector has its highest spectral responsivity at approximately

Figure 4.2. Crosshead of the drop weigh impact tester with mounted double edged flag [30].

750-nm [29], meaning it outputs a maximum of 12-volts when exposed to 750-nm wavelength light. The laser module was chosen based on the output wavelength of light which was 650-nm for the model utilized. When the laser was turned on and facing the Si-detector, the detector outputted a constant voltage of approximately 12-volts. Figure 4.3 shows the biased detector with laser module signal (oriented towards the detector) used to measure the instantaneous velocity. The laser/detector system was positioned so that the double-edged flag passed through the laser signal just before the tup impacted the test specimen. When the double-edged flag passed through the laser signal, the signal was blocked from the detector which subsequently output no voltage. The double-edged

Figure 4.3. Si-biased detector with applied laser signal used to measure instantaneous velocity.

geometry of the flag caused two troughs in the signal where no light was seen by the detector.

Figure 4.4. Si-biased detector (left) and laser (right) on either side of the falling double edged flag.

Measuring the dimensions of the flag and dividing it by the time difference between the two troughs led to the experimental determination of instantaneous velocity prior to impact. Figure 4.4 shows the biased detector and laser oriented so as to face each other on either side of the double edged flag attached to the falling crosshead. The differential voltage was read from the biased detector utilizing a BNC to bare wire cable connected to a National Instruments (NI) USB-9162 DAQ card. In addition a 3-volt DC source was required to operate the laser module and this was supplied by a NI SC-2345 signal conditioning box with an NI SCC-A010 isolated voltage output carrier.

In order to attain the force vs. time history of the impact event, a Transducer Techniques THD-3K-W load cell was used to measure the impact force. This load cell is capable of measuring forces up to 3000-lb_f with an accuracy of $\pm 1\%$ of the measured force. It is a thru-hole type load cell mounted between the impacting tup and the crosshead assembly, as shown in fig. 4.5. Voltage is measured across a full-bridge circuit, in reference to a constant excitation voltage. The output of the device ranges from 0-mV/V to 20-mV/V with respect to the excitation voltage, which corresponds to a force range of 0-lb_f to 3000-lb_f. The output voltage was measured using an NI SC-2345 signal conditioning box with an NI SCC-

Figure 4.5. Thru-hole load cell, mounted between impacting tup and crosshead assembly, to measure impacting force.

SG24 two-channel load cell input module. The module supplied the load cell a constant 10-V DC excitation source and applied a 1.6 KHz lowpass filter to the signal. Figure 4.6 below shows the full-bridge circuit configuration of the compression load cell device.

Figure 4.6. Full-bridge circuit configuration of the compression load cell [31].

In order to obtain acceleration time history of the impacting tup, a single axis accelerometer was mounted to the falling crosshead. A VIP sensors model 1011a piezoelectric accelerometer was used to measure change in acceleration of the falling crosshead throughout the entirety of the impact test. In order to amplify the signal, a VIP sensors model 5004-10 remote charge converter was utilized. The charge converter is a low-noise, wideband, front-end signal conditioner that transforms the high impedance charge signals from piezoelectric transducers to low impedance voltage signals. In addition the charge converter provides a

Figure 4.7. Single axis accelerometer used to measure kinetic energy dissipation of the impact tup throughout the impact event.

gain of 10-mV/pC to amplify the signal. An NI SC-2345 signal conditioning box with a NI-ACC01 single channel accelerometer input module was used to obtain the amplified accelerometer signal. The accelerometer was mounted to the top of the load cell and secured using petro wax as shown in fig. 4.7.

The signals obtained using the NI USB-9162 (with previously discussed modules) and NI SC-2345 DAQ devices were then conditioned and analyzed using testing software written in NI LabVIEW and MATLAB.

Signals were first obtained from the data acquisition hardware through the program NI DAQmx, which is DAQ driver software with an interface for programming the analog inputs and analog outputs of the system. Within DAQmx, the types of signals for each testing hardware component were specified and scaled to corresponding units of acceleration (in g's), load (in lb_f), differential DC voltage (in V), and output DC voltage (in V) for the accelerometer, load cell, Si detector, and laser module, respectively.

Once the system was programmed in NI DAQmx, a LabVIEW .vi file was written to acquire and plot the signals from input devices (load cell, accelerometer, and Si-detector), control the output signal to the laser module, initialize data acquisition for testing, and finally save the raw data obtained from the test. The DAQ Assistant block was used in order to obtain the signals previously programmed and defined in the NI DAQmx software. Two DAQ Assistant blocks were designed for each of the DAQ devices used to obtain test data. From these blocks, the raw data were sent to three waveform graphs, which plotted live data acquisition of force vs. time, acceleration vs. time, and voltage vs. time for the load cell, accelerometer, and Si-detector, respectively. The raw data were also written to a .lvm extension in order to save and organize the data from the test. In addition, remote control of the laser was programmed so that it could be turned on and off simply by clicking a switch on the LabView control panel. Figure 4.8 below shows the LabVIEW code written to acquire and generate signals, write raw test data to a file, and initiate data acquisition for experimental impact testing.

Figure 4.8. LabVIEW code written to generate and acquire signals from the data acquisition devices, initialize testing, and save test data.

After writing and testing the LabVIEW code, an executable file was created so that the user no longer had to open LabVIEW and search for the .vi. Instead, a stand-alone file is easily accessed from the desktop of the computer. “Dynatup DAQ.exe” is a simple executable file that acquires test data and provides instructions to the user for testing (including data acquisition, test hardware functions, test initialization, and raw data saving). Prior to running a test, the user must turn on the Si detector (sliding the switch on the left side of the body from “O” to “I”) and also turn on the laser in the software (switch will turn green). Next, a path and filename must be specified to save the raw data obtained from the test. The test data can only be saved as a .lvm file which is later read into MATLAB. Next, data acquisition is initialized by pressing the “RUN” arrow button at the top of the window. At this time data are visible in the three plots, also the Si-detector plot should show approximately 12 volts output, any less meaning there is off alignment between the detector and laser. Finally, the impact test is run and user presses “STOP” at the top of the window when the test is completed. Figure 4.9 shows a screenshot of the Dynatup DAQ software window while data acquisition was in progress.

Figure 4.9. Dynatup DAQ software window with data acquisition in progress.

Once the test was run and saved to a .lvm file, the raw data were read into a MATLAB script file. MATLAB was used to calculate instantaneous velocity of the tup at impact and maximum impact force, as well as provide force vs. time and acceleration vs. time plots of the impact event. A graphical user interface (GUI) was written so that the user could select multiple raw data files and quickly view the results from each test. Figure 4.10 below shows the GUI used for quick and easy access to the relevant results of the impact test including impact force vs. time plot, acceleration of the tup vs. time plot, instantaneous velocity at impact, and maximum impact force. Further detailed instructions on the impact testing procedures and how to run the testing software are provided in Appendix A.1.

Figure 4.10. MATLAB guided user interface programmed to analyze and plot impact test data.

4.1.2 Overview of Test (ASTM D7136)

The impact resistance properties of the test specimen plates and beams were determined utilizing the ASTM standard test – “Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event” [32]. While most of the standard test was followed to determine the impact properties of the specimens, a few parameters deviated from the standard test. First,

the mass of the impactor for the test specified in the standard is 12-lb_m, whereas the actual weight of the impactor for this test was 7.56 lb_m. Next, the dimensions of the test specimens specified in the test standard are 6-inches in height by 4-inches in width. The actual test specimen dimensions for the tests were 1-inch wide by 11-inches long for the beams, and 3.5-inches wide by 11-inches long for plates. These dimensions were driven by the 4-point bending and vibration tests following the impact event. Finally, testing of sandwich composites is not specifically specified in the standard; it only specifies the use of unidirectional and woven laminates following a specific ply-stacking sequence and lay-up.

In order to conform to the ASTM standard test, a test specimen support fixture and impacting tup were machined and manufactured by Daniel Barath, a Cal Poly Aerospace Engineering undergraduate student for his senior project. The test specimen support fixture was machined and assembled to standard specifications, with a 3-inch wide by 5-inch long unsupported section where the impacting tup was centrally located. The clamping mechanism of the fixture involves four pneumatic air cylinders, located at each corner of the fixture. The air cylinders clamp an aluminum plate

Figure 4.11. Test specimen clamped in test support fixture.

securing the test specimen in the testing fixture as shown in fig. 4.11. The clamping pressure and mechanism are controlled by the Dynatup 8250 frame. Clamping pressure is easily adjusted by the user and was set to 60-psi for all of the tests in this study. In addition, a hemispherical impact tup was manufactured following the test standard specifications. The diameter of the tup is 0.625-inches and the hardness of the material is 62 HRC. The tup was also machined so that it fit to the existing crosshead support and was able to secure and fit the compression load cell.

4.2 Static 4-Point Bend Test

4.2.1 Overview of Test (ASTM D6272)

The flexural properties of the sandwich beams were determined utilizing the ASTM D6272 standard test – *“Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical*

Insulating Materials by Four-Point Bending" [33]. In this testing procedure, a beam of rectangular cross section is simply supported on either end of the length specimen and loaded by two point forces as shown in fig. 4.12. The distance between the loading point forces was one third the length of the support distance and the roller supports were distanced sixteen times the thickness of the specimen apart from each other. The support span determined for the test was 9.904 inches, which corresponded to a loading width of 3.301 inches.

Figure 4.12. Schematic of 4-point bending test specified by the ASTM 6272 standard test [33].

The specimen was then loaded until fracture or until the maximum fiber strain of 5% was reached. The constant crosshead loading rate of the testing machine was dictated by the test specimen dimensions and found using eqn. 4.1.

$$R = 0.185 \frac{ZL^2}{d} \quad (4.1)$$

where 0.185 is dictated in the standard by the one third load span and Z was the minimum straining rate of the outer fibers and was 0.01. The crosshead rate was determined to be 0.3692 in/min for all the tests. Figure 4.13 below shows a sandwich beam in the testing fixture prior to loading.

Figure 4.13. Composite sandwich beam specimen in 4-point bending test fixture prior to loading.

4.3 Vibration Test

4.3.1 Overview of Test

The vibrational characteristics of the composite sandwich plate test specimens were measured utilizing the Unholtz-Dickie vibration table located in the Cal Poly Aerospace Structures/Composites laboratory, shown in fig. 4.14. The vibration table can perform dynamic testing in both vertical and horizontal orientations. It is ideally suited for sequential 3-axis test capability with minimized cross axis response; for testing heavy, oversized, or non-symmetrical loads; and for products where orientation with respect to gravity is necessary. The vibration table is also capable of sine wave, random noise, chirping, and white noise forcing functions up to frequencies of 5000-Hz.

Figure 4.14. Unholtz-Dickie shake table utilized for vibration testing of the composite sandwich plate specimens.

For testing the vibrational characteristics of the composite sandwich plate test specimens, the table was oriented so that it induced a horizontal force into the specimen. The test specimen was oriented in a vertical orientation and was secured from the base of the table and up 1-inch by two 6061-aluminum blocks. The securing blocks were mounted to the table and screwed together with the test specimen clamped between the two as shown in fig. 4.15. When the clamping fixture was tightened, it effectively created a cantilever beam for vibrational testing.

Two PCB Piezotronics 353B04 single access accelerometers, with an axial sensitivity of 9.74-mV/g, were used to obtain the excitation amplitude and frequencies of the vibration response (test specimen) and vibration input (vibration table). The input accelerometer was mounted and secured to the aluminum clamping fixture in the direction of the applied table force using petro wax as shown in fig. 4.15. The response accelerometer was mounted to the test specimen plate and secured using petro wax. In total, nine vibration tests were run on each test specimen with varying response accelerometer locations. The response accelerometer was centrally placed along the width of the plate but was varied in 1-inch increments along the length

Figure 4.15. Secured composite sandwich plate specimen with mounted accelerometers prior to vibration loading.

of the plate for each test. This was done to determine the effect the accelerometer had on the vibrational response of the plate and if the accelerometer could detect the presence of a delamination between the face sheet and core of the composite sandwich test specimen. Each test specimen was subjected to one forced sine sweep ranging from 10-Hz to 2000-Hz with a 1-g peak acceleration, 6.14-inch/second peak velocity, and a 7.7-inch maximum peak-to-peak displacement.

Chapter 5. Experimental Test Results

This section discusses the results of the experimentally investigated impact behavior of the test specimen beams, static 4-point bending of the test specimen beams, impact behavior of the test specimen plates, and forced vibration of the test specimen plates. Failure modes are examined and discussed in detail for the test specimen beams under impact loading and static 4-point bending, and for the test specimen plates under impact loading. Ultimate load, maximum stress and strain in the outer fibers, and bending modulus of elasticity were determined for the test specimen beams under static 4-point bend testing (both without impact and after impact) and compared. Time domain analysis and damping ratios were determined for the test specimen plates at nine locations along the length and compared both before and after impact.

5.1 Impact Test for Beams

5.1.1 Control Case

Impact tests were first conducted on the control case test specimen beams with no DAD keys or initial delamination. In total, ten specimens were subjected to a drop weight impact test by a 7.56-lb_f impactor dropped from an initial resting height of 37.5-inches above the specimen. The beam test specimens were clamped on either end with approximately a 0.5-inch overhang on either end of the support fixture. The beam was centrally located along the width of the support fixture so the tup impacted in the exact geometrical center of the beam. Figure 5.1 shows a test specimen beam secured in the testing support fixture prior to an impact test. The

Figure 5.1. Beam test specimen secured in the test support fixture prior to an impact test.

Dynatup DAQ software (discussed in section 4.1.1 and in detail in appendix A.1) was used to obtain the instantaneous velocity at impact, force vs. time history, and acceleration-time history of the impact event.

Utilizing the testing software, the average maximum impact force experienced by the test specimen was found to be 310.79-lbf with a standard deviation of $\pm 5.89\%$, and the average impact velocity was 13.57-ft/s with a standard deviation of $\pm 4.56\%$. The instantaneous velocity at impact measured correlates closely with classical free fall kinematics, with the experimentally obtained value reaching 91.3% of the theoretical 14.86-ft/s velocity from free fall at a 37.5-inch initial height. Errors to account for this disparity include friction between the rails and the crosshead, and any off-alignments in the crosshead as it fell. In addition, it was determined from the experimental data that the initial impact event lasted approximately 8-ms before the tup bounced back from the test specimen. An important aspect of the all impact tests to call attention to is that multiple rebounds of the tup occurred on the test specimen after initial impact. Without the resources for pneumatic rebound-arresting hardware, shock absorbers were used instead to dissipate the remaining kinetic energy of the crosshead. This was an improvement to using the standard elastomeric stop blocks, but approximately 4-5 rebounds still occurred on the specimen, while using the shock absorbers, after the initial impact event. Figure 5.2 below shows a typical force vs. time history of the initial impact on the test specimen.

Figure 5.2. Force vs. time impact history of a control case test specimen beam with no DAD key or initial delamination.

Upon completion of each impact test, the test specimen was removed from the support fixture and the observed failure mode was recorded. In addition, a Fowler dial depth gauge was used to measure the impact penetration as a means of non-destructive testing. The observed failure mode was nearly identical for each of the tested specimens of the control case with no DAD key or initial delamination. At first, it appeared as if there was no damage to the specimen due the impact. Slight matrix cracking was visible on the top face sheet but there were no signs of tup penetration or fiber breakage. The impact penetration ranged from 0.002 to 0.004-inches which were within the overall thickness tolerance of the beams themselves. Upon examining the foam core, it was found that near catastrophic failure had occurred through the thickness of the core. Initial core fracture occurred on either side of the impact location at the upper face sheet-core interface, and propagated at an angle through the thickness to the lower face sheet. Face-core delamination was visible at the point of impact and on either side where core fracture propagated to the lower face sheet. Figure 5.3 below shows a typical control case test specimen beam with no DAD key or initial delamination immediately following impact testing. Notice matrix cracking on the impacted face sheet (left) and catastrophic failure through the foam core (right).

Figure 5.3. Matrix cracking on the impacted face sheet (left) and catastrophic failure through the foam core (right) for the control case beam with no DAD key or initial delamination after impact.

5.1.2 Control Case with Initial Delamination

Next, the control case beams with no DAD key and a 1-inch long centrally located initial delamination were impacted under the same testing conditions as discussed in the previous section. Again the beams were secured in the test support fixture so that the impact occurred in the geometric center of the specimen, which correspondingly was the centrally located face-core initial delamination region. The average maximum

impact force experienced by the test specimen was 292.05-lb_f with a standard deviation of $\pm 5.14\%$, and the average impact velocity was 13.85-ft/s with a standard deviation of $\pm 4.32\%$. The lower average impact force was caused by the initial delamination between face and core at the impacted location. The load cell measures the reaction force of the impact, which correlates to the stiffness of the test specimen. Since there was no bonding between the face sheet and the core surrounding the impact location, the face sheet was forced to take the majority of the load instead of transferring it through the composite sandwich by means of shear loading at the face-core interface.

In total, ten control beams with no DAD key or initial delamination were tested under impact loading. The impact penetration made by the tup was slightly higher (0.003 to 0.005-inches) than what was seen in the previous control case with no initial delamination. The observed failure mode of the test specimens were similar to the control case with no DAD key or initial delamination, with slight matrix cracking in the top face sheet and catastrophic failure through the foam core. The difference was that the initial core fracture that occurred on either side of the impact location at the upper face sheet-core interface was much more prominent and continued further along the length of the beam, as can be seen in fig. 5.4.

Figure 5.4. Observed failure mode for test specimen beams with no DAD key and an initial 1-inch delamination after impact.

5.1.3 DAD key Case with No Initial Delamination

After testing the control case beams, the DAD key beams with no initial delamination were impacted under the same testing conditions as discussed in section 5.1.1. Again, the beams were secured in the test support fixture so that the impact occurred in the geometric center of the specimen, which was between the transversely oriented DAD keys. The average maximum impact force experienced by the test specimen was

266.94-lb_f with a standard deviation of $\pm 8.68\%$, and the average impact velocity was 13.81-ft/s with a standard deviation of $\pm 3.43\%$. The lower average impact force was caused by the presence of the DAD keys themselves. Fiberglass has a much more tolerant impact resistance than carbon fiber, and dampens high rate loading quicker. The lower impact force was not caused by a lower stiffness in the beam than the previously discussed control case, but by the ability of the DAD key to absorb more of the impact energy. In total, eight DAD key beams with no initial delamination were tested under impact loading.

The observed failure mode of the test specimens included slight matrix cracking in the upper impacted face sheet and near catastrophic failure through the core, as was seen in the previously discussed control cases. The primary difference between the DAD key specimens and the control case beams tested previously was the extent of face-core delamination in surrounding the impacted region. Figure 5.5 below shows a typical observed failure mode of a DAD key beam with no initial delamination. One can see from the figure that the initial face-core delamination is arrested immediately upon reaching the DAD keys, and subsequently propagates through the foam core. This indicates that the face-core bonding interface is weaker than the foam core until a certain point when the upper face sheet provides a significant reduction in overall beam that the DAD key provides a means for arresting delamination at the face-core interface, but the overall impact resistance of the beam is driven by the flexural strength of the foam core.

Figure 5.5. Typical failure mode observed for a DAD key beam with no initial delamination after impact.

5.1.4 DAD Key Case with Initial Delamination

Finally, the DAD key beams with a 1-inch long initial delamination located between the keys were tested. The beams were impacted under the same testing conditions as discussed in section 5.1.1. Again the beams were secured in the test support fixture so that the impact occurred in the geometric center of the specimen, which corresponded to the centrally located face-core initial delamination region between the DAD keys. The average maximum impact force experienced by the test specimen was 285.5-lb_f with a standard

deviation of $\pm 7.93\%$, and the average impact velocity was 13.52-ft/s with a standard deviation of $\pm 3.57\%$. The presence of an initial delamination between the DAD keys resulted in an impact force that was very similar to the control case beams with an initial delamination. This indicates that the face sheet was forced to take the majority of the load instead of transferring it through the core and DAD keys by means of shear loading at the face-core and DAD key-core interfaces. In total, nine DAD key beams with an initial centrally located delamination between the keys were tested under impact loading.

The observed failure mode of the test specimens included slight matrix cracking in the upper impacted face sheet and near catastrophic failure through the core, as was seen in the three previously discussed cases. The failure mode was similar to what was observed for the DAD key beams with no initial delamination, where face-core delamination (which was forced in this case) was arrested at the DAD key and subsequent through-the-thickness core failure occurred down to the lower face sheet. When compared to the control case with no DAD key but a centrally located initial delamination, this case shows improvement in arresting the face-core delamination. With the presence of DAD keys, the failure mode was much more similar to the control case beam with no initial delamination.

Figure 5.6. Typical failure mode observed for the DAD key beam specimens with a 1-inch initial delamination after impact.

5.2 Comparison of Static 4-Point Bend Test

5.2.1 Control Case

The control case with no delamination or DAD key was first tested under static 4-point bending only. In total, ten specimens were tested to failure as specified by the ASTM D7627 standard discussed in section 4.2.1. After testing, the determined average maximum load before failure was 285.34 lb_f with a standard deviation of $\pm 3\%$.

Figure 5.7. Observed failure mode of control case beam with no DAD key or delamination subjected only to 4-point bending.

The failure mode observed was nearly identical for all the tested specimens in the control case beams with no DAD key or initial delamination as shown in fig. 5.7. Failure initiated with face-core delamination on the upper loaded face sheet over the left loading cylinder and propagated approximately 1 inch before fracturing through the core. Complete fracture propagated through the depth of the core and subsequent face-core delamination on the support end continued through to the end of the beam. All of the tested specimens failed at the left support indicating that there may be a very slight off-alignment of the testing fixture. No failure was visible in the composite face sheet, which indicates that the flexural strength of the control case beam with no DAD key or initial delamination was largely driven by the flexural strength of the foam core and the shear strength of the face-core bond interaction. After testing, subsequent bending stress vs. strain and load vs. displacement curves of the ten test specimens were obtained from the testing software. Figure 5.8 below shows the resulting flexure stress-strain curves determined for the control case beams with no DAD key or initial delamination subjected only to 4-point bending.

Figure 5.8. Resulting flexural stress-strain curves of control case specimens with no DAD key or initial delamination subjected only to 4-point bending.

After testing the control group with no DAD key or initial delamination under only 4-point bending, the beams which were previously impacted were tested. To ensure that no creep or relaxation effects due to impact would occur, the beams were tested under 4-point bending immediately following impact testing. The ten impacted specimens were tested under the same ASTM 6272 standard test discussed in section 4.2.1. During the 4-point bending tests, it became apparent that the impact test discussed in section

5.1.1 did lead to near catastrophic damage in the foam core. Impacted specimens retained less than 34% of the flexural strength compared to the group which was not impacted. Fig. 5.9 shows the resulting failure

Figure 5.9. Failure of the control case beam with no DAD key or initial delamination under 4-point bending, following impact testing.

mode of the pre-impacted test control case test specimens. Failure

occurred where the initial-face sheet core delamination propagated through the foam core. Results indicated that the impact event had not completely fractured through the core, but the majority of the strength was lost

after impact. Once testing was completed, resulting flexural stress-strain curves were determined, and are shown in fig. 5.10.

Figure 5.10. Resulting flexural stress-strain curves of control case specimens with no DAD key or initial delamination subjected to 4-point bending following impact testing.

After testing both the control case (with no DAD key or initial delamination) groups, flexural parameters were determined from the experimentally obtained curves in order to compare the performance of each of the four test cases. These performance parameters are given in the ASTM testing standard and include: maximum stress in the outer fiber throughout the load span, maximum strain in the outer fibers, and modulus of elasticity in bending [33]. Maximum stress was determined utilizing eqn. 5.1:

$$\sigma_{max,f} = \frac{P_{max}L}{bd^2} \quad (5.1)$$

where P_{max} was the maximum applied compressive load prior to failure. Maximum strain was determined utilizing eqn. 5.2:

$$\varepsilon_{max,f} = 4.70 \frac{w_{max}d}{L^2} \quad (5.2)$$

where w_{max} was the maximum deflection prior to failure and 4.70 is a correction factor indicating that the specimen was tested under a load span that was one-third the total support span. In addition the elastic modulus of the test specimen in bending was determined utilizing eqn 5.3:

$$E_B = 0.2 \frac{L^3 n}{bd^3} \quad (5.3)$$

where n was the slope of the tangent to the initial straight line of the test specimen load vs. displacement curve and 0.2 is a correction factor indicating that the specimen was tested under a load span with one-third the total load span.

Table 5.1 below shows the resulting ultimate load, maximum stress, maximum strain, and modulus of elasticity in bending for the control case beams subjected to 4-point bending with no impact loading, and after impact loading. One can see that significant strength and stiffness was lost in the structure after impact testing. The impacted specimen retained approximately 34.1% and 35.6% of the maximum stress before failure and modulus of elasticity in bending, respectively.

Table 5.1. The effect of impact loading on the flexural properties of the control case beams with no DAD key or initial delamination.

	Ultimate Load (lb _f)	$\sigma_{\max,f}$ (psi)	$\epsilon_{\max,f}$ (in/in)	E_B (Msi)
No Impact	285.24 ± 3.48%	7,436 ± 3.38%	0.011 ± 5.00%	1.057 ± 2.17%
After Impact	96.56 ± 5.56%	2,542 ± 5.47%	0.004 ± 2.44%	0.379 ± 9.93%

5.2.2 Control Case with an Initial Delamination

Next, the control case beams with no DAD key but a centrally located 1-inch initial delamination were tested. In total, ten specimens were tested and an average ultimate flexural load of 300.00-lb_f with a deviation of ±2% error was determined. The failure mode observed in the control case with an initial delamination involved the same face-core failure and foam core fracture as the control case, except that the failure occurred on either side of the forced delamination region. This ultimately resulted in a 5% increase in flexural strength of the control case with an initial delamination compared to the control case with no delamination. The

Figure 5.11. Failure mode of control case beam with an initial 1-inch centrally located delamination and no DAD key subjected to only 4-point bending.

observed failure mode is shown in fig. 5.11. No failure was visible in the composite face sheet, which indicated that the flexural strength of the control case beam with an initial 1-inch delamination was largely driven by the flexural strength of the foam core, as was with the control case beams with no initial delamination. After

testing, subsequent stress vs. strain and load vs. displacement curves of the ten test specimens were obtained from the testing software. Figure 5.8 below shows the resulting flexural stress vs. strain curves determined for the control case beams with no DAD key but an initial 1-inch long delamination subjected only to static 4-point bending.

Figure 5.12. Resulting flexural stress-strain curves of control case specimens with no DAD key but an initial 1-inch long delamination subjected only to 4-point bending.

After testing the control case group with no DAD key but an initial 1-inch long delamination under only static 4-point bending, the beams which were previously impacted were tested. To ensure that no creep or relaxation effects due to impact would occur, the beams were tested under static 4-point bending immediately following impact testing. Impacted specimens retained less than 33.01% of the flexural strength compared to the group which was not impacted. Fig. 5.13 shows the resulting failure mode of the pre-impacted test

Figure 5.13. Failure mode of control case beam with an initial 1-inch centrally located delamination and no DAD key subjected to 4-point bending following impact.

control case test specimens with a 1-inch initial delamination. Failure occurred where the initial-face sheet

core delamination propagated through the foam core. Once testing was completed, resulting flexural stress-strain curves were determined, and are shown in fig. 5.14.

Figure 5.14. Resulting flexural stress-strain curves of control case specimens with no DAD key but an initial 1-inch delamination subjected to 4-point bending following impact testing.

Table 5.2 below shows the resulting ultimate load, maximum stress, maximum strain, and modulus of elasticity in bending for the control case beams with a 1-inch initial delamination subjected to static 4-point bending with no impact loading, and after impact loading. One can see that significant strength and stiffness was lost in the structure when loaded under static 4-point bending, after impact testing. The impacted specimen retained approximately 33.53% and 23.31% of the maximum stress before failure and modulus of elasticity in bending, respectively. When compared to the control case beams with no delamination, the control case beams with an initial delamination retained significantly less strength after it had been impacted.

Table 5.2. The effect of impact loading on the flexural properties of the control case beams with an initial 1-inch delamination and no DAD key.

	Ultimate Load (lb _f)	$\sigma_{\max,f}$ (psi)	$\epsilon_{\max,f}$ (in/in)	E_B (Msi)
Before Impact	300.00 ± 2.01%	7,829 ± 3.04%	0.012 ± 5.80%	1.057 ± 3.20%
After Impact	99.18 ± 4.19%	2,624 ± 5.02%	0.005 ± 5.21%	0.246 ± 2.14%

5.2.3 DAD Key Case

After testing both of the control case beams, the DAD key case beams with no initial delamination were tested. As with the control case tests, ten specimens were tested to failure and an average ultimate flexural load of 284.6-lb_f with a deviation of 3.54% error was determined for the DAD key case subjected to only static 4-point bending. The failure mode observed for all of the test specimens in this

Figure 5.15. Failure mode of the DAD key case beam and no initial delamination subjected to only 4-point bending.

case showed a similar face-core interface failure and foam fracture as the control case with no delamination or DAD, except that the shear key delayed fracture through the core. As seen in fig. 5.15, the face-core delamination propagated both left and right of the loading cylinder, with fracture occurring at the end of the beam, similar to what was observed in the control cases. But to the right of the loading cylinder, the DAD key arrested fracture through the foam core and face-core delamination continued around the shear key and further propagated between the upper face sheet and core. This again indicated that the flexural strength of the sandwich beam was driven by the flexural strength of the foam core and shear strength of the face-core bond. The resulting stress-strain curve obtained from the testing software for the DAD key case with no delamination is shown in fig. 5.16.

Figure 5.16. Resulting flexural stress-strain curves of DAD key case specimens with no initial delamination subjected only to 4-point bending.

After testing the DAD key group with no initial delamination under only static 4-point bending, the impacted DAD key beams were tested. Upon testing, it was found that impacted specimens retained approximately 38.4% of the flexural strength compared to the test specimen group that was not impacted. The retention in flexural strength was greater than what was seen in both of the control case beams, indicating that DAD keys increase the impact resistance of the structure and residual strength after impact. Failure occurred where the initial face sheet-core delamination propagated through the foam core, as seen in fig. 5.17. One can see from

the figure that once the face sheet-face sheet core delamination reached DAD key, the delamination propagated half way around the circumference of DAD key before fracturing

Figure 5.17. Typical observed failure mode of the DAD key case beam with no initial delamination subjected to 4-point bending following impact.

through the core. Once testing was completed, resulting flexural stress-strain curves were determined, and are shown in fig. 5.18.

Figure 5.18. Resulting flexural stress-strain curves of the DAD key case specimens with no initial delamination under 4-point bending following impact.

Table 5.3 below shows the resulting ultimate load, maximum stress, maximum strain, and modulus of elasticity in bending for the DAD key case beams with no initial delamination subjected to 4-point bending with no impact loading, and after impact loading. One can see that significant strength and stiffness was lost in the structure when tested after impact testing. The impacted specimen retained approximately 38.2% and 47.7% of the maximum stress before failure and modulus of elasticity in bending, respectively. As indicated previously, the DAD key case beams with no delamination retained significantly more flexural strength after impact when compared to both of the investigated control cases with no DAD keys.

Table 5.3. The effect of impact loading on the flexural properties of the DAD key case beam with no initial delamination.

	Ultimate Load (lb_f)	$\sigma_{max,f}$ (psi)	$\epsilon_{max,f}$ (in/in)	E_B (Msi)
No Impact	$284.60 \pm 3.56\%$	$7,451 \pm 4.66\%$	$0.012 \pm 11.44\%$	$1.031 \pm 4.07\%$
After Impact	$109.39 \pm 9.63\%$	$2,850 \pm 11.41\%$	$0.004 \pm 6.06\%$	$0.492 \pm 10.30\%$

5.2.4 DAD Key Case with Initial Delamination

Finally, nine test specimens of the DAD key case with a 1-inch centrally located initial delamination between the DADs were tested to ultimate failure. An average ultimate load of 288.67-lb_f with a standard deviation of $\pm 2\%$ was determined for the test specimens subjected only to static 4-point bending. The failure mode was similar to the three previously tested cases in that face-core delamination and core fracture propagated to the towards

the end of the beam from the left roller load, but face-core delamination and core fracture occurred at the right roller support as well.

Figure 5.19. Typical observed failure mode of the DAD key case beam with an initial 1-inch long delamination subjected to only 4-point bending.

Figure 5.19 shows a typical observed failure mode for the DAD key case beams with an initial 1-inch long centrally located delamination. One can see from the figure that core fracture occurs near both of the DAD key locations. Once testing was completed for all nine test specimens, resulting flexural stress vs. strain curves were obtained from the testing software for each specimen, and are shown in fig. 5.20 below.

Figure 5.20. Resulting flexural stress-strain curves of DAD key case specimens with an initial 1-inch delamination subjected only to 4-point bending.

After testing the DAD key group with a 1-inch initial delamination under only static 4-point bending, the impacted DAD key beams with an initial delamination were tested. After testing the eight specimens, it was found that impacted specimens retained

Figure 5.21. Typical observed failure mode of the DAD key case beam with an initial 1-inch long delamination subjected to 4-point bending after impact.

approximately 40% of the flexural strength compared to the test specimen group that was not impacted. This retention in flexural strength was greater than what was found in any of the other three test case groups. Failure occurred where the initial face sheet-core delamination propagated through the foam core, as seen in fig. 5.21. Once testing was completed, resulting flexural stress-strain curves were determined, and are shown in fig. 5.22.

Figure 5.22. Resulting flexural stress-strain curves of the DAD key case beam specimens with an initial 1-inch long delamination under 4-point bending following impact.

Table 5.4 below shows the resulting ultimate load, maximum stress, maximum strain, and modulus of elasticity in bending for the DAD key case beams with an initial 1-inch delamination subjected to static 4-point bending with no impact loading, and after impact loading. One can see that significant strength and

stiffness was lost in the structure when tested after impact testing. The impacted specimen retained approximately 39.7% and 70.6% of the maximum stress before failure and modulus of elasticity in bending, respectively. The retention in maximum fiber stress, as well as bending modulus of elasticity was higher than any of the other tested beam cases. This indicates that DAD keys improve both the residual stiffness and ultimate strength of a composite sandwich structure that has been subjected to a drop weight impact event, even in the presence of an initial face-core delamination.

Table 5.4. The effect of impact loading on the flexural properties of the DAD key case beam with an initial 1-inch long delamination.

	Ultimate Load (lb _f)	$\sigma_{\max,f}$ (psi)	$\epsilon_{\max,f}$ (in/in)	E_B (Msi)
Before Impact	288.93 $\pm$ 2.09%	7,720 $\pm$ 1.67%	0.013 $\pm$ 3.90%	1.068 $\pm$ 1.74%
After Impact	115.14 $\pm$ 2.58%	3,067 $\pm$ 2.51%	0.004 $\pm$ 8.17%	0.754 $\pm$ 3.03%

One can see from table 5.5 below that there was no distinct advantage in beams, subjected only to static bending, containing transversely oriented DAD keys with the presence of an initial delamination within the structure. When the residual flexural strength after an impact was investigated, experimental results indicate that DAD keys increase the impact resistance of the structure and residual strength after impact. The retention in maximum fiber stress, as well as bending modulus of elasticity of the DAD key case beam with an initial delamination was higher than any of the other tested beam cases. This indicates that DAD keys improve both the residual stiffness and ultimate strength of a composite sandwich structure that has been subjected to a drop weight impact event, even in the presence of an initial face-core delamination.

Table 5.5. Results from experimentally investigated static 4-point bend testing for all test cases.

		Ultimate Load (lb _f)	$\sigma_{\max,f}$ (psi)	$\epsilon_{\max,f}$ (in/in)	E_B (Msi)
Control with no DAD key or Delamination	No Impact	285.24	7,436	0.011	1.057
	After Impact	96.56	2,542	0.004	0.379
Control with an Initial Delamination	Before Impact	300.00	7,829	0.012	1.057
	After Impact	99.18	2,624	0.005	0.246
DAD key with no Delamination	No Impact	284.60	7,451	0.012	1.031
	After Impact	109.39	2,850	0.004	0.492
DAD key with an Initial Delamination	Before Impact	288.93	7,720	0.013	1.068
	After Impact	115.14	3,067	0.004	0.754

5.3 Impact Test for Plates

5.3.1 Control Case

After testing the composite sandwich beams under static 4-point bending and impact loading, the test specimen plates were tested under both vibration and impact loading. Impact tests were first conducted on the control case test specimen plate with no DAD keys or initial delamination. Only one plate test specimen, for each of the eight cases, was subjected to the same drop weight impact test discussed in sections 4.1.1 and 5.1.1. The plate test specimens were clamped on either end as

Figure 5.23. A test specimen plate secured in the testing support fixture prior to an impact test.

well as either side of the plate. Approximately 0.5-inches of the plate overhung on either end of the support fixture, as was with the beam case. In addition, approximately 0.5-inches of either side of the plate were clamped by the testing support fixture, fully constraining the specimen on all four sides. The beam was centrally located along the width of the support fixture so the tup impacted in the exact geometrical center of the plate. Figure 5.1 shows a test specimen plate secured in the testing support fixture prior to impact testing.

In total, four control case test specimen plates with no DAD keys were impacted. The test specimens included a control case plate with no initial delamination and three control case plates with varying initial delamination locations at the 1st, 2nd, and 3rd bending mode-nodes (discussed in detail in section 3.2). From the testing software, the average maximum impact force experienced by the test specimens was determined to be 315.85-lb_f with

Figure 5.24. Typical impact damage observed in test specimen plates with no DAD key.

a standard deviation of $\pm 4.33\%$, and the average impact velocity was 13.27-ft/s with a standard deviation of $\pm 3.83\%$. Upon completion of each impact test, the test specimen was removed from the support fixture and the observed impact damage was recorded. In addition, a Fowler dial depth gauge was used to measure the impact penetration, as was done when the test specimen beams. The impact damage experienced by the plates was drastically different than experienced by the test specimen beams previously investigated. Figure 5.24 shows a typical indentation made by the impacting tup on a test specimen plate immediately following an impact event. One can see from the figure that significant tup indentation and fiber fracture was visible. The response of the plate differed from the beam specimens because of the constraints applied by the testing support fixture. The plates were constrained around the entire perimeter, while the beams were only constrained on either end. Constraining the plates fully around the perimeter allowed for less displacement and no rotation during impact, and forced the upper face sheet absorb the impact energy. The average indentation depth for the control plates was 0.110-inches with a standard deviation of 10.55%, indicating that indentation and fiber fracture occurred through the entire thickness of the impacted laminate and into the foam core.

5.3.2 DAD Key Case

After impact testing of the control case plates with no DAD keys, four DAD key case test specimen plates were tested. As with the control case, the test specimens included a DAD key plate with no initial delamination and three DAD key case plates with varying initial delamination locations at the 1st, 2nd, and 3rd bending mode-nodes (discussed in detail in section 3.2). The plate specimens were secured in the testing fixture so that the tup impacted the geometric center of the plate. The average maximum impact

Figure 5.25. Typical impact damage observed in DAD key case test specimen plates.

force experienced by the test specimens were 343.57-lb_f with a standard deviation of $\pm 4.06\%$, and the average impact velocity was 13.72-ft/s with a standard deviation of $\pm 1.99\%$. The average impact force experienced by the DAD plates was approximately 10% higher than the impact force experienced by the

control case plates. The reason the DAD key plates experienced a higher impact force was because the impact on the face sheet was directly over the DAD key. In this orientation and location, the DAD key provided extra stiffness to the structure and a means to disperse the impact energy from the face sheet through the length of the DAD key and into the core. The average impact indentation observed in the DAD key specimens was 0.056-inches with a standard deviation of $\pm 11.66\%$, which was 50% less than what was measured in the control case plates. A typical impact indentation made in a DAD key case plate is shown in fig. 5.25

5.4 Comparison of Vibration Tests

5.4.1 Control Case

The control case plate with no DAD key or initial delamination was the first test specimen to undergo a forced sine sweep vibration test. The response accelerometer was centrally placed along the width of the plate, and varied in location along the length of the plate. Nine forced vibration tests were run with the response accelerometer varied at 1-inch increments along the length of the plate. The location of the accelerometer was varied to determine if it could detect the presence of a delamination, and damage in the structure following an impact event. The location of the response accelerometer was also varied to determine the effect of the accelerometer on the vibrational response of the test specimen. Once the nine vibration tests were completed at each location, measured excitation vs. frequency curves were obtained from the testing software and were plotted on a log-log scale. A typical response of all nine vibration tests for one test specimen case is shown in fig. 5.26.

Figure 5.26. Excitation amplitude vs. frequency plot measured by the response accelerometer for the control case plate with no DAD key or initial delamination.

One can see from the figure that the first bending mode is clearly defined by the successive first peaks for each accelerometer location. Theoretically, the first peak for each location should occur at the same resonant frequency, and excitation amplitude should increase as the accelerometer is placed further from the base. In fact, the first bending natural frequencies increased linearly from 183.5-Hz at 9-inches from the base up to 202.3-Hz at 1-inch from the constrained base. This indicated that response accelerometer did affect the measurement of the vibrational characteristics of the plate. After testing, the weight of the accelerometer and control case plate were measured and recorded. It was determined that accelerometer weighed approximately 7.5% of the test specimen plate weight. While the actual weight of the accelerometer doesn't affect the vibrational response, the added inertia of the accelerometer does. In order to decrease the interfering effects of an accelerometer, a smaller accelerometer should be used in experimental investigation.

After measuring the vibrational frequency response of the control case plate with no initial delamination, the time-domain response of the structure was determined. In general, the vibrational characteristics in a structure decay with time due to various damping characteristics, whether externally applied (viscoelastic materials and piezoelectric dampers) or internally present in the structure (stiffness and damping ratio of the constituent materials). First, the damping ratios of the 1st and 2nd bending modes were

determined at each response accelerometer location along the length of the plate. The damping ratios were determined utilizing the half-power bandwidth, as shown in fig. 5.27. The half-power bandwidth method works by obtaining the resonant excitation and finding the natural frequency at which the excitation occurs (f_n). Next, the determined resonant amplitude is divided by the square root of two, and the corresponding

Figure 5.27. Half-power bandwidth method used to determine damping ratios [34].

frequencies are determined for that value, both left (f_a) and right (f_b) of the resonant peak. Once the respective resonant and half-power frequencies are determined the damping ratio of the mode is then determined utilizing eqn. 5.4:

$$\zeta_n = \frac{f_b - f_a}{2f_n} \quad (5.4)$$

where n is the corresponding bending mode.

Once the damping ratios were determined for the 1st and 2nd bending modes at all nine accelerometer locations along the plate, the time domain response was determined. In order to obtain the time response solution, the frequency range was converted to time (t) by inverting the frequency and the time-domain response amplitude was determined utilizing eqn. 5.5 [34]:

$$u_n(t) = e^{-\zeta_n \omega_n t} (\cos \omega_n t + \frac{\zeta_n}{\sqrt{1 - \zeta_n^2}} \sin \omega_n t) \quad (5.5)$$

After determining the time-domain response for the 1st and 2nd bending modes at each of the nine accelerometer locations along the length of the plate, subsequent deflection-time decay plots were generated for each mode. Figure 5.28 below shows the time-domain response for the 1st bending mode at each of the nine response accelerometer locations along the length of the plate.

Figure 5.28. Time-domain decay response of the 1st bending mode for the control plate with no DAD key or initial delamination.

From the figure, one can see that there is no obvious distinction between the amount of damping in the structure and the location of the accelerometer along the length of the plate for the first bending mode. This was found to be similar for the rest of the test specimen plates experimentally investigated, so it was omitted from the rest of this study (subsequent 1st mode time response plots are found in appendix A.2). Similarly, the time-domain decay response was determined from the 2nd bending mode as shown in fig. 5.29.

Figure 5.29. Time-domain decay response of the 2nd bending mode for the control plate with no DAD key or initial delamination.

Figure 5.29 shows that the internal damping in the structure varies significantly along the length of the plate. In order to determine the amount of damping with respect to the response accelerometer location, a steady-state response time was determined for each case. First, the least damped amplitude at a time of 0.1-seconds was found from fig. 5.29 and the correlating time of the last peak was set as the steady-state time. The steady-state time was determined for each accelerometer location by finding the corresponding steady-state amplitude for each response accelerometer location along the length of the plate.

After determining the damping response of the system and time to steady-state for each accelerometer location, the plate was tested under impact loading discussed in section 5.3.1. Following impact testing, the control case plate with no DAD key or initial delamination was again tested under same vibration loading with the same response accelerometer locations as was done prior to impact testing. Figure 5.30

Figure 5.30. Impacted control case test specimen plate with DAD key or delamination subjected to a forced sine sweep vibration test.

shows the impacted control case specimen with no DAD key or initial delamination undergoing a forced sine sweep vibration test. Again, amplitude-frequency response curves were obtained from the testing software for each accelerometer location and the damping ratios of the 1st and 2nd bending modes were determined utilizing the half-power bandwidth method. The frequency response was then converted to the time-domain response and the time to steady-state was determined for each accelerometer location along the length of the impacted control case plate specimen.

Once the steady-state time was found for the control case plate with no DAD key or initial delamination at 1-inch increments along the length of the plate, they were compared both before and after impact. This was done to determine the effect of an impact event on the internal damping of the structure. Figure 5.31 shows the time to steady-state (2nd bending mode) damping characteristics of the plate with respect to the accelerometer location, both before and after impact. In addition, the 2nd bending mode shape of the test specimen plate was plotted for a visual representation of the structure.

Figure 5.31. Time to steady-state response for each accelerometer location along the control plate with no DAD key or initial delamination (both before and after impact).

One can see from the figure above that the damping characteristics differ throughout the length of the plate, and changed significantly after the plate was impacted. At the first two accelerometer locations from the base, the damping characteristics actually improved after impact. The greatest disparity between time to steady-state before and after impact occurred when the accelerometer was 3 and 6-inches from the constrained base, respectively. The impact location occurred between 4 and 5-inches from the base, which indicated that the difference (before and after impact) in excitation measured by the accelerometer was most prevalent approximately 1.5-inches from the impacted center. At 1-inch from the base, the impacted control case plate with no DAD key or initial delamination damped to steady-state approximately 21.6% faster than the same plate vibrated prior to impact.

Figure 5.32 shows the time domain response of the control case plate with no delamination, both before and after impact, when the response accelerometer was located 3-inches above the constrained base. This location had the largest difference in time to steady-state between before and after impact of any of the locations along the length of the control case plate with no DAD key or initial delamination. One can see from the figure that the damping ratio is higher at this location prior to impact, and significant damping in the structure was lost once the plate was impacted.

Figure 5.32. Time domain response of the 2nd bending mode with the response accelerometer located 3-inches from the base (both before and after impact).

5.4.2 Control Case with Varying Delamination Locations

The control case plate with an initial 1-inch long delamination at the 1st bending mode-node and no DAD key next underwent a forced sine sweep vibration test. As before, the response accelerometer was centrally placed along the width of the plate, and varied in location along the length of the plate. Nine forced vibration tests were run with the response accelerometer varied at 1-inch increments along the length of the plate. Amplitude vs. frequency response curves were obtained from the testing software for each accelerometer location along the length and the damping ratios of the 1st and 2nd bending modes were determined utilizing the half-power bandwidth method discussed in section 5.4.1. The frequency response was then converted to the time-domain response and the time to steady-state was determined for each accelerometer location along the length of the control case plate specimen with an initial 1-inch delamination at the 1st bending mode-node.

After determining the damping response of the system and time to steady-state for each accelerometer location, the plate was tested under the impact loading discussed in section 5.3.1. Following impact testing, the control case plate with an initial 1-inch long delamination at the 1st bending mode-node was again tested under same vibration loading with the same response accelerometer locations as was done

prior to impact testing. Time to steady-state was determined utilizing the same method discussed above (and in detail in section 5.4.1) for the impacted plate. Once the steady-state time was found for the plate at 1-inch increments along its length, they were compared both before and after impact, in order to determine the effect of an impact on the internal damping of a structure and to determine if the accelerometer could detect the presence of a delamination in the structure. Figure 5.33 shows the time to steady-state (2nd bending mode) damping characteristics of the plate with respect to the accelerometer location both before and after impact.

Figure 5.33. Time to steady-state response for each accelerometer location along the control plate with an initial 1-inch long delamination at the 1st bending mode and no DAD key (before and after impact).

The control case plate with an initial 1-inch delamination at the 1st bending mode-node and no DAD key had the most affected damping ratios after impact when the accelerometer was placed 2 and 6-inches from the base. While different than the control case with no DAD key and delamination, the largest difference in damping ratios before and after impact occurred at approximately 1.5 and 2.5-inches from the constrained base, respectively. When the accelerometer was placed 1-inch from the constrained base, the impacted plate decayed to steady-state approximately 4% faster when vibrated compared to the plate prior to impact. The 1-inch accelerometer location correlated with the edge of the initial delamination in the composite sandwich.

Figure 5.34 shows the time domain response of the control case plate with an initial delamination at the 1st bending mode-node, both before and after impact, when the response accelerometer was located 6-inches above the constrained base. This location had the largest difference in time to steady-state between before and after impact of any of the locations along the length of the plate. One can see from the figure that the damping ratio is higher at this location prior to impact, and significant damping in the structure was lost once the plate was impacted. At this location, the structure dampens approximately 40% faster before it was impacted than after impact.

Figure 5.34. Time domain response of the 2nd bending mode with the response accelerometer located 6-inches from the base (both before and after impact).

After comparing the time to steady-state response of the control plate with an initial delamination at the 1st bending mode-node both before and after impact testing, the control plate with an initial 1-inch delamination at the 2nd bending mode-node and no DAD key was tested under vibration loading. Again, time to steady-state response was determined at nine 1-inch increments along the length of the plate both before and after impact, as discussed in section 5.4.1. The time to steady-state damping characteristics of the plate were compared both before and after impact and are shown in fig. 5.35.

Figure 5.35. Time to steady-state response for each accelerometer location along the control plate with an initial 1-inch long delamination at the 2nd bending mode and no DAD key (before and after impact).

From fig. 5.35, one can see that the control case beam with an initial 1-inch delamination at the 2nd bending mode-node had its largest differences in damping ratios (before and after impact) at 6 and 8-inches above the base, which corresponded to either side of the initial delamination location. When the response accelerometer was placed 1-inch above the base, the plate damped to steady-state approximately 26% faster prior to impact when compared to after impact. This was opposite of what was observed for the control case with no delamination and with an initial delamination at the 1st mode-node locations.

Figure 5.36 shows the time domain response of the control case plate with an initial delamination at the 2nd bending mode-node, both before and after impact, when the response accelerometer was located 8-inches above the constrained base. This location had the largest difference in time to steady-state, between before and after impact, of any of the locations along the length of the plate. One can see from the figure that the damping of the structure is much higher before impact than after impact, indicating that the presence of impact damage actually improved the damping characteristics at this location on the plate. The location of the initially placed delamination occurred between 7.1 and 8.1-inches from the constrained base, which means that the accelerometer response detected the presence of damage in the structure at the initially delaminated location, after impact.

Figure 5.36. Time domain response of the 2nd bending mode with the response accelerometer located 8-inches from the base (both before and after impact).

After comparing the time to steady-state response of the control plates with an initial delamination at the 1st bending mode and 2nd bending mode-nodes both before and after impact, the control plate with initial 1-inch delamination locations at the 3rd bending mode-nodes and no DAD key was tested under vibration loading. Again, time to steady-state response was determined at nine 1-inch increments along the length of the plate both before and after impact, as discussed in section 5.4.1. The time to steady-state damping characteristics of the plate were compared both before and after impact and are shown in fig. 5.37.

Figure 5.37. Time to steady-state response for each accelerometer location along the control plate with initial 1-inch long delamination locations at the 3rd bending mode-nodes and no DAD key (before and after impact).

As with the control case plate with a 1-inch initial delamination at the 2nd bending mode-node, the control case beam with 1-inch initial delamination at the 3rd bending mode-nodes experienced a faster damping to steady-state at 1-inch above the base, prior to impact. The plate (prior to impact) damped approximately 27% faster than after it was impacted. The highest differences in damping ratios before and after impact occurred at 2-inches from the base of the plate (just below the lower initial face-core delamination), and at 9-inches from the base (on the higher initial face-core delamination region). The differences in damping ratios were due to the accelerometers location with respect to the initially delaminated locations along the length of the plate.

Figure 5.38 shows the time domain response of the control case plate with initial delamination locations at 3rd bending mode-nodes, both before and after impact, when the response accelerometer was located 2-inches above the constrained base. This location had the largest difference in time to steady-state between before and after impact of any of the locations along the length of the plate. One can see from the figure that the damping ratio is higher at this location prior to impact, and significant damping in the structure was lost once the plate was impacted. As discussed, this location corresponds to just below the lower initial delamination location of the test specimen.

Figure 5.38. Time domain response of the 2nd bending mode with the response accelerometer located 2-inches from the base (both before and after impact).

5.4.3 DAD Key Case

Once the control case plate specimens were tested under a sine sweep forced vibration test, the DAD key case plate with no initial delamination was investigated. The response accelerometer was centrally placed along the width of the plate, and varied in location along the length of the plate. Nine forced vibration tests were run with the response accelerometer varied at 1-inch increments along the length of the plate. The location of the accelerometer was varied to determine if it could detect the presence of a delamination, and damage in the structure following an impact event. Once the nine vibration tests were completed at each location, measured excitation vs. frequency curves were obtained from the testing software and were plotted on a log-log scale. Again, the time to steady-state response was determined at nine 1-inch increments along the length of the plate for vibration tests both before and after impact, as discussed in section 5.4.1. Figure 5.39 shows the time to steady-state (2nd bending mode) damping characteristics of the plate with respect to the accelerometer location both before and after impact. In addition, the 2nd bending mode shape was plotted for a visual representation of the structure.

Figure 5.39. Time to steady-state response for each accelerometer location along the DAD key plate with no initial delamination (both before and after impact).

One can see from fig. 5.35 the greatest disparity between the damping time to steady-state before and after impact occurred when the accelerometer was 6 and 8-inches from the constrained base, respectively. At 1-inch from the base, the DAD key case with no initial delamination damped to steady-state approximately 16% faster before being impacted than after it was impacted.

Figure 5.40 shows the time domain response of the DAD key case plate with no initial delamination, both before and after impact, when the response accelerometer was located 8-inches above the constrained base. This location had the largest difference in time to steady-state, between before and after impact, of any of the locations along the length of the plate. One can see from the figure that the damping characteristics of the structure degrade after impact, but the plate retains more damping after impact than the control case plate with no DAD key investigated in section 5.4.1. This indicates that the DAD key provides an impact resistance to the structure, and vibrational characteristics can be retained after it has been damaged.

Figure 5.40. Time domain response of the 2nd bending mode with the response accelerometer located 8-inches from the base (both before and after impact).

5.4.4 DAD Key Case with Varying Delamination Locations

The DAD key case plate with an initial 1-inch long delamination at the 1st bending mode-node was the next test specimen to undergo a forced sine sweep vibration test. As before, the response accelerometer was centrally placed along the width of the plate, and varied in location along the length of the plate. Nine forced vibration tests were run with the response accelerometer varied at 1-inch increments along the length of the plate. Amplitude-frequency response curves were obtained from the testing software for each accelerometer location along the length and the damping ratios of the 1st and 2nd bending modes were determined utilizing the half-power bandwidth method discussed in section 5.4.1. The frequency response was then converted to the time-domain response and the time to steady-state was determined for each accelerometer location along the length of the DAD key case plate specimen with an initial 1-inch delamination at the 1st bending mode-node.

After determining the damping response of the system and time to steady-state for each accelerometer location, the plate was tested under impact, as discussed in section 5.3.1. Following impact testing, the DAD key case plate with an initial 1-inch long delamination at the 1st mode was again tested under same vibration loading with the same response accelerometer locations as was done prior to impact testing.

Time to steady-state was determined utilizing the same method discussed above (and in detail in section 5.4.1) for the impacted plate. Once the steady-state time was found for the plate at 1-inch increments along its length, they were compared both before and after impact, in order to determine the effect of an impact on the internal damping of a structure and to determine if the accelerometer could detect the presence of delamination or impact damage in the structure. Figure 5.41 shows the time to steady-state (2nd bending mode) damping characteristics of the plate with respect to the accelerometer location both before and after impact.

Figure 5.41. Time to steady-state response for each accelerometer location along the DAD key plate with an initial 1-inch long delamination at the 1st bending mode (before and after impact).

The DAD case plate with an initial 1-inch delamination at the 1st bending mode-node had the most affected damping ratios after impact when the accelerometer was placed 6 and 9-inches from the base. When the accelerometer was placed 1-inch from the constrained base, the impacted plate decayed to steady-state approximately 14.2% faster when vibrated compared to the plate prior to impact. Compared to the control case plate with an initial delamination at the 1st bending mode-node, the DAD key case damped to steady-state approximately 10% faster than the control case plate. It should also be noted that the both the DAD key and control case plates with an initial delamination at the 1st bending mode-node both experienced worse

damping characteristics prior to impact than after impact. This is largely due to the accelerometer location being at the initially delaminated face sheet.

Figure 5.34 shows the time domain response of DAD case plate with an initial delamination at the 1st bending mode-node, both before and after impact, when the response accelerometer was located 6-inches above the constrained base. This location had the largest difference in time to steady-state between before and after impact of any of the locations along the length of the plate. One can see from the figure that the damping characteristics of the structure degrade after impact, but the plate retains more damping after impact than the control case plate with no DAD key investigated in section 5.4.2. This indicates that the DAD key provides an impact resistance to the structure, and vibrational characteristics can be retained after it has been damaged.

Figure 5.42. Time domain response of the 2nd bending mode with the response accelerometer located 6-inches from the base (both before and after impact).

After comparing the time to steady-state response of the DAD key plate with an initial delamination at the 1st bending mode-node both before and after impact, the DAD key plate with an initial 1-inch delamination at the 2nd bending mode-node was subjected to a sine sweep forced vibration. Again, the time to steady-state response was determined at the nine accelerometer locations along the length of the plate both

before and after impact, as discussed in section 5.4.1. The time to steady-state damping characteristics of the DAD key plate were compared both before and after impact and are shown in fig. 5.43.

Figure 5.43. Time to steady-state response for each accelerometer location along the DAD key plate with an initial 1-inch long delamination at the 2nd bending mode (before and after impact).

From fig. 5.43, one can see that the DAD key case beam with an initial 1-inch delamination at the 2nd bending mode-node had its largest differences in damping ratios (before and after impact) at 1 and 5-inches above the base. When the response accelerometer was placed 1-inch above the base, the plate damped to steady-state approximately 49% faster prior to impact when compared to after impact. When compared to the control case plate, the DAD key improved the time to steady-state damping by more than 50%.

Figure 5.44 shows the time domain response of the DAD key case plate with an initial delamination at the 2nd bending mode-node, both before and after impact, when the response accelerometer was located 5-inches above the constrained base. This location had the largest difference in time to steady-state, between before and after impact, of any of the locations along the length of the plate. One can see from the figure that the damping of the structure is higher before impact than after impact, which was opposite of the control case plate with the same initial delamination location.

Figure 5.44. Time domain response of the 2nd bending mode with the response accelerometer located 5-inches from the base (both before and after impact).

After comparing the time to steady-state response of the control plates with an initial delamination at the 1st bending mode-node and 2nd bending mode-node both before and after impact testing, the DAD key plate with initial 1-inch delamination locations at the 3rd bending mode-nodes was tested under vibration loading. Again, time to steady-state response was determined at nine 1-inch increments along the length of the plate both before and after impact, as discussed in section 5.4.1. The time to steady-state damping characteristics of the plate were compared both before and after impact and are shown in fig. 5.45.

Figure 5.45. Time to steady-state response for each accelerometer location along the DAD key plate with initial 1-inch long delamination locations at the 3rd bending mode-nodes (before and after impact).

As with the previously investigated control case plate with an initial delamination at the 1st bending mode-node, the DAD key case plate with 1-inch initial delamination locations at the 3rd bending mode-nodes experienced a faster damping to steady-state at 1-inch above the base after impact. The plate (after impact) damped approximately 53% faster than before it was impacted. The highest differences in damping ratios before and after impact occurred at 1-inches from the base of the plate (at the lower initial face-core delamination), and at 4-inches from the base (just below the impacted region). The differences in damping ratios were due to the accelerometers location with respect to the initially delaminated locations and impact location along the length of the plate.

Figure 5.46 shows the time domain response of the DAD key case plate with initial delamination locations at 3rd bending mode-nodes, both before and after impact, when the response accelerometer was located 4-inches above the constrained base. This location had the largest difference in time to steady-state between before and after impact of any of the locations along the length of the plate. One can see from the figure that the damping ratio is slightly higher at this location prior to impact, and minor damping in the structure was lost once the plate was impacted. This indicates that the presence of a DAD key in the structure

resists damping degradation due to an impact, and that the damping characteristics are more readily retained in a damaged structure.

Figure 5.46. Time domain response of the 2nd bending mode with the response accelerometer located 4-inches from the base (both before and after impact).

Chapter 6. Numerical Analysis Methodology

This section discusses the methodology and approach to modelling and analyzing the experimentally investigated tests utilizing numerical methods. The finite element method (FEM) has become the prevalent technique used for analyzing physical phenomena in the fields of structural, solid, and fluid mechanics. Finite elements have also been successfully used for the analysis and design of composite materials and composite structures.

This study examines the impact and vibration responses of the experimental test specimen plates, as well as the impact and flexural strength of the experimental test specimen beams. The impact event was modeled utilizing the LS-Dyna explicit FE solver, which generated complete force vs. time history and resulting deformations of the impact event. Static 4-point bending and vibration analyses were solved utilizing the LS-Dyna implicit solver. A damaged mesh was obtained from the explicit impact solution, for both the plates and beams, and subjected to subsequent static 4-point bending and vibration analyses to numerically determine the residual mechanical behavior after impact. LS-PrePost pre- and post-processing software was utilized for mesh generation, constraint and load application, material model definitions, and resulting deformation analysis.

LS-Dyna follows a similar format to many FE solvers in that it is a card-based program, meaning that meshes, material properties, boundary conditions, loads, etc. are each generated as individual cards in the pre-processor and read into the solver one at a time. Once the solution is determined, the solver writes cards for resulting deformation, stress, interface forces, etc. and these cards are read by the post-processor.

Explicit finite element analysis was utilized in order to numerically analyze the structure under impact loading. Equation 6.1 is the governing equation for explicit analysis.

$$F = ma \quad (6.1)$$

With explicit analysis, the FE code calculates the acceleration of the body and then uses a time step to translate the acceleration into displacement. The displacement is then used to calculate the reaction force between the structure and the impacting tup. The reaction force is then used by the FE solver to calculate the corresponding acceleration. Once completed, the process is repeated without assuming a displacement

function. With explicit methods, one must carefully model and constrain the mesh because the method is not subject to singular matrix errors as are implicit methods.

Implicit finite element analysis was utilized in order to numerically analyze the 4-point bend tests of the test specimen beams (both without impact and after impact) and the vibration tests of the test specimen plates (both before and after impact). Equation 6.2 is the governing equation for implicit analysis.

$$F = K\delta \quad (6.2)$$

With implicit analysis, the FE code assumes a displacement function (1-, 2-, or 3-dimensional and n^{th} order). The assumed displacement function is then utilized to solve for the stiffness of the structure (K) and resulting forces are calculated. The forces are then used to solve for resulting displacements process is repeated. As with most implicit methods, the process is iterated a number of times until a certain tolerance between iterations steps are achieved.

6.1 Explicit Beam Impact Analysis

6.1.1 Control Case Beam

The control case beam with no DAD key or initial delamination was the first configuration modeled in LS-PrePost. The beam was modeled 11-inches long, 1-inch wide, and a total of 0.64-inches thick. The ACG LTM45EL/CF1803 face sheets were modeled using four-node Belytschko-Tsay shell elements with 88-elements along the length and 8-elements across the width (for uniform 0.125-inch node spacing). The composite face sheets were modeled using a composite progressive damage and failure material model. This material model (MAT 54 material card in LS-Dyna) is based on the Chang-Chang failure criterion. With Chang-Chang, failure occurs when tensile fiber, compressive fiber, tensile matrix, and compressive matrix modes are exceeded within the structure. There is one limit, though, to MAT 54 and that is that the material model is only suitable for shell elements. In order to properly model and analyze the face sheets, the shells were given a thickness of 0.07-inches (equivalent to a four layer laminate) and offset 0.035-inches from the core. This was done because shell thickness in LS-Dyna builds out from either side of the element, making the node surface the mid-plane of the face sheet. Table 6.1 shows the mechanical characteristics, both experimentally determined and from [35], used to model the composite face sheets.

Table 6.1. Mechanical characteristics of the ACG LTM45EL/CF1803 face sheets used for FEA.

Mechanical Property	Value		
ρ	$1.371 \times 10^{-4} \text{-lb}_f\text{-s}^2/\text{in}^4$	α	0.1
E_{11}	$6.651 \times 10^6 \text{-psi}$	SOFT	0.75
E_{22}	$6.651 \times 10^6 \text{-psi}$	FBRT	0.75
ν_{21}	0.098	YCFAC	1.2
G_{12}	$4.687 \times 10^5 \text{-psi}$	ϵ_{FAILT}	0.0167-in/in
G_{23}	$4.687 \times 10^5 \text{-psi}$	ϵ_{FAILC}	-0.0037-in/in
G_{31}	$3.687 \times 10^5 \text{-psi}$	$X_C = Y_C$	$-4.083 \times 10^4 \text{-psi}$
ϵ_{FAILM}	0.0325-in/in	$X_T = Y_T$	$9.787 \times 10^4 \text{-psi}$
t_{FAIL}	$1.153 \times 10^{-9} \text{-s}$	β	0

Within MAT54, there are a few parameters that are purely mathematical that cannot be found empirically, and can only be determined through trial-and-error. These parameters are α , SOFT, FBRT, YCFAC, and β . The term α is a shear stress nonlinear term after yielding has occurred, SOFT is the crush-front strength reducing parameter, FBRT is the softening factor for fiber tensile strength after matrix failure, YCFAC is the softening factor for fiber compressive strength after matrix failure, and β is the weighing factor for shear term in tensile fiber mode. These parameters were determined from a trial-and-error study and [35] was also used as a numerical baseline. Once the material model was defined for the face sheets, an hourglassing control term was specified for the face sheet models. Hourglass modes are nonphysical, zero-energy modes of deformation that produce zero strain and no stress, and often occur in under-integrated shells and solids [37]. For the composite face sheets, an hourglass control of type Flanagan-Belytschko stiffness form with a coefficient of 0.001 was applied.

In order to simulate the number of layers through the specified thickness of the face sheet, four integration points were added to each shell element of either face sheet. Integration points are stacked vertically from the mid-plane of the element and define the thickness of each layer within the laminate. When one integration point fails through the thickness, the remaining points are forced to bear the load being applied to the mesh. For each face sheet, the integration points were equally spaced through the thickness of the shell. Finally, the laminated shell theory was invoked through the Control_Shell card. Lamination theory was applied to correct for the assumption of a uniform constant shear strain through the thickness of the shell. Unless this correction is applied, the stiffness of the shell can be grossly incorrect if there are drastic differences in the elastic constants from ply to ply, especially for sandwich type shells. Generally, without this correction the results are too stiff [37].

Next, the foam core was modeled with eight node solid elements with 88-elements along the length, 8-elements across the width, and 10-elements through the thickness. The GP Last-A-Foam FR-6710 core was modeled as crushable foam (MAT 63 material card in LS-Dyna). This material model allows for the addition of a compressive stress vs. strain curve, shown in fig. 6.1, and has been used extensively in prior studies, yielding good agreement with experimental tests [38]. The crushable foam material model follows an elasto-plastic behavior in which the material behaves elastically until a yield point is reached, and behaves plastically beyond the yielding point.

Figure 6.1. Experimentally obtained compressive stress-strain curve applied to crushable foam material model in LS-Dyna.

Table 6.2 shows the mechanical characteristics, obtained from experimental investigation (section 2.2) and from the manufacturer, used to model the foam core [27].

Table 6.2. Mechanical characteristics of the GP Last-A-Foam FR-6710 crushable foam utilized for FEA.

Mechanical Property	Value
ρ	$1.499 \times 10^{-5} \text{ lb}_f \cdot \text{s}^2 / \text{in}^4$
E	6127.9-psi
ν	0.3

Once the composite face sheets and foam core were modeled, a sphere was modeled to simulate the impacting tup fixed to the falling crosshead of the Dynatup 8250 drop weight impact tester. The sphere was modeled with a 0.625 inch diameter to match the hemispherical tip of the impacting tup used in the experimental analysis. Although the tup modeled did not match the geometry of the actual tup, the density of

the sphere was adjusted so that it included the entire mass of the crosshead for comparable impacting energies. The sphere was modeled as a rigid material (MAT card 20 in LS-Dyna) with the mechanical properties shown in table 6.3 below. Also, the sphere was constrained in the x- and y-translational and all three rotational degrees of freedom within the material model.

Table 6.3. Mechanical characteristics of the impacting tup utilized in FEA.

Mechanical Property	Value
ρ	$0.163 \text{ lb}_f\text{-s}^2/\text{in}^4$
E	$30 \times 10^6\text{-psi}$
ν	0.3

Once the test specimen composite sandwich beam and impacting tup with crosshead mass were modeled, boundary conditions and initial velocities were applied to the finite element model. The control case test specimen with no DAD key or initial delamination was fully constrained on both of the face sheets only from each end of the beam and in 3-inches towards the center to simulate the clamp applied by the testing support fixture. In addition, an average initial experimental velocity of 13.5-ft/s was applied to the impacting tup to simulate the crosshead free-falling from 37.5-inches. Figure 6.2 shows the meshed finite element model with applied nodal boundary conditions to the control case beam with no DAD key or initial delamination.

Figure 6.2. Control case beam with no DAD key or initial delamination with applied nodal boundary conditions.

Once the test specimen beam was constrained and velocity was applied to the impacting tup, contacts were defined between each of the constituent parts of the model. The LS-Dyna finite element solver utilizes contact definitions to accurately simulate the response of a structure subjected to an impact event. Rather than merging nodes to connect constituents within the finite element model, contacts provide a means for accurately specifying the type and strength of bonding between them. The contact defined between the rigid steel impacting tup and the top composite layer was an Automatic_Surface_to_Surface contact. Automatic contact definitions are a recommended contact type since, in impact simulations, the orientation of parts relative to each other cannot always be anticipated as the model undergoes large deformations. Automatic

contacts also check for penetration on either side of an element [37]. The contact definition between the crushable foam core and composite face sheets was an Automatic_One_Way_Surface_to_Surface_Tiebreak definition. One-way contacts are generally more efficient than a two-way treatment of contacts but are non-symmetric and master-slave segments must be specified as shown in fig. 6.3. This contact has also been utilized extensively to successfully model sandwich type structures, as well as composite delamination [11].

Figure 6.3. Master-slave interface treatment of one-way contacts in LS-Dyna [39].

After applying contact definitions to the constituent elements of the finite element model, a termination time of 8-milliseconds was set. This was done so that the code would run until the termination time was reached, which was deemed sufficient to capture the entirety of the impact even similar to the initial impact in experimental investigation. In addition, a time step of 1×10^{-4} -seconds was determined sufficient to write all of the resulting data including: stress, displacement, energy, and force. Once termination time and time step were set, the model was run using the LS-Dyna explicit solver.

6.1.2 Control Case Beam with Delamination

The control case beam with an initial 1-inch long delamination and no DAD key was next test case modeled in LS-PrePost and validated through numerical analysis. The beam was modeled to the same dimensions as the control case beam, and with the same number of elements in the lower face sheet and foam core. This beam differed from the control case in that an initial delamination region was added to between the upper face sheet and foam core centrally located along the length of the beam and was 1-inch long and 1-inch wide. This was accomplished by modeling three separate shell regions for the upper face sheet and merging

the connecting nodes. The face sheet on either side of the delamination was modeled 5-inches long with forty elements to match the 0.125-inch node spacing in the core and lower face sheet. The centrally located delamination was then modeled 1 inch long with nine elements to offset the nodes from the nodes in the foam core, creating disconnect between the volumes. Figure 6.3 shows the meshed delaminated region; notice how the nodes in the foam core are offset with the upper face sheet.

Figure 6.4. Close up of the delaminated region between the upper face sheet and foam core [shell thickness added for visual enhancement].

Once the components were modeled, the same constraints were applied to the beam as the control case beam with no initial delamination and the same initial velocity was applied to the impacting tup. The contacts applied were also the same except an Automatic_Surface_to_Surface contact was defined between the delaminated region and the foam core. Defining this contact, as well as offsetting nodes, was deemed sufficient to correctly model and analyze the delaminated region. After applying boundary conditions, initial velocities, and contact definitions, the termination time was set to 8-milliseconds with a time step of 1×10^{-4} -seconds to agree with what was applied to the control model.

6.1.3 DAD Key Beam Case

Once both of the control beams were successfully modeled and analyzed, the DAD key case beam with no initial delamination was modeled in LS-PrePost. In order to mesh the DAD keys and surrounding foam core, the block mesher function in LS-PrePost was utilized. This function allows for full control over mesh generation, starting with a block of elements that the user cuts down to the appropriate shape, similar

to a sculptor and a block of granite. The DAD keys were created using three separate blocks, each containing 72-elements. The blocks were then cut down to semicircular wedges and then combined to create a half-cylinder shaped DAD key. The foam surrounding the shear key was then created using the block mesher function similar to the generation of the DAD keys. This was done to ensure that the nodes in the foam core correctly aligned with the shear keys, creating a successful bond in the model. Figure 6.4 shows the meshed shear key along with the surrounding foam core.

Figure 6.5. Close-up view of shear key mesh and surrounding foam core.

The composite face sheets were meshed with the same dimensions as the control case with no DAD key and no initial delamination. Once the entire model was meshed, the same material properties were applied to the composite face sheets, foam core, and impacting tup. An elastic material model was applied to the shear keys (MAT card 001 in LS-Dyna). Table 4 shows the mechanical characteristics of the shear keys, determined from experimental investigation, utilized in the FEA model.

Table 6.4. Mechanical characteristics of the unidirectional fiberglass DAD keys utilized for FEA.

Mechanical Property	Value
ρ	$9.43 \times 10^{-5} \text{ lb}_f\text{-s}^2/\text{in}^4$
E	$3.304 \times 10^6 \text{ psi}$
ν	0.26

Once the components were modeled, the same constraints were applied to the beam as the previously analyzed control beams and the same initial velocity was applied to the impacting tup. The contacts applied were also the same control beam. Additionally another contact was defined between the shear key and composite face sheet, as well as between the DAD key and foam core. This contact definition applied was Automatic_One_Way_Surface_to_Surface_Tiebreak, as was done between the face sheets and the foam core. After applying boundary conditions, initial velocities, and contact definitions, the termination time was set to 8 milliseconds with a time step of 1×10^{-4} seconds to agree with what was applied to both of the control case beams with no DAD keys.

6.1.4 DAD Key Beam Case with Delamination

After modeling and analyzing the three previous beams, the DAD key case beam with an initial 1-inch delamination centrally located between the keys, was modeled and meshed in LS-PrePost. This finite element model incorporated all of the aspects from all of the beams previously analyzed. DAD keys and the surrounding foam were meshed utilizing the block mesher function with the same amount of elements as the DAD key case beam with no initial delamination. The lower composite face sheet and foam core were generated with the same dimensions and amount of elements as the DAD key case. The upper face sheet was modeled as three separate volumes and the nodes connecting each of the volumes were merged. The face sheet on either side of the delamination was modeled 5-inches long with 40-elements to equal the node spacing in the core and lower face sheet. The centrally located delamination was then modeled 1-inch long with 9-elements to offset the nodes from the nodes in the foam core, creating disconnect between the volumes. Figure 6.6 shows the meshed shear keys, surrounding foam core, and the delamination between the upper composite face sheet and foam core.

Figure 6.6. Close-up view of shear key mesh and delaminated region between the shear keys. Notice the offset nodes between the shear keys.

Once the components were modeled, the same constraints were applied to the beam as the previously analyzed beams and the same initial velocity was applied to the impacting tup. The contacts applied were also the as the DAD key case beam, except an Automatic_Surface_to_Surface contact was defined between the delaminated region and the foam core. Defining this contact, as well as offsetting nodes was deemed sufficient to correctly model the delaminated region. After applying boundary conditions, initial velocities, and contact definitions, the termination time was set to 8-milliseconds with a time step of 1×10^{-4} -seconds to agree with what was applied to all previously analyzed beams.

6.2 Implicit 4-Point Bend Analysis

Implicit 4-point bending analysis was accomplished utilizing the same beam models generated for explicit impact analysis in LS-PrePost. For the implicit case, the impacting tup was no longer included in the analysis. Also, the face sheet and foam core were modeled utilizing the elastic material model (card 001 in Ls-Dyna). The material models were changed because the progressive failure models have time-dependent rates which break down when used in an implicit solution, and don't allow the analysis to converge. In addition, nodal constraints were applied to the model simulate the 4-point bend fixture utilized in the experimental investigation discussed in section 4.2. The finite element model was constrained in the along the entire length in the y-direction and at the center of the beam in the x-direction to resist any translational motion in the analysis. The finite element model was also constrained on either end of the beam, and in 1-inch, in the z-direction to simulate the roller supports of the testing fixture. Once the mesh was constrained in all three

translational degrees of freedom, a uniform load was applied as shown in fig. 4.12. A static load of 75-lb_f was applied to each of the four beam cases and equally distributed to the nodes along the width of the upper face sheet at two locations along the length. Implicit analysis was invoked using the Control_Implicit_General with an initial time step size of 5-milliseconds. Figure 6.7 shows the meshed control case beam with applied boundary condition constraints (denoted by crosses) and static load (denoted by arrows).

Figure 6.7. Meshed control case beam, with applied boundary condition constraints and static load, for 4-point bend implicit analysis.

Once the explicit impact analysis was completed, the damaged meshed was subjected to implicit static 4-point bend analysis in order to numerically validate the residual flexural strength of the sandwich beams after an impact event. This was accomplished by exporting the mesh, at a specified time step, as a Dynain binary file. The file stores stresses and strains in the structure the time step it's exported at, as well as the nodal deflections. The damaged mesh was exported when the impacting tup deflected the beam 0.1-inches, which was the measured indentation immediately following the experimental impact test for the plate specimens discussed in section 5.3.1. The damaged mesh was then written to a new file and new boundary constraints were applied in all three translational degrees of freedom at the same nodes as the implicit model that was not impacted. A static load of 75-lb_f was applied to each of the four beam cases and equally

distributed to the nodes along the width of the upper face sheet at two locations along the length. After applying the boundary conditions, nodal static loads, material models, and contact definitions to the mesh, implicit analysis was invoked using the Control_Implicit_General command, as was done in the previous implicit analysis.

Figure 6.8. Control case beam with damaged mesh, with applied boundary condition constraints and static load, for 4-point bend implicit analysis.

6.3 Explicit Plate Impact Analysis

6.3.1 Control Plate Case

After numerical analysis on the beam cases under impact and 4-point bend loading, the control case plate with no DAD key or initial delamination was modeled in LS-PrePost. The plate was modeled to experimental test specimen dimensions: 11-inches long, 3.5-inches wide, and a total of 0.64-inches thick. The ACG LTM45EL/CF1803 face sheets were modeled using four-node Belytschko-Tsay shell elements with 88-elements along the length and 28-elements across the width (for uniform 0.125-inch node spacing). The composite face sheets were modeled using a composite progressive damage and failure material model based on the Chang-Chang failure criterion as use utilized in the beam case analysis.

The foam core was modeled with eight node solid elements with 88-elements along the length, 28-elements across the width, and 10-elements through the thickness. The GP Last-A-Foam FR-6710 core was modeled as crushable foam (MAT 63 material card in LS-Dyna), as was used in the beam case analysis. The impacting tup was modeled and meshed to the same specifications described in section 6.1.1, except it was located so that it impacted the exact geometric center of the plates, as shown in fig. 6.9.

Figure 6.9. Control case plate finite element model with applied constraint boundary conditions and impact tup.

Once the components were modeled, the same initial velocity was applied to the impacting tup but the constraints applied were different than the beam case. Both face sheets were fully constrained in all six degrees of freedom from the end of the plate and 3-inches in towards the center. In addition, both face sheets were fully constrained on each side of the beam and in 0.5-inches (shown in fig. 6.9) to simulate the clamping force of the testing support fixture used in experimental investigation. The contact definitions between the constituent parts of the model were the same as the control case beam with no DAD key or initial delamination. After applying boundary conditions, initial velocities, and contact definitions, the termination time was set to 8-milliseconds with a time step of 1×10^{-4} -seconds to agree with experimental testing and the beam case numerical models.

6.3.2 Control Plate Case with Varying Delamination Locations

The control case plates with varying initial delamination locations and no DAD key were next numerically validated under impact loading. The plates were modeled and meshed to the same dimensions as the control case plate with no DAD key or initial delamination, and with the same number of elements in the lower face sheet and foam core. These plates differed from the control case in that an initial delamination region was added to between the upper face sheet and foam core that was 1-inch long and 3.5-inches wide located at the 1st, 2nd, and 3rd bending mode-nodes, respectively. This was accomplished by modeling separate shell regions for the upper face sheet and merging the connecting nodes. The face sheet on either side of the delamination was to match the 0.125-inch node spacing in the core and lower face sheet. The centrally located delamination was then modeled 1 inch long with nine elements to offset the nodes from the nodes in the foam core, creating disconnect between the volumes. Figure 6.10 shows the meshed delaminated regions of the 1st, 2nd, and 3rd bending mode-nodes; notice how the nodes in the foam core are offset with the upper face sheet.

Figure 6.10. Meshed delaminated regions of the control case plates for the 1st (top), 2nd (middle), and 3rd (bottom) bending mode-nodes.

Once the components were modeled, the same constraints were applied to the beam as the control case beam with no initial delamination and the same initial velocity was applied to the impacting tup. The contacts applied were also the same except an Automatic_Surface_to_Surface contact was defined between the delaminated region and the foam core. Defining this contact, as well as offsetting nodes was deemed

sufficient to correctly model and analyze the delaminated region. After applying boundary conditions, initial velocities, and contact definitions, the termination time was set to 8-milliseconds with a time step of 1×10^{-4} -seconds to agree with what was applied to the control model.

6.3.3 DAD Key Plate Case

Once the control case plates were meshed and analyzed under explicit impact loading, the DAD key plate with no initial delamination was modeled in LS-Prepost. In order to mesh the DAD keys and surrounding foam core, the block mesher function was utilized, as was done with the DAD key beam cases in sections 6.1.3 and 6.1.4. The shear keys were created using three separate blocks, each containing 792-elements. The blocks were then cut down to semicircular wedges and then combined to create a half-cylinder shaped DAD key. The foam surrounding the shear key was then created using the block mesher function similar to the generation of the shear keys. This was done to ensure that the nodes in the foam core correctly aligned with the shear keys, creating a successful bond in the model. Figure 6.11 shows the meshed DAD key along with the surrounding foam core.

Figure 6.11. Meshed DAD key with surrounding foam core for plate impact numerical analysis.

The composite face sheets were meshed with the same dimensions as the control case with no DAD key and no initial delamination. Once the entire model was meshed, the same material properties were applied to the composite face sheets, foam core, and impacting tup. An elastic material model was applied to the shear keys, as was done with the DAD key case beams. Once the components of the finite element modeled were defined, the same constraints were applied to the beam as the previously analyzed control case plates with no DAD key and the same initial velocity was applied to the impacting tup. The contacts applied

were also the same control case plate with no DAD key or initial delamination. Additionally another contact was defined between the shear key and composite face sheet, as well as between the DAD key and foam core. This contact definition applied was Automatic_One_Way_Surface_to_Surface_Tiebreak, as was done between the face sheets and the foam core. After applying boundary conditions, initial velocities, and contact definitions, the termination time was set to 8 milliseconds with a time step of 1×10^{-4} seconds to agree with what was applied to both of the control case plates with no DAD key.

6.3.4 DAD Key Plate Case with Varying Delamination Locations

Finally, the DAD key case plates with varying initial delamination locations were numerically modeled and validated under impact loading. The plates were modeled and meshed to the same dimensions as the DAD key case plate with no initial delamination and with the same number of elements in the lower face sheet and foam core. These plates differed from the DAD key case in that an initial delamination region was added to between the upper face sheet and foam core that was 1-inch long and 3.5-inches wide located at the 1st, 2nd, and 3rd bending mode-nodes, respectively. This was accomplished by modeling separate shell regions for the upper face sheet and merging the connecting nodes. The face sheet on either side of the delamination was to match the 0.125-inch node spacing in the core and lower face sheet. The centrally located delamination was then modeled 1 inch long with nine elements to offset the nodes from the nodes in the foam core, creating disconnect between the volumes, as shown in fig. 6.10 of section 6.3.2.

6.4 Implicit Vibration Analysis

Numerical modal analysis was accomplished utilizing the same plate models generated for explicit impact loading in LS-PrePost. One significant difference was that the impacting tup was no longer included in the analysis. Also, the material models of the face sheet and foam core were modeled utilizing the elastic material model (card 001 in Ls-Dyna). The material models were changed because the progressive failure models have time-dependent rates which break down when used in implicit analysis, and doesn't allow the solution to converge. In addition, the constraints were added to simulate the aluminum clamping blocks utilized in experimental investigation as shown in fig. 4.15 in section 4.3.1. Implicit analysis was invoked using the Control_Implicit_General and Control_Implicit_Eigenvalue commands. With these control parameters, the solver performs a linear implicit analysis that determines the first five natural frequency

modes using the block shift and invert Lanczos method solution for eigenvalue extraction. Figure 6.12 shows the meshed control case plate with no DAD or initial delamination and applied boundary conditions to simulate the aluminum clamping blocks.

Figure 6.12. Meshed control case plate with applied boundary condition constraints for implicit modal analysis

Once the explicit impact analysis was completed, the damaged meshed was subjected to implicit vibration analysis to numerically determine the effect of an impact on the modal analysis of the plate. This was accomplished by exporting the mesh, at a specified time step, as a Dynain binary file. The file stores stresses and strains in the structure at the time of export, as well as the nodal deflections. The damaged mesh was exported when the impacting penetrated approximately 0.1-inches into the core, which was the measured indentation immediately following the experimental impact test. The damaged mesh was then written to a new file and new boundary constraints were applied to the base of the plate and up 1-inch to simulate the aluminum blocks used to clamp the test specimens to the vibration table, as shown in fig. 6.13. After applying the boundary conditions, material models, and contact definitions to the mesh, implicit analysis was invoked using the two previously described control_implicit options.

Figure 6.13. Control case plate with damaged mesh and applied boundary condition constraints for implicit modal analysis

Chapter 7. Analytical Analysis

This section discusses the methodology and approach in developing analytic results for the static 4-point bend and dynamic vibration test cases as a means of validation to both the experimental and numerical models and results. The equivalent flexural rigidity of both the control case beam and plate with no initial delamination were determined utilizing experimentally determined properties, and properties from previous research efforts. The static case beam deflection was determined utilizing classical Euler-Bernoulli beam theory and the method of superposition to accurately represent the static 4-point bend test from the experimental investigation . Resonant natural bending frequencies were determined using a simple ad-hoc approach which considers flexural rigidity, equivalent mass, and equivalent stiffness of the system.

7.1 Static Case

Many analytic methods and equations have been developed in order to determine the properties of sandwich panels under various loading conditions including bending (3-point and 4-point), buckling, and vibration. For a sandwich composite beam with symmetric face sheets and a considerably thicker core, the flexural rigidity of the beam can be approximated by eqn. 7.1.

$$D = E_f I_f + E_c I_c \quad (7.1)$$

where f and c are the face sheet and core, respectively [41]. It is important to note that the moduli used are the out-of-plane flexural modulus due to the orthotropic and anisotropic nature of the constituent sandwich materials. The flexural modulus for the Last-A-Foam core utilized for analysis is given in [27], while the out-of-plane flexural modulus of the LTM45EL/CF1803 face sheets was determined from the rule of mixtures formulation [42] given in eqn. 7.3.

$$E_f = \frac{E_{matrix} E_{fiber,T}}{V_{fiber} E_{matrix} + (1 - V_{fiber}) E_{fiber,t}} \quad (7.2)$$

V_f was experimentally determined in this study (discussed in section 2.1), but E_{matrix} and $E_{\text{fiber},t}$ were obtained from [43] who made significant research efforts to obtain the constituent elastic moduli of the laminate. Once the properties of the face sheet and core are determined, the sandwich flexural rigidity can be substituted in to classical Euler-Bernoulli beam governing equation for the moment of a beam, given in eqn. 7.4.

$$M = -D \frac{d^2 w}{dx^2} \quad (7.3)$$

Integrating eqn. 7.2 twice and applying the roller support boundary conditions shown in fig. 7.1 gives the deflection of the beam in terms of the moment.

Figure 7.1. Sandwich panel schematic under static 4-point bend conditions including analytical variables.

Then applying the method of superposition [41] to solve for the beam moment, given two equally applied loads, gives the beam deflection of the sandwich beam under 4-point bending as a function of the length of the beam.

$$\begin{aligned} \delta(x) &= \frac{Px}{6D}(3Lc - 3c^2 - x^2) & \text{for } x < c \\ \delta(x) &= \frac{Pc}{6D}(3Lc - 3x^2 - c^2) & \text{for } x > c \text{ and } x < L \\ \delta(x) &= \frac{P(L-x)}{6D}(3Lc - 3c^2 - (x-L)^2) & \text{for } x > L \end{aligned} \quad (7.4)$$

7.2 Vibration Case

An analytic solution approximated by Salam et al. [44] has been developed utilizing a simple ad-hoc analytical approach to determine the vibration frequencies and damping characteristics of sandwich composite panels. The generalized flexural rigidity model utilized for this analytic solution has shown good agreement with both numerical and experimental analysis in previous studies. The flexural rigidity determined from equation 7.1 in the previous section is used in conjunction with the equivalent mass and stiffness of the system to determine the modes of natural frequency given in eqn. 7.5.

$$f_i = \frac{\varphi_i^2}{2\pi} \sqrt{\frac{K_e}{m_e}} \quad (7.5)$$

Where φ_i^2 is a constant dependent on the boundary conditions (1 and 5.5 for the first two bending modes of a fixed-free boundary), and K_e and m_e are given in eqns. 7.6 and 7.7 below.

$$K_e = 3000 \frac{D}{L^3} \quad (7.6)$$

$$m_e = 2bt\rho_f + bd\rho_c \quad (7.7)$$

where b is the width of the specimen and L is the unclamped length of the sandwich (10-inches in the case of the test specimen plates).

Chapter 8. Comparison of Experimental, Numerical, and Analytic Results

This section discusses and compares the results of both the experimentally investigated and numerically analyzed impact of the test specimen beams, static 4-point bending of the test specimen beams, impact of the test specimen plates, and vibration of test specimen plates. Experimentally and numerically obtained force vs. time history curves are compared for each of the four beam test specimen cases, and for two of the plate cases (control case and DAD key case with no initial delamination locations). The experimental deflection of the beam test specimens under static 4-point bending are compared with results from numerical analysis both after impact loading, and without impact loading. The control and DAD key case plates are compared both before and after impact, utilizing the numerically and experimentally obtained natural frequencies of the first and second pure bending mode natural frequencies. Finally, the analytic solutions for the control case plate and beam with no initial delamination are compared with numerical and experimental results as a means for further validation.

8.1 Beam Case Impact Test

8.1.1 Control Case

The experimental and numerical impact force vs. time histories of the control case beam with no initial delamination show close correlation and good agreement. One can see from fig. 8.1 that a higher ultimate impact force was seen in the finite element model. The average maximum experimentally obtained impact force was 310.79-lb_f compared to the maximum numerically obtained impact force of 332.5-lb_f. The numerical model lies just outside of the upper limit standard deviation of experimental results. Discrepancies between these results are due to a number of factors including the sampling rate of the load cell in experimental testing and many factors in numerical analysis. One significant factor was the inability to properly model the effect of the crosshead shock absorbers. Once the impacting tup displaced the specimen approximately 0.125-inches in experimental test, the shock absorbers dissipated the kinetic energy of the

crosshead. This was not modeled in the numerical analysis due to the difficulty in determining the stiffness of absorber and implementing it into the FE model.

One can see from the figure that significantly more oscillations occur in the experimental impact force vs. time history curve. This is likely due to a combination of the residual ringing in the test fixture and inherent noise in the electronics of the load cell and data acquisition device. Due to the dynamic high-rate loading nature of impact events, high resonant frequencies are reached especially between stiff constituents. Without damping agents, ringing occurs in the system resulting in small amplitude high frequency oscillations. One method of reducing the inherent ring in the system would be installing a rubber gasket on the testing support fixture, where the test specimens make contact with the aluminum clamping plates.

Figure 8.1. Impact force vs. time history comparison between experimental investigation and numerical analysis for the control case beam with no DAD key or initial delamination.

In addition, the resulting finite element stress was generated, and the resulting failure modes were compared with previously investigated experimental analysis (discussed in detail in section 5.1.1). Figure 8.2 shows the resulting stress at the point of the maximum tup penetration in the experimental analysis. The maximum resulting stress seen in the structure was 45.9-ksi. One can see from the figure that no element deletion due to failure occurred in within the face sheets or core. This follows with experimentally observed failure modes of the control case beam with no initial delamination or DAD key in that no visible failure

occurred in the face sheet, but no failure occurred between the face and core, or within the foam core as seen in the experimental investigation. In order properly simulate the face sheet and fracture within the core, a complete characterization of the core's mechanical behavior needs to be experimentally investigated.

Figure 8.2. Resulting impact stress determined from numerical analysis for the control case beam with no delamination.

8.1.2 Control Case with Initial Delamination

As with the control case beam with no initial delamination, the control case beam with an initial delamination shows very close correlation between experimentally obtained and numerically obtained force vs. time history curves. The average maximum experimentally obtained impact force was 292.05-lb_f compared to the maximum numerically obtained impact force of 281.1-lb_f, which lies well within the experimental standard deviation. Figure 8.3 indicates that the high-impact load duration (approximately the first 2-milliseconds of impact) are nearly identical between the numerical and experimental results. Once failure initiated, the impact force for both cases decreased but higher loads were sustained in the numerical model. This was likely due to the contact definition and the presence of offset nodes between the foam core and impacted face sheet to model the initially placed delamination in the structure.

Figure 8.3. Impact force vs. time history comparison between experimental investigation and numerical analysis for the control case beam with a 1-inch initial delamination and no DAD key.

The resulting finite element stress was also generated, and the failure modes were compared with previously investigated experimental analysis (discussed in detail in section 5.1.2). Figure 8.4 shows the resulting stress at the point of the maximum tup penetration in the experimental analysis. The maximum resulting stress seen in the structure was 40.2-ksi, which was approximately 12.5% less than the control with no delamination. This correlates closely with the impact force seen in the experimental investigation, where the control case beams with an initial delamination experienced lower impact loads than the control case beams with no initial delamination. One can see from the figure that no element deletion due to failure occurred in within the face sheets or core. This follows with experimentally observed failure modes of the control case beam with an initial 1-inch delamination

Figure 8.4. Resulting impact stress determined from numerical analysis for the control case beam with an initial delamination.

and no DAD key in that no visible failure occurred in the face sheet, but no failure occurred between the face and core, or within the foam core as seen in the experimental investigation. The fracture may have also

occurred due to the multiple rebounds after the initial impact, further damaging the structure more than expected.

8.1.3 DAD Key Case

After comparing the numerical and experimental impact results for the control case beams, the DAD key case beam with no initial delamination was then investigated. Figure 8.5 shows the impact force vs. time history comparison between experimental investigation and numerical analysis. One can see from the figure that significantly higher impact loads resulted in the numerical model. The average maximum experimentally obtained impact force was 266.94-lb_f compared to the maximum numerically obtained impact force of 335.1-lb_f, which lies well outside the experimental standard deviation. The results show very similar high impact load duration between cases, and similar tail-off occurs after maximum loading as well. Discrepancies in the maximum load determined between experimental and numerical analysis are likely due to the finite element generation of the DAD keys. Because the DAD keys were analyzed using an elastic material model, neither failure or energy absorption characteristics of the fiberglass were included in the analysis and present in the results. In order to increase the fidelity of the of the DAD key material model, a complete characterization of the material's mechanical behavior should be determined experimentally and implemented into the finite element model utilizing a composite progressive failure model suitable for solid elements.

Figure 8.5. Impact force vs. time history comparison between experimental investigation and numerical analysis for the DAD key case beam with no initial delamination.

The resulting finite element stress was also generated, and the failure modes were compared with previously investigated experimental analysis (discussed in detail in section 5.1.3). Figure 8.6 shows the resulting stress at the point of the maximum tup penetration in the experimental analysis. The maximum resulting stress seen in the structure was 41.1-ksi. One can see from the figure that no element deletion due to failure occurred in within the face sheets or core. This follows with experimentally observed failure modes of the DAD key case with no delamination in that no visible failure occurred in the face sheet, but no failure occurred between the face and core, or within the foam core as seen in the experimental investigation.

Figure 8.6. Resulting impact stress determined from numerical analysis for the DAD key case beam with no initial delamination.

8.1.4 DAD Key Case with Initial Delamination

The experimentally and numerically obtained force vs. time histories of the DAD key case beam with a 1-inch long centrally located initial delamination were then examined under impact loading. One can see

from fig. 7.4 that a significantly higher impact load was determined from numerical analysis compared to the experimentally obtained data, as was also observed in the DAD key case beams with no initial delamination. The average maximum experimentally obtained impact force was 285.5-lb_f compared to the maximum numerically obtained impact force of 341.7-lb_f, which lies well outside the experimental standard deviation. Discrepancies in the maximum load determined between experimental and numerical analysis are likely due to the finite element generation of the DAD keys as was discussed previously with the DAD key case with no initial delamination. The results also indicate that this test retains impact force for a significantly shorter duration than the DAD key case beam (approximately 1.5-milliseconds), which was present in both the experimental results and numerical models.

Figure 8.7. Impact force vs. time history comparison between experimental investigation and numerical analysis for the DAD key case beam with an initial 1-inch delamination.

Finally, the resulting finite element stress was also generated, and the failure modes were compared with previously investigated experimental analysis (discussed in detail in section 5.1.4). Figure 8.8 shows the resulting stress at the point of the maximum tup penetration in the experimental analysis. The maximum resulting stress seen in the structure was 45.6-ksi. One can see from the figure that no element

Figure 8.8. Resulting impact stress determined from numerical analysis for the DAD key case beam with an initial 1-inch delamination.

deletion due to failure occurred in within the face sheets or core. This follows with experimentally observed failure modes of the DAD key case with no delamination in that no visible failure occurred in the face sheet, but no failure occurred between the face and core, or within the foam core as observed in the experimental investigation.

8.2 Static 4-Point Bend Test

8.2.1 Control Case

Results for the control case beam with no initial delamination were compared numerically utilizing finite element analysis and experimentally both without impact, and after impact. In addition, the analytically determined deflection was compared with numerically and experimentally obtained deflections at a 100-lb_f load equally distributed between the two loading locations on the test specimen beams not impacted. For the impacted case, experimental and numerical deflections were compared at 75-lb_f. It should be noted that the manufacturer's mechanical characteristics for the ACG LTM45EL/CF1803 face sheets and GP Last-A-Foam FR-6710 foam core were utilized for all the implicit finite element models. Table 8.1 shows the material properties utilized for numerical analysis obtained from the manufacturer's technical data sheets. Experimentally obtained mechanical characteristics of the constituents (from section 2) were first utilized but significant discrepancies were seen all of the models. This was likely due to a combination of inherent errors in the testing equipment, as well as the inability to test for bending and out-of-plane moduli of the face sheets and foam core.

Table 8.1. Mechanical characteristics of the face sheet and foam core utilized for the numerical implicit finite element analysis.

	ACG LTM45EL/CF1803	GP Last-A-Foam FR-6710
ρ	$1.371 \times 10^{-4} \text{-lb}_f\text{-s}^2/\text{in}^4$	$1.499 \times 10^{-5} \text{-lb}_f\text{-s}^2/\text{in}^4$
E_B	$7.8 \times 10^6 \text{-psi}$	14,092-psi
ν_{12}	0.098	0.3

One can see from table 8.1 that there is good agreement between the numerically and experimentally obtained deflections of the control case beam without impact, yielding an error of 4.64%. After impact, the deflections were compared both numerically and experimentally at a lower load of 75-lb_f. This was done because the ultimate load of the beam test specimens after impact was approximately 100-lb_f. One can see from table 8.2 that significant error occurred between the experimental and numerical deflections at 75-lb_f, indicating that significant damage was present in the beam prior to the implicit static analysis. This same trend was seen in all of the implicit statically analyzed cases after impact loading.

Table 8.2. Experimental, numerical, and analytic deflections of the control case beam without delamination.

Control Case with No Delamination	Maximum Deflection (inches)	
	Without Impact (100-lb _f)	After Impact (75-lb _f)
Experimental	0.0840	0.0822
Numerical	0.0801	1.639
Analytical	0.0998	N/A

The analytically determined deflection at 100-lb_f differs from the numerical and experimental results by 15.83% and 19.74%, respectively. Figure 8.9 below shows the analytically determined deflection along the entire span of the control case beam with no DAD key or initial delamination, between the roller supports. Errors between the analytical model and the experimental and numerical results are due to primarily to the assumptions made in the analytic analysis which includes that perfect bonding occurs between the stiff face sheets and soft core, and that the entire length of the beam is equal to the loading span of 9.9-inches.

Figure 8.9. Analytically determined deflection of the control case beam with no DAD keys or initial delamination.

8.2.2 Control Case with Initial Delamination

The control case beam with an initial 1-inch delamination shows even better agreement between the numerical and experimental results without an impact, yielding an error of approximately 3.7%. One can see from table 8.2 that significant error occurs between the experimental and numerical deflections at 75-lb_f,

indicating that significant damage was present in the beam prior to the implicit static analysis, as was seen with the control case beam with no initial delamination.

Table 8.3. Experimental and numerical deflections of the control case beam with an initial delamination.

Control Case with Initial Delamination	Maximum Deflection (inches)	
	Without Impact (100-lb _f)	After Impact (75-lb _f)
Experimental	0.0798	0.0804
Numerical	0.0801	1.670

8.2.3 DAD Key Case

With the addition of the DAD keys to finite element model, the maximum deflection at 100-lb_f differs very slightly indicating that the DAD key do not provide a significant benefits when subjected to pure bending and transversely oriented with respect to the length of the beam. One can see from table 8.3 that an error of 3.85% exists between the numerical and experimental results for the beam specimens that were not impacted. As with both of the control case beams, significant error occurs between the experimental and numerical deflections at 75-lb_f, indicating that significant damage was present in the beam prior to the implicit static analysis.

Table 8.4. Experimental and numerical deflections of the DAD key case beam with no delamination.

DAD Key Case with No Delamination	Maximum Deflection (inches)	
	Without Impact (100-lb _f)	After Impact (75-lb _f)
Experimental	0.0832	0.0805
Numerical	0.0800	1.615

8.2.4 DAD Key Case with Initial Delamination

The DAD key case plate with an initial delamination numerical model shows a slightly higher deflection than the DAD key case with no delamination. One can see from table 8.4 the numerical and experimental deflections of the DAD key case beam with an initial delamination show an error of 3.96%. As with all of the previously analyzed cases, significant error occurs between the experimental and numerical deflections at 75-lb_f, indicating that significant damage was present in the beam prior to the implicit static analysis.

Table 8.5. Experimental and numerical deflections of the DAD key case beam with an initial delamination.

DAD Key Case with Initial Delamination	Maximum Deflection (inches)	
	Before Impact (100-lb _f)	After Impact (75-lb _f)
Experimental	0.0834	0.0803
Numerical	0.0801	1.625

8.3 Plate Case Impact Test

8.3.1 Control Case Plate

The experimental and numerical impact force vs. time histories of the control case plate with no initial delamination show that the numerical model experienced a significantly higher impact force than the experimentally investigated results. The average maximum experimentally obtained impact force was 315.85-lb_f compared to the maximum numerically obtained impact force of 426.1-lb_f, which lies well outside the experimental standard deviation. Figure 7.5 below shows the impact force vs. time history comparison between numerical investigation and numerical analysis for the control case plate with no DAD key or initial delamination. One can see from the figure below that the high impact load duration is similar between experimental and numerical results, but the numerically obtained maximum impact force is approximately 30% higher than the experimentally obtained results. Error between the numerical and experimental results is likely due to the introduction of shear forces within finite element model because it was fully constrained on all sides. A failure criterion due to shear strain was not considered in the finite element material model since it was not investigated in the experimental analysis to determine the mechanical characteristics of the composite face sheets.

Figure 8.10. Impact force vs. time history comparison between experimental investigation and numerical analysis for the control case plate with no DAD key or initial delamination.

In addition, the resulting finite element stress was also generated, and the failure modes were compared with previously investigated experimental analysis (discussed in detail in section 5.3.1). Figure 8.11 shows the resulting stress at the point of the maximum tup penetration in the experimental analysis. The maximum resulting stress seen in the structure (obtained from finite element analysis) was 143.7-ksi. One can see from the figure that element deletion due to failure occurred in within the face sheets, as was observed in the experimental investigation of the plate impact cases.

Figure 8.11. Resulting impact stress determined from numerical analysis for the control case plate with no delamination.

8.3.2 DAD Key Plate Case

After comparing the numerical and experimental impact results for the control case plates, the DAD key case plate with no initial delamination results were compared. Figure 8.12 shows the impact force vs.

time history comparison between experimental investigation and numerical analysis of the DAD key plate with no initial delamination. One can see from the figure that high impact load duration is similar between experimental and numerical results, but the numerically obtained maximum impact force is approximately 30% higher than the experimentally obtained results. Such discrepancies between the numerical model and experimental analysis are again highly likely to the finite element generation of the DAD keys, as was found with the DAD key case beams discussed in sections 8.2.3 and 8.2.4. The average maximum experimentally obtained impact force was 343.57-lb_f compared to the maximum numerically obtained impact force of 512.6-lb_f, which lies well outside the experimental standard deviation. One can see from the figure below that high impact load duration is similar between experimental and numerical results, but the numerically obtained maximum impact force is approximately 50% higher than the experimentally obtained results. This showed a significantly higher increase in impact load, compared to experimental results, than the DAD key case beams did because the tup impacted the test specimen plate directly over the DAD key as opposed to between the DAD keys.

Figure 8.12. Impact force vs. time history comparison between experimental investigation and numerical analysis for the DAD key case plate with no initial delamination.

The resulting finite element stress was also generated, and the failure modes were compared with previously investigated experimental analysis (discussed in detail in section 5.3.2). Figure 8.13 shows the resulting stress at the point of the maximum tup penetration in the experimental analysis. The maximum resulting stress seen in the structure was 132.7-ksi. One can see from the figure that element deletion due to failure occurred in within the face sheets, as was observed in the experimental investigation of the plate impact cases.

Figure 8.13. Resulting impact stress determined from numerical analysis for the DAD key case plate with no delamination.

8.4 Vibration Test

8.4.1 Control Plate Case

Results for the control case plate with no initial delamination were compared numerically utilizing finite element analysis and experimentally both before impact and after impact. In addition, the analytically determined first bending natural frequency was compared with numerically and experimentally obtained natural frequencies. The analytically obtained frequency shows good agreement with both the numerical and experimental models yielding errors of 2.74% and 8.23% between experimental and numerical results, respectively. One can see from table 8.1 that there is good agreement between the numerically and experimentally obtained 1st mode natural frequencies of the control case beam before impact, yielding an error of 6.05%. In addition, the first mode natural frequencies after impact show close correlation, with an error of between numerical and experimental first mode frequencies of 4.84%.

Larger discrepancies were seen between the numerically and experimentally obtained 2nd mode natural frequencies. Prior to impact, an error of 13.10% existed between the numerical and experimentally results, and increased to 14.58% after the specimen was impacted. As can be seen in fig. 5.26 in section 5.4.1, the higher bending modes become much less distinguishable and uniform with respect to the location of the response accelerometer of the plate. Theoretically, the frequencies at each resonant mode should remain

constant and deflection should increase as the accelerometer is moved further from the constrained base, which was not observed in experimental investigation.

Table 8.6. Experimental, numerical, and analytical natural frequencies of the control case plate with no delamination.

No Delamination	Before Impact		After Impact	
	f_1 (Hz)	f_2 (Hz)	f_1 (Hz)	f_2 (Hz)
Experimental	202.3	741.3	199.9	743.5
Numerical	190.07	644.16	190.22	635.13
Analytical	208	N/A	N/A	N/A

8.4.2 Control Plate Case with Varying Delamination Locations

Next, the numerically and experimentally obtained control case plates with varying initial delamination locations were investigated and compared. The control case plate with an initial delamination at the 1st bending mode-node shows good agreement between numerical and experimental results yielding errors of 6.34% and 5.95% before and after impact, respectively. The control case plate with an initial delamination at the 2nd bending mode-node shows good agreement between numerical and experimental results yielding errors of 6.34% and 5.95% for f_1 before and after impact, respectively. The control case plate with initial delamination locations at the 3rd bending mode-nodes shows good agreement between numerical and experimental results yielding errors of 9.62% and 8.51% for the 1st bending natural frequency before and after impact, respectively.

Larger discrepancies were seen between the numerically and experimentally obtained 2nd mode natural frequencies. For the control case beam with an initial delamination at the 1st bending mode-node, an error of 15.86% existed between the numerical and experimental results prior to impact, and increased to 16.87% after the specimen was impacted. The control case beam with an initial delamination at the 2nd bending mode-node showed that an error of 11.11% existed between the numerical and experimental results prior to impact, and increased significantly to 19.63% after the specimen was impacted. For the control case beam with initial delamination at the 3rd bending mode-nodes, an error of 17.18% existed between the numerical and experimental results prior to impact, and similarly was 17.24% after the specimen was impacted. As was discussed previously, the higher bending modes become significantly less distinguishable and uniform with respect to the location of the response accelerometer of the plate.

Table 8.7. Experimental and numerical natural frequencies of the control case plate with varying delamination locations.

		Before Impact		After Impact	
		f_1 (Hz)	f_2 (Hz)	f_1 (Hz)	f_2 (Hz)
1 st Bending Mode-Node Delamination	Experimental	200.5	745.7	199.9	745.7
	Numerical	187.78	627.43	188	618.38
2 nd Bending Mode-Node Delamination	Experimental	207.1	705.1	205.3	770.2
	Numerical	188.33	626.76	188.26	618.98
3 rd Bending Mode-Node Delamination	Experimental	204.7	763.4	202.9	752.3
	Numerical	185	632.23	185.64	622.61

8.4.3 DAD Key Plate Case

Results for the DAD case plate with no initial delamination were compared numerically utilizing finite element analysis and experimentally both before impact and after impact. One can see from table 8.1 that much higher discrepancies exist between experimentally and numerically obtained natural frequencies with the addition of a DAD key in the finite element model. The experimentally obtained 1st mode natural frequencies differed from numerically obtained frequencies by 11.67% and 19.93% before and after impact, respectively.

Smaller discrepancies were seen between the numerically and experimentally obtained 2nd mode natural frequencies, which was opposite of what was observed for the control case plates with no DAD keys. Prior to impact, an error of 9.70% existed between the numerical and experimentally results, and decreased to 3.52% after the specimen was impacted.

Table 8.8. Experimental and numerical natural frequencies of the DAD key case plate with no delamination.

No Delamination	Before Impact		After Impact	
	f_1 (Hz)	f_2 (Hz)	f_1 (Hz)	f_2 (Hz)
Experimental	167	711.3	151.6	666.7
Numerical	189.07	642.18	189.34	634.25

8.4.4 DAD Key Plate Case with Varying Delamination Locations

Finally, the numerically and experimentally obtained DAD key case plates with varying initial delamination locations were investigated and compared. The DAD key case plate with an initial delamination at the 1st bending mode-node shows good agreement between numerical and experimental results yielding errors of 7.65% and 15.98% before and after impact, respectively. The DAD case plate with an initial delamination at the 2nd bending mode-node shows good agreement between numerical and experimental results yielding errors of 6.65% and 14.68% for f_1 before and after impact, respectively. The DAD case plate with initial delamination locations at the 3rd bending mode-nodes shows good agreement between numerical

and experimental results yielding errors of 4.94% and 1.59% for the first bending mode natural frequency before and after impact, respectively.

Larger discrepancies were seen between the numerically and experimentally obtained 2nd mode natural frequencies. For the control case beam with an initial delamination at the 1st bending mode-node, an error of 16.25% existed between the numerical and experimentally results prior to impact, and decreased to 11.46% after the specimen was impacted. The control case beam with an initial delamination at the 2nd bending mode-node showed that an error of 11.64% existed between the numerical and experimentally results prior to impact, and decreased slightly to 10.26% after the specimen was impacted. For the control case beam with initial delamination at the 3rd bending mode-nodes, an error of 9.19% existed between the numerical and experimentally results prior to impact, and increased to 11.09% after the specimen was impacted.

Table 8.9. Experimental and numerical natural frequencies of the DAD key case plate with varying delamination locations.

		Before Impact		After Impact	
		f_1 (Hz)	f_2 (Hz)	f_1 (Hz)	f_2 (Hz)
1 st Bending Mode-Node Delamination	Experimental	202.7	750.1	157.5	700.9
	Numerical	187.19	628.18	187.46	620.57
2 nd Bending Mode-Node Delamination	Experimental	201.1	711.3	160.3	692.7
	Numerical	187.72	628.54	187.88	621.62
3 rd Bending Mode-Node Delamination	Experimental	194.7	696.8	192.4	713.4
	Numerical	185.09	632.78	189.34	634.25

Chapter 9. Conclusions

The objective of this study was to determine the effectiveness of damage arrestment devices (DADs) placed in composite sandwich structures subjected to static and dynamic loading, after a low-velocity impact. The static 4-point bend test was implemented in order to determine if the DAD keys increased flexural strength with the presence of an initial face-core delamination in the composite sandwich structure, after a low-velocity impact. The dynamic vibration test was implemented in order to determine if the presence of DAD keys improved the vibrational damping characteristics of the structure and increased vibrational performance in the presence of a face-core delamination in the composite sandwich structure, after a low-velocity impact. In addition, the location of the accelerometer was studied in order to detect the presence of a delamination and impact damage within the structure.

The static 4-point bend test showed:

- There was no distinct structural advantage seen in beams, subjected only to static bending without being impacted, containing transversely oriented DAD keys with the presence of an initial delamination within the structure. The results of the test differed from [17] because the face sheet thickness was increased.
- No failure was visible in the face sheet due to bending, indicating that the flexural strength of the beams was largely driven by the flexural strength of the foam core and the shear strength of the face-core bonding interaction.
- When the residual flexural strength after an impact was investigated, experimental results indicated that DAD keys increased the impact resistance of the structure and residual strength after impact.
- The retention in maximum face sheet stress as well as bending modulus of elasticity, after impact, of the DAD key case beam with an initial delamination was higher than any of the other tested beam cases.

- DAD keys significantly improved both the stiffness and ultimate strength of a composite sandwich structure that has been subjected to a low-velocity impact, even in the presence of an initial face-core delamination.
- Based on these results, it is concluded that the presence of DAD keys in composite sandwich structures will increase their performance under bending, after damage due to a low-velocity impact.

The forced vibration testing showed:

- The presence of DAD keys improved the vibrational characteristics of a composite sandwich structure, such as damping, when oriented longitudinally along the length of the beam.
- The damping characteristics of the composite sandwich structure degraded after impact, but the DAD key case retained more damping after impact than the control case with no DAD key.
- The presence of a longitudinally oriented DAD key provides a better means of impact resistance to the structure, and vibrational characteristics were better retained after it had been damaged.
- Results from the experimental time domain analysis indicated that varying the location of an accelerometer could affectively detect the presence of a face-core delamination, especially on an impacted specimen.
- Based on these results, it is concluded that the presence of DAD keys in composite sandwich structures will increase the damping characteristics under vibration, after damage due to a low-velocity impact. In addition, accelerometers can effectively detect the effect of any damage in the structure, lowering the cost of maintenance and repair.

Numerical analysis utilizing the finite element method (FEM) was employed to validate experimental testing, as well as provide a means to examine the stress distribution and impact absorption of the structure. All cases showed good agreement between the numerical and experimental results with errors ranging from approximately 3% to 15%. In order to increase the fidelity of the finite element model, a complete characterization of the each constituent material's mechanical behavior should be determined experimentally and implemented.

Chapter 10. Future Work

Many additional studies and investigations are needed to further understand the effectiveness of DAD keys in improving the performance characteristics in composite sandwich structures under various loading conditions and applications. More investigation into size of the initial delamination, geometry of the DAD keys, and the orientation of the DAD keys is essential. This includes determining the residual flexural strength of composite sandwich beams with DAD keys oriented longitudinally along the length of the beam, and increasing the size of the initial face-core delamination. In addition, placing transverse DAD keys between both face-core interfaces might increase the flexural strength and the vibrational characteristics of the structure.

In order to increase the fidelity of the finite element model, a complete characterization of each constituent material's mechanical behavior should be determined experimentally and incorporated. To accurately model the failure characteristics of the composite face sheets, including ply-by-ply failure, elastic moduli, shear moduli, and Poisson's ratio in all three principal material planes should be experimentally measured and determined through coupon level tests. In addition, tensile and shear properties should be determined for the rigid polyurethane foam in order to accurately model through-the-thickness failure as was seen during the experimental testing in this research project.

Now that the Dynatup 8250 drop weight impact tester has a functional data acquisition system and means for testing, a multitude of cases and applications can be studied to further characterize the impact behavior of DAD keys, and sandwich composites in general. The research efforts published by Eswonia [13], Tran [14], Balatbat [15], Surano [16], and Davis [17] could all be re-investigated under impact loading to determine the effectiveness of DAD keys on the residual characteristics determined in each of the studies.

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Appendix

See Attached.

A.1 Dynatup 8250 Drop Weight Tester Instructions

Cal Poly Aerospace Structures/Composites Laboratory

Impact Machine Testing Procedures

Safety Precautions:

- Make sure no foreign objects are within the testing chamber during testing.
- Take Care in handling damaged test specimens, impacted composites can contain very sharp splinters.
- Once testing is complete, clean the chamber and testing support fixture of any debris.

Instructions for Use:

1. Ensure air supply hose is connected to the control panel located behind the testing chamber on the left side of the impact machine, as shown in point 1 of fig. 1.
2. Next ensure the pneumatic fixture hoses are properly connected to the control panel, as shown in point 2 of fig.1
3. Begin by switching the main power to the machine from “OFF” to “ON”. The switch will light up as shown in point 3 of fig. 1.
4. Once the main power is switched on, the machine will make a clicking sound indicating pressure is supplied to the crosshead hook.
5. The “CLAMP AIR PRESSURE” should rise from zero and indicate the pressure supplied to the testing support fixture clamp (shown in fig. 1). Depending on the test, the clamping pressure of the testing fixture can be adjusted by turning knob just below the gauge.

Figure 132. Control panel located behind the testing chamber on the left side of the impact machine (left) and close up view of testing support fixture pressure (right).

6. In order to place test specimen in the support fixture, switch pneumatic clamp, point 1 in fig. 5, from “OFF” to “ON”. The fixture should open (shown in fig. 2) and pressurized air release should be audible.
7. Open the chamber door, place the test specimen in the testing support fixture, align specimen according to test, and close the chamber door.
8. Once the door is closed, switch the pneumatic clamp, point 1 in fig. 5, from “ON” to “OFF” and turn on the test computer (the computer password is dynatup).

Figure 133. Testing support fixture in open position (right) and closed with a test specimen clamped (left).

9. From the desktop, open the “Dynatup DAQ” executable file.
10. The testing control panel should open, as shown in fig. 3.

Figure 134. Dynatup DAQ testing control panel.

11. Next, click the file folder button to the right of the “Save Test Data” field (point 1 in fig. 3) and a prompt window should open, as shown in fig. 4.

Figure 17. Save raw test data prompt window.

12. Specify a folder and file name to save the raw test data obtained by each of the measuring devices. The file extension must be a “.lvm” extension in order to analyzed the data.
13. Once a folder and file name are specified, click the save button, and the program will return to the control panel.
14. Next click the “Laser ON/OFF” switch. The switch should light up as shown in point 2 of fig. 3, but the laser itself will not.
15. Open the chamber door, slide the switch on the Si-Detector from “0” to “1” to power on the device, and close the chamber door.
16. Switch pneumatic clamp, point 1 in fig. 5, from “OFF” to “ON” again.
17. Adjust the height of the crosshead by pressing the “UP” or “DOWN” buttons located on the control remote shown in fig. 5.
18. Once the crosshead is adjusted to the correct height, ensure that point 6 in fig. 5 is switched to “MAN” and that point 5 in fig. 5 is switched to the correct setting for the test. “GRAV” means a gravity only drop test and “PNEU” engages to the pneumatic assist mechanism to the crosshead, supplying higher energies to the crosshead.

19. Testing is now ready to begin. Initiate data acquisition by pressing the “RUN” arrow on the control panel as indicated by point 3 in fig. 3.
20. The laser should now turn on.
21. Ensure that the “Si Detector Data” plot (point 5 in fig. 3) is outputting at least 10V, preferably 12V. If it is not, open the test chamber door and adjust the Si-detector so that the beam from the laser contacts the detector as shown in fig. 6.

Figure 137. Si-detector aligned with laser.

Figure 136. Impact machine control remote.

22. In order to fire the crosshead, press the “CLEAR” switch to the right (point 2 in fig. 5) and press the “ARM-CLAMP” button (point 3 in fig. 5) at the same time. The machine will produce a ringing sound and the testing support fixture will clamp the specimen as shown in fig. 2.
23. With the “CLEAR” switch and “ARM-CLAMP” button still pressed, press the “FIRE” button as shown as point 4 in fig. 5. The crosshead will then fall and impact the specimen.
24. Next, switch the pneumatic clamp, point 1 in fig. 5, from “ON” to “OFF”, turn the laser off on the control panel, and turn the data acquisition off by press the stop sign button on the control panel (point 4 of fig. 3).
25. Open the chamber door and return the crosshead to the release mechanism.
26. In order to remove the test specimen from the support fixture, switch pneumatic clamp, point 1 in fig. 5, from “OFF” to “ON”. The fixture should open (shown in fig. 2) and pressurized air release should be audible.
27. Close the test chamber door and switch the machine off by switching the main power to the machine from “ON” to “OFF” as shown in point 3 of fig. 1.
28. Next, open the MATLAB software from the desktop and specify the working directory as C:\Users\Composite\Desktop\Dynatup DAQ\Dynatup GUI\.
29. Open the “Impact_Test_Interface.m” file and press the run button. The following interface will open up as shown in fig. 7.

Figure 20. Impact test interface GUI in MATLAB.

30. In order to acquire the test data, press the “GET DATA” button, point 1 in fig. 7, and a prompt window will open up as shown in fig. 8.

Figure 21. Open raw data prompt window.

31. Select the data path folder and file name(s) and press the “Open” button.
32. Once open the “TEST DATA FILES” box will fill. Select a test run and press the “PLOT” button (point 2 in fig. 7) and the Interface will generate the test data as shown in fig. 8.

Figure 22. Impact test interface with loaded test data.

33. Press the “EXPORT TO FIGURES” button, shown as point 3 in fig. 7, to generate editable MATLAB figure windows for the Load Cell, Si Detector, and Accelerometer test data.
34. Press the “EXPORT TO EXCEL” button, shown as point 4 in fig. 7, to open a prompt window to generate excel spreadsheet file containing all of the raw test data as shown in fig. 10.

Figure 23. Save raw test data to an excel spreadsheet prompt window.

A.2 LabVIEW DAQ Code

A.3 MATLAB DAQ GUI Code

```
function varargout = Impact_Test_Interface(varargin)
% IMPACT_TEST_INTERFACE M-file for Impact_Test_Interface.fig
%     IMPACT_TEST_INTERFACE, by itself, creates a new IMPACT_TEST_INTERFACE
or raises the existing
%     singleton*.
%
%     H = IMPACT_TEST_INTERFACE returns the handle to a new
IMPACT_TEST_INTERFACE or the handle to
%     the existing singleton*.
%
%     IMPACT_TEST_INTERFACE('CALLBACK', hObject,eventData,handles,...) calls
the local
%     function named CALLBACK in IMPACT_TEST_INTERFACE.M with the given
input arguments.
%
%     IMPACT_TEST_INTERFACE('Property','Value',...) creates a new
IMPACT_TEST_INTERFACE or raises the
%     existing singleton*. Starting from the left, property value pairs are
%     applied to the GUI before Impact_Test_Interface_OpeningFcn gets
called. An
%     unrecognized property name or invalid value makes property application
%     stop. All inputs are passed to Impact_Test_Interface_OpeningFcn via
varargin.
%
%     *See GUI Options on GUIDE's Tools menu. Choose "GUI allows only one
%     instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help Impact_Test_Interface

% Last Modified by GUIDE v2.5 13-May-2012 22:20:21

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                  'gui_Singleton',   gui_Singleton, ...
                  'gui_OpeningFcn', @Impact_Test_Interface_OpeningFcn, ...
                  'gui_OutputFcn',  @Impact_Test_Interface_OutputFcn, ...
                  'gui_LayoutFcn',  [], ...
                  'gui_Callback',    []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
end
% End initialization code - DO NOT EDIT
```



```

% --- Executes just before Impact_Test_Interface is made visible.
function Impact_Test_Interface_OpeningFcn(hObject, eventdata, handles,
varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)
% varargin    command line arguments to Impact_Test_Interface (see VARARGIN)

% Choose default command line output for Impact_Test_Interface
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes Impact_Test_Interface wait for user response (see UIRESUME)
% uiwait(handles.figure1);
end

% --- Outputs from this function are returned to the command line.
function varargout = Impact_Test_Interface_OutputFcn(hObject, eventdata,
handles)
% varargout    cell array for returning output args (see VARARGOUT);
% hObject      handle to figure
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;
end

% --- Executes on selection change in Test_Data_Box.
function Test_Data_Box_Callback(hObject, eventdata, handles)
% hObject      handle to Test_Data_Box (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)
guidata(gcbo,handles);
end

% Hints: contents = cellstr(get(hObject,'String')) returns Test_Data_Box
%           contents as cell array
%           contents{get(hObject,'Value')} returns selected item from
%           Test_Data_Box

% --- Executes during object creation, after setting all properties.
function Test_Data_Box_CreateFcn(hObject, eventdata, handles)
% hObject      handle to Test_Data_Box (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      empty - handles not created until after all CreateFcns called

% Hint: listbox controls usually have a white background on Windows.
%           See ISPC and COMPUTER.

```



```

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
guidata(gcbo,handles);
end

% --- Executes on button press in Get_Data_Button.
function Get_Data_Button_Callback(hObject, eventdata, handles)
% hObject    handle to Get_Data_Button (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global pathname

%READ IN TEST DATA COMMAND
[filename, pathname] = uigetfile('*.lvm', 'Select Test Data',
'MultiSelect','on');

set(handles.Test_Data_Box,'String',filename);
drawnow();
guidata(gcbo,handles);
end

% --- Executes on button press in Plot_Button.
function Plot_Button_Callback(hObject, eventdata, handles)
% hObject    handle to Plot_Button (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global pathname
global Velocity
global MaxForce
global d
global dat

contents = cellstr(get(handles.Test_Data_Box,'String'));
testdat = contents(get(handles.Test_Data_Box,'Value'));
testplots = char(testdat);

% Import Raw Test Data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
d = lvm_import([pathname,testplots]);
time = d.Segment1.data(:,1); %seconds
voltage = d.Segment1.data(:,4); %Si-Detector Data (V)
load = d.Segment1.data(:,3); %Load Cell Data (lbf)
acc = d.Segment1.data(:,2); %Accelerometer Data (g)
dat = [time voltage load acc]; %Concatenate Data for Excel

%Si Detector Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
delta_t = peakfinder(voltage,1,5,-1); %seconds
delta_x = 0.3850/12; %distance measured on double edged flag (ft)
Velocity = delta_x/(time(delta_t(2))-time(delta_t(1))); %ft/s
vtime = time(delta_t(1)-250:delta_t(2)+250); %for plot (s)
volt = voltage(delta_t(1)-250:delta_t(2)+250); %for plot (s)

```

```

%Load Cell Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tfmax = find(load == max(load)); %find peak load (lbf)
tend = tfmax+750; %end of first impact
load = load - (sum(load(1:10000))/length(load(1:10000))); %offset from labview
fimpact = load(tfmax-120:tend); %first impact load duration (lbf)
ftime = time(1:length(fimpact)).*1000; %first impact time duration (ms)
MaxForce = max(load); %maximum measured force (lbf)

%Accelerometer Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tfall = Velocity/32.174; %time to fall (s)
ta_end = delta_t(4); %end of impact (s)
ti = ta_end - (min(find(time > tfall))); %time when crosshead falls (s)
acc = acc - (sum(acc(1:10000))/length(acc(1:10000))); %offset from labview (g)
accelimpact = acc(ti:ta_end); %impact acceleration (g)
acctime = time(ti:ta_end); %time duration of impact (s)
accvelo = 32.2.*cumtrapz(accelimpact); %Crosshead velocity throughout impact (ft/s)
KEacc = (0.5)*(7.56).*(accvelo.^2); %Kinetic Energy (lbf-ft)

%Plots
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
plot(handles.Accelerometer_Plot,time,acc) %Accelerometer
plot(handles.Load_Cell_Plot,ftime,fimpact) %Load Cell
plot(handles.Si_Detector_Plot,vtime,volt) %Si Detector

guidata(gcbo,handles);

%Maximum Force and Velocity Data Written to Text Boxes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
set(handles.ImpactVelocity,'String',[num2str(Velocity),' ','ft/s'])
set(handles.ImpactForce,'String',[num2str(MaxForce),' ','lbf'])
end

% --- Executes on button press in ExportButton.
function ExportButton_Callback(hObject, eventdata, handles)
% hObject    handle to ExportButton (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global d

%Read in Excel Data and Parse
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
time = d.Segment1.data(:,1);
voltage = d.Segment1.data(:,4);
load = d.Segment1.data(:,3);
acc = d.Segment1.data(:,2);

%Plots Generated for 'Export to Figures' Button
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
plot(time,acc)

```

```

title('Acclerometer Data')
xlabel('Time (s)')
ylabel('Acceleration (g)')

figure(2)
plot(time,load)
title('Load Cell Data')
xlabel('Time (s)')
ylabel('Load (lbf)')

figure(3)
plot(time,voltage)
title('Si Detector Data')
xlabel('Time (s)')
ylabel('Voltage (V)')

guidata(gcbo,handles);
end

function ImpactVelocity_Callback(hObject, eventdata, handles)
% hObject      handle to ImpactVelocity (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of ImpactVelocity as text
%         str2double(get(hObject,'String')) returns contents of ImpactVelocity
%         as a double
end

% --- Executes during object creation, after setting all properties.
function ImpactVelocity_CreateFcn(hObject, eventdata, handles)
% hObject      handle to ImpactVelocity (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
guidata(gcbo,handles);
end

function ImpactForce_Callback(hObject, eventdata, handles)
% hObject      handle to ImpactForce (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of ImpactForce as text
%         str2double(get(hObject,'String')) returns contents of ImpactForce as
%         a double
end

% --- Executes during object creation, after setting all properties.

```

```

function ImpactForce_CreateFcn(hObject, eventdata, handles)
% hObject    handle to ImpactForce (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
guidata(gcbo,handles);
end

% --- Executes on button press in excelwrite.
function excelwrite_Callback(hObject, eventdata, handles)
% hObject    handle to excelwrite (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global dat
[FILENAME, PATHNAME] = UIPUTFILE('.xls','Save As');
SUCCESS = xlswrite([PATHNAME,FILENAME],dat);
guidata(gcbo,handles);
end

```

A.4 Beam Specimen Impact Tests

A.4.1 Control Case Beam with No Delamination

A.4.2 Control Case Beam with an Initial 1-Inch Delamination

A.4.3 DAD Key Case Beam with No Delamination

A.4.4 DAD Key Case Beam with an Initial 1-Inch Delamination

A.5 Plate Specimen Impact Tests

A.5.1 Control Case Plate with No Delamination

A.5.2 Control Case Plate with an Initial Delamination at the 1st Bending Mode-Node

A.5.3 Control Case Plate with an Initial Delamination at the 2nd Bending Mode-Node

A.5.4 Control Case Plate with an Initial Delamination Locations at the 3rd Bending Mode-Nodes

A.5.5 DAD Key Case Plate with No Delamination

A.5.6 DAD Key Case Plate with an Initial Delamination at the 1st Bending Mode-Node

A.5.7 DAD Key Case Plate with an Initial Delamination at the 2nd Bending Mode-Node

A.5.8 DAD Key Case Plate with Initial Delamination Locations at the 3rd Bending Mode-Nodes

A.6 LS-DYNA FEA Tutorial

Cal Poly Aerospace Structures/Composites Laboratory

LS-DYNA FEA TUTORIALS

I. Explicit Impact Analysis

1. Open LS-PrePost from the Start Menu

2. Create the plate (see fig. 1)

- Select the shape mesher function from the FEM -> Element and Mesh tab
- Select entity: 4N_Shell
- Enter P1=0,0,0
- Enter P2= 10,0,0
- Enter P3= 10,10,0
- Enter P4= 0,10,0
- Enter NxNo.=10
- Enter NyNo.=10
- Enter Target Name: plate
- Click Create
- Click Accept

Figure 24. Plate mesh generation.

3. Create the ball (see fig. 2)

- Select the shape mesher function FEM -> Element and Mesh tab
- Select entity: Sphere_Solid
- Enter Radius= 1
- Enter Density= 5
- Enter x center= 5
- Enter y center= 5
- Enter z center=2.5
- Enter Target Name: ball
- Click Create
- Click Accept

Figure 25. Ball mesh generation

4. Specify the Plate Material (see figure 3)

- Select the Keyword Manager from FEM -> Model and Part tab
- Select MAT
- Select 001-ELASTIC from the list
- Click Edit
- Click NewID in the KEYWORD INPUT popup form
- Enter TITLE: plate material
- Enter RO=2.44e-4
- Enter E=1e7
- Enter PR=0.3
- Click Accept, click Done

Figure 26. Plate material specification.

5. Specify the Ball Material (see figure 4)
 - Select the Keyword Manager from FEM -> Model and Part tab
 - Select MAT
 - Select 020-RIGID from the list
 - Click Edit
 - Click NewID in the KEYWORD INPUT popup form
 - Enter TITLE: ball material
 - Enter RO=7.33e-4
 - Enter E=3e7
 - Enter PR=0.3
 - Click Accept, click Done

Figure 27. Ball material specification.

6. Specify the Plate Section (see Figure 5)

- Select the Keyword Manager from FEM -> Model and Part tab
- Select SECTION
- Select SHELL from the list
- Click Edit
- Click NewID in the KEYWORD INPUT popup form
- Enter TITLE: shell section
- Enter T1= 0.1
- Press Enter
- Click Accept, click Done

Figure 28. Plate shell element specification.

7. Specify the Ball Section (see Figure 5)

- Select the Keyword Manager from FEM -> Model and Part tab
- Select SECTION
- Select Solid from the list
- Click Edit
- Enter TITLE: solid section
- Click NewID in the KEYWORD INPUT popup form
- Click Accept, click Done

Figure 29. Ball solid element section specification

8. Assign Section to Mesh

- Select the Keyword Manager from FEM -> Model and Part tab
- Select PART
- Select PART from the list
- Click Edit
- For the 1 plate mesh, enter 1 under SECID and 1 under MID
- Click Accept
- For the 2 ball mesh, enter 2 under SECID and 2 under MID
- Click Accept, click Done

Figure 30. Define material properties and element type to mesh.

9. Set Boundary Conditions

- Select the Create Entity from FEM -> Model and Part tab
- Select Boundary
- Select Spc from the list
- Click Create
- In the Sel. Nodes window, click area.
- Click and drag cursor to select the edge nodes of the plate
- Click Apply
- White crosses should appear around all of the edges of the plate
- Click Done

Figure 31. Define and apply boundary conditions to the mesh.

10. Define Velocity of the Ball

- Select the Keyword Manager from FEM -> Model and Part tab
- Select INITIAL
- Select VELOCITY_RIGID_BODY from the list
- Click Edit
- Enter 2 under PID
- Enter -25 under VZ
- Click Accept, click Done

Figure 32. Ball velocity definition.

12. Define Contact between Ball and Plate

- Select the Keyword Manager from FEM -> Model and Part tab
- Select CONTACT
- Select AUTOMATIC_SURFACE_TO_SURFACE from the list
- Click Edit
- Click NewID in the KEYWORD INPUT popup form
- Enter TITLE: ball plate contact
- Select 3 from the SSTYPE drop down menu
- Select 3 from the MSYTP drop down menu
- Enter 2 under SSID
- Enter 1 under MSID
- Click Accept, click Done

Figure 33. contact definition between ball and plate.

13. Define Termination Time

- Select the Keyword Manager from FEM -> Model and Part tab
- Select CONTROL
- Select TERMINATION from the list
- Click Edit
- Enter 0.1 under ENDTIM
- Click Accept, click Done

Figure 34. Define termination time to end analysis.

14. Specify the Results Files for Post-Processing

- Select the Keyword Manager from FEM -> Model and Part tab
- Select DATABASE
- Select ASCII_option from the list
- Click Edit
- Enter 0.01 in Default DT and Press Enter.
- Select GLSTAT, MATSUM, and RCFORC check boxes.
- Click Accept, click Done

Figure 35. Define force vs. time history and material energy vs. time plots

- Select BINARY_D3PLOT from the list
- Click Edit
- Enter 0.01 in under DT.
- Click Accept, click Done

Figure 36. Define mesh deformation plot.

15. The model is now ready for analysis. Save the file by selecting Save Keyword under the File -> Save tab.

16. Open the LS-DYNA Manager from the start menu.
 - Select Start LS-DYNA Analysis under the Solver tab. A window will appear as shown in fig. 14
 - Select saved keyword file by pressing the Browse button under Input File I.
 - Select 8 from the NCPU drop down menu.
 - Click run

Figure 37. Run LS-Dyna solver through the manager.

17. Once analysis is complete, re-open LS-PrePost from the start menu.
- Access the results by selecting Open LS-DYNA Binary Plot under the File -> Open tab
 - Select the d3plot file and click Open
 - The model will open, along with an animate window as shown in fig.15. This allows the user to animate the impact event and select time steps.

Figure 38. D3plot file to access results from analysis.

18. Access Resulting Stresses and Displacements

- Select Fringe Component from the FEM -> Post tab.
- Click Stress to access stress components
- Select component and stresses will appear on model
- Click Ndv to access nodal displacements, velocities, accelerations, etc.

Figure 39. Maximum Von Mises stress plot.

15. Access force vs. time history and kinetic energy of the ball vs. time history plots

- Select ASCII Component from the FEM -> Post tab.
- Select rcfrc* from the top cell
- Click Load
- Select SI-1:ball plate contact from the Rcfrc Data cell
- Select 4-Resultant Force
- Click Plot
- A plot window should appear as shown in fig. 17

Figure 40. Impact force vs. time history

- Select matsum* from the top cell
- Click Load
- Select Mat Id 2 from the Matsum Data cell
- Select 2-Kinetic Energy
- Click Plot
- A plot window should appear as shown in fig. 18.

Figure 41. Ball kinetic energy vs. time history.

II. Implicit Vibration Analysis

1. Follow steps (1), (2), (4), and (6) from the previously discussed Explicit Impact Analysis.

2. Assign Section to Mesh

- Select the Keyword Manager from FEM -> Model and Part tab
- Select PART
- Select PART from the list
- Click Edit
- Enter 1 under SECID and 1 under MID
- Click accept, click done

Figure 42. Define material properties and element type to mesh.

3. Set Boundary Conditions

- Select the Create Entity from FEM -> Model and Part tab
- Select Boundary
- Select Spc from the list
- Click Create
- In the Sel. Nodes window, click area.
- Click and drag cursor to select the one edge of the plate
- Click Apply
- White crosses should appear on the over the selected nodes
- Click Done

Figure 43. Define and apply boundary conditions to the mesh.

4. Define Termination Time

- Select the Keyword Manager from FEM -> Model and Part tab
- Select CONTROL
- Select TERMINATION from the list
- Click Edit
- Enter 1 under ENDTIM
- Click Accept, click Done

Figure 44. Define termination time to end analysis.

5. Specify Implicit Vibration Analysis

- Select the Keyword Manager from FEM -> Model and Part tab
- Select CONTROL
- Select IMPLICIT_GENERAL from the list
- Click Edit
- Enter 1 under IMPFLAG
- Enter 0.01 under DT0
- Click Accept, click Done

Figure 45. Define implicit analysis option

- Select IMPLICIT_EIGENVALUE from the list
- Click Edit
- Enter 5 under NEIG
- Click Accept, click Done

Figure 46. Specify the number of eigenvalues to extract.

6. Specify the Results Files for Post-Processing

- Select the Keyword Manager from FEM -> Model and Part tab
- Select DATABASE
- Select BINARY_D3PLOT from the list
- Click Edit
- Enter 0.01 in under DT.
- Click Accept, click Done

Figure 47. Specify the resulting deformation plots.

7. The model is now ready for analysis. Save the file by selecting Save Keyword under the File -> Save tab.

8. Open the LS-DYNA Manager from the start menu.

- Select Start LS-DYNA Analysis under the Solver tab. A window will appear as shown in fig. 25
- Select saved keyword file by pressing the Browse button under Input File I.
- Select 8 from the NCPU drop down menu.
- Click run

Figure 48. Run LS-Dyna solver through the manager.

9. Once analysis is complete, re-open LS-PrePost from the start menu.
 - Access the results by selecting Open LS-DYNA Binary Plot under the File -> Open tab
 - Select the d3eigv file and click Open
 - The model will open, along with an animate window as shown in fig. 26. This allows the user to animate the vibration and specify mode shapes
 - Change the Div: drop down menu to 1 to show a more pronounced deflection.

Figure 49. D3eigv file to access results from analysis.

- 1st through 5th modes are shown below:

Figure 50. First five resonant modes determined from analysis

III. Implicit Static Analysis

1. Follow steps (1), (2), (4), and (6) from the previously discussed Explicit Impact Analysis.

2. Assign Section to Mesh

- Select the Keyword Manager from FEM -> Model and Part tab
- Select PART
- Select PART from the list
- Click Edit
- Enter 1 under SECID and 1 under MID

Figure 51. Define material properties and element type to mesh.

3. Set Boundary Conditions

- Select the Create Entity from FEM -> Model and Part tab
- Select Boundary
- Select Spc from the list
- Click Create
- In the Sel. Nodes window, click area.
- Click and drag cursor to select the edge nodes of the plate
- Click Apply
- White crosses should appear around all of the edges of the plate
- Click Done

Figure 52. Define and apply boundary conditions to the mesh.

4. Define Load Curve

- Select the Keyword Manager from FEM -> Model and Part tab
- Select DEFINE
- Select CURVE from the list
- Click Edit
- Enter TITLE: Load Curve
- Click NewID in the KEYWORD INPUT popup form
- Enter 0 under A1 and 0 under O1
- Click Insert
- Enter 1 under A1 and -1e5
- Click Insert
- Click Accept
- Click Plot and a new plot window should show up with the entered A1 and O1 points
- Click Done

Figure 53. Define load curve for static analysis.

5. Set Static Load

- Select the Create Entity from FEM -> Model and Part tab
- Select Load
- Select Node from the list
- Click Create
- In the Sel. Nodes window, click Pick.
- Select the Node in the center of the plate (Node61)
- Enter 1 in LCID cell
- Click Apply
- A white arrow pointing in the positive z-direction should appear
- Click Done

Figure 54. Apply nodal force with previously specified load curve.

5. Specify Implicit Vibration Analysis

- Select the Keyword Manager from FEM -> Model and Part tab
- Select CONTROL
- Select IMPLICIT_GENERAL from the list
- Click Edit
- Enter 1 under IMPFLAG
- Enter 0.01 under DT0
- Click Accept, click Done

Figure 55. Define implicit analysis option.

6. Define Termination Time

- Select the Keyword Manager from FEM -> Model and Part tab
- Select CONTROL
- Select TERMINATION from the list
- Click Edit
- Enter 1 under ENDTIM
- Click Accept, click Done

Figure 56. Define termination time to end analysis.

7. Specify the Results Files for Post-Processing

- Select the Keyword Manager from FEM -> Model and Part tab
- Select DATABASE
- Select BINARY_D3PLOT from the list
- Click Edit
- Enter 0.01 in under DT
- Click Accept, click Done

Figure 57. Specify the resulting deformation plots.

8. The model is now ready for analysis. Save the file by selecting Save Keyword under the File -> Save tab.

9. Open the LS-DYNA Manager from the start menu.

- Select Start LS-DYNA Analysis under the Solver tab. A window will appear as shown in fig. 35
- Select saved keyword file by pressing the Browse button under Input File I.
- Select 8 from the NCPU drop down menu.
- Click run

Figure 58. Run LS-Dyna solver through the manager.

10. Once analysis is complete, re-open LS-PrePost from the start menu.
- Access the results by selecting Open LS-DYNA Binary Plot under the File -> Open tab
 - Select the d3plot file and click Open
 - The model will open, along with an animate window as shown in fig. 36. This allows the user to animate the vibration and specify mode shapes
 - Change the Div: drop down menu to 1 to show a more pronounced deflection.

Figure 59. D3plot file to access results from analysis.

11. Access Resulting Stresses and Displacements

- Select Fringe Component from the FEM -> Post tab.
- Click Stress to access stress components
- Select component and stresses will appear on model
- Click Ndv to access nodal displacements, velocities, accelerations, etc.

Figure 60. Maximum z-displacement determined from implicit analysis.

IV. Things to Keep in Mind/Resources

LS-DYNA has its own unit format. Below is a conversion table:

MASS	LENGTH	TIME	FORCE	STRESS	ENERGY	DENSITY	YOUNG'S	35MPH 56.33KMPH	GRAVITY
kg	m	s	N	Pa	J	7.83e+03	2.07e+11	15.65	9.806
kg	cm	s	1.0e-02 N			7.83e-03	2.07e+09	1.56e+03	9.806e+02
kg	cm	ms	1.0e+04 N			7.83e-03	2.07e+03	1.56	9.806e-04
kg	cm	us	1.0e+10 N			7.83e-03	2.07e-03	1.56e-03	9.806e-10
kg	mm	ms	KN	GPa	KN-mm	7.83e-06	2.07e+02	15.65	9.806e-03
g	cm	s	dyne	dy/cm ²	erg	7.83e+00	2.07e+12	1.56e+03	9.806e+02
g	cm	us	1.0e+07 N	Mbar	1.0e+07 Ncm	7.83e+00	2.07e+00	1.56e-03	9.806e-10
g	mm	s	1.0e-06 N	Pa		7.83e-03	2.07e+11	1.56e+04	9.806e+03
g	mm	ms	N	MPa	N-mm	7.83e-03	2.07e+05	15.65	9.806e-03
tonne	mm	s	N	MPa	N-mm	7.83e-09	2.07e+05	1.56e+04	9.806e+03
lbf-s ² /in	in	s	lbf	psi	lbf-in	7.33e-04	3.00e+07	6.16e+02	386
slug	ft	s	lbf	psf	lbf-ft	1.52e+01	4.32e+09	51.33	32.17
kgf-s ² /mm	mm	s	kgf	kgf/mm ²	kgf-mm	7.98e-10	2.11e+04	1.56e+04	9.806e+03
kg	mm	s	mN	1.0e+03 Pa		7.83e-06	2.07e+08		9.806e+03
g	cm	ms		1.0e+05 Pa		7.83e+00	2.07e+06		9.806e-04

1 force unit = 1 mass unit * 1 acceleration unit

1 acceleration unit = 1 length unit / (1 time unit)²

1 density unit = 1 mass unit / (1 length unit)³

SOME GOOD RESOURCES FOR LS-DYNA:

<http://www.dynasupport.com/>

<http://www.lstc.com/lspc/content/tutorials.shtml>

www.dynaexamples.com/

<http://www.dynalook.com/>

A.7 Beam Case Numerical Impact stress

A.7.1 Control Case with No DAD Key or Initial Delamination

A.7.2 Control Case with an Initial 1-inch Delamination

A.7.3 DAD Key Case with no Initial Delamination

A.7.4 DAD Key Case with an Initial 1-inch Delamination

A.8 Beam Case Numerical Analysis Maximum Deflection

A.8.1 Control Case with No Initial Delamination (No Impact with 100-lb_f Load)

A.8.2 Control Case with No Initial Delamination (After Impact with 75-lb_f Load)

A.8.3 Control Case with an Initial 1-inch Delamination (No Impact with 100-lb_f Load)

A.8.4 Control Case with an Initial 1-inch Delamination (After Impact with 75-lb_f Load)

A.8.5 DAD Key Case with No Delamination (No Impact with 100-lb_f Load)

A.8.6 DAD Key Case with an Initial 1-inch Delamination (Before Impact with 100-lb_f Load)

A.9 Plate Case Numerical Impact Analysis

A.9.1 Control Case with No Delamination

A.9.2 Control Case with an Initial Delamination at the 1st Bending Mode-Node

A.9.3 Control Case with an Initial Delamination at the 2nd Bending Mode-Node

A.9.4 Control Case with Initial Delamination Locations at the 3rd Bending Mode-Nodes

A.9.5 DAD Key Case with No Delamination

A.9.6 DAD Key Case with an Initial Delamination at the 1st Bending Mode-Node

A.9.7 DAD Key Case with an Initial Delamination at the 2nd Bending Mode-Node

A.9.8 DAD Key Case with Initial Delamination Locations at the 3rd Bending Mode-Nodes

A.10 Plate Case Numerical Analysis Mode Shapes

A.10.1 Control Case Plate with No Delamination (Before Impact)

A.10.2 Control Case Plate with No Delamination (After Impact)

A.10.3 Control Case Plate with an Initial Delamination at the 1st Bending Mode-Node (Before Impact)

A.10.4 Control Case Plate with an Initial Delamination at the 1st Bending Mode-Node (Before Impact)

A.10.5 Control Case Plate with an Initial Delamination at the 2nd Bending Mode-Node (Before Impact)

A.10.6 Control Case Plate with an Initial Delamination at the 2nd Bending Mode-Node (After Impact)

A.10.7 Control Case Plate with Initial Delamination Locations at the 3rd Bending Mode-Nodes (Before Impact)

A.10.8 Control Case Plate with Initial Delamination Locations at the 3rd Bending Mode-Nodes (After Impact)

A.10.9 DAD Key Case Plate with No Delamination (Before Impact)

A.10.10 DAD Key Case Plate with No Delamination (Before Impact)

A.10.11 DAD Key Case Plate with an Initial Delamination at the 1st Bending Mode-Node (Before Impact)

A.10.12 DAD Key Case Plate with an Initial Delamination at the 1st Bending Mode-Node (After Impact)

A.10.13 DAD Key Case Plate with an Initial Delamination at the 2nd Bending Mode-Node (Before Impact)

A.10.14 DAD Key Case Plate with an Initial Delamination at the 2nd Bending Mode-Node (After Impact)

A.10.15 DAD Key Case Plate with Initial Delamination Locations at the 3rd Bending Mode-Nodes (Before Impact)

A.10.16 DAD Key Case Plate with Initial Delamination Locations at the 3rd Bending Mode-Nodes (After Impact)

A.11 Impact Force Time History Comparison

A.11.1 Control Case Plates with Varying Delamination Locations

A.11.2 DAD Key Case Plates with Varying Delamination Locations

A.12 Vibration Analysis Plots

A.12.1 Control Case Plate with No Delamination (Before Impact)

A.12.2 Control Case Plate with No Delamination (After Impact)

A.12.3 Control Case Plate with an Initial Delamination at the 1st Bending Mode-Node (Before Impact)

A.12.4 Control Case Plate with an Initial Delamination at the 1st Bending Mode-Node (After Impact)

A.12.5 Control Case Plate with an Initial Delamination at the 2nd Mode-Node (Before Impact)

A.12.6 Control Case Plate with an Initial Delamination at the 2nd Mode-Node (After Impact)

A.12.7 Control Case Plate with Initial Delamination Locations at the 3rd Bending Mode-Nodes (Before Impact)

A.12.8 Control Case Plate with Initial Delamination Locations at the 3rd Bending Mode-Nodes (After Impact)

A.12.9 DAD Key Case Plate with No Delamination (Before Impact)

A.12.10 DAD Key Case Plate with No Delamination (After Impact)

A.12.11 DAD Key Case Plate with an Initial Delamination at the 1st Bending Mode-Node (Before Impact)

A.12.12 DAD Key Case Plate with an Initial Delamination at the 1st Mode-Node (After Impact)

A.12.13 DAD Key Case Plate with an Initial Delamination at the 2nd Bending Mode-Node (Before Impact)

A.12.14 DAD Key Case Plate with an Initial Delamination at the 2nd Bending Mode-Node (After Impact)

A.12.15 DAD Key Case Plate with Initial Delamination Locations at the 3rd Bending Mode-Nodes (Before Impact)

A.12.16 DAD Key Case Plate with Initial Delamination Locations at the 3rd Bending Mode-Nodes (After Impact)

A.12.17 MATLAB Code

```
%                               Vibration Analysis and Calculations                               %
%                               Control Case Beam with No Delamination                           %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

close all;
clear all;
clc;

%Read in Raw Data and Parse
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C1 = csvread ('Control_1_inch.csv',17);
C2 = csvread ('Control_2_inch.csv',17);
C3 = csvread ('Control_3_inch.csv',17);
C4 = csvread ('Control_4_inch.csv',17);
C5 = csvread ('Control_5_inch.csv',17);
C6 = csvread ('Control_6_inch.csv',17);
C7 = csvread ('Control_7_inch.csv',17);
C8 = csvread ('Control_8_inch.csv',17);
C9 = csvread ('Control_9_inch.csv',17);

f1 = C1(:,2);
A1 = C1(:,9);
f2 = C2(:,2);
A2 = C2(:,9);
f3 = C3(:,2);
A3 = C3(:,9);
f4 = C4(:,2);
A4 = C4(:,9);
f5 = C5(:,2);
A5 = C5(:,9);
f6 = C6(:,2);
A6 = C6(:,9);
f7 = C7(:,2);
A7 = C7(:,9);
f8 = C8(:,2);
A8 = C8(:,9);
f9 = C9(:,2);
A9 = C9(:,9);

r9f = [183.5 726.2 1430];
r9A = [33.59 8.586 5.243];
r8f = [187.4 754 1472];
r8A = [32.71 5.862 2.215];
r7f = [190.7 772.5 1356];
r7A = [30.05 0.9557 7.892];
r6f = [194.1 741.3 1336];
r6A = [25.67 9.054 8.926];
r5f = [197.6 707.2 1430];
r5A = [21.02 16.47 6.156];
r4f = [199.9 688.7 1477];
r4A = [16.67 20.03 2.625];
```



```

r3f = [201.7 690.7 1380];
r3A = [12.2 13.44 24.88];
r2f = [202.9 715.5 1305];
r2A = [7.616 13.44 9.556];
r1f = [202.3 741.3 1348];
r1A = [3.263 13.03 7.589];

d = [1 2 3 4 5 6 7 8 9]; %response accelerometer locations

% natural frequencies (Hz)
modf1 = [r1f(1) r2f(1) r3f(1) r4f(1) r5f(1) r6f(1) r7f(1) r8f(1) r9f(1)];
%1st Mode
modf2 = [r1f(2) r2f(2) r3f(2) r4f(2) r5f(2) r6f(2) r7f(2) r8f(2) r9f(2)];
%2nd Mode
modf3 = [r1f(3) r2f(3) r3f(3) r4f(3) r5f(3) r6f(3) r7f(3) r8f(3) r9f(3)];
%3rd Mode

% Amplitude at resonance (g)
modA1 = [r1A(1) r2A(1) r3A(1) r4A(1) r5A(1) r6A(1) r7A(1) r8A(1) r9A(1)];
%1st Mode
modA2 = [r1A(2) r2A(2) r3A(2) r4A(2) r5A(2) r6A(2) r7A(2) r8A(2) r9A(2)];
%2nd Mode
modA3 = [r1A(3) r2A(3) r3A(3) r4A(3) r5A(3) r6A(3) r7A(3) r8A(3) r9A(3)];
%3rd Mode

wn1 = 2*pi.*modf1; %first circular natural frequencies (rad/s)
wn2 = 2*pi.*modf2; %second circular natural frequencies (rad/s)

% Experimental Plots
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
loglog(f1,A1,'--',f2,A2,'--',f3,A3,'--',f4,A4,'--',
,f5,A5,f6,A6,f7,A7,f8,A8,f9,A9)
set(gca,'FontSize',16)
title('Control Case with no DAD Key or Initial Delamination')
xlabel('Frequency (Hz)')
ylabel('Amplitude (g)')
legend('1 inch','2 inch','3 inch','4 inch','5 inch','6 inch','7 inch', ...
'8 inch','9 inch')

figure(2)
plot(d,modf1,d,modf2,d,modf3)
set(gca,'FontSize',16)
title('Control Case with no DAD Key or Initial Delamination')
xlabel('Distance from Base (inches)')
ylabel('Frequency (Hz)')
legend('1st mode','2nd mode','3rd mode')
axis([1 9 0 2000])

figure(3)
plot(d,modA1,d,modA2,d,modA3)
set(gca,'FontSize',16)
title('Control Case with no DAD Key or Initial Delamination')
xlabel('Distance from Base (inches)')
ylabel('Amplitude (g)')

```

```

legend('1st mode','2nd mode','3rd mode')
axis([1 9 0 45])

% Damping Ratio at 1st and 2nd Mode Determination
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
rres1 = modA1./sqrt(2);
rres2 = modA2./sqrt(2);

f1a = [197.6 199.3 198.1 196.5 194.1 191 187.6 184.1 180.1];
f1b = [206.5 207.1 206.5 204.7 202 198.7 194.9 191.8 188.1];
f2a = [730.5 698.9 670.7 678.6 696.8 730.5 761 741.3 712];
f2b = [747.9 728.3 709.3 696.8 715.5 752.3 799 765.7 743.3];

for i = 1:length(d)
    zeta1(i) = ((f1b(i)-f1a(i))/(2*modf1(i)));
    zeta2(i) = ((f2b(i)-f2a(i))/(2*modf2(i)));
end

figure(4)
plot(d,zeta1.*100,d,zeta2.*100)
set(gca,'FontSize',16)
title('Damping Ratio of Control Case with no DAD key or Delamination')
xlabel('Distance from Base (in)')
ylabel('Damping Ratio (%)')
legend('First Mode','Second Mode')
axis([1 9 0 5])

% Time Domain Analysis
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
t = 1./f1;

for i = 1:length(d)
    for j = 1:length(t)
        u1(j,i) = exp(-
zeta1(i)*wn1(i)*t(j))*((cos(wn1(i)*t(j)))+(zeta1(i)/sqrt(1-
zeta1(i)^2))*sin(wn1(i)*t(j)));
        u2(j,i) = exp(-
zeta2(i)*wn2(i)*t(j))*((cos(wn2(i)*t(j)))+(zeta2(i)/sqrt(1-
zeta2(i)^2))*sin(wn2(i)*t(j)));
    end
end

figure(5)
set(gca,'FontSize',16)
plot(t,u1(:,1),'--',t,u1(:,2),'--',t,u1(:,3),'--',t,u1(:,4),'--
',t,u1(:,5),t,u1(:,6),t,u1(:,7),t,u1(:,8),t,u1(:,9))
legend('1 inch','2 inch','3 inch','4 inch','5 inch','6 inch','7 inch', ...
'8 inch','9 inch')
Title('1st Mode Damping Ratio Time Response -- Control Case with no DAD key
or Delamination')

figure(6)
set(gca,'FontSize',16)
plot(t,u2(:,1),'--',t,u2(:,2),'--',t,u2(:,3),'--',t,u2(:,4),'--
',t,u2(:,5),t,u2(:,6),t,u2(:,7),t,u2(:,8),t,u2(:,9))

```

```

legend('1 inch','2 inch','3 inch','4 inch','5 inch','6 inch','7 inch', ...
      '8 inch','9 inch')
Title('2nd Mode Damping Ratio Time Response -- Control Case with no DAD key
or Delamination')

TSS = [0.09971 0.06008 0.04636 0.09596 0.09345 0.08089 0.04664 0.07297
0.05782]; %time to steady state (s)

figure(7)
set(gca,'FontSize',16)
plot(d,TSS)
xlabel('Distance from Base (inches)')
ylabel('Time to Steady State (seconds)')
title('2nd Mode Time Domain Response -- Control Case with no DAD Key or
Initial Delamination')

```

A.13 ACG LTM45EL/CF1803 Mechanical Characteristics

MATLAB Code

A.13.1 Tensile Test Calculations

```
%           Advanced Composites Group LTM45EL/CF1803 Carbon Fiber           %
%           ASTM D3039 Tensile Test Calculations                         %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

close all;
clear all;
clc;

% Read in Raw Data from Excel and Parse
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
S1 = csvread('Group1_1.csv',2,1);
Ex1 = S1(:,1);
Lo1 = S1(:,2);
S2 = csvread('Group1_2.csv',2,1);
Ex2 = S2(:,1);
Lo2 = S2(:,2);
S3 = csvread('Group1_3.csv',2,1);
Ex3 = S3(:,1);
Lo3 = S3(:,2);
S4 = csvread('Group2_1.csv',2,1);
Ex4 = S4(:,1);
Lo4 = S4(:,2);
S5 = csvread('Group2_2.csv',2,1);
Ex5 = S5(:,1);
Lo5 = S5(:,2);
S6 = csvread('Group2_5.csv',2,1);
Ex6 = S6(:,1);
Lo6 = S6(:,2);
S7 = csvread('Group2_6.csv',2,1);
Ex7 = S7(:,1);
Lo7 = S7(:,2);
S8 = csvread('Group2_7.csv',2,1);
Ex8 = S8(:,1);
Lo8 = S8(:,2);
S9 = csvread('Group2_8.csv',2,1);
Ex9 = S9(:,1);
Lo9 = S9(:,2);
S10 = csvread('Group3_1.csv',2,1);
Ex10 = S10(:,1);
Lo10 = S10(:,2);
S11 = csvread('Group3_2.csv',2,1);
Ex11 = S11(:,1);
Lo11 = S11(:,2);
S12 = csvread('Group3_4.csv',2,1);
Ex12 = S12(:,1);
Lo12 = S12(:,2);
S13 = csvread('Group3_5.csv',2,1);
Ex13 = S13(:,1);
Lo13 = S13(:,2);
```

```

S14 = csvread('Group3_6.csv',2,1);
Ex14 = S14(:,1);
Lo14 = S14(:,2);
S15 = csvread('Group3_7.csv',2,1);
Ex15 = S15(:,1);
Lo15 = S15(:,2);
S16 = csvread('Group3_8.csv',2,1);
Ex16 = S16(:,1);
Lo16 = S16(:,2);

lim = length(S1);

% Specimen Dimensions [Length, Cross Sectional Area]
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
L1 = 9.002;
A1 = 0.069 * .991;
L2 = 9.001;
A2 = 0.069 * .997;
L3 = 9.003;
A3 = 0.069 * .996;
L4 = 8.997;
A4 = 0.069 * 1.004;
L5 = 8.997;
A5 = 0.068 * 1.003;
L6 = 8.997;
A6 = 0.069 * 1.005;
L7 = 8.998;
A7 = 0.069 * 1.003;
L8 = 8.995;
A8 = 0.068 * .995;
L9 = 8.997;
A9 = 0.069 * 1.003;
L10 = 9;
A10 = 0.064 * 1.005;
L11 = 8.999;
A11 = 0.064 * 1.003;
L12 = 8.999;
A12 = 0.063 * 1;
L13 = 9;
A13 = 0.067 * 1;
L14 = 9;
A14 = 0.066 * 1.005;
L15 = 9;
A15 = 0.066 * 1.002;
L16 = 9;
A16 = 0.067 * 1.003;

% Stress and Strain Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ep1 = smooth(Ex1./L1);
sig1 = Lo1./A1;
ep2 = smooth(Ex2./L2);
sig2 = Lo2./A2;
ep3 = smooth(Ex3./L3);
sig3 = Lo3./A3;
ep4 = smooth(Ex4./L4);

```

```

sig4 = Lo4./A4;
ep5 = smooth(Ex5./L5);
sig5 = Lo5./A5;
ep6 = smooth(Ex6./L6);
sig6 = Lo6./A6;
ep7 = smooth(Ex7./L7);
sig7 = Lo7./A7;
ep8 = smooth(Ex8./L8);
sig8 = Lo8./A8;
ep9 = smooth(Ex9./L9);
sig9 = Lo9./A9;
ep10 = smooth(Ex10./L10);
sig10 = Lo10./A10;
ep11 = smooth(Ex11./L11);
sig11 = Lo11./A11;
ep12 = smooth(Ex12./L12);
sig12 = Lo12./A12;
ep13 = smooth(Ex13./L13);
sig13 = Lo13./A13;
ep14 = smooth(Ex14./L14);
sig14 = Lo14./A14;
ep15 = smooth(Ex15./L15);
sig15 = Lo15./A15;
ep16 = smooth(Ex16./L16);
sig16 = Lo16./A16;

% Elastic Modulus and Max Tensile Strength Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

epmin = 1e-3;
epmax = 10e-3;

sigma = [sig1(1:lim) sig2(1:lim) sig3(1:lim) sig4(1:lim) sig5(1:lim)...
         sig6(1:lim) sig7(1:lim) sig8(1:lim) sig9(1:lim) sig10(1:lim)...
         sig11(1:lim) sig12(1:lim) sig13(1:lim) sig14(1:lim) sig15(1:lim)...
         sig16(1:lim)];

epsilon = [ep1(1:lim) ep2(1:lim) ep3(1:lim) ep4(1:lim) ep5(1:lim)...
           ep6(1:lim) ep7(1:lim) ep8(1:lim) ep9(1:lim) ep10(1:lim) ep11(1:lim)...
           ep12(1:lim) ep13(1:lim) ep14(1:lim) ep15(1:lim) ep16(1:lim)];

for i = 1:16
    E(i) = YoungsCalc(epsilon(:,i), sigma(:,i), epmin, epmax);
end

E_ave = sum(E)/length(E)
E_SDev = std(E)
Error_E = E_SDev/E_ave

SigmaMax = [max(sig1) max(sig2) max(sig3) max(sig4) max(sig5) max(sig6)...
            max(sig7) max(sig8) max(sig9) max(sig10) max(sig11) max(sig12)...
            max(sig13) max(sig14) max(sig15) max(sig16)];

SigmaT_ave = sum(SigmaMax)/length(SigmaMax)
SigmaT_SDev = std(SigmaMax)

```

```

Error_SigmaT = SigmaT_SDev/SigmaT_ave

ep1max = ep1(sig1 == max(sig1));
ep2max = ep2(sig2 == max(sig2));
ep3max = ep3(sig3 == max(sig3));
ep4max = ep4(sig4 == max(sig4));
ep5max = ep5(sig5 == max(sig5));
ep6max = ep6(sig6 == max(sig6));
ep7max = ep7(sig7 == max(sig7));
ep8max = ep8(sig8 == max(sig8));
ep9max = ep9(sig9 == max(sig9));
ep10max = ep10(sig10 == max(sig10));
ep11max = ep11(sig11 == max(sig11));
ep12max = ep12(sig12 == max(sig12));
ep13max = ep13(sig13 == max(sig13));
ep14max = ep14(sig14 == max(sig14));
ep15max = ep15(sig15 == max(sig15));
ep16max = ep16(sig16 == max(sig16));

EpMax = [ep1max ep2max ep3max ep4max ep5max ep6max ep7max ep8max ep10max ...
         ep11max ep12max ep13max ep14max ep15max ep16max];

EpMax_Ave = sum(EpMax)/length(EpMax)
Error_EpMax = std(EpMax)/EpMax_Ave

% Remove Data after Failure
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ep1 = ep1(1:find(sig1 == max(sig1)));
Sig1 = sig1(1:find(sig1 == max(sig1)));
Ep2 = ep2(1:find(sig2 == max(sig2)));
Sig2 = sig2(1:find(sig2 == max(sig2)));
Ep3 = ep3(1:find(sig3 == max(sig3)));
Sig3 = sig3(1:find(sig3 == max(sig3)));
Ep4 = ep4(1:find(sig4 == max(sig4)));
Sig4 = sig4(1:find(sig4 == max(sig4)));
Ep5 = ep5(1:find(sig5 == max(sig5)));
Sig5 = sig5(1:find(sig5 == max(sig5)));
Ep6 = ep6(1:find(sig6 == max(sig6)));
Sig6 = sig6(1:find(sig6 == max(sig6)));
Ep7 = ep7(1:find(sig7 == max(sig7)));
Sig7 = sig7(1:find(sig7 == max(sig7)));
Ep8 = ep8(1:find(sig8 == max(sig8)));
Sig8 = sig8(1:find(sig8 == max(sig8)));
Ep9 = ep9(1:find(sig9 == max(sig9)));
Sig9 = sig9(1:find(sig9 == max(sig9)));
Ep10 = ep10(1:find(sig10 == max(sig10)));
Sig10 = sig10(1:find(sig10 == max(sig10)));
Ep11 = ep11(1:find(sig11 == max(sig11)));
Sig11 = sig11(1:find(sig11 == max(sig11)));
Ep12 = ep12(1:find(sig12 == max(sig12)));
Sig12 = sig12(1:find(sig12 == max(sig12)));
Ep13 = ep13(1:find(sig13 == max(sig13)));
Sig13 = sig13(1:find(sig13 == max(sig13)));
Ep14 = ep14(1:find(sig14 == max(sig14)));
Sig14 = sig14(1:find(sig14 == max(sig14)));
Ep15 = ep15(1:find(sig15 == max(sig15)));

```

```

Sig15 = sig15(1:find(sig15 == max(sig15)));
Ep16 = ep16(1:find(sig16 == max(sig16)));
Sig16 = sig16(1:find(sig16 == max(sig16)));

% Plot(s)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
plot(Ep1, Sig1, Ep2, Sig2, Ep3, Sig3, Ep4, Sig4, Ep5, Sig5, Ep6, Sig6, Ep7, Sig7, ...
     Ep8, Sig8, Ep9, Sig9, Ep10, Sig10, Ep11, Sig11, Ep12, Sig12, Ep13, Sig13, Ep14, ...
     Sig14, Ep15, Sig15, Ep16, Sig16)
xlabel('strain (in/in)')
ylabel('stress (psi)')
title('Advanced Composites Group LTM45/CF1803 ASTM D3039 Test Results')

function E = YoungsCalc(epsilon, sigma, epmin, epmax)
% This function determines the Elastic modulus (E) given a strain vector
% (epsilon), stress vector (sigma), the strain bounds of the linear region
% of the stress-strain curve (epmin:epmax)

minep = min(find(epsilon >= epmin)); %find minimum index
maxep = max(find(epsilon <= epmax)); %find maximum index

linstrain = epsilon(minep:maxep); %linear strain vector
linstress = sigma(minep:maxep); %linear stress vector

for i = 2:length(linstrain)
    linsig(i) = linstress(i);
    linep(i) = linstrain(i);
    if linstrain(i) == linstrain(i-1)
        linsig(i) = []; %removes repeat data in vector
        linep(i) = [] %removes repeat data in vector
    end
end
slope = diff(linsig)./diff(linep);
E = sum(slope)/length(slope); %Elastic Modulus (psi)
end

```


A.13.2 Poisson's Ratio Calculations

```
%
    Advanced Composites Group LTM45EL/CF1803 Carbon Fiber
%
    ASTM E132 Poisson's Ratio Calculations
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;
clc;

% Read Raw Data from Excel and Parse
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
S1 = xlsread('Group1_Raw_Data','Specimen 1');
S2 = xlsread('Group1_Raw_Data','Specimen 2');
S9 = xlsread('Group3_Raw_Data','Specimen 3');
S10 = xlsread('Group3_Raw_Data','Specimen 4');
clc;
lim = length(S2);

S1L = smooth(S1(:,4));
S1el = smooth(S1(:,14)./9.001);
S1et = -smooth(S1(:,15)./9.995);
S2L = smooth(S2(:,4));
S2el = smooth(S2(:,14)./9.001);
S2et = -smooth(S2(:,15)./9.995);
S9L = smooth(S9(:,4));
S9el = smooth(S9(:,14)./9.001);
S9et = -smooth(S9(:,15)./1.005);
S10L = smooth(S10(:,4));
S10el = smooth(S10(:,14)./9.001);
S10et = -smooth(S10(:,15)./1.005);

% Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
L = [S1L(1:lim) S2L(1:lim) S9L(1:lim) S10L(1:lim)];
epl = [S1el(1:lim) S2el(1:lim) S9el(1:lim) S10el(1:lim)];
ept = [S1et(1:lim) S2et(1:lim) S9et(1:lim) S10et(1:lim)];

Lmin = 500;
Lmax = 2500;

for i = 1:4
    nu(i) = PoissonsCalc(L(:,i),ept(:,i),epl(:,i),Lmin,Lmax);
end

nu_ave = sum(nu)/length(nu)
nu_SDev = std(nu)
Error_nu = nu_SDev/nu_ave

% Plots
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
plot(S1L,S1et,S1L,S1el,S2L,S2et,S2L,S2el,S9L,S9et,S9L,S9el,S10L,S10et,S10L,S10el)
xlabel('Applied Load (lbf)')
```

```

ylabel('Average Strain (in/in)')
title('Advanced Composites Group LTM45/CF1803 ASTM E0132 Test Results')
function nu = PoissonsCalc(L,ept,epl,Lmin,Lmax)
%This function determines the Poisson's ratio given applied load (L),
%transverse strain (ept), longitudinal strain (epl), and the applied load
%bounds of the linear region of the strain-load curve (Lmin:Lmax)

minL = min(find(L >= Lmin)); %minimum index
maxL = max(find(L <= Lmax)); %maximum index

linept = ept(minL:maxL); %linear transverse strain
linepl = epl(minL:maxL); %linear longitudinal strain
linLoad = L((minL:maxL)); %linear applied load

for i = 2:length(linLoad)
    linet(i) = linept(i);
    linel(i) = linepl(i);
    linL(i) = linLoad(i);
    if linet(i) == linet(i-1)
        linet(i) = []; %remove repeat data
        linL(i) = []; %remove repeat data
    end
    if linel(i) == linel(i-1)
        linel(i) = []; %remove repeat data
        linL(i) = []; %remove repeat data
    end
end
slope1 = diff(linet)./diff(linL); %transverse strain slope
detdL = sum(slope1)/length(slope1); %det/dL
slope2 = diff(linel)./diff(linL); %longitudinal strain slope
deldL = sum(slope2)/length(slope2); %del/dL
nu = detdL/deldL; %Poisson's Ratio
end

```

A.13.3 Compression Test Calculations

```
%           Advanced Composites Group LTM45/CF1803 Carbon Fiber           %
%           ASTM D3410 Compression Test Calculations                     %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;
clc;

% Read in Raw Data from Excel and Parse
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
S1 = xlsread('Compression_Raw_Data', 'Specimen 1');
S2 = xlsread('Compression_Raw_Data', 'Specimen 2');
S3 = xlsread('Compression_Raw_Data', 'Specimen 3');
S4 = xlsread('Compression_Raw_Data', 'Specimen 4');
S5 = xlsread('Compression_Raw_Data', 'Specimen 5');
S6 = xlsread('Compression_Raw_Data', 'Specimen 6');
S7 = xlsread('Compression_Raw_Data', 'Specimen 7');
S8 = xlsread('Compression_Raw_Data', 'Specimen 8');
S9 = xlsread('Compression_Raw_Data', 'Specimen 9');
S10 = xlsread('Compression_Raw_Data', 'Specimen 10');
S11 = xlsread('Compression_Raw_Data', 'Specimen 11');
S12 = xlsread('Compression_Raw_Data', 'Specimen 12');
clc;

e1 = S1(:,2);
p1 = S1(:,3);
e2 = S2(:,2);
p2 = S2(:,3);
e3 = S3(:,2);
p3 = S3(:,3);
e4 = S4(:,2);
p4 = S4(:,3);
e5 = S5(:,2);
p5 = S5(:,3);
e6 = S6(:,2);
p6 = S6(:,3);
e7 = S7(:,2);
p7 = S7(:,3);
e8 = S8(:,2);
p8 = S8(:,3);
e9 = S9(:,2);
p9 = S9(:,3);
e10 = S10(:,2);
p10 = S10(:,3);
e11 = S11(:,2);
p11 = S11(:,3);
e12 = S12(:,2);
p12 = S12(:,3);

% Specimen Dimensions
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
A1 = .985*.064;
L1 = 5.49;
```

```

A2 = .995*.065;
L2 = 5.52;
A3 = .994*.065;
L3 = 5.51;
A4 = .995*.064;
L4 = 5.51;
A5 = .991*.065;
L5 = 5.51;
A6 = .993*.065;
L6 = 5.51;
A7 = .993*.065;
L7 = 5.52;
A8 = .991*.066;
L8 = 5.50;
A9 = .993*.066;
L9 = 5.48;
A10 = .991*0.065;
L10 = 5.52;
A11 = .989*.065;
L11 = 5.51;
A12 = .993*.066;
L12 = 5.52;

% Stress and Strain Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ep1 = e1./L1;
sig1 = p1./A1;
ep2 = e2./L2;
sig2 = p2./A2;
ep3 = e3./L3;
sig3 = p3./A3;
ep4 = e4./L4;
sig4 = p4./A4;
ep5 = e5./L5;
sig5 = p5./A5;
ep6 = e6./L6;
sig6 = p6./A6;
ep7 = e7./L7;
sig7 = p7./A7;
ep8 = e8./L8;
sig8 = p8./A8;
ep9 = e9./L9;
sig9 = p9./A9;
ep10 = e10./L10;
sig10 = p10./A10;
ep11 = e11./L11;
sig11 = p11./A11;
ep12 = e12./L12;
sig12 = p12./A12;

smax1 = max(abs(sig1));
smax2 = max(abs(sig2));
smax3 = max(abs(sig3));
smax4 = max(abs(sig4));
smax5 = max(abs(sig5));
smax6 = max(abs(sig6));

```

```

smax7 = max(abs(sig7));
smax8 = max(abs(sig8));
smax9 = max(abs(sig9));
smax10 = max(abs(sig10));
smax11 = max(abs(sig11));
smax12 = max(abs(sig12));

Max_Comp_Stress = [smax1 smax2 smax3 smax4 smax5 smax6 smax7 smax8 ...
    smax9 smax10 smax11 smax12]';

Ave_SigmaComp = sum(Max_Comp_Stress)/length(Max_Comp_Stress)
SDev = std(Max_Comp_Stress)
Error = SDev/Ave_SigmaComp

ep1max = ep1(sig1 == min(sig1));
ep2max = ep2(sig2 == min(sig2));
ep3max = ep3(sig3 == min(sig3));
ep4max = ep4(sig4 == min(sig4));
ep5max = ep5(sig5 == min(sig5));
ep6max = ep6(sig6 == min(sig6));
ep7max = ep7(sig7 == min(sig7));
ep8max = ep8(sig8 == min(sig8));
ep9max = ep9(sig9 == min(sig9));
ep10max = ep10(sig10 == min(sig10));
ep11max = ep11(sig11 == min(sig11));
ep12max = ep12(sig12 == min(sig12));

EpMax = [ep1max ep2max ep3max ep4max ep5max ep6max ep7max ep8max ep10max ...
    ep11max ep12max];

EpMax_Ave = sum(EpMax)/length(EpMax)
Error_Ep = std(EpMax)/EpMax_Ave

% Remove Data after Failure
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ep1 = ep1(1:find(sig1 == min(sig1)));
Sig1 = sig1(1:find(sig1 == min(sig1)));
Ep2 = ep2(1:find(sig2 == min(sig2)));
Sig2 = sig2(1:find(sig2 == min(sig2)));
Ep3 = ep3(1:find(sig3 == min(sig3)));
Sig3 = sig3(1:find(sig3 == min(sig3)));
Ep4 = ep4(1:find(sig4 == min(sig4)));
Sig4 = sig4(1:find(sig4 == min(sig4)));
Ep5 = ep5(1:find(sig5 == min(sig5)));
Sig5 = sig5(1:find(sig5 == min(sig5)));
Ep6 = ep6(1:find(sig6 == min(sig6)));
Sig6 = sig6(1:find(sig6 == min(sig6)));
Ep7 = ep7(1:find(sig7 == min(sig7)));
Sig7 = sig7(1:find(sig7 == min(sig7)));
Ep8 = ep8(1:find(sig8 == min(sig8)));
Sig8 = sig8(1:find(sig8 == min(sig8)));
Ep9 = ep9(1:find(sig9 == min(sig9)));
Sig9 = sig9(1:find(sig9 == min(sig9)));
Ep10 = ep10(1:find(sig10 == min(sig10)));
Sig10 = sig10(1:find(sig10 == min(sig10)));
Ep11 = ep11(1:find(sig11 == min(sig11)));

```

```

Sig11 = sig11(1:find(sig11 == min(sig11)));
Ep12 = ep12(1:find(sig12 == min(sig12)));
Sig12 = sig12(1:find(sig12 == min(sig12)));

%Plots
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
plot(e1,p1,e2,p2,e3,p3,e4,p4,e5,p5,e6,p6,e7,p7,e8,p8,e9,p9,e10,p10,...
     e11,p11,e12,p12)
xlabel('Extension (inches)')
ylabel('Load (lbf)')
set(gca,'XDir','reverse')
title('Advanced Composites Group LTM45/CF1803 ASTM D3410 Test Results')

figure(2)
plot(Ep1,Sig1,Ep2,Sig2,Ep3,Sig3,Ep4,Sig4,Ep5,Sig5,Ep6,Sig6,Ep7,Sig7,Ep8,Sig8,
     ...
     Ep9,Sig9,Ep10,Sig10,Ep11,Sig11,Ep12,Sig12)
xlabel('Strain (in/in)')
ylabel('Stress (psi)')
set(gca,'XDir','reverse')
title('Advanced Composites Group LTM45/CF1803 ASTM D3410 Test Results')

```

A.13.4 Fiber Volume Ratio and Out of Plane Properties

```
%
    Advanced Composites Group LTM45EL/CF1803 Carbon Fiber
%
    Volume Ratio and Out-of-Plane Properties
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;
clc;

% Measured Data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
L = [1.959 1.948 1.959 1.957 1.982 1.979 1.932]; %burn specimen length
(inches)
W = [0.989 0.996 0.994 0.986 0.996 0.997 0.994 0.996]; %burn specimen width
(inches)
T = [0.066 0.066 0.067 0.067 0.066 0.067 0.067]; %burn specimen thickness
(inches)

Meas_Mi = [0.0970 0.0970 0.0975 0.0975 0.0975 0.0975 0.0975]; %measured mass
-- before burn test (lb)
Meas_Mf = [0.0955 0.0950 0.0955 0.0945 0.0955 0.0950 0.0955]; %measured mass
-- after burn test (lb)
M_Plate = 0.0905; %mass of burn plate (lb)

rhom = 0.0433; %density of LTM45EL matrix (from technical data sheet)

% Calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i = 1:length(L)
    Mi(i) = Meas_Mi(i) - M_Plate; %initial specimen mass
    Mf(i) = Meas_Mf(i) - M_Plate; %final specimen mass
    Vol(i) = L(i)*W(i)*T(i); %specimen volume (in^3)
    rhoc(i) = Mi(i)/Vol(i); %specimen density (lb/in^3)
    rhof(i) = Mf(i)/Vol(i); %fiber density (lb/in^3)
    Wf(i) = Mf(i)/Mi(i); %weight fraction
    Vf(i) = (Wf(i)/rhof(i))/((Wf(i)/rhof(i))+(1-Wf(i))/rhom)); %fiber volume
fraction
end

Vf_ave = sum(Vf)/length(Vf) %average volume fraction
Vf_SDev = std(Vf)
Error = Vf_SDev/Vf_ave

% Out-of Plane Mechanical Properties
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ef = 55e6; %tensile modulus of CF1803 fiber -- from paper (psi)
Em = 420609; %tensile modulus of LTM45EL resin -- from paper (psi)

E3 = (Em*Ef)/((Vf_ave*Em)+(1-Vf_ave)*Ef); %Out-of-Plane Elastic Modulus
(psi)
```

A.14 GP Last-A-Foam Mechanical Characteristics MATLAB Code

A.14.1 Compression Test Calculations

```
%                               General Plastics LAST-A-FOAM FR 6710                               %
%                               ASTM D1621 Compression Test Calculations                               %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

close all;
clear all;
clc;

% Read in Raw Data from Excel and Parse
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
S1 = csvread('Group1_1.csv',2,1);
Ex1 = S1(:,1);
Lo1 = S1(:,2);
S2 = csvread('Group1_2.csv',2,1);
Ex2 = S2(:,1);
Lo2 = S2(:,2);
S3 = csvread('Group1_3.csv',2,1);
Ex3 = S3(:,1);
Lo3 = S3(:,2);
S4 = csvread('Group1_4.csv',2,1);
Ex4 = S4(:,1);
Lo4 = S4(:,2);
S5 = csvread('Group1_5.csv',2,1);
Ex5 = S5(:,1);
Lo5 = S5(:,2);
S6 = csvread('Group2_1.csv',2,1);
Ex6 = S6(:,1);
Lo6 = S6(:,2);
S7 = csvread('Group2_2.csv',2,1);
Ex7 = S7(:,1);
Lo7 = S7(:,2);
S8 = csvread('Group2_3.csv',2,1);
Ex8 = S8(:,1);
Lo8 = S8(:,2);
S9 = csvread('Group2_4.csv',2,1);
Ex9 = S9(:,1);
Lo9 = S9(:,2);
S10 = csvread('Group2_5.csv',2,1);
Ex10 = S10(:,1);
Lo10 = S10(:,2);
S11 = csvread('Group2_6.csv',2,1);
Ex11 = S11(:,1);
Lo11 = S11(:,2);

lim1 = length(S3);
lim2 = length(S10);

% Specimen Dimensions [Length , Cross Sectional Area] (inches)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```



```

L1 = .995;
A1 = 2.075*2.02;
L2 = 1.001;
A2 = 2.070*2.011;
L3 = .997;
A3 = 2.071*2.010;
L4 = .996;
A4 = 2.079*2.009;
L5 = 1.010;
A5 = 2.074*1.999;
L6 = 1.040;
A6 = 2*2.005;
L7 = 1.039;
A7 = 1.997*1.995;
L8 = 1.035;
A8 = 1.996*2.001;
L9 = 1.034;
A9 = 2.001*2.005;
L10 = 1.045;
A10 = 2.002*2.011;
L11 = 1.040;
A11 = 2.001*2.014;

% Stress and Strain Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ep1 = -Ex1./L1;
sig1 = -Lo1./A1;
ep2 = -Ex2./L2;
sig2 = -Lo2./A2;
ep3 = -Ex3./L3;
sig3 = -Lo3./A3;
ep4 = -Ex4./L4;
sig4 = -Lo4./A4;
ep5 = -Ex5./L5;
sig5 = -Lo5./A5;
ep6 = -Ex6./L6;
sig6 = -Lo6./A6;
ep7 = -Ex7./L7;
sig7 = -Lo7./A7;
ep8 = -Ex8./L8;
sig8 = -Lo8./A8;
ep9 = -Ex9./L9;
sig9 = -Lo9./A9;
ep10 = -Ex10./L10;
sig10 = -Lo10./A10;
ep11 = -Ex11./L11;
sig11 = -Lo11./A11;

% Elastic Modulus and Max Tensile Strength Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
epmin1 = 0.02;
epmax1 = 0.04;
epmin2 = 0.01;
epmax2 = 0.025;

sigma1 = [sig1(1:lim1) sig2(1:lim1) sig3(1:lim1) sig4(1:lim1) sig5(1:lim1)];

```

```

sigma2      =      [sig6(1:lim2)      sig7(1:lim2)      sig8(1:lim2)      sig9(1:lim2)
sig10(1:lim2)...
      sig11(1:lim2)];

epsilon1 = [ep1(1:lim1) ep2(1:lim1) ep3(1:lim1) ep4(1:lim1) ep5(1:lim1)];
epsilon2 = [ep6(1:lim2) ep7(1:lim2) ep8(1:lim2) ep9(1:lim2) ep10(1:lim2)
ep11(1:lim2)];

for i = 1:5
    E1(i) = YoungsCalc(epsilon1(:,i),sigma1(:,i),epmin1,epmax1);
end
for i = 1:6
    E2(i) = YoungsCalc(epsilon2(:,i),sigma2(:,i),epmin2,epmax2);
end

E1_ave = sum(E1)/length(E1)
E1_SDev = std(E1)
Error_E1 = E1_SDev/E1_ave
E2_ave = sum(E2)/length(E2)
E2_SDev = std(E2)
Error_E2 = E2_SDev/E2_ave

SigMax1 = [max(sig1) max(sig2) max(sig3) max(sig4) max(sig5)];
SigMax2 = [max(sig6) max(sig7) max(sig8) max(sig9) max(sig10) max(sig11)];

SigmaMax1_ave = sum(SigMax1)/length(SigMax1)
SigmaMax1_SDev = std(SigMax1)
Error_SigmaMax1 = SigmaMax1_SDev/SigmaMax1_ave
SigmaMax2_ave = sum(SigMax2)/length(SigMax2)
SigmaMax2_SDev = std(SigMax2)
Error_SigmaMax2 = SigmaMax2_SDev/SigmaMax2_ave

% Density Calc
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
V6 = A6*L6;
V7 = A7*L7;
V9 = A9*L9;
V10 = A10*L10;
V11 = A11*L11;

rhoall = [.023/V6 .0225/V7 .0235/V9 0.023/V10 0.0235/V11];
rho = sum(rhoall)/length(rhoall)

% Plot(s)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
plot(ep1,sig1,ep2,sig2,ep3,sig3,ep4,sig4,ep5,sig5)
xlabel('strain (in/in)')
ylabel('stress (psi)')
title('GP LAST-A-FOAM FR 6710 ASTM D1621 -- Perpendicular to Rise')
legend('specimen1','specimen2','specimen3','specimen4','specimen5')

figure(2)
plot(ep6,sig6,ep7,sig7,ep8,sig8,ep9,sig9,ep10,sig10,ep11,sig11)
xlabel('strain (in/in)')

```

```

ylabel('stress (psi)')
title('GP LAST-A-FOAM FR 6710 ASTM D1621 -- Parallel to Rise')
legend('specimen1','specimen2','specimen3','specimen4','specimen5','specimen6
')

figure(3)
plot(Ex1,Lo1,Ex2,Lo2,Ex3,Lo3,Ex4,Lo4,Ex5,Lo5)
xlabel('Extension (in)')
ylabel('Load (lbf)')
title('GP LAST-A-FOAM FR 6710 ASTM D1621 -- Perpendicular to Rise')
legend('specimen1','specimen2','specimen3','specimen4','specimen5')

figure(4)
plot(Ex6,Lo6,Ex7,Lo7,Ex8,Lo8,Ex9,Lo9,Ex10,Lo10,Ex11,Lo11)
xlabel('Extension (in)')
ylabel('Load (lbf)')
title('GP LAST-A-FOAM FR 6710 ASTM D1621 -- Parallel to Rise')
legend('specimen1','specimen2','specimen3','specimen4','specimen5','specimen6
')

%FEA CURVES
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
SPEC1X = smooth(ep2,100);
SPEC1Y = smooth(sig2,100);
SPEC2X = smooth(ep10,100);
SPEC2Y = smooth(sig10,100);
LC22X = smooth(-Ex2,100);
LC22Y = smooth(-Lo2,100);
LC11X = smooth(-Ex10,100);
LC11Y = smooth(-Lo10,100);

```

A.15 DAD Key Mechanical Characteristics MATLAB Code

A.15.1 Tensile Test Calculations

```
%                               Unidirectional Fiberglass (DAD Keys)                               %
%                               ASTM D3039 Tensile Test Calculations                             %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;
clc;

% Read in Raw Data from Excel and Parse
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
L1 = csvread('Long_1.csv',2,1);
Ex1 = L1(:,1);
Lo1 = smooth(L1(:,2));
L2 = csvread('Long_2.csv',2,1);
Ex2 = L2(:,1);
Lo2 = smooth(L2(:,2));
L3 = csvread('Long_3.csv',2,1);
Ex3 = L3(:,1);
Lo3 = smooth(L3(:,2));
L4 = csvread('Long_4.csv',2,1);
Ex4 = L4(:,1);
Lo4 = smooth(L4(:,2));
L5 = csvread('Long_5.csv',2,1);
Ex5 = L5(:,1);
Lo5 = smooth(L5(:,2));
L6 = csvread('Long_6.csv',2,1);
Ex6 = L6(:,1);
Lo6 = smooth(L6(:,2));
T1 = csvread('Trans_1.csv',2,1);
Ex7 = T1(:,1);
Lo7 = smooth(T1(:,2));
T2 = csvread('Trans_2.csv',2,1);
Ex8 = T2(:,1);
Lo8 = smooth(T2(:,2));
T3 = csvread('Trans_3.csv',2,1);
Ex9 = T3(:,1);
Lo9 = smooth(T3(:,2));
T4 = csvread('Trans_4.csv',2,1);
Ex10 = T4(:,1);
Lo10 = smooth(T4(:,2));
T5 = csvread('Trans_5.csv',2,1);
Ex11 = T5(:,1);
Lo11 = smooth(T5(:,2));
T6 = csvread('Trans_6.csv',2,1);
Ex12 = T6(:,1);
Lo12 = smooth(T6(:,2));
T7 = csvread('Trans_7.csv',2,1);
Ex13 = T7(:,1);
Lo13 = smooth(T7(:,2));

lim1 = length(L4);
```

```

limt = length(T3);

% Specimen Dimensions [Length , Cross Sectional Area] (inches)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Le1 = 8.994;
A1 = 0.011 * 1.001;
Le2 = 8.995;
A2 = 0.012 * .998;
Le3 = 8.992;
A3 = 0.012 * 1.002;
Le4 = 8.991;
A4 = 0.013 * .996;
Le5 = 8.995;
A5 = 0.012 * 1.003;
Le6 = 8.991;
A6 = 0.013 * 1.001;
Le7 = 8.995;
A7 = 0.011 * 1.009;
Le8 = 8.997;
A8 = 0.021 * 1.003;
Le9 = 8.999;
A9 = 0.011 * 1.006;
Le10 = 8.998;
A10 = 0.012 * 1.005;
Le11 = 8.997;
A11 = 0.010 * 1.001;
Le12 = 8.996;
A12 = 0.014 * .998;
Le13 = 8.996;
A13 = 0.013 * 1.002;

% Stress and Strain Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ep1 = smooth(Ex1./Le1);
sig1 = Lo1./A1;
ep2 = smooth(Ex2./Le2);
sig2 = Lo2./A2;
ep3 = smooth(Ex3./Le3);
sig3 = Lo3./A3;
ep4 = smooth(Ex4./Le4);
sig4 = Lo4./A4;
ep5 = smooth(Ex5./Le5);
sig5 = Lo5./A5;
ep6 = smooth(Ex6./Le6);
sig6 = Lo6./A6;
ep7 = smooth(Ex7./Le7,100);
sig7 = smooth(Lo7./A7,100);
ep8 = smooth(Ex8./Le8,100);
sig8 = smooth(Lo8./A8,100);
ep9 = smooth(Ex9./Le9,100);
sig9 = smooth(Lo9./A9,100);
ep10 = smooth(Ex10./Le10,100);
sig10 = smooth(Lo10./A10,100);
ep11 = smooth(Ex11./Le11,100);
sig11 = smooth(Lo11./A11,100);
ep12 = smooth(Ex12./Le12,100);

```

```

sig12 = smooth(Lo12./A12,100);
ep13 = smooth(Ex13./Le13,100);
sig13 = smooth(Lo13./A13,100);

% Elastic Modulus and Max Tensile Strength Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
epmint = 5e-4;
epmaxt = 1.55e-3;

epminl = 1e-3;
epmaxl = 5e-3;

signal = [sig1(1:liml) sig2(1:liml) sig3(1:liml) sig4(1:liml)...
          sig5(1:liml) sig6(1:liml)];
sigmat = [sig7(1:limt) sig8(1:limt) sig9(1:limt) sig10(1:limt)...
          sig11(1:limt) sig12(1:limt) sig13(1:limt)];

epsilon1 = [ep1(1:liml) ep2(1:liml) ep3(1:liml) ep4(1:liml) ep5(1:liml)...
            ep6(1:liml)];
epsilont = [ep7(1:limt) ep8(1:limt) ep9(1:limt) ep10(1:limt) ep11(1:limt)...
            ep12(1:limt) ep13(1:limt)];

for i = 1:6
    El(i) = YoungsCalc(epsilon1(:,i),signal(:,i),epminl,epmaxl);
end
for i = 1:7
    Et(i) = YoungsCalc(epsilont(:,i),sigmat(:,i),epmint,epmaxt);
end

El_ave = sum(El)/length(El)
El_SDev = std(El)
Error_El = El_SDev/El_ave
Et_ave = sum(Et)/length(Et)
Et_SDev = std(Et)
Error_Et = Et_SDev/Et_ave

SigmaMax = [max(sig1) max(sig2) max(sig3) max(sig4) max(sig5) max(sig6)...
            max(sig7) max(sig8) max(sig9) max(sig10) max(sig11) max(sig12)...
            max(sig13)];

TSigmat_ave = sum(SigmaMax(7:13))/length(SigmaMax(7:13))
TSigmat_SDev = std(SigmaMax(7:13))
Error_TSigmat = TSigmat_SDev/TSigmat_ave
TSignal_ave = sum(SigmaMax(1:6))/length(SigmaMax(1:6))
TSignal_SDev = std(SigmaMax(1:6))
Error_TSignal = TSignal_SDev/TSigmat_ave

% Remove Data after Failure
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ep1 = ep1(1:find(sig1 == max(sig1)));
Sig1 = sig1(1:find(sig1 == max(sig1)));
Ep2 = ep2(1:find(sig2 == max(sig2)));
Sig2 = sig2(1:find(sig2 == max(sig2)));
Ep3 = ep3(1:find(sig3 == max(sig3)));
Sig3 = sig3(1:find(sig3 == max(sig3)));

```

```

Ep4 = ep4(1:find(sig4 == max(sig4)));
Sig4 = sig4(1:find(sig4 == max(sig4)));
Ep5 = ep5(1:find(sig5 == max(sig5)));
Sig5 = sig5(1:find(sig5 == max(sig5)));
Ep6 = ep6(1:find(sig6 == max(sig6)));
Sig6 = sig6(1:find(sig6 == max(sig6)));
Ep7 = ep7(1:find(sig7 == max(sig7)));
Sig7 = sig7(1:find(sig7 == max(sig7)));
Ep8 = ep8(1:find(sig8 == max(sig8)));
Sig8 = sig8(1:find(sig8 == max(sig8)));
Ep9 = ep9(1:find(sig9 == max(sig9)));
Sig9 = sig9(1:find(sig9 == max(sig9)));
Ep10 = ep10(1:find(sig10 == max(sig10)));
Sig10 = sig10(1:find(sig10 == max(sig10)));
Ep11 = ep11(1:find(sig11 == max(sig11)));
Sig11 = sig11(1:find(sig11 == max(sig11)));
Ep12 = ep12(1:find(sig12 == max(sig12)));
Sig12 = sig12(1:find(sig12 == max(sig12)));
Ep13 = ep13(1:find(sig13 == max(sig13)));
Sig13 = sig13(1:find(sig13 == max(sig13)));

% Plot(s)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
plot(Ep1, Sig1, Ep2, Sig2, Ep3, Sig3, Ep4, Sig4, Ep5, Sig5, Ep6, Sig6)
xlabel('strain (in/in)')
ylabel('stress (psi)')
title('Shear Key Longitudinal Direction ASTM D3039 Test Results')
figure(2)
plot(Ep7, Sig7, Ep8, Sig8, Ep9, Sig9, Ep10, Sig10, Ep11, Sig11, Ep12, Sig12, Ep13, Sig13)
xlabel('strain (in/in)')
ylabel('stress (psi)')
title('Shear Key Transverse Direction ASTM D3039 Test Results')

```