THE EFFECTIVENESS OF DAMAGE ARRESTMENT DEVICES IN DELAYING FASTENER-HOLE INTERACTION
FAILURES IN CARBON FIBER POLYURETHANE FOAM COMPOSITE SANDWICH PANELS
SUBJECTED TO STATIC AND DYNAMIC LOADING UNDER INCREASED TEMPERATURES

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Dominic Enea Surano
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TITLE: The Effectiveness of Damage Arrestment Devices in Delaying Fastener-Hole
Interaction Failures in Carbon Fiber Polyurethane Foam Composite Sandwich
Panels Subjected to Static and Dynamic Loading Under Increased Temperatures

AUTHOR: Dominic Enea Surano

DATE SUBMITTED: December 2010

COMMITTEE CHAIR: Dr. Fayasal Kolkailah, Ph. D., P.E.

COMMITTEE MEMBER: Dr. Elthary Elghandour, Ph.D.

COMMITTEE MEMBER: Dr. Eric A. Mehiel, Ph.D.

COMMITTEE MEMBER: Dr. Eric Kasper Ph.D., P.E.

COMMITTEE MEMBER: Dr. Susan C. Opava, Ph.D.

ABSTRACT

The Effectiveness of Damage Arrestment Devices in Delaying Fastener-Hole
Interaction Failures in Carbon Fiber Polyurethane Foam Composite Sandwich Panels
Subjected to Static and Dynamic Loading Under Increased Temperatures
Dominic Enea Surano

A study was conducted to investigate simple, cost-effective manufacturing techniques to delay skin-core delamination, micro-buckling and bearing stress failures resulting from fastener-hole interactions. Composite sandwich panels, with and without damage arrestment devices (DADs), were subjected to monotonic compression at a rate of 5mm per second, and compression-compression fatigue at 50% yield at an amplitude of 65%, under temperatures of 75, 100, 125, 150, 175, and 200 °F.

The sandwiches tested were composed of two-layer cross-weave carbon fiber facesheets, a polyurethane foam core, and an epoxy film adhesive to join the two materials. The most successful method to delay the aforementioned failures involved milling rectangular slots in the foam core perpendicular to the holes and adding three additional layers of carbon fiber cross-weave. For the monotonic cases, the ultimate load increases were 97, 87, 100, 131, 96, and 119% for each of the respective temperatures listed above with a negligible weight increase. For the fatigue cases, the number of cycles for each test case was nearly identical. This still represents a large improvement because the yield used in the loading condition for the specimens with DADs was 97% greater than the specimens without DADs.

The experimental results were compared with a finite element model (FEM) built in Abaqus/CAE. The numeric and experimental results showed a strong correlation. All test specimens were manufactured and tested in the California Polytechnic State University Aerospace/Composites Laboratory.

Keywords: Sandwich Composites, Skin-Core Delamination, Micro-Buckling, Bearing Stress, Fasteners, Rivets, Bolts, Foam-Core, Crack Propagation, Fracture Mechanics, Compression, Compression-Compression Fatigue , Damage Arrestment, Temperature, Thermal Environment

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NOMENCLATURE

A	Amplitude
A	Extensional stiffness matrix
E	Elastic Modulus (lbs/in ²)
f	Frequency (Hz)
h	Height (in)
K	Stress concentration factor
k	Stiffness (lbs/in)
N	Force/load (lbs)
P	Force/load (lbs)
Q	Reduced stiffness matrix
R ²	Coefficient of determination
t	Thickness (in)
V	Volumetric fraction
v	Volume (in ³ or cm ³)
W	Weight fraction
w	Weight (oz or g)
X	Coordinate Direction
Y	Coordinate Direction
Z	Coordinate Direction
ε	Strain
ρ	Density (g/cm ³)
σ	Stress (lbs/in ²)
u	Poisson's Ratio

Subscript

c	Composite
cr	Critical
crit	Critical
cu	Longitudinal strength of composite
e _f	Matrix stress at fiber fracture strain
f	Fiber
fu	Ultimate strength of fiber
i	Matrix row
j	Matrix column
k	Layer of laminate from center
m	Matrix
sb	Shear Stress
tb	Tensile Stress
y	Yield
ult	Ultimate
1	Longitudinal direction
2	Axial direction

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1 INTRODUCTION

Composite materials are composed of two or more materials combined on a macroscopic scale to form a useful material that exhibits properties unavailable from the individual constituent materials. The component materials fall into one of two classifications, matrix and reinforcement—at least one portion of each type is required. The matrix material surrounds and supports the reinforcement material by maintaining its relative position—its characteristics usually include high shear strength, low density, and easy of fabrication. The matrix is usually made of a thermoplastic such as nylon, polycarbonate, or polyester, or a thermoset polymer such as epoxy or polyurethane. Examples of matrix based composites include:

- ✓ Metal Matrix Composites (MMC) which use metal as a matrix and ceramic or stronger metal as a reinforcement;
- ✓ Ceramic Matrix Composites (CMC) which use ceramics as both the matrix and reinforcements;
- ✓ Polymer Matrix Composites (PMS) which use polymers as the primary matrix ingredient and glass, carbon, steel, or Kevlar as the reinforcement.

The reinforcements (typically fibers) maintain the structural rigidity of the material primarily in tension—its characteristics usually include brittleness, high strength, high stiffness, and low density. The wide variety of matrix and reinforcement materials allows the material designer to choose an optimum combination for a specified loading. Examples of fiber constituent materials include glass, carbon (graphite), aramid (Kevlar), boron, alumina, and metal wires.

Examples of reinforcement based composites include:

- ✓ Particulate Composites which can be reinforced by particles like carbon nano tubes;
- ✓ Fibrous Composites which have continuous members such as unidirectional or bidirectional weaves, or discontinuous members such as chop strand;
- ✓ Laminate Composites, a multilayer material with several layers positioned at different fiber orientations.

Composite materials, if designed well, can exhibit the best qualities of their components or constituents and often some qualities that neither constituents possesses including but not limited to improved strength, stiffness, corrosion resistance, wear resistance, attractiveness, reduced weight, extended fatigue life, improved temperature-dependent behavior, plus better thermal insulation, thermal conductivity, and acoustical insulation. Additional advantages include low cost assembly, freedom of design, decreased maintenance cost, and high material utilization factors. Disadvantages include the decrease in bearing strength and impact resistance, the ability to health monitor, increased compression loads, potential for moisture damage, and increased cost.

1.1 INTRODUCTION TO MANUFACTURING TECHNIQUES

Composites can be manufactured in a number of ways depending on their specific application. Choosing a type of composite manufacturing consist of many different factors including part size and shape, schedule, cost, and experience. Factors that affect the quality of part processes include moisture, temperature, the cure cycle (including ramp up and down, temperature duration, and vacuum pressure), surface preparation and condition, and material condition. Each discussed layup technique below seeks to maximize the quality of parts for specific applications by minimizing the contribution of adverse factors.

1.1.1 WET LAYUP

For quick, low fidelity, low strength parts, a “wet” hand layup can be performed. This includes taking dry fibers (reinforcement), laying them on a plastic sheet, painting them with epoxy (matrix), sealing the plastic sheet with an adhesive, vacuuming the air out, and applying weight. “Wet” layups are typically used to make flat plates, but can also be used with molds, as long as a thin shell¹ type part is being manufactured.

¹ A shell type element is characterized as having a much smaller thickness than it’s width or length. Typical applications of shells include the body portions of racecars, the skin of a composite fuselage, and the skin of composite sandwich panels.

1.1.2 PULTRUSION

Alternatively, composites can be fabricated using a pultrusion method which pulls resin impregnated fibers² through a mandrel in a continuous, automated process. This method allows extremely high output while reducing scrap materials. Unfortunately, the equipment is typically expensive, hence, this method is only used by some of the larger aerospace companies.

1.1.3 RESIN-TRANSFER MOLDING (RTM)

Resin-transfer molding (RTM) is a process that uses dry fibers or textile sheets and resin sheets that are put in a mold or tool and then heated and compressed together to form the desired part. Instead of using resin sheets, the resin is often injected from the outside into the tool. After closing the mold, the tool is heated, so that the fibers are fully impregnated. A vent in the mold allows a simultaneous escape of air. The reactivity of the resin is set so that networking only begins when the mold is completely filled. After curing the resin, the form is opened, and the finished part can be removed. The time for one cycle depends on the geometry and the resin-hardener mixture used and varies between fifteen minutes and one hour. It is also possible to integrate metallic load introduction elements into the fibers before curing. An important factor in the process is the injection velocity and the resulting flow front velocity of the resin, which greatly determines the later quality of the part. If the flow in front progresses too fast, air bubbles can be trapped inside the resin or certain areas of the part can stay dry. If the velocity is too low, the chemical reaction in the resin starts before the whole part has been injected with resin. The injection point has to be chosen carefully in order to guarantee equal flow to every area of the part, especially stiffeners to be filled with resin. Sometimes the use of a computer program is needed for optimal placement of the injection point.

² Resin impregnated composites (or pre-preg) comes with the fibers already covered in resin and typically have to remain below room temperature until just before use.

1.1.4 REACTION INJECTION MOLDING

In reaction injection molding, two different types of resin are used to take advantage of their material characteristics and cure cycles. This manufacturing method is a great example of how design engineers and materials engineers have optimized material composition for specific applications.

1.1.5 FILAMENT WINDING

Filament winding consists of passing a fiber through liquid resin, or in some cases, combining fibers with strings of epoxy and then wrapping them in different directions onto the mandrel. “Wet” winding combines the resin and fibers separately and is usually slightly less expensive. Subsequently, the whole assemble is cured and the mandrel is removed. The mandrel can either be a reusable aluminum profile or sand, which has to be removed using a high pressure water hose. Another possibility is the automated manufacturing of composite structures by robot assisted braiding, or pre-preg winding which uses fibers already impregnated with resin before winding on a mandrel. In this technique, up to 216 carbon fiber yarns are placed around a core to form a net shaped fiber structure with optimized reinforcing fiber geometry. By appropriate impregnation processes, a cost-effective manufacturing of high performance composite structures is possible. An example of winding is shown below in Figure 1.

Figure 1: Filament winding around a mandrel to make a woven carbon tube.⁽¹⁾

1.1.6 VACUUM RESIN INFUSION (VRI)

Vacuum resin infusion places the composite part in a vacuum bag and sucks resin through a small straw onto a wet part in the shear direction. To perform this layup, the composite constituents are cut down to size, covered in peel ply (a thin strong material that allows the removal of the bag and all other non-desired material from the composite post cure), flow media (a breather that prevents the vacuum bag from completely sticking to the composite), and the vacuum bag. A spiral piece of tubing is placed on one edge of the composite, connected to a t-connector, and finally a piece of tubing that goes through the vacuum bag. An additional tube is connected to the vacuum and the other end of the bag with cotton running along the edge to soak up some of the flow. A cup is then filled with resin, the vacuum is turned on, and the resin is sucked from one end to the other, equally wetting the part. The piece is then left to cure for 16 hours. Weight can also be added to the part to help prevent non-favorable characteristics such as skin-core delamination. Figure 2 shows a picture and schematic of a completed VRI layup.

Figure 2: VRI layout. The left tube connects to the cup and the right tube connects to the vacuum. The green material is the flow media, the white material on the right is the cotton, and the yellow tape is the adhesive that seals the vacuum bag.⁽¹⁾⁽²⁾

VRI is extremely advantageous for evenly distributing resin through the part but is difficult to take apart after cure.

1.2 INTRODUCTION TO COMPOSITE SANDWICH PANELS

Composite sandwich panels are made up of two major elements, the skin (or facesheet) and the core. Sandwich panel skins are the outer layers and are constructed out of a variety of materials. Wood, aluminum, and plastics have been used in the past, but more recently, advanced composite fibers and resins have been adopted.

A sandwich panel exhibits characteristics similar to an I-beam, but with the flanges and web extended in all directions. The skins of a sandwich panel correlate with the flanges of the I-Beam, and the sandwich core is similar to the I-beam web. However, because it is a panel, there is bending strength in all planes, not just the traditional bending plane. When a sandwich panel is bent, one skin experiences tension, and the other skin experiences compression. This is where the majority of strength is created in a sandwich structure. The core functions to hold the skins together, so the panel doesn't buckle, snap, deform, or break. The core keeps the skins fixed and relative to each other.

The main stress the core experiences is "shear stress", as the skins attempt to slide past the foam or pop off of it. The stiffness of the core is determined by the core material "shear properties". The stiffness of the panel is mainly determined by the core material properties and the thickness of the core.

Figure 3 shows some cross sections of some of the sandwich composites used in industry today.

Figure 3: Cross-sections of various composite sandwich materials. Top Left: Nomex honeycomb core with carbon fiber facesheets. Top Right: Aluminum honeycomb core with carbon fiber facesheets. Bottom Left: Analytic model of composite weave. Bottom Middle: Foam core with carbon facesheets, Bottom Right: Fiberglass.

The combination and thickness of skin and core used depends on the specific application.

1.2.1 SANDWICH COMPOSITE CORE

Flexible cores that bend easily are known to have a "low shear modulus" while very stiff cores have a "high shear modulus". If, for example, a glued paperback book is bent enough, eventually the side in tension will crack and fail. The top layer of paper will tear when the "tensile strength" of the paper is exceeded by the bending force. A solution to this would be to bond another material to the surface, creating a skin with higher tensile and compressive strength. This skin would work in conjunction with the core. However, this approach usually leads to skin-core delamination.

Examples of composite cores include⁽³⁾:

- ✓ Polyurethane (PUR), a thermosetting material; widely used;
- ✓ Polyisocyanurate (PIR), a thermosetting material;
- ✓ Phenolic foam (PF), a thermosetting material; not yet widely used;
- ✓ Polystyrene (expanded, EPS and extruded, XPS), a thermoplastic material ;
- ✓ Rohacell foam, which acts like a foam filled web core.

1.2.2 SANDWICH COMPOSITE SKIN

If a sandwich panel is bent downward, the part of the sandwich above the neutral axis will stretch, and the part below the neutral axis will compress. Although the skin and core stretch and compress evenly at the location of the bond, the core and the skins have different material properties, and will in turn act differently to this bending. Additionally, because most composite materials are anisotropic, that is, they have different material properties in tension and compression, one side is usually prone to fail before the other. This allows failures to be predictable, at least in cause.

1.3 ADVANTAGES, DISADVANTAGES, AND APPLICATIONS OF SANDWICH COMPOSITE PANELS

The composite panel structure is one of the most promising in the design of lightweight structural design. Much like the concept of using stiffeners like stringers or ribs on an airplane, a sandwich panel incorporates separation of tasks. Take the example of a wing box of a typical aircraft. The flanges carry bending and uniaxial loads, whereas the skin carries the shear. In a composite sandwich structure, the stiff skins carry the load and the core carries the shear stress. Sandwich construction results in lower lateral deformations, higher buckling resistance (by means of increase the bending moment of inertia of a structure ⁽⁴⁾), higher natural frequencies, and lower weight.⁽³⁾

As a result of these unique properties, tailored sandwich composites are found in nearly all disciplines of engineering. Sandwich composite panels have been substantially utilized in the automotive, civil engineering, marine, and aerospace industries due to their high stiffness and strength to low weight ratio, relatively low construction/maintenance costs, electromagnetic shielding, recyclability, and high energy absorption qualities.

Figure 4 shows some of the different types of sandwich composites including the (a) foam core, (b) honeycomb core, (c) web core (usually includes plies cured perpendicular to one another), and (d) truss core (usually includes plies cured at 45° from one another). In all cases, the primary loading, both in-plane and bending, are carried by the skin, while the core resists transverse shear loads, and keeps the faces in place.⁽³⁾ However, in web-core and truss-core construction, a portion of the in-plane bending loads are also carried by the core elements.⁽³⁾

Figure 4: Different geometric configurations of sandwich composites.⁽³⁾

In the transportation industry, sandwich composites are used in the construction of non-critical components such as doors and trailer floors, saving weight and increasing fuel efficiency. Current sandwich construction is typically for vehicles is currently limited to trailers or high performance race cars

due to their high cost of maintainability, but many car companies are now investing into research and development for lighter and stronger alternatives to plastics and aluminum.

In the nautical industry, sandwich composites are used in the design of cruise ship balconies, bulk heads⁽³⁾ in high speed ferries, doors and decks, motor mounts, pressure hulls of submarine structures, and propellers.⁽⁵⁾ Sandwich composites in the marine industry are typically manufactured out of laminated polymers, glass fiber reinforced polymers, or carbon fiber reinforced polymers.⁽⁵⁾ The cores are typically constructed from balsa wood or polyethylene, polyurethane, or polyvinylchloride foams.⁽⁵⁾

Low structural weight, cost-effective construction and maintenance, low acoustic, electromagnetic, and thermal signatures all prove to be appealing when dealing with composite materials. In addition, sandwich composite panels are inherently known to be blast-proof, signifying the ability for the material to better withstand localized impact and indentation forces than their conventional counterparts. Thus, sandwich composite panels have been historically used for underwater mine countermeasure ships. The unintentional overdesign of such vessels under every day usage eventually was optimized for a wider array of use, from high speed ferries to naval weapon crafts. Eventually, absolute weight reduction became a key driver in vessel design, thus the overdesign trend shifted more towards narrow design limits.

In the aircraft industry, overhead storage bins, passenger cabin class dividers, galleys and lavatories, insulation, control surfaces (such as ailerons)—etc., generally modules that do not require the support of primary loads—can all be manufactured from sandwich composites. In the spacecraft industry, structural sandwich elements with metal or fiber reinforced plastic facesheets and polymeric foam, nomex, or aluminum cores are used extensively for lightweight structures.⁽⁶⁾ Although many of the aforementioned components do not serve a primary structural purpose, they help decrease the weight and cost of the vehicle and still have to occasionally carry extremely large loads. Sandwich composites can also be used in primary structural roles in aircraft—some of the advantages include light-weight design, efficient energy absorption, increased mechanical damping and good thermal and acoustic insulation (depending on the foam).⁽⁷⁾⁽⁸⁾⁽³⁾ To get an idea of the widespread use of sandwich composites, Table 1 lists various Boeing aircraft with their percent use of honeycomb sandwiches.

Table 1: Use of sandwich construction in Boeing aircraft.

Boeing Aircraft	% Wetted Surface
707	8
727	18
737	26
747	36
757/767	46

Unfortunately, sandwich panels are weak at bearing concentrated loads, making them difficult to join.⁽⁸⁾ Especially difficult is the task of joining sandwich composites to one another. Although adhesive joints are the most beneficial method because they reduce part count, lower cost, and distribute load paths, mechanical fastening is preferred because of repeatability of loads, good resistance to environmental effects, ease of inspection and disassembly, and high reliability.⁽⁸⁾ Sandwich panels are also susceptible to in-plane shearing, core compression failure, indentation of facesheets from impact, global buckling, wrinkling instability, and facesheet delamination.⁽⁵⁾

Composite sandwiches are not always one piece. Thus, in many instances, they must be fastened together with bolts, rivets, or another type of fastener. Skin core interactions with fasteners are extremely unpredictable especially because composite sandwich panels are less stiff than metal fasteners. Although sandwich composites have high specific stiffness and strength values, they have weaknesses related to jointing. The core is typically lightweight, low density, and soft—it cannot directly support mechanical joints such as bolts and rivets. Thus, it's necessary to reinforce the core with some sort of material or potted insert to sustain the fasteners and prevent tear through.⁽⁴⁾

1.4 FAILURE MODES

One of the most important aspects of composite research are the various types of failure that can occur. A combination of different loads, manufacturing defects, and layup techniques lead composites to fail in a variety of ways, many of which are unpredictable. Being able to predict, and analytically or numerically model such failure is key to safe design.

1.4.1 IN GENERAL

There are a variety of modes (ways) that a designed part can fail. Knowing and or predicting the most likely mode is imperative to developing an accurate Finite Element Model (FEM) and appropriate

test procedures to determine material allowables. The modes of failure can be classified into four main areas.

The first major area is failures induced by material strength. These are the most common types of failures experienced, and include:

- ✓ Ductile failures due to excessive plastic strain (primarily a concern for metallic based parts);
- ✓ Brittle failures due to fracture or snapping in tension (primarily a concern in composite, especially fiber composite parts);
- ✓ Temperature failures, which can result in melting or severely reducing mechanical strength which can lead to other failure modes;
- ✓ Tension, compression, shearing, bearing, or bending beyond the allowable range allowed by the material properties;
- ✓ Tearout resulting from excessive loads on lugs or fastener holes;
- ✓ Surface failures occurring from bearing stress, adverse contact, or fastener interference fits;
- ✓ Stress concentrations caused by notches or holes.

Typically, the best ways to prevent or delay failures caused by material strength is to increase the local strength by reinforcing the part, decrease the loading on the part by tracing the load path of the assembly and constraining its operating limits, or choosing a different material.

The second type of failure mode is due to structural instability. This failure mode can be excited by the following loading conditions:

- ✓ Bucking or collapse due to lateral bending or shear;
- ✓ Bending caused by plastic collapse or rupture in bending;
- ✓ Torsion due to rupture;
- ✓ Crushing or crippling due to local wrinkling;

To prevent such failures, the load path is typically redirected or reinforced in certain direction to decrease the chance of instability. In many instances, parts are shortened to reduce total potential displacement which can cause instability.

The fourth type of failure mode is failure due to loss of function which is usually caused by excessive deformation. In a complicated assembly such as a plane or car, parts that deform too much can intersect other parts, endangering the basic functions of the entire system. It's always necessary to check not only that the parts are strong enough, but that when assembled, the experienced loads will not cause unintended contacts or collisions. This has notoriously been a difficult problem in the design of turbine engines.

The fifth and final type of failure mode is fatigue. Fatigue loading typically causes crack growth (which leads to a variety of other failure modes), stress corrosion and cracking (which happen over a long period of time), and fretting. Fatigue failures are typically not preventable (unless the loading maintains levels below the endurance amplitude), but can be delayed primarily by modifying the geometry of the part in question.

The research presented here deals with composite failure modes specifically including the following modes of failure:

- ✓ Material Strength: brittle and temperature failures;
- ✓ Structural Instability: buckling / collapse;
- ✓ Fatigue: crack growth.

The research aims to prevent and delay such failures by modifying geometric properties of the studied part.

1.4.2 IN SANDWICH COMPOSITES

Because the skin and core in sandwich composite panels are made from different materials and thus exhibit unique material characteristics, they deform at different rates. When a specimen is placed in shear, bending, fixed boundary condition compression, or Euler buckling, the skin has a propensity to break continuum with the foam causing delamination. The Euler buckling delamination failure mode is shown in Figure 5.

Figure 5: Delamination caused by Euler buckling.

When placed in pin-pin compression, rather than the skin delaminating from the foam core, the individual fibers buckle causing discontinuities in the skin, drastically reducing the strength of the part. This failure mode is shown in Figure 6.

Figure 6: Micro-buckling of individual fibers caused by pin-pin compression.

It is important to note that this is only one potential mode of failure for pin-pin compression. Tension pull-out, shearing, bearing, and fracture can all happen as a result of pin-pin tension or compression depicts a summary of these failure modes.

Figure 7: Top: Failure modes from pin-pin compression (left to right): tension, shearing, and bearing; (Bottom) Failure modes from pin-pin tension (left to right): crack propagation, shearing, bearing, tearing, fracture.⁽⁹⁾

Although it's normally possible to know the specific failure mode a part will experience (or the potential combination of failure modes), it is extremely difficult to estimate when such a failure will occur. This is primarily due to manufacturing defects, flaws in the creation and processing of constituent materials, non-favorable thermal environments, and other environmental effects such as corrosion and moisture. The more complicated the loading, the more difficult prediction becomes—vibration and fatigue test cases normally have a ultimate load standard deviation of 60% whereas compression or tension test cases fall between 5% and 10%.

More specifically, sandwich composites can experience all of the failure modes shown below in Figure 8. This research primarily deals with intra cell buckling (also called micro-buckling), skin wrinkling, and panel buckling.

Figure 8: Failure modes of sandwich composites.

1.5 REVIEW OF PAPERS AND PREVIOUS WORK

Although sandwich composite fastener research is relatively new, many researchers have already made significant contributions to the field. This section will review the scope of their research, its potential applications, any novel methods developed to either analyze sandwich composites or prevent or delay a specific failure, and a description of their experimental setups.

1.5.1 COMPOSITE DOUBLE-LAP JOINT WITH STAGGERED BOLTS—HANAUSKA, KRADINOV, AND. MADENCI⁽¹⁰⁾

The authors addressed the problem of composite fasteners by looking at the stress concentrations caused by staggered bolts and measuring the strain values around the holes. The goal was to formulate an analytic method and finite element model (FEM) to predict the load distribution, stress state, and damage around multiple fasteners. Their method showed contact stresses around the bolt holes while accounting for interaction of the bolts. They then examined the damage with x-rays.

Their specimens were made of carbon fiber/epoxy quasi-isotropic laminates in a stacking sequence of $[+45 -45 0 90]_{2s}$ and tested in uniaxial tension. Figure 9 shows the geometry and loading of the tested specimens.

Figure 9: Geometry and loading of lap joint with staggered bolts.⁽¹⁰⁾

The results indicate the presence of expected symmetry and the holes closer to the loaded edge carry the majority of the load. One of the potential sources of error examined was the hole/bolt mismatch—the clearance between one hole and its bolt was greater than another. As their applied load increased, the holes with less clearance started carrying the load first, and as the holes became damaged and deformed, the other holes came into contact and started carrying some of the applied load.

The comparison of the experimental strain measurements with the analytical and FEM measurements matched well, establishing the accuracy of the method. This research did not consider thermal effects or foam cores.

1.5.2 DESIGN AND ANALYSIS OF MECHANICALLY FASTENED COMPOSITE JOINTS AND REPAIRS—ZHANG⁽¹¹⁾

The author utilized boundary element models (BEMs) as a means to analyze mechanically bolted composite joints and repairs. The fasteners were modeled as 1-D springs governed by linear relationships between fastener forces and displacements to get the resultant contact forces for all involved fasteners. The numerical predictions agreed with experimental results.

Mechanical fasteners provide the primary means to transfer load to composite components and are used for bolted repairs of damaged or cracked aircraft structures. Thus, accurate knowledge of stress is imperative to efficient design. This research is unique because previous authors had not used BSMs to analyze the strength of joints with multiple fasteners. There are many different configurations to join and repair composite services, as seen in Figure 10.

Figure 10: Common joint and repair configurations.⁽¹¹⁾

After validating the BEM with the FEM, the author went on to test the accuracy in a composite-to-metal joint with six fasteners and adjacent circular cut-out in the laminate. The analytic, numeric, and experimental results were compared—the BEM formulated in the paper provided a good prediction for fastener resultant forces but predicted a higher failure load.

1.5.3 BOLT-HOLE CLEARANCE EFFECTS IN DOUBLE-LAP, MULTI-BOLT COMPOSITE JOINTS—LAWLOR, MCCARTHY, AND STANLEY⁽¹²⁾

The effects on load distribution in quasi-static strength, fatigue life, and failure modes of variable bolt-hole clearance in double-lap, multi-bolt joints were presented. Previous research investigated the effect clearance has on bolt-hole contact area in pin-loaded joints. Figure 11 shows the geometry used in the study. The laminates were manufactured from graphite/epoxy HTA/6376 with balanced, symmetric quasi-isotropic layups of $[45\ 0\ -45\ 90]_{2s}$. The bolts used were made of steel.

Figure 11: Double-lap specimen geometry (all dimensions in mm).⁽¹¹⁾

The clearances in the study ranged from near-fit to clearances slightly larger than those allowed in the aircraft industry. The results found that load is transferred to the near-fit bolts and at higher loads the distribution tends to even out. For joints tested under fully reversed, constant amplitude fatigue loading, joints with one loose-fit hole had a significantly shorter fatigue life than joints with all neat-fit holes; hole elongation initiated sooner, and failure initiation began earlier.

1.5.4 INSERT JOINT STRENGTH OF COMPOSITE SANDWICH STRUCTURES—SONG⁽⁴⁾

An experimental study was conducted to examine the pull-out and shear failure loads of composite sandwich insert joints. The specimens were constructed of a nomex honeycomb core, carbon-epoxy facesheets, and a FM73 film-type adhesive for core and face co-cured bonding. Figure 12 shows a schematic of the shear test. All specimens were fabricated in an autoclave by co-curing. A diamond wheel saw was used to cut the specimens.

Figure 12: Schematic of shear test.⁽⁴⁾

The results showed that core height, core density, and facesheet thickness all affect pull-out loading. Potted inserts were used to show that larger failure loads could be achieved. Shear failure was only affected by facesheet thickness.

1.5.5 'THROUGH-THE-THICKNESS' AND 'FULLY POTTED' INSERTS—THOMSEN⁽⁶⁾

A theory was adapted to study sandwich plates with inserts of the 'through-the-thickness' and 'fully potted' types. Figure 13 shows the different between 'through-the-thickness' and 'fully potted' inserts.

Figure 13: 'Through-the-thickness' v. 'fully potted' inserts.⁽⁶⁾

It was discovered that insert/potting and potting/honeycomb interaction effects play an important role in build-up of local stress concentrations. Fasteners tend to force regions close to the inserts to bend locally, resulting in local stress concentrations in the facesheets, the core, and the interface between the two. This has the potential to cause premature failure especially in sandwich panels with transversely flexible cores such as polymeric foams or honeycombs. The failure mode in these instances is typically delamination, shear rupture of the core, or direct bending of the facesheets.

The research concluded by examining the failure modes and their likely locations.

1.5.5.1 FACESHEET FAILURE MODES AND LIKELY LOCATIONS

- 1) Failure caused by bending stress concentrations induced adjacent to the insert.
- 2) Inter-laminar failure caused by traverse shear stress concentrations, adjacent to the insert.
- 3) 'Bearing' failure at the insert/face sheet intersection caused by inplane compression.
- 4) 'Overall' buckling mode or 'local' buckling mode ('wrinkling' or 'dimpling') caused by inplane compression.

1.5.5.2 CORE MATERIAL FAILURE MODES AND LIKELY LOCATIONS

- 1) Failure at intersection of potting/insert or potting/facesheet due to induced traverse normal and shear stress.
- 2) Failure at intersection of core/facesheet due to transverse normal and shear stress concentrations.

- 3) Failure in potting/core interface due to traverse shear stress concentrations.
- 4) Failure in core due to pure traverse shear, or combined action of compressive transverse normal and transverse shear stress (micro-buckling of the core cells).

1.5.6 EXPERIMENTAL INVESTIGATION OF STATIC AND FATIGUE BEHAVIOR OF COMPOSITE PANELS JOINED BY FASTENERS—DEMELIO, GENOVESE, AND PAPPALETTERE⁽⁸⁾

An experiment was carried out to estimate the static and fatigue pull-out and shear strength of sandwich composite panels joined by mechanical fasteners. The specimens were composed of a nomex honeycomb core, glass/graphite/Kevlar facesheets, and epoxy matrix and fastened to two rectangular steel plates. The load was applied directly to the steel plates for different types of fasteners. Figure 14 shows a picture and schematic of the experimental configuration. This asymmetric setup assumes that no bending occurs in the bolts, the sandwich composite, or the steel plates—which could produce inaccurate results under high loads, repeated fatigue tests, or adverse environmental conditions. Although it's often permissible to assume the fasteners are infinitely rigid in numeric models, doing so in experimental testing could skew data collected from the Instron servo-hydraulic machine.

Figure 14: Schematic and picture of experimental setup.⁽⁸⁾

Special care taken in drilling and machining the panels—a 3,000 RPM CNC drill moving at the rate of 4mm/min was used—to prevent delamination and fuzzing of skins and resin due to overheating.⁽⁸⁾ In the absence of a clean surface, cracks will form earlier reducing the total load a specimen can withstand before failure.

Because the composite sandwiches have to survive in a range of different environments, specimens were tested in humidity from 0 to 100% and temperature from -40 to 70 °C. It was discovered that resin has a propensity to absorb between 1 and 10% by weight of moisture which can migrate along the fiber/matrix interface. Delamination can then result due to the formation of blisters and cracking in the matrix. For static shear loading, it was observed that the load displacement curve of shear specimens generally has three different sections:

- 1) An initial line related to the structure settling over the load.
- 2) A second line in which slope increases until yield.
- 3) A third line when the load drops down as the fastener begins to tear through the hole.

Figure 15 shows the damage resulting from a static shear test.

Figure 15: Damage resulting from static shear loading.⁽⁸⁾

It's important to note that this specific failure mode is heavily dependent on the failure criteria. This specific research had very relaxed failure criteria which allowed the fasteners to tear through the specimens well after yield and ultimate loads had already been reached. The authors concluded that the best static shear resistance was achieved using a Kevlar skin. The fatigue shear test results were inconclusive.

1.5.7 COMPRESSION TESTING OF COMPOSITE LAMINATED FOAM WITH CENTRAL HOLES WITH AND WITHOUT HEAT—SURANO ET AL.⁽¹⁾, BALABAT ET AL.⁽²⁾

A parametric study was conducted to investigate monotonic in-plane compression loading for conventional specimens and shear key specimens with and without heat. The specimens were 6 in by 8 in foam panels placed between skins of fiberglass with center holes and were manufactured through the vacuum resin infusion process (VRI). The specimens had 2 alternate layers of chopped strand mat and woven roving. Some of the specimens contained shear keys, with a semicircular diameter of 5/16 in., surrounding the hole. Some specimens contained straight shear keys on either one side, or both sides of the part. The hole diameters were varied from 0.5 to 4 in. The circular shear key sizes were varied from 2 to 4 in and placed in coaxial alignment with the holes. 2 in straight shear keys were placed 0.75 in from the edge of the part. The compressive loading rate was set at 0.04 in/min (1 mm/min). It was determined that adding a circular shear key to one side of a composite sandwich panel did not substantially increase the strength or stiffness of the part for small sized to moderate sized holes (1 in or 2 in holes). Some improvement in stiffness and ultimate strength were seen from the circular shear keys in specimens

containing holes with diameters equal to or larger than half of the width of the part (3 in and 4 in hole diameter specimens). Circular shear keys were successful in delaying a failure on the side of the part that did not contain the shear key, which made the failure more predictable. Straight shear keys also made the failure occur away from the center hole at the end of the shear key.

For the thermal tests, the specimens were placed in a thermal chamber at temperatures of 120 and 160 degrees Fahrenheit and tested under compression loading. The specimens at 160 degrees Fahrenheit failed at 20 to 60% of the maximum yielding force as compared to the same specimens at 120 degrees. It was also discovered that the smaller the hole in combination with the largest shear key resulted in the strongest and most reliable specimens. Figure 16 shows all of the thermal specimens after testing. Notice that the specimens with the shear keys had a tendency to deflect the crack propagation, delaying failure.

Figure 16: Composite sandwich specimens with center holes, shear keys, and cracks.⁽¹⁾

The results from this study can be viewed on the next page in Figure 17.

This study also concluded that it is not safe in an experimental setting to heat polyvinyl chloride (PVC) foam above 250 °F. As a result, a different core was chosen for this thesis investigation. More about laboratory safety can be found in §5.5.

Figure 17: Room temperature results of notched sandwich composite specimens with circular and straight shear keys.⁽²⁾⁽¹⁾

1.6 SUMMARY OF LITERATURE REVIEW

Although the above literature review in §1.5 shows many strides have been made in the investigation of faster hole interaction in sandwich composites, the field is still in its developmental stages. The literature review demonstrated researchers have:

- ✓ Experimentally tested the pull-through strength of fasteners in composite sheets and composite sandwiches with honeycomb cores;^{(5) (8)(7)}
- ✓ Performed static and dynamic shear tests in composite sheets with single, double, and multi-fastener configurations;⁽⁴⁾⁽⁸⁾⁽¹⁰⁾⁽¹²⁾
- ✓ Developed first order analytical techniques to estimate bearing stress and pull through strength;⁽¹¹⁾
- ✓ Traded the difference between multiple types of potted inserts;⁽⁶⁾
- ✓ Subjected composite sandwiches to environmental effects such as humidity and increased and decreased temperatures.⁽⁸⁾

1.7 SCOPE OF RESEARCH

It is not feasible to develop a single solution to solve all problems discussed in §1.3 or prevent all the failure modes addressed in §1.4. Thus, the following research deals with a specific method to delay the failure induced by fastener bearing stress in static and dynamic in-plane pin-pin compression in foam composite sandwiches subjected to increased temperatures.

1.7.1 ORIGINALITY OF RESEARCH

The research covered by this thesis is separated into three main areas which all make unique contributions to the study of sandwich composites.

1.7.1.1 CREATION AND MANUFACTURING OF A NEW MATERIAL

With the birth of composites came the ability to tailor materials for specific applications. For the purpose of this thesis, a new material with unique properties was created. This involved:

- ✓ Finding a core capable of withstanding increased temperatures—covered in §2.5;

- ✓ Optimizing the cure cycle to co-cure the facesheets to the core in order to maximize strength—covered in §4.6;
- ✓ Testing multiple methods to adhere the facesheet to the core—covered in 2.5.3;
- ✓ Figuring out how to drill through carbon facesheets without initiating delamination or fuzzing⁽⁸⁾—covered in §4.9;
- ✓ Developing proper cutting procedures to maximize layup usage and decrease statistical deviation between parts—covered in §4.8.

1.7.1.2 DEVELOPMENT OF DAMAGE ARRESTMENT DEVICES (DADS)

Although ‘through-the-thickness’ potted inserts,⁽⁶⁾ ‘fully potted’ inserts,⁽⁶⁾ and shear keys⁽⁵⁾ have all been used to prevent, delay, or minimize damage, milling out slots of the foam perpendicular to the hole and adding additional composite layers during the curing cycle represents a novel technique.

Damage arrestment devices (DADs) increase the stiffness around the hole and have the potential to reduce cost, weight, and manufacturing time in composite fabrication. Currently, most industries use potted inserts to prevent or delay premature failure that can result from adverse loading found in fastener-hole interaction. Figure 18 shows an image of a typical potted insert. Most importantly, DADs work to delay failure—chapter 2 covers their design and chapter 6 covers their effectiveness.

Figure 18: A typical ‘potted’ insert used as an industry standard today.

Although not all potted inserts are metal, all inserts are added after the composite has already been fabricated. Adding the inserts post curing has the potential to cause skin/core delamination and induce micro-buckling, both of which can induce premature failure. Another down side of using potted inserts is the manufacturing time and tooling involved. This research has the potential to simplify the manufacturing process and help move the aviation, boating, and transportation industries away from the “black-aluminum” methodology towards a less costly, safer solution.

1.7.1.3 TESTING FOAM CORE COMPOSITES SANDWICHES IN A THERMAL ENVIRONMENT

Polyurethane foam—as an anisotropic material—has unique material characteristics that are directly affected by heat—this is covered in §2.5.2. This research is the first to study those thermal characteristics in the context of fastener-hole interaction. To date, the most current research in this area examined the effect of compression on polyvinylchloride foam with fiberglass facesheets and central hole under thermal loading.⁽¹⁾ But previous research was mostly inconclusive due to the inaccuracy of the thermal chamber used and limited number of specimens tested; fatigue was also not considered.

2 DESIGN OF EXPERIMENT

This section details the design methodology that went into developing the experiment.

Optimization of the fabrication methods is covered in §4. The experimental setup, testing procedures, and safety considerations are found in §5.

2.1 ASTM STANDARDS

Although there are no specified standards for testing composite sandwich panels with fasteners, it was possible to adopt some ASTM methods as a starting point for developing testing methods.

ASTM C364/C364M is the standard test method for sandwich composite compressive strength. The composite sandwich is either fixed, or placed between two plates. A compressive, monotonic force is then applied until failure. The data are collected in terms of cross-section area of the facesheet not including the core. The method specifies that the test is only successful if the failure does not occur at either of the supports. If the specimen is too long, buckling effects could cause premature failure and are not considered valid by the standard. The standard defines dimensions based on the thickness of the facesheet, since it carries the majority of the load. Lastly, the standard specifies that no less than five specimens should be tested and the rate should be such that each test lasts between three and six minutes.

Figure 19: ASTM C364/C364M test specimen dimensions.

ASTM D3410/D3410M, used to determine in-plane compressive properties of composite sandwich panels, is used to find the material characteristics of the sandwich composites, such as ultimate compressive strength, ultimate compressive strain, compressive modulus of elasticity, and Poisson's ratio. The dimensions are the same as specified in ASTM C364/C364M, but the loading condition is purely shear.

The one ASTM standard that deals with composites and fasteners is ASTM D5961/D5961M-05, which standardizes the bearing response of composite laminates under shear loading. A hole is drilled, and a fastener is loaded in tension or compression with the other end of the specimen fixed. The geometry of this standard is shown below in Figure 20.

Figure 20: ASTM D5961/D5961M-05 Testing Geometry.

Lastly, ASTM D68873-03 adopts ASTM D5961 to determine the bearing fatigue characteristics of composite laminates. The standard specifies using a repetitive constant amplitude force, cycled at a

constant frequency. This testing can use tension-tension, compression-compression, or tension-compression loading. The failure is either based on a number of cycles or static tests.

2.2 DESIGN OF EXPERIMENT

In order to properly assess the correlation between temperature and damage arrestment techniques, it was necessary to design an experiment that would test a variety of conditions. Because another graduate student was already assessing optimizations in geometry⁽¹³⁾, temperature was selected as the primary variable. Two loading cases were considered, monotonic compression and compression-compression fatigue. And, finally, two geometry configurations were adopted; without DADs and with DADs. Table 2 shows the number of specimens for each respective test case.

Table 2: Design of experiment.

	No Inserts		Inserts	
Temp (°F)	Monotonic	Fatigue	Monotonic	Fatigue
75	10	10	10	10
100	10		10	
115		10		10
125	10		10	
130		10		10
145		10		10
150	10		10	
160		10		10
175	10		10	
200	10		10	
TOTAL	60	50	60	50
Total Pieces= 220				

It is important to note that the temperature range for fatigue is not the same as for monotonic. This is because the failure criteria fatigue is defined as the average displacement at monotonic compressive yield at room temperature. This value is higher than the ultimate loads reached by specimens that were tested at 175 °F. Thus, fatigue specimens were only tested up to temperatures of 160 °F.

2.3 EARLY DAMAGE ARRESTMENT TECHNIQUE CONSIDERATIONS

Before the DAD geometry was selected, numerous ideas were considered. This section covers those ideas, and the primary reason they were not selected.

2.3.1 DESCRIPTION AND MANUFACTURING OF SHEAR KEYS

Previous research ⁽¹⁾⁽¹³⁾ examined the utilization of fiberglass inserts into the foam core of composite sandwiches before layups. Figure 16 in §1.5.7 showed the geometry of such specimens. The researched showed that skin core delamination and crack growth could be mitigated or delayed under compression with a plate-plate boundary condition. In order to manufacture such specimens, circular shear keys had to be created. Figure 21 shows the jig used to manufacture such circular shear keys.

Figure 21: Jig used to manufacture shear keys ⁽¹⁾.

This manufacturing includes pouring resin into the channels as shown in Figure 21 (left), adding the fibers as shown in Figure 22 (left), and vacuuming bagging the entire part to cure as shown in Figure 22 (right).

Figure 22: Shear key manufacturing process.

Figure 23 shows the final result of a shear key imbedded into the skin core bonding region of the specimen.

Figure 23: Specimen with circular shear key.⁽²⁾

Although effective, this type of DAD was not selected for a number of reasons:

- ✓ The thesis specimens were manufactured out of pre-preg carbon, not dry fiberglass, adhesion between the DAD and skin could have been a problem;
- ✓ This type of DAD requires an extra day of manufacturing and is difficult to get out of the aluminum jig—manufacturing time was unreasonable;
- ✓ Complex CNC milling is required which takes a considerable amount of time;
- ✓ The boundary condition changed, forcing the holes to bear the load as opposed to the top and bottom—having any type of gap between the hole and the DAD would prove ineffective.

2.3.2 COMPLEX INSERT GEOMETRY

Various methods to delay damage initiation were initially considered. Previous research tested the viability of circular shear keys and straight shear keys with some success. Figure 24 shows two of these specimens.

(a)

(b)

Figure 24: Previous test specimens with DADs (shear keys). (a) Circular shear key just around the outside diameter of the hole, (b) straight shear keys on either side of the hole.⁽²⁾

The two main factors that formulated the final design of the DADs were previous experience and manufacturability. Figure 25 below shows a CAD drawing of some of the conceptual DAD designs. The gradient parts represent the damage arrestment devices, and the dark circles represent holes.

Figure 25: Possible insert candidates.

Nearly all of the geometries were factored out due to the difficulty associated with manufacturing them.

Both the circular and straight DADs require a multi-step process: manufacturing the circular DAD, milling the foam where the DAD will sit, laying up the entire part, and cutting the part after it's cured. When dealing with fiberglass, the cutting is relatively easy, because the DAD is visible through the skin, however carbon is not as translucent. Thus, cutting such specimens would require precision beyond the

capabilities of the laboratory in which the research was performed. Even if cutting within precision were possible, there would be no rigorous way to verify that the DAD were in the assumed places without advanced non-destructive inspection (NDI) techniques. It was speculated, although not experimentally verified that the strength of the specimens would decrease if two independent layups were performed.

Thus, a simple DAD manufacturing technique was developed which required milling the foam, but only one layup. The finished specimen is shown in §2.5.5 and the manufacturing process is described in detail in §4.7.2.

2.4 DRIVING FACTORS IN SPECIMEN DESIGN

In addition to the design factors described above, other driving factors in the final design of the test specimens were:

- ✓ Minimizing the size of the part while still achieving diameter/width constraints for the specimen geometry so as to stay in the infinite range—this allowed for the maximization of materials and reduced overall labor time;
- ✓ Manufacturability, the specimens had to be mass producible with as little effort as possible—the easier the specimens were to manufacture, the more time we could spend testing different configurations;
- ✓ Fitting in the Instron servo-hydraulic machine; like any experiment, the testing equipment places physical limitations on the design of the experiment. In this specific case, the specimens and their self contained grips had to fit within the thermal chamber. This effectively limited the specimen to a maximum height of five inches and maximum width of four inches. A width of two inches was chosen to help maximize the number of specimens per layup,
- ✓ Usable for variable load conditions—although this experiment dealt exclusively with compression, it's important for the geometry to work for other (future) loading conditions.

It was with these factors that the final geometry and layup configuration was decided upon. They are discussed in more specific in the following sections.

2.4.1.1 HOLE PROPORTIONS

In order to properly analyze the specimens numerically and have stresses within predictable ranges, it was necessary to fulfill some geometric requirements. Previous researchers, Camanho and Lambert⁽⁹⁾ suggest that in lap joint and/or bearing configuration, the diameter (d) needs to be less than 20% of the width (w) of the part and the width needs to be less than twice the distance from the center of the hole. Figure 26 shows a schematic of the width, w , diameter, d , and distance from the center of the hole to the edge of the part (e).

Figure 26: Schematic of d/w and $w < 2e$ relationships⁽⁹⁾.

Camanho and Lambert also performed stress concentration tensile tests which helped them formulate their proportions. Figure 27 shows the results from one of their experimental tests.

Figure 27: Experimental results from tensile stress concentration factor tests.⁽⁹⁾

This is extremely important, because full system tests of aircraft, satellites, boats, missiles, etc. are costly and time consuming. Thus, when a company wants to test a small portion of the overall system, it's important that the designed experiment meets those requirements.

2.5 MATERIAL SELECTION

Prior to full scale manufacturing, critical decisions such as which materials to use were made. The primary driving factors included cost, ease and speed of manufacturing, consistency of results, and availability of material.

2.5.1 FACESHEET CANDIDATES AND SELECTION

The original facesheet candidates included pre-impregnated carbon, regular carbon, and woven fiberglass. A picture of each material is show below in Figure 28. Although each material has different advantages and disadvantages which dictate their specific application in various industries, pre-impregnated carbon was chosen for its abundance and manufacturability. Using dry carbon fiber and performing wet layups would have taken much longer, and required more specimens due to the high fluctuations of resin content from layup to layup.

Figure 28: Candidate facesheet materials. (a) Pre-impregnated carbon, (b) dry carbon, (c) fiber glass chop strand, (d) fiber glass weave.

Although adopting vacuum resin infusion (VRI), briefly covered in §1.1.6, could have solved the fluctuations in resin content, the process as a whole is much more arduous and time consuming. Such a process had the potential to restrict the scope of the experiment. A carbon fiber weave provided an adequate material for research because both axial and shear force are exhibited in the loading condition studied. Furthermore, the pre-impregnated carbon had already been donated to the laboratory and was in abundant supply.

The selected pre-impregnated carbon is infused with a low temperature curing matrix resin known as LTM45, which was manufactured into rolls by The Advanced Composite Group, and has a weight of 0.123 lbs/ft². Advantages of LTM45 include:

- ✓ The material can be sustained up to temperature of 356 °F;
- ✓ The material is suitable for use in autoclaves, vacuum bags with applied heat, or press moldings;
- ✓ It's well suited for low cost prototype mold development.

The material properties for LTM45 can be found in §6.2.1.2.

2.5.2 CORE CANDIDATES AND SELECTION

Two core materials were available, one made of polyvinyl chloride (PVC), and one made of polyurethane. Although previous research was performed with PVC foam, numerous health hazards were discovered primarily related to the inhalation of particulates which can result in respiratory issues such as coughing, wheezing, and increased amounts of phlegm.⁽¹⁾ Of particular worry however, are the toxic fumes released when heating PVC phone which have the potential to cause seizures, comas, and liver, central nervous system, kidney, and skin cancers.⁽¹⁾ The dangerous thermal expansion of the PVC foam is show below in Figure 29. The figure shows an example of what can happen to PVC foam when heated above the specified temperatures.

Figure 29: Thermal expansion resulting from overheating PVC foam.

Figure 30 below shows the two candidate foams. Aside from the health issues, there were multiple reasons to select the polyurethane over the PVC foam.

(a)

(b)

Figure 30: Candidate Foams. (a) Chosen foam, Last-A-Foam FR-6710, (b) runner up foam, PVC foam used in previous research.

It was necessary for the foam core to withstand temperatures seen during curing time and testing. Last-A-Foam FR-6710, a polyurethane closed cell foam from General Plastics was adopted. It has a density of 10 lbs per cubic foot and has been certified by the FAA to withstand temperatures up to 275 °F. The foam has many industrial applications including as close-out for aircraft interior sandwich panels, creating molds, transporting hazardous materials, and insulating structural panels. The foam was also the least expensive material with heat resistance. The material properties of the foam can be found in §6.2.1.1.

2.5.3 THE NEED FOR A FILM ADHESIVE

Early testing and manufacturing difficulties led to the adoption of a film adhesive, which is basically an extra layer of resin. When drilling the holes in the specimens, the back facesheet had a propensity to fall off when stressed by the drilling bit and associated vibrations as shown in Figure 31.

Figure 31: Back facesheet falling off during the drilling process.

Before the addition of the film adhesive, this happened to nearly 50% of the specimens. Of the specimens that didn't fail during drilling, nearly 60% of the test failures were from skin-core delamination rather than compression. Such failures drastically skewed initial results. Figure 32 shows the results from a test that failed due to skin core-delamination.

Figure 32: Early test skin-core delamination failure due to inadequate adhesion.

The delamination problems were so bad that it was possible to peel the skin right off the core after a layup had cured. This phenomenon is shown below in Figure 33.

Figure 33: Peeling the skin from the core after curing the layup.

One of the initial worries was that the addition of the film adhesive would drastically change the material properties of the specimens and oversaturate the part, although the majority of the excess resin was pushed out of the press used to layup the part during the manufacturing process. The resin content was found using a burn test, the results of which can be found in §6.1.1. Oversaturation has the ability to make the composite panel more ductile and decrease the linear elastic stiffness.

An additional worry was that the addition of the film adhesive would change the thickness of the specimens. However, even with the film adhesive, the specimen thickness only varied from 0.571" to 0.580", an acceptable variance.

2.5.4 SPECIMEN EVOLUTION

Through trial and error, all of the previous delays and problems described were found. A general evolution of the specimens is shown below in Figure 34. Notice how the specimens started with a width of 1.5" and hole diameter of 0.125", and evolved to a width of 2" and a hole diameter of 0.375". This evolution was to maintain the consistency of bearing strength as described in §0.

Figure 34: Test specimen evolution.

2.5.5 FINAL SPECIMEN DESIGN

With all of the above factors taken into account, the control specimens were designed according to the geometric parameters in Table 3. Most importantly, these characteristics allowed the maximum number of specimens to be manufactured per batch and the specimens to properly interface with the test equipment.

Table 3: Critical geometric characteristics of the specimen.

Bolt Diameter	0.25"
Bolt Location from edge	1.5"
Hole Diameter	0.375"
Thickness of foam	0.05"
Thickness of each face sheet	0.026"
Specimen Length	5.0"
Specimen Width	1.5"
Specimen Thickness	0.552"

Notice in Figure 35 that the hole diameter and location fall within the range discussed in §0. This allowed bearing stress and micro-buckling to be studied in a controlled test environment.

Figure 35: Final control specimen design.

Table 4 lists some of the critical design parameters for the DAD specimens. Most importantly, it was necessary to know the cured thickness of a single layer of LTM45 in order to mill the foam down to the correct depth. Additionally, it was necessary to make the DADs a width of 0.75" to remain within the ranges discussed in within the range discussed in §0. The layups created with these geometric properties gave a final DAD thickness of 0.039".

Table 4: Critical geometric characteristics of the specimen with inserts.

DAD Width	0.75"
DAD Location	1.5"
LTM Thickness	0.013"
DAD Thickness	0.039"

Figure 36 shows the final geometry of the specimen designed with damage arrestment devices (DADs).

Although the DAD thickness was not varied explicitly in this thesis, it was in the overall experiment.

Results from that study can be found in §6.4.

Figure 36: Final specimen design with inserts.

3 THEORETICAL ANALYSIS

This chapter focuses on the derivation and use of theoretical equations that describe composite laminates and sandwich composites. Although these equations can be used in the most general form to analyze complex problems, their accuracy is usually dependent upon a set of assumptions that are not always true. Thus, a theoretical analysis is usually beneficial to get a rough idea of the material response of composites under various loading conditions before performing a complex experiment or developing a computationally expensive model.

3.1 CALCULATING VOLUME FRACTION OF COMPOSITE LAMINATES

As stated in §1, composite materials are typically composed of a matrix or glue and a fiber. In this thesis, as discussed in §2.5, a pre-impregnated carbon was used. Numerous sources ⁽¹⁴⁾⁽¹⁵⁾ discuss the importance of balancing the amount of fiber and matrix in order to obtain maximum strength. The metrics used to measure the ratio of fiber to matrix are called weight and volume fractions. A weight fraction is easily measurable as shown in §5.4.4, but not much use in theoretical calculations. Volume fractions, used in determining the mechanical response of composites under specified loading, can be calculated from weight fractions.

The volume, v , of a composite (c) is made up of the volume of fiber (f) and the volume of the matrix (m) as shown below in equation (1).

$$v_c = v_f + v_m \quad (1)$$

The volume fractions, V , can then be calculated as shown below in equation (2).

$$V_f = \frac{v_f}{v_c}, V_m = \frac{v_m}{v_c} \quad (2)$$

The weight fractions are similarly defined in terms of the composite (c), fiber (f), and matrix (m) as shown below in equations (3) and (4).

$$w_c = w_f + w_m \quad (3)$$

$$W_f = \frac{w_f}{w_c}, W_m = \frac{w_m}{w_c} \quad (4)$$

The relationship between the measured weight fractions and calculated volume fractions is governed by density. Volume fractions can be calculated as a ratio of either of the constituent materials as shown below in equations (5) and (6).

$$V_f = \frac{\rho_c}{\rho_f} W_f \quad (5)$$

$$V_m = \frac{\rho_c}{\rho_m} W_m \quad (6)$$

The volume fractions serve two purposes. The first is to identify if the part is over-saturated with resin (defined as usually more than 60% of the composite ⁽¹⁴⁾⁽¹⁵⁾). The second is to calculate theoretical elastic moduli, E , in the longitudinal (1) and axial (2) directions. The formulations to calculate the two elastic moduli from volume fractions are shown below in equation (7) and (8). The equations are in terms of the volume fractions and the constituent material elastic moduli and Poisson's ratios (which are determined experimentally).

$$E_1 = V_f E_f + V_m E_m \quad (7)$$

$$E_2 = \frac{E_f E'_m}{V_f E'_m + V_m E_f (1 - v_m^2)}, \text{ where } E'_m = \frac{E_m}{1 - 2v_m^2} \quad (8)$$

This analysis assumes a plate or shell theory formulation which doesn't take thickness into account because it's so small in comparison to the width and length of the composite facesheet.

To ensure that the composition of the composite is in the range to maximize strength, V_{crit} , the critical fiber volume fraction must not be exceeded. This is shown below in equation (9).

$$V_{crit} = \frac{\sigma_{mu} - (\sigma_m)_{ef*}}{\sigma_{fu} - (\sigma_m)_{ef*}} \quad (9)$$

As a prerequisite, σ_{cu} , the ultimate strength of the composite, σ_{fu} , the ultimate strength of the fibers, and $\sigma_{fm,ef*}$, the matrix stress at the fiber fracture strain, must be calculated as shown below in equations (10) and (11).

$$\sigma_{cu} = \sigma_{fu} V_f + (\sigma_m)_{ef*} (1 - V_f) \quad (10)$$

$$\sigma_{cu} = \sigma_m (1 - V_f) \quad (11)$$

Finally, the elastic moduli of the constituent materials and their relative stresses can be calculated using equation (12).

$$\frac{\sigma_c}{E_c} = \frac{\sigma_f}{E_f} = \frac{\sigma_m}{E_m} \quad (12)$$

The ultimate composite failure stress can also be used to calculate its constituent stress for the fiber and matrix.

3.2 MECHANICAL STRESS ANALYSIS

The elastic modulus of a composite sandwich panel can be calculated using the elastic moduli of its constituents. The extension matrix, labeled A, is used to perform this conversion. A is shown in its generalized form below in equation

$$A_{ij} = \sum_{k=1}^n (\bar{Q}_{ij})_k (h_k - h_{k-1}) \quad (13)$$

The equation is calculated from the reduced stiffness matrix (composed of the A, B, and D matrices) and the layer of the laminate from the center of the sandwich, h_k . The height of each layer, starting from the center of the sandwich is shown below in Figure 37.

Figure 37: Laminate relative heights from the center.⁽¹⁴⁾

The reduced stiffness matrix can be calculated for each layer in the composite lamina. From such matrices, stresses and loads in each individual layer can be calculated.⁽¹⁴⁾ Additionally, using the material properties of the constituent materials, macro lamina properties can be calculated, such as the elastic modulus, E, the thickness of the sandwich panel, t, and the overall Poisson's ratio, ν . This relationship is shown below in equation (14).

$$[A] = \begin{bmatrix} \frac{Et}{1-\nu^2} & \frac{\nu Et}{1-\nu^2} & 0 \\ \frac{\nu Et}{1-\nu^2} & \frac{Et}{1-\nu^2} & 0 \\ 0 & 0 & \frac{Et}{2(1-\nu)} \end{bmatrix} \quad (14)$$

Lastly, for a symmetric lamina, the A matrix can be used to calculate loads, N, or strains, ϵ , in each constituent layers as demonstrated by equation (15).

$$\{N\} = [A]\{\epsilon^0\} \quad (15)$$

Unfortunately, this relationship only works for purely mechanical forces and does not take thermal effects into account.

3.3 THERMAL AND MECHANICAL STRESS ANALYSIS ⁽¹⁵⁾

Traditional stress analysis does not account for laminates that have been cured at temperatures different than their design operating temperature. Because thermal stresses arise under such situations, and are extremely important in the scope of this research, the mechanical stress equations must be modified.

The three dimensional thermoelastic anisotropic strain-stress relations are shown below in equation (16),

$$\epsilon_i = S_{ij}\sigma_{ij} + \alpha_i\Delta T \quad i, j=1,2,\dots,6 \quad (16)$$

where the total strains, ϵ_{ij} , are the sum of the mechanical strains, $S_{ij}\sigma_{ij}$, and the six free thermal strains, $\alpha_i\Delta T$, for a temperature change of ΔT . The three dimensional stress-strain relationships can be obtained by a matrix inversion as show in equation (17) below.

$$\sigma_i = C_{ij}(\epsilon_j - \alpha_j\Delta T) \quad i, j=1,2,\dots,6 \quad (17)$$

In both the above equations, (16) and (17), the six α_i 's are the coefficients of thermal expansion and ΔT is the change in temperature. In equation (17), $C_{ij}\alpha_j\Delta T$ are the thermal stresses if the total mechanical strain is zero.

The plane stresses on an orthotropic³ lamina in principal material directions are defined below in equation (18).

³An orthotropic material is defined in terms of its behavior in response to loading. Application of normal stress in a principal material direction (along one of the three orthogonal planes of material symmetry) results in extension in the direction of the stress and contraction perpendicular to the stress. The

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 - \alpha_1 \Delta T \\ \varepsilon_2 - \alpha_2 \Delta T \\ \gamma_{12} \end{Bmatrix} \quad (18)$$

In the above equation, (18), Q_{ij} represents the reduced stiffness matrix, the components of which are defined below in equation (19).

$$\begin{aligned} Q_{11} &= \frac{E_1}{1 - \nu_{12}\nu_{21}} \\ Q_{22} &= \frac{E_2}{1 - \nu_{12}\nu_{21}} \\ Q_{12} &= \frac{\nu_{12}E_2}{1 - \nu_{12}\nu_{21}} = \frac{\nu_{21}E_1}{1 - \nu_{12}\nu_{21}} \\ Q_{66} &= G_{12} \end{aligned} \quad (19)$$

It's important to notice that the coefficients of thermal expansion only affect extension strains, not the shearing strain. To find the stresses in laminate coordinates for the k^{th} layer, the coordinates can be transformed as shown below in equation (20).

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{Bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x - \alpha_x \Delta T \\ \varepsilon_y - \alpha_y \Delta T \\ \gamma_{12} - \alpha_{xy} \Delta T \end{Bmatrix} \quad (20)$$

In the above equation, (20), α_{xy} represents an apparent coefficient of thermal shear, and $\bar{Q}_{ij}$ represents the transposed reduced stiffness matrix. The components of $\bar{Q}_{ij}$ are defined below in equation (21)

$$\begin{aligned} \bar{Q}_{11} &= Q_{11} \cos^4 \theta + 2(Q_{12} + 2Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{22} \sin^4 \theta \\ \bar{Q}_{12} &= (Q_{11} + Q_{22} - 4Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{12} (\sin^4 \theta + \cos^4 \theta) \\ \bar{Q}_{22} &= Q_{11} \sin^4 \theta + 2(Q_{12} + 2Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{22} \cos^4 \theta \end{aligned} \quad (21)$$

magnitudes of the extension in each respective principal material direction under normal stress are different from the magnitudes of the extension resulting from a normal stress applied in an orthogonal direction—different Young's moduli exist in the principal material direction and different Poisson's ratios are associated with different pairs of principal directions.

Application of shear stress causes shearing deformation independent of the various Young's moduli and Poisson's ratio. Thus, at least five material properties are necessary to describe the mechanical behavior of an orthotropic material. These stiffness characteristics are E_1 , E_2 , ν_{12} , ν_{21} , and G_{12} .

$$\overline{Q_{16}} = (Q_{11} - Q_{12} - 2Q_{66})\sin\theta\cos^3\theta + (Q_{12} - Q_{22} + 2Q_{66})\sin^3\theta\cos\theta$$

$$\overline{Q_{26}} = (Q_{11} - Q_{12} - 2Q_{66})\sin^3\theta\cos\theta + (Q_{12} - Q_{22} + 2Q_{66})\sin\theta\cos^3\theta$$

$$\overline{Q_{66}} = (Q_{11} + Q_{22} - Q_{12} - Q_{66})\sin^2\theta\cos^2\theta + Q_{66}(\sin^4\theta + \cos^4\theta)$$

The above modifications allow thermal stresses to be calculated for specific temperatures.

Similar modifications can be made for moisture content ⁽¹⁴⁾, but will not be covered because such material is outside of the scope of this thesis.

4 SPECIMEN MANUFACTURING AND JIG DESIGN

Manufacturing the specimens and developing a rigorous, repeatable process was the most time consuming part of the research. The main goals were to develop a layup process that could be completed on a daily basis while producing consistently high quality parts. This included preparing the materials, converging on a curing cycle, and laying up the composite sandwich plates in a reasonable amount of time.

4.1 MATERIAL PREPARATION

Prior to completing the layups, the materials had to be prepped. This was an iterative process that became more efficient and standardized over time.

4.2 CUTTING THE PRE-IMPREGNATED CARBON AND FILM ADHESIVE

Because the pre-impregnated carbon can only be out of the freezer for a maximum of 45 minutes before it needs to begin its cure cycle, various changes to the manufacturing procedure were adopted. Early in the manufacturing development process, the carbon and film adhesive were cut directly from the racks inside the freezer. This resulted in a variety of problems:

- ✓ It was difficult to mark and make straight lines with the carbon and adhesive roles still on the racks;
- ✓ Once marked, it was difficult and time consuming to cut straight. In many instances, material was wasted. Once a sheet was removed from the freezer, it needed to be cut down even more to fit the dimensions of the layup, a redundant step;
- ✓ Staying in the freezer for prolonged periods of time was uncomfortable for the people cutting
- ✓ Keeping the door open in the freezer risked altering the material properties of the pre-impregnated materials

To solve this problem, the rolls were taken out of the freezer and cut on the work bench prior to each layup. This procedural change also had some downsides:

- ✓ It took two people to remove each roll;

- ✓ Moving the rolls in and out of the freezer everyday could have harmed the material;
- ✓ It was still time consuming.

Finally, it was decided to take the rolls out of the freezer and cut as many 12" squares as possible within 45 minutes. This saved a lot of time and allowed layups to be manufactured every day. The final procedure for cutting the carbon is shown below in Figure 38. The procedure was identical for cutting the adhesive.

Figure 38: Cutting Pre-impregnated carbon.

4.3 CUTTING THE FOAM

Because the foam was mass manufactured, it was delivered in 4' by 8' sheets. Thus, it was necessary to cut it down to size. Using a table saw and three people, it was possible to cut the foam down to 12" squares--the size needed for manufacturing. The process is shown below in Figure 39.

Figure 39: Cutting the foam sheets with a table saw.

Because dangerous particulates that can cause or exacerbate the respiratory problems discussed in §2.5.2, safety equipment including face masks, safety glasses and gloves were worn during the cutting procedure.

4.4 MILLING THE FOAM

In order to prepare the foam to have inserts placed in them, the now 12" by 12" foam cores were milled to have two 0.75" by 0.039" (thickness of three layers of carbon) slots on each side. This process is shown below in Figure 40.

Figure 40: Slots being milled out of the foam blocks.

A CNC end mill with a 0.75" four-flute straight bit was used to complete the job. A CAD model of the foam was made in SolidWorks and uploaded to the CAMWORKS software to create a CNC code that

the mill used to accurately cut the slots. Unfortunately, a vice grip would damage the foam, so six toe clamps were used with horizontal rulers across the foam to stabilize the piece. It was particularly important to make sure the slots were milled in the same locations when the foam was flipped. If inaccurate, the offset could bring about problems while drilling and skew the test results.

4.5 CLEANING THE PRESS PLATES

In order to maintain a smooth surface on the final layups, it was necessary to clean and buff the press plates before each layup. This process is shown below in Figure 41.

Figure 41: Buffing the press steel plates to maintain a clean surface to prevent imperfections in layups.

Maintaining a clean surface finish was important to prevent the development of surface stress concentrations and minimize deviations in results. Figure 42 shows the difference between a smooth composite surface (when the press plates were properly buffed and cleaned) and a rough composite surface (when the plates were not buffed or cleaned).

Figure 42: Comparison of specimens (a) with imperfections, and (b) without imperfection except for the failure region just below the hole.

4.6 CURING CYCLE OPTIMIZATION

Prior to adopting a rigorous layup technique, numerous curing cycles were attempted. The machine used to cure all of the composite sandwich plates was the Tetrahedron Composite Airpress shown in Figure 43.

Figure 43: Layup press.

The press applied a constant pressure and variable heat to create the specimens. The manufacturer of the LTM45 carbon specified the curing cycle shown below in Figure 44. The cycle starts with a constant load of 100 lbs with temperature ramping at 2 °F per second until reaching 150 °F. This temperature was then

maintained for 16 hours, and then decreased to 73 °F at 2 °F per second. Once at 73 °F, the pressure of 1000 lbs was maintained for an additional 2 hours.

Figure 44: Final curing cycle.

The manufacturer states with a six sigma confidence interval that at the conclusion of the curing cycle, the composite is 98% cured. The final 2% cures over a long period of time.

Although the sheet resin was added to the layup, as discussed in §2.5.3, and had a slightly different curing temperature, its properties were not drastically modified. The majority of the literature states that when multiple materials with different cure cycles are combined, the one that requires the most heat should be adopted. This makes intuitive sense because it is more beneficial for a composite part to over cure than under cured.

4.7 FINAL LAYUP TECHNIQUES

Although many layup techniques were attempted, for consistency, it was important to converge on a single, repeatable, efficient method. This method was first created for the control specimens, and then adopted to the specimens with inserts.

4.7.1 LAYUP WITHOUT DAD

Four sheets of pre-impregnated carbon and two sheets of film adhesive were removed from the freezer. Two sheets of non-porous material were cut to approximately 14" squares. The foam was then laid on the non-porous material, then one layer of the film adhesive, and two layers of carbon. Although the carbon is supposed to be symmetric, care was taken to insure that the sheets were always laid up in

the same direction. The foam, with half of the layup was then flipped and placed upside down on to the non-porous material. The remaining film adhesive and carbon sheets were placed on the exposed side of the foam in the same orientations as before. The second sheet of non-porous material was then added to the top of the completed layup. The two 0.25" thick steel plates were then added to the outside of the layup in contact with the non-porous material, placed in the press, and set to cure according to the cycle shown in §4.6. The final layup schematic can be seen in Figure 45.

Figure 45: Final layup schematic, including the press.

Unfortunately, it was not initially known that the foam had different material properties in the longitudinal and transverse directions. It is possible that the small differences in the material properties produced some deviation in the results.

4.7.2 LAYUP WITH DAD

The insert layups were performed identically to the regular layups with two key differences. First, the foam was milled to make room for the inserts as discussed in §4.4. Second, it was necessary to cut 24 strips of carbon fiber 12" by 0.75" to fill the milled out sections. It was not possible to mass cut the strips and store them in the freezer because doing so could have potentially altered the material properties over time. Thus, they were cut just before each layup. Initially, the strips were cut using a razor blade as shown in Figure 46. This technique was time consuming and produced inconsistently sized strips. After being cured, resin would fill in the gaps not occupied by the carbon, altering the material characteristics of the insert.

Figure 46: Cutting strips of pre-impregnated carbon for inserts.

To solve this problem, a heavy duty paper cutter was used to cut multiple strips at once. This partially reduced the deviation in strip width, and greatly reduced the manufacturing time. The process is shown below in Figure 47.

(a)

(b)

Figure 47: Cutting insert strips. (a) Marking the individual sheets, (b) cutting the strips with a paper cutter.

Once the strips were cut, the film adhesive was laid on top of the foam and pressed into the milled out slots using latex gloves. The strips were then added individually, 3 per slot. This process is shown in Figure 48.

Figure 48: Adding the strips of carbon to the milled foam.

The carbon sheets were then added to the top of the layup and the same process for the normal layup discussed in §4.7.1 was followed. Figure 49 shows a completed insert layup in the press.

Figure 49: Completed layup inside the press.

It was necessary to finish preparing the entire layup in 45 minutes or less because the carbon would become extremely sticky, difficult to work with, and start to cure. Waiting too long before starting the cure cycle in the press could have resulted in poor or inconsistent results.

4.7.3 OVERALL MATERIAL PROPERTIES LAYUP

This section describes the layup technique used to create the plate necessary to test the overall material properties of the sandwich composite.

4.7.4 THERMOCOUPLE LAYUP

The thermocouple layup was performed identically to the regular layup described in §4.7.1 with one major change. A thermocouple was positioned in-between the film adhesive and foam, and then the layup was placed inside the press to cure. This process is shown in Figure 50 below.

Figure 50: Thermocouple being (a) positioned, (b) layed up, and (c) cured inside the press.

The goal of this layup was to create a way to accurately measure the time required for the bond between the carbon and core to heat up to the necessary temperatures. It was important to position the thermocouple as close to the center of the part as possible. The final result is shown in Figure 51 below.

Figure 51: Thermocouple (a) imbedded in a plate, (b) inside the part, and (c) connected to the thermocouple reader used in calibration.

Although there was not a thermocouple part layed up for the insert specimens, it was assumed that the difference in heat up times would be negligible.

4.8 CUTTING SPECIMENS

After fully curing, the sandwich composite plates were cut using the Target tile saw shown below in Figure 52.

Figure 52: Cutting the specimens down to size with the tile saw.

The specimens were cut down to a size of 5" by 2" by 0.552". A total of 10 specimens were manufactured from a single 12" by 12" plate.

4.8.1 CUTTING SPECIMENS WITHOUT INSERTS

Cutting the cured composite layups into individual specimens was challenging for a couple of reasons. When the composite layups were pulled out of the press, they did not have perfectly straight orthogonal edges. In many cases, because the layups were typically larger than the press steel plates, the top and bottom were not entirely planar. In order to compensate for these issues, the layups were 12" squares, when only a 10" square was necessary to obtain ten 2" by 5" specimens (excluding the width of the blade which is about 0.125"). This extra margin was used to square the plate and line up the fiber direction. The first cut would be made by aligning the fiber direction with the blade. From there, all sides were squared using the tile saw sliding guide. Although the tile saw blade is approximately 1° off from 90°s, the specimens cut fell within the statistical limits required.

Once the plates were squared, 2" strips were cut, and then the strips were cut down to two segments of 5". Because the ruler on the tile saw is not entirely accurate or within the statistical limits which were required, scrap material was cut with the tile saw using a metal stopper, and measured. This metal stopper is shown above in Figure 52. The before and after images of the cut plates are shown below in Figure 53.

Figure 53: The (a) plate before cutting, and (b) after cutting.

4.8.2 SPECIMENS WITH INSERTS

Cutting the plates with inserts exhibited all of the challenges of the regular specimens explained in §4.8.1. In addition, this process was complicated by the necessity to keep the inserts of the finished specimens perpendicular to the edges and in the correct locations. To accomplish this, after the plate was squared, a precision tool made out of carbon fiber, shown below in Figure 54, was used to mark the center of all four eight exposed insert regions.

Figure 54: A precision tool (a) by itself, and (b) on a specimen being used to mark the center locations of the inserts.

From there, a line was drawn to divide the surface of the plate into what would become the boundary of the two rows of specimens. Unfortunately, when milling the foam, the thickness of the blade was not taken into account making all specimens with inserts slightly shorter on one side. This did not impact the results because the lengths of the specimens were still within the required statistical limits and

outside of the main stressed region. Had the specimens been tested in tension, this could have presented a problem.

Once the plate was cut into two pieces along the boundary that was parallel to the inserts, each piece was squared on its remaining three sides, and cut down to size like the control specimens as described in §4.8.1.

This process can be summarized in an easy to follow procedure listed below:

- ✓ Cut along one edge as close to the fiber contour as possible
- ✓ Square the other three edges
- ✓ Use carbon tool to mark the center of the four inserts
- ✓ Draw 4 lines on the top of the sandwich (these will later be used for drilling holes)
- ✓ The distance between the centers of the two center inserts should be 3" (forgot to account for the eighth inch blade)
- ✓ Put calipers to 1.5" and mark the center on both sides
- ✓ Draw a 5th line (it separates the two rows)
- ✓ Line up center line on the saw using a straight edge
- ✓ Cut along center
- ✓ Square the remaining three sides on each piece
- ✓ Line the saw up to 5"
- ✓ Use the square edge to cut
- ✓ Line the saw up to 2"
- ✓ Use the square edge to cut
- ✓ Mark with calipers (in half)
- ✓ Drill holes

4.9 DRILLING OPTIMIZATION

This section details the alterations made to the drilling procedure to maximize the quality of the parts.

4.9.1 PROBLEMS IN DRILLING HOLES THROUGH GRAPHITE/CARBON SHEETS

Three of the major issues that arise when drilling holes in composite parts are delamination, fiber pull-out, and excess cutting temperatures affecting on the quality of the part.⁽¹⁶⁾ The most difficult issue encountered in the research of this thesis was skin core delamination. This issue was overcome by a combination of adopting a film adhesive as explained in §2.5.3 and utilizing a special bit while drilling as discussed in §4.9.3. Figure 55 shows the results of drilling holes with conventional twist drill bits which causes significant fiber pull-out.

Figure 55: Fiber pull-out in composite parts. (a) Pull-out that results from using conventional drill bits and (b) the bits used to drill the specimens.⁽¹⁶⁾

Additional research found that utilizing bits used to cut ceramic tiles generated tolerable results. In order to prevent fiber pull-out and changing the material properties of the epoxy resin by heating it too much, it's important to slowly initiate the hole, ream it, and be able to remove material.⁽¹⁷⁾ Figure 56 shows an idealized bit that includes an initiator, venting flats, and a reamer. The paper that published the below image indicates that such a drill bit could be used without a solid backing without causing skin core delamination.⁽¹⁷⁾

Figure 56: Idealized composite bit.⁽¹⁷⁾

Unfortunately, such drills are extremely expensive. So instead, a similar approach that uses a backing was adopted as explained in § 4.9.3.

4.9.2 POSSIBLE DRILLING METHODS

The open literature criticizes the use of ordinary twist drills because they heat up excessively, dull quickly, and require significant backing to avoid pull-out.⁽¹⁸⁾ The four main types of drill bits that can successfully drill holes while minimizing delamination, pull-out, and thermal effects are shown below in Table 5 with their respective advantages and disadvantages.

Table 5: Description and disadvantage of various drill bits and techniques.

Drill Bit Type	Description	Disadvantages
Dagger Bit	<ul style="list-style-type: none"> ✓ Constructed of solid carbide ✓ Flat with two cutting edges 	<ul style="list-style-type: none"> ✓ Generates substantial amount of heat ✓ Lots of fraying on backside of hole
Diamond Hole Saw	<ul style="list-style-type: none"> ✓ Utilizes a pilot hole ✓ Drill speed is extremely quick 	<ul style="list-style-type: none"> ✓ Only beneficial for holes much larger than 0.25" ✓ Requires constant cleaning
Tapered Drill Reamer	<ul style="list-style-type: none"> ✓ One of the first bits designed for composites ✓ Has three straight flutes ✓ Tapered 	<ul style="list-style-type: none"> ✓ Some fraying ✓ Bits are extremely brittle ✓ Requires speed control
Countersinking	<ul style="list-style-type: none"> ✓ Uses a carbide countersink mounted on a mill 	<ul style="list-style-type: none"> ✓ Requires a mill ✓ Supporting the part can be difficult

Additionally, Figure 57 shows the results of each respective drilling process. Although ideally counter-sinking should have been adopted, the process would have been extremely time consuming because a mill was not constantly available. A tapered hole reamer also provides extremely beneficial results, however, solid carbide parts are extremely expensive and not very damage tolerant.

Figure 57: Holes resulting from using various drill bits and techniques. (a) Dagger bit, (b) diamond hole saw, (c) tapered hole reamer, and (d) counter sinking.⁽¹⁸⁾

Another strategy that was briefly used adopted a high RPM (rotations per minute) dremel in conjunction with a sanding bit to slowly remove material at an increasing diameter. The parts used to perform the procedure are found below in Figure 58. The conical sand paper bits stepped from a small diameter of 0.125" and gradually increased to 0.375" Although this method prevented fiber pull-out and skin core delamination; it generated far too much heat and in some cases melted the epoxy resin. The method also generated holes that were slightly too large due to the excessive vibration caused from the

high RPMs. Because the main objective of the thesis was to experimentally measure and explain fastener hole interactions in composite sandwiches, the potential of drastically changing material properties in the region of interest could not be tolerated.

(a)

(b)

Figure 58: Dremel temporarily used to drill holes. (a) The dremel setup and (b) the utilized bit.

4.9.3 FINAL DRILLING METHOD

The final tooling bit adopted was a glass and tile drill bit manufactured by Black and Decker. It is made out of high strength steel and diamond dusted on the edges. It was fortunate that Black and Decker manufactures a 0.375" diameter bit. The drill bit is shown below in Figure 59.

Figure 59: Black and Decker drill bit used to drill the holes in the composite sandwiches.

Although not extremely intuitive, carbon fiber exhibits similar behavior to glass and tile when drilled; all are extremely brittle materials. This drill bit exhibited more precision than the conical sanding bit, generated less heat than the dagger bit, and was more cost effective than the tapered drill reamer.

However, the method also generated quite a bit of fraying on both the front and back surface.

Additionally, the bit would wear down over time making the holes too small to fit the brass bushings.

Fortunately, the bits costs less than \$20.

To help resolve some of the fraying issues, after the drilling was complete, a deburring tool was used to remove the excess fibers. This process is shown below in Figure 60.

Figure 60: Deburring after drilling the holes. (a) The part and deburring tool and (b) the deburring process.

4.9.4 MARKING HOLE LOCATIONS

Prior to drilling holes, it was necessary to mark the hole locations at each point on the specimen. Unfortunately, a felt-tip marker was not accurate enough to accomplish the task. Thus, a set of calipers was used to gently scratch the surface. The width of the specimen was measured, the value was cut in half, and the calipers were set at that length. Then, using the lengthwise direction of the specimen as a guide, a line was scratched right down the center. This process is shown below in Figure 61.

Figure 61: Marking the specimen for drilling. (a) Caliper set to 1.5" and, (b) scratching the surface of the specimen to make the mark.

This process doesn't harm the structural integrity of the specimens because it only makes a small scratch in the surface of the epoxy and does not affect the fiber (which is where all the strength comes from). For the control specimens, the calipers were then set at a length of 1.5", and marked the location of the hole. For the specimens with inserts, it was not possible to measure 1.5" from the top because as explained in §4.8, the center location of the inserts was not always in the intended location. The location of the inserts of most specimens were marked during the cutting process as explained in §4.8 and shown in Figure 54. The ones that were not marked during the cutting staged were re-marked using a similar method. Once the center location was marked, drilling could begin.

4.10 LABELING

A labeling system was used to keep track of all manufactured specimens. The first four numbers represented the date the specimen was manufactured and the last two numbers represented which specimen of that layup it was. Thus, a specimen named 0425-02 was the second specimen from the plate manufactured on April 25th. As explained in §4.6, it was necessary to wait a week for a full cure on the composite sandwich plates, so this labeling system worked as a constant reminder. In addition, each specimen with its respective dimensions, test data, environmental conditions, and test description were all kept in a Google Docs spreadsheet for easy recording and reference. An image of the spreadsheet is shown below in Figure 62.

Test Specimen (Date-#)	Test Date	Test Type	Length	Width	Thickness	Max Load	Notes
0401-01	4/9/2010	3 Layer Insert Lay-up Method 1	5.048	2.012	0.571	1708	
0401-02	4/9/2010	3 Layer Insert Lay-up Method 1	5.012	2.013	0.575	1796	
0401-03	4/9/2010	3 Layer Insert Lay-up Method 1	4.949	2.008	0.58	1741	
0401-04	4/9/2010	3 Layer Insert Lay-up Method 1	4.886	2.009	0.578	1690	
0401-05	4/9/2010	3 Layer Insert Lay-up Method 1	4.972	2.006	0.577	1747	
0401-06	4/9/2010	3 Layer Insert Lay-up Method 1	4.944	2.003	0.569	1675	
0401-07	4/9/2010	3 Layer Insert Lay-up Method 1	5.058	2	0.574	1711	
0401-08	4/9/2010	3 Layer Insert Lay-up Method 1	4.918	2.011	0.579	1655	
0401-09	4/9/2010	3 Layer Insert Lay-up Method 1	4.84	2.01	0.579	1677	
0401-10	4/9/2010	3 Layer Insert Lay-up Method 1	5.056	1.981	0.576	1985	
0406-01	4/14/2010	3 Layer Insert Lay-up Method 2	5.032	1.979	0.575	2007	
0406-02	4/14/2010	3 Layer Insert Lay-up Method 2	4.989	1.989	0.574	1903	
0406-03	4/14/2010	3 Layer Insert Lay-up Method 2	5.008	1.989	0.575	2022	
0406-04	4/14/2010	3 Layer Insert Lay-up Method 2	5.013	1.985	0.574	1893	
0406-05	4/14/2010	3 Layer Insert Lay-up Method 2	4.946	2.014	0.574	1506	
0406-06	4/14/2010	3 Layer Insert Lay-up Method 2	5.019	1.96	0.573	1949	
0406-07	4/14/2010	3 Layer Insert Lay-up Method 2	4.948	1.984	0.579	1957	
0406-08	4/14/2010	3 Layer Insert Lay-up Method 2	5.013	1.987	0.576	1998	
0406-09	4/14/2010	3 Layer Insert Lay-up Method 2	5.046	1.972	0.583	1927	
0406-10	4/14/2010	3 Layer Insert Lay-up Method 2	4.968	1.991	0.579	1835	
0412-01	4/10/2010	3 Layer Insert Lay-up Method 1	4.789	1.933	0.585	2011	

Figure 62: Google Doc spreadsheet used to record all specimen values and test results.

The labels were written onto the specimens with a whiteout pen at the conclusion of manufacturing. This process is shown below in Figure 63.

Figure 63: Labeling the specimens using a whiteout pen.

4.11 JIG CONSTRUCTION AND OPTIMIZATION

In order to construct an experimental setup adequate to perform the testing, several requirements had to be fulfilled. These requirements included:

- 1) Attaching the test specimens to the Instron servo-hydraulic machine: The equipment in the lab prior to the experiment included a set of large and small pneumatically operated grips and a set of mechanically operated grips shown below in Figure 64.

Figure 64: Different grips for the Instron servo-hydraulic machine. (a) Large grips controlled by pneumatically and (b) smaller grips tightened by hand.

Constructing a jig would require interfacing with the hydraulic grips, or connecting directly to the rigid shafts of the Instron machine. This requirement was complicated by the nature of adding the thermal chamber and the necessity for the tests with and without heat to be as similar as possible.

- 2) Heat the specimens in a reasonable amount of time and maintain that heat until failure: It was important that the time to heat the specimens was consistent for each temperature because thermal fatigue had the potential to modify results. Maintaining a constant temperature was also extremely important because if there were peaks or valleys in the temperature profiles without record, the results could be a misrepresentation of the physical system.
- 3) Construction of a durable set of jigs: Without durable jigs, the test results had the potential to vary over time. If the jigs deformed in any way, the data would not be representative and there would be no way to measure it short of applying local strain gauges.
- 4) Isolation of studied variable: The total isolation of the test specimens independent of immeasurable variables was a high priority. The primary variable studied in the test was the effect of bearing stress induced by bolts under compression on composite sandwich holes.

4.11.1 FIRST JIG

The first jig was constructed to interface with jigs (a) and (b) shown in Figure 64. However, it was necessary for the thickness of the top part to be slim enough to fit in the (b) grips, which are much more constraining. Without fitting in that section, the test specimen would not be in perfect line with the axis of the machine which could induce bending, a loading not studied in this thesis. The jig was cut out of quarter inch low quality steel using a metal band saw. The jig is shown below in Figure 65.

Figure 65: First jig design. (a) A specimen after uneven failure, (b) specimens connected to the large pneumatically controlled grips, (c) entire assembly not connected to grips.

One of the primary problems with this jig design was the ability to fulfill requirement number 4 (isolation of studied variables). Composite sandwiches, no matter how similar, all have small differences, which cause different types of failures at different loads. One hole in each specimen would always fail before the other—if one specimen failed in the top hole, and another in the bottom hole, the deformation and tearing of each specimen would be inconsistent causing, the entire system to induce unintended loads on the specimens, thus undermining the entire experiment. Additionally, using this jig would require twice the amount of material, and thus, twice the amount of manufacturing. Although, in hindsight, given the length of some of the thermal tests, if it was possible to notch the specimens to force them to deform in a consistent way, it would have been possible to acquire the same amount of data in half the tests (i.e. 5 tests per condition rather than 10). Although, there would still only be force-

displacement data for the loading on the entire system and no accurate way to uncouple the data into separate force-displacement curves.

An alternative method was to only attach one specimen as was done by⁽⁸⁾ shown in Figure 14 in §1.5.6.⁽⁸⁾ This method would have required different size bolts and still had the potential to induce bending on the specimen as a result of it not being in perfect alignment with the axis of the Instron servo-hydraulic machine.

4.11.2 SECOND JIG

The second jig constructed was intended to test one specimen at a time. Like the first jig, it was designed to be able to interface with grips (a) and (b) shown in Figure 64. The completed jig is shown below in Figure 66.

Figure 66: Second jig design. Manufactured out of sheet metal welded together.

This jig was constructed with the same material as the first jig, but was cut into four separate parts per jig. Once cut, the four different pieces were welded together to form the jig shown above in Figure 66. Unfortunately, the jig was not nearly as strong as it needed to be due to the weak points caused by the welds. Additionally, the jig was not tempered after welding which could have contributed to its lack of strength. Lastly, the jig was not straight enough for consistent results because the welding induced some permanent deformations. The jig was used for a few test sets including the rate determination tests described in §6.3, and some of the insert sizing tests described in §6.4. Overtime, the jig weakened and deformed which required another solution to be developed.

4.11.3 FINAL JIG

The final jig adopted for the remainder of the tests, shown in (b) of Figure 67 was constructed out of a solid cylinder of steel. Rather than joining individual, imprecise and structurally questionable parts, the cylinder of steel was precision CNC milled as shown in Figure 68 to the CAD drawing shown below in (a) of Figure 67.

(a)

(b)

Figure 67: Final Jig used in all experimental testing.

This design enabled the jig to directly attach to the machine, allowing it to be in line with the axial load avoiding potential bending effects that resulted from the first two designs.

(a)

(b)

Figure 68: CNC manufacturing of the final jig. (a) Turning the jig raw material and (b) facing the jig raw material.

To connect to the Instron servo-hydraulic machine, a hole was drilled on the grip side to make room for a steel dowel which supports the axial load of the machine.

This jig design, however, did have some problems because the steel was not tempered after the milling was complete. Overtime, the jigs began to deform. The small differences in each grip, the top and the bottom led to an imbalance of the machine which would rotate the specimen and deform the entire Instron servo-hydraulic machine. The phenomenon is shown in (a) of Figure 69.

Figure 69: Specimen rotation due to jig deformations. (a) Jigs, specimens, and Instron servo-hydraulic machine in rotated position, (b) attempt at straightening jigs, (c) bolts bent.

In an attempt to fix this problem, a 0.25" steel plate with two holes was loaded to 4,000 lbs using the nuts and bolts used in the experiment. The goal was to attempt to straighten the jigs. This process is shown above in (b) of Figure 69. Unfortunately, this bent the bolts as shown in (c) of Figure 69, which required a high powered metal saw to cut through due to the tight tolerance between the jigs and the bolts.

Attempting to fix this problem also cause a malfunction with the Instron servo-hydraulic machine which caused permanent deformation in the top of the jig where it interfaces the shaft of the machine. This caused the jig to stick to the Instron interface shaft as shown below in Figure 70.

Figure 70: Final jig deformation issues. (a) Removing the jig from the interface shaft using a plumber's wrench and a vice, and (b) sanding down the deformed section.

Using a plumber's wrench, it was possible to remove the jig from the interface shaft as shown in (a) of Figure 70 above. It was then necessary to sand the deformed in order to prevent the same mistake as shown in (b) of Figure 70. Throughout all of the testing, it was discovered that bearing stress also had an effect on the jigs causing plastic deformation as shown below in Figure 71.

Figure 71: The plastically deformed jig caused by bearing stress while under compression. (a) Jig after sanding, and (b) jig immediately after removing from interface shaft.

4.11.4 FULFILLMENT OF JIG REQUIREMENTS

The majority of the requirements discussed above in §4.11 were met with a few exceptions:

- 1) Attaching test specimens to the Instron servo-hydraulic machine: This requirement was fully fulfilled using the third constructed jig.
- 2) Heat the specimen in a reasonable amount of time and maintain that heat until failure: This requirement was fulfilled using the thermal chamber discussed in §5.2. As can be seen by the test data in §6, the time required to heat the composite specimen to each temperature was relatively consistent. Additionally, temperature in the chamber was monitored throughout the test using a thermocouple not imbedded in a composite sandwich to make sure no large changes occurred.
- 3) Construction of a durable set of jigs: Although some deformation did occur as discussed in §4.11.3, the deformation was not in the area of interest.
- 4) Isolation of studied variable: Unfortunately, the studied variable was not entirely isolated because there were two holes in each specimen rather than one, meaning that failure occurred in both the top and bottom hole. However, all specimens were symmetric about all three axes, which should have factored out different failure locations. Of larger concern than failure location was type of failure discussed in §6.11. The studied variable could have been further isolated by creating a fixed condition at one end of the test. However, creating fixed ends with composite sandwiches is difficult without crushing the core and typically leads to failures at the boundary conditions.⁽¹⁾

5 EXPERIMENTAL SETUP AND PROCEDURE

The following sections detail the experimental setup used to test the specimens.

5.1 PREVIOUS THERMAL CHAMBER

The first thermal chamber created for the purpose of this research was constructed from aluminum, fiberglass insulation, four heat pads, and a thermal regulator which adjusted current to the heat pads in order to maintain a certain temperature.⁽¹⁾ This thermal chamber is shown below in Figure 72 with a specimen inside.

Figure 72: Previous thermal chamber used during senior project research.⁽¹⁾ (a) The thermal chamber up close with a specimen inside and (b) the thermal blanket which was required for insulation.

The chamber was designed and manufactured poorly. After only a few thermal trials, the thermal regulator broke causing the chamber to overheat, which led to the health hazards discussed in §2.5.2 and shown in Figure 29. Once the thermal regulator was properly fixed, it was necessary to insulate the entire assembly to get it up to temperature. A thermal blanket was used to do this as is shown above in Figure 72.

5.2 CURRENT THERMAL CHAMBER

As a result of the problems encountered in using the previous thermal chamber, an Instron recommended temperature controlled chamber was adopted. The Instron-SFL 3199-407 Temperature Controlled Chamber, shown below in Figure 73, provides a means of carrying out materials tests in an accurately controlled air temperature environment between the temperatures of $-150\text{ }^{\circ}\text{C}$ and $350\text{ }^{\circ}\text{C}$.⁽¹⁹⁾ For the purposes of this thesis, no tests were performed at any lower than room temperature because additional equipment would have been required. In the future, additional cooling pack and associated control equipment can be purchased if testing at temperature below ambient temperatures is desired.⁽¹⁹⁾

Figure 73: The Instron-SFL 3199-409 Temperature Controlled Chamber used in all thermal experiments.

The chamber consists of a rigid metal painted box, with a full frame door and window, designed to fit between the columns of a physical servo hydraulic machine.⁽¹⁹⁾ Pull rod access is provided on the top and bottom of the chamber as shown above in Figure 73 and all heating and light functions are controlled by a handset—all electrical control equipment is fitted into a compartment at the rear of the chamber.⁽¹⁹⁾

A perforated stainless steel frame surrounds the door and the inner chamber is insulated with Microtherm insulation.⁽¹⁹⁾ A centrifugal fan motor is mounted behind the inner box with a shaft which extends through the insulation into the inner chamber to the impeller fan.⁽¹⁹⁾ The fan pulls air through the

meshed center of a baffle plate via a type K control thermocouple and drives it behind the baffle, over the Inconel sheathed heating elements and the Ln2 coolant injector, and back into the top and bottom of the chamber.⁽¹⁹⁾ The fan motor also drives a second impeller mounted outside the insulation which circulates the air from the rear of the chamber into the inner space between the insulation and outer panels.⁽¹⁹⁾ An incandescent bulb in a holder, which can be controlled by the handset, can provide internal illumination.

Figure 74 below shows an internal schematic of the thermal chamber.

Figure 74: Internal schematic of the thermal chamber.⁽¹⁹⁾

The extensimeter shown above does not exist in the chamber used in the experiment.

Air circulation from the centrifugal fan within the inner chamber directs air as shown below in Figure 75.⁽¹⁹⁾ The airflow enables heat losses (or gains) from the testing machine pull rods to be counter balanced before the air circulates over the specimen at the center of the load train and then across the control thermocouple. To minimize any residual heat loss, the top pull rod hole was moved as close as possible to the load cell without touching.

Figure 75: Thermal chamber heat flow.⁽¹⁹⁾

A simple handset was used to control the internal temperature of the chamber, the light, and the fan. A schematic of the handset is shown below in Figure 76. Because the chamber temperature is measured in Celsius, conversions to degrees Fahrenheit were made prior to performing thermal trials. Additionally, the chamber had a propensity to display a lower than actual temperature. Extensive thermal trials were performed with a thermocouple inside a representative sandwich composite prior to performing any actual tests as explained in §4.7.4.

Figure 76: Thermal chamber handset.⁽¹⁹⁾

5.2.1 THERMAL CHAMBER HANDSET PROBLEM

Before any thermal trials took place, it was noticed that the handset was not working properly. No lights worked, and the handset would not deliver input to the thermal chamber circuit board. The operational manual⁽¹⁹⁾, recommended checking the fuses shown below in Figure 77. Unfortunately, this didn't solve the problem and the handset had to be replaced, which set back the experiment by about two months.

Figure 77: Fusel locations in the back of the thermal chamber.⁽¹⁹⁾

5.2.2 MOUNTING THE THERMAL CHAMBER

Because the thermal chamber is physically large and weighs about 150 lbs, mounting it was no trivial task. Initially, the chamber was lifted manually by four students. However, it was decided that this was an extremely dangerous process after two students were almost injured and expensive equipment almost broken. To solve this problem, a crane was purchased as recommended ⁽¹⁹⁾. The chamber was fastened to four chains, hoisted, and then fastened down to the high strength steel plates as shown below in Figure 78. This method was much safer and could be accomplished comfortably by two people.

Figure 78: Hoisting the thermal chamber with a crane to attach to the servo hydraulic machine.

5.3 TESTING APPARATUS

The testing apparatus used in all experiments was composed of two computers (one to collect summary data, and one to control the Instron servo hydraulic machine and generate stress-strain data), the thermal chamber, the thermocouple reader, and a fan. All of these components are shown below in Figure 79.

Figure 79: Final testing apparatus: (1) Computer for recording data, (2) Instron servo-hydraulic control computer, (3) Instron servo-hydraulic machine, (4) Instron environmental chamber, (5) fan to speed up cooling process.

The fan was used to cool the chamber in between tests to speed up the testing procedure. The thermocouple reader was extremely important in the thermal trials because it's what determined the temperature to set the thermal chamber whose temperature display was usually a few degrees off).

5.4 TESTING PROCEDURE

A rigorous set of procedures were developed prior to full scale testing to insure that no portion of the procedure would bias the results in any way. Throughout the preliminary tests, these procedures evolved over time as new and efficient methods were developed. Once full scale testing started however, the procedures were not changed. The following sections describe these procedures for the thermal trials, the static tests, and the fatigue tests.

5.4.1 THERMAL TRIALS

During the thermal trials, no specimens were tested. The goal of all thermal trials was to figure out the time required for the chamber to heat the specimen to the necessary temperature for the test. At

least five thermal trials were performed prior to each test condition. The time required to heat the specimens would vary with ambient temperature, humidity, and time of day, thus, such trials were always necessary before static or fatigue tests.

The first part of the procedure was to fasten in the specimen with the thermocouple as shown below in Figure 80.

Figure 80: Thermocouple part fastened inside the thermal chamber.

Then, the thermal chamber door was closed and the chamber was turned on and time was started. The temperature was originally set to the direct conversion from Fahrenheit to Celsius, however because the chamber only has whole numbers, and typically heats up a little more than specified, the handset value was typically varied. This is reflected below in §6 in all the table summaries of the thermal trials.

In addition to the thermocouple in the part (T2), there was one inside of the chamber which measured the chamber air temperature (T1). The thermocouple reader is shown below in Figure 81. Notice that the reader has a button labeled T1 and T2. These are two separate channels, one for each thermocouple used in the experiment.

Figure 81: Thermocouple reader.

Once the absolute value of $T_1 - T_2$ was less than two degrees, time was stopped, and the heating function of the chamber was turned off. The fan was then turned on to cool the chamber and the thermocouple part as quickly possible.

This procedure was repeated a minimum of five time before testing at any given temperature with the exception of 75 °F.

5.4.2 STATIC TESTS

Before starting a static test, it was important to measure the length, width, and thickness of the specimen with a set of calipers. These values were then recorded on the Google Document, and in the Instron Blue Hill software. The specimen was put in the grips and the external fan was turned off (unless it was the first test). A picture was taken of the specimen, and then the doors were closed. Using the Instron Blue Hill software, the load was balanced to zero (it was extremely important to do this, otherwise the load and stress calculations would not be accurate).

Then, the timer, heat and chamber fan were started. After the average time for each specific temperature passed, the temperature was recorded, the timer was reset, and the test was started. Each test typically lasted less than five minutes. After those five minutes, the chamber fan and heat were turned off and the final temperature was recorded in the Google Document. This was important to ensure

that no great temperature fluctuations occurred during the test. The time of the test was also recorded because thermal fatigue has the potential to weaken specimens that are in the chamber for longer periods of time. Lastly, the maximum load was recorded to quickly compare to other tests.

After the test, the chamber was opened, the external fan was turned on to help cool down the chamber, a picture was taken, and the specimen was taken out. After the specimen was removed, additional pictures were taken to examine the damage.

5.4.3 FATIGUE TESTS

The fatigue procedure was identical to the static procedure with the exception of the loading condition. In typical fatigue tests, the part is ramped to a value below yield and then cycled at constant amplitude (A). The amplitude is usually a sinusoidal wave with the amplitude varying as a percentage of yield force.

For the purpose of this research, each specimen was ramped to 50% yield at room temperature (defined as the first drop in a stress-strain curve), and then loaded at a constant sinusoidal amplitude of 65% yield. Such a low amplitude was chosen because yield at room temperature plus half of 70% amplitude is greater than yield at 200 °F. A frequency (f) of 5 Hz was chosen because in preliminary tests it provided a smaller standard deviation as shown in Table 6.

Table 6: Summary of Fatigue Frequency Testing Results

Frequency	Avg. # of Cycles	Std Dev
(Hz)	(-)	(-)
5	5555	69.46%
10	7032	87.41%

Figure 82 shows a typical test profile for the fatigue tests performed. A represents the amplitude and f represents the frequency. Six total conditions were tested, one for each temperature.

Figure 82: Profile of a typical fatigue test.

The Instron servo hydraulic machine would run until it reached the failure criteria, which was chosen as the average displacement of room temperature specimens at their yield condition, a value of 0.0544" for control specimens and 0.0597" for specimens with inserts. The only value of interest in the fatigue tests are the number of cycles. A cycle in this instance is defined as starting at 50% yield, increasing to 82.5% yield, decreasing to 17.5% yield, and then increasing back to 50% yield. Due to the mechanical nature of fatigue tests, extremely high standard deviations between specimens were expected.

5.4.4 BURN TEST PROCEDURE

In order to perform a burn test, it was first necessary to remove the carbon fiber LTM45 facesheets from the foam core. This was done using a box knife. The result is shown below in Figure 83.

Figure 83: Separating the facesheet from the foam core.

After separating the facesheet, it was necessary to cut it into small 1" by 1" squares. In reality any dimension can be used. In this instance, oven size and facesheet size determined the size of the squares. The cutting process and final results are shown below in Figure 84.

(a)

(b)

Figure 84: Burn test preparation. (a) Cutting the facesheet into 1" by 1" squares, and (b) The final result.

After cutting and drying the squares, they were weighed. Unfortunately, the scale used doesn't have high sensitivity at low weights, so their weight was a relatively rough estimation. The weighing process is shown below in Figure 85.

Figure 85: Weighing the 1" by 1" carbon fiber squares prior to the burn test.

Once weighed, the square specimens were all placed on a piece of sheet steel, placed in the oven, burned, and reweighed to find how much resin had burned off. This process is shown below in Figure 86.

(a)

(b)

Figure 86: Performing the burn test. (a) The oven used to burn the resin off the fibers, and (b) The square specimens placed on a sheet of steel to be placed in the oven.

The results of the burn test are available in §6.1.

5.4.5 COEFFICIENT OF THERMAL EXPANSION TEST PROCEDURE

As discussed in §3.3, the coefficient of thermal expansion, or simply α , describes how the size of an object changes with respect to temperature. More specifically, it's a measure of the fractional change

in size per degree change in temperature at constant pressure. All substances expand or contract with a change in temperature.

In order to properly model the heat characteristics of the carbon fiber and the foam in the numerical analysis presented in chapter 7, it was necessary to measure the coefficient of thermal expansion. To do this, strain gages were attached separately to the foam and carbon fiber as shown below in Figure 87.

Figure 87: Specimens of constituent materials equipped with thermal resistant strain gages. (a) Carbon fiber and (b) foam.

The strain gages used could withstand temperatures up to 275 °F. The strain gage pamphlet recommends using a gage factor of 2.0. Gage factor or strain factor is the ratio of relative change in electrical resistance to the mechanical strain, which is relative to the change in length as described by equation (22) below.

$$GF = \frac{\frac{\Delta R}{R}}{\frac{\Delta \rho}{\rho}} = \frac{\frac{\Delta \rho}{\rho}}{\frac{\Delta \rho}{\rho}} + (1 + 2\nu) \quad (22)$$

$$\frac{\Delta R}{R} = GF\varepsilon + \alpha\theta$$

In the above equation, ϵ is strain, ν is Poisson's ratio, ρ is resistivity, ΔR is the change in strain gage resistance, R is the unstrained resistance of the strain gage, α is the coefficient of thermal expansion, and θ is the change in temperature.

With the gage factor set on the reader box, shown below in Figure 88 (a), the specimens were individually placed in the thermal chamber shown below in Figure 88 (b).

(a)

(b)

Figure 88: Strain gage setup for thermal expansion test. (a) Strain gage reader and (b) specimens inside of the thermal chamber.

Once inside the chamber, readings were taken at temperatures of 75, 100, 115, 125, 130, 145, 150, 160, 175, and 200 °F respectively. The temperatures in intervals of 25 °F were measured for static testing, and the temperatures in intervals of 15 °F were measured for fatigue testing. The actual temperatures set on the thermal chamber were found during the thermal trials described throughout chapter 6. Prior to recording values, it was important to wait a few minutes at each temperature for the part to fully warm up and expand.

The test results can be found in §0.

5.5 SAFETY CONSIDERATIONS

The initial testing period had several key elements that had a high level of danger. The layup procedure has virtually no mechanical safety concerns. The testing procedure, on the other hand, has inherent risks involved.

The Instron servo-hydraulic machine operates in the hundreds and often thousands of pounds range, which means that all Instron procedures need to be closely regulated. The test procedure outlined above was deemed to have a more than adequate level of safety. The safety regulations were followed precisely throughout the entire testing procedure and led to no injuries or accidents throughout the entire experiment.

The original heating chamber was also a large source of safety concern due to its homemade design and high operating temperatures. High temperature risks were easily mitigated with the use of certified heat resistant welding gloves. As a result of these gloves the insertion and removal of the test specimens led to only superficial accidents and injuries. In the future the thermal chamber would need to be redesigned and remanufactured in order to make it more user-friendly and more reliable which would severely reduce the possible safety concerns.

6 EXPERIMENTAL RESULTS AND DISCUSSION

This section details the comprehensive results of all experiments performed. These experiments included some preliminary research such as weight and volume fractions which aided in the determination of the material characteristics of the sandwich composite for use in numerical modeling and troubleshooting unintended failures. The material properties tests were used to determine the bulk modulus of elasticity of the individual parts of the composite sandwich and the sandwich as a whole. The effect of strain rate on statistical deviation tests, which were performed in conjunction with another graduate student, examine how rate determine standard deviation. These results were obtained in conjunction with another graduate student to examine how insert thickness effects ultimate load.⁽¹³⁾

After the preliminary research was completed, the bulk of the research concentrated on the effect of temperature on control specimens and specimens with DADs under static compression-compression loading and fatigue.

6.1 WEIGHT AND VOLUME FRACTIONS

Burn tests were performed, as described in §5.4.4 to find the volume and weight fractions of the carbon fiber LTM45 facesheets to determine whether or not to use the film adhesive and to measure values used in theoretical calculations.

6.1.1 BURN TEST RESULTS

The results of the two burn test results are shown below in Table 7. Wt stands for weight and the two subscripts i and f stand for initial and final.

Table 7: Burn test results for composite sandwich manufactured with and without film adhesive.

Trial:	Without Film Adhesive		With Film Adhesive	
Specimen	Wt _i (g)	Wi _f (g)	Wt _i (g)	Wi _f (g)
1	1.4	0.8	0.9	0.5
2	1.4	0.8	0.9	0.5
3	1.6	0.8	0.9	0.6
4	1.4	0.8	0.9	0.5
5	1.2	0.6	0.9	0.6
6	1.4	0.8	0.9	0.6
Average	1.4	0.767	0.9	0.55

Six specimens were tested for each group and averaged. The addition of the film adhesive increased the resin content of the facesheets by about 6%, from 54.8% to 61.1% by weight. Although these values are informative, the majority of the reviewed literature⁽⁵⁾⁽¹⁴⁾⁽¹⁵⁾ examines volume fractions for the many reasons explained in §3.1. Thus, the weight fractions were converted to volumetric fractions using the formulations derived in §3.1 and the densities. The densities for the specimens manufactured with the film adhesive were 6.57 g/cm³ for the composite, 5.60 g/cm³ for the pre-impregnated carbon fiber, and 1.24g/cm³ for the matrix. Then, the critical volumetric fraction, V_{crit} , was found. The results are shown below in Table 8.

Table 8: Volumetric fractions calculated from weight fractions.

V_f w/o Film Adhesive	64.2%
V_m w/o Film Adhesive	35.7%
V_f w/ Film Adhesive	71.7%
V_m w/ Film Adhesive	28.3%
V_{crit}	68.5%

These results show that the matrix volume fraction dropped by 7.5% in contrast to the 6% increase in mass. This inconsistency most likely arose from the inaccuracy of the scale and/or variations in the burn technique. Nevertheless, the volume fraction of the composite with the film adhesive, the design adopted for all experimental results, is 3.2% higher than V_{crit} , indicating that the composite exceeded the strain hardening and plastic flow of the matrix, making the composite more brittle than it would be if it were manufactured for optimum strength. Nevertheless, the research was intended to study the damage effects between bolts and holes that occur regardless of how optimally saturated the specimens. Without the film adhesive, it was impossible to manufacture specimens as described in §2.5.3.

6.2 MATERIAL PROPERTIES RESULTS

Each of the constituent materials, the LTM45 and the FR-6710 were tested to obtain their material properties which were subsequently used for theoretical and numeric analysis. The most important material property was the modulus of elasticity, because although inter-laminar effects are important, the stiffness of the material is primarily what determines the specimen's maximum load in

pure compression. The values tested for below were all used to generate an accurate finite element model as discussed in §7.

6.2.1 BULK MODULUS OF ELASTICITY AND POISSON'S RATIO

The first important results to obtain were the stiffness and Poisson's ratio. The testing and results are covered in this section for the foam, carbon fiber, and overall composite sandwich.

6.2.1.1 POLYURETHANE FOAM

The FR-6710 was cut into five 2" by 2" by 0.5" specimens and tested with plate-plate boundary condition as shown in Figure 89.

Figure 89: Testing for the material properties of FR-6710 foam.

The modulus of elasticity and Poisson's ratio were calculated from the stress-strain curves generated from the load-extension curves acquired during the tests. The load-extension curves are shown below in Figure 90.

Figure 90: Load-extension results for FR-6710 foam plate-plate compression.

The calculated material properties were then compared to manufacturer claims. The compared results are shown below in Table 9.

Table 9: Material characteristics of FR-6710 acquired from test data compared to manufacturer values.

	Compressive Strength (psi)	Percent Difference (-)	Elastic Modulus (psi)	Percent Difference (-)	Poisson's Ratio (-)	Percent Difference (-)
Manufacturer	340	-20.6%	11,240	-34.8%	0.30	-63.3%
Experimental Testing	270		7,330		0.11	

The compressive strength of the foam decreased by 20.6% and the elastic modulus decreased by 38.4%. The decreases in strength and stiffness could be caused by a variety of sources. The manufacturer didn't disclose how their material properties were acquired. It's extremely likely that their testing procedure was different than the one described above. Foam also has a large propensity to degrade and lose strength over time.⁽⁵⁾ Humidity, sunlight, and prolonged air exposure can all contribute to the loss in quality of foam over time. Additionally, the manufacturer states that the foam may behave differently in the longitudinal and transverse directions. This could have contributed to the discrepancy as well as some of the experimental error encountered in the research.

6.2.1.2 CARBON FIBER

The LTM45 carbon fiber was tested using ASTM D3410 and analyzes to acquire material properties. The testing apparatus is shown below in Figure 91.

(a)

(b)

Figure 91: Testing apparatus for carbon fiber material properties. (a) Instron servo-hydraulic machine with carbon fiber specimen and (b) multiple carbon fiber specimens.

During the test, force displacement data was gathered. From the specimen dimensions, a stress strain curve was generated which allows the elastic modulus and Poisson's ratio to be calculated. A strain gage was also used in the measurement of the Poisson's ratio. The results can be seen below in Table 10.

Table 10: Material properties for LTM45 carbon fiber.

	Compressive Strength (psi)	Percent Difference (-)	Elastic Modulus (psi)	Percent Difference (-)	Poisson's Ratio (-)	Percent Difference (-)
Manufacturer	214,000	-35.0%	17,260,000	-58.6%	(N/A)	N/A
Experimental Testing	130,000		7,149,000		0.11	

When compared with manufacturer stated values, the LTM45 lost 35% of its compressive strength and 58.6% of its stiffness. These decreases can be attributed to degradation of the material over time. It was donated by Boeing in 2005 because it didn't meet Federal Aviation Administration (FAA) specifications. It was stored in a freezer for three years at a temperature 10 °F warmer than recommended by the manufacturer, and often exposed to room temperature for long periods of time. These poor

environmental conditions also could have contributed to the form adherence problems explained in §2.5.3. Regardless of the decreases in strength and stiffness, the carbon fiber was still an adequate candidate for facesheet selection because it is much stiffer than the foam.

6.2.1.3 OVERALL COMPOSITE SANDWICH

The elastic modulus and Poisson's ratio were also tested for the overall composite sandwich panel. The sandwiches were prepared as discussed in §0, and then tested in compression to acquire force-displacement data, which was turned into stress-strain data, which was then used to calculate the material properties. The generated stress-strain plots are shown below in Figure 92.

Figure 92: True yield results for sandwich specimens manufactured for material properties calculation.

Only some of the specimens were included in the final calculations because the ASTM standard used specified that a fracture on the boundary condition is not a true failure. As shown below in Figure 93, many of the specimens failed at the boundary condition. Fortunately, regardless of the type of failure, the failure forces were all extremely close. To fix this problem in the future, it might be advisable to use aluminum or steel blocks instead of wood. However doing so would require more time because cutting the specimen down to size could not be done with the tile saw as described in §4.8.

Figure 93: Fractured specimens of the overall material properties test.

With the stress-strain data, the equations discussed in §3.2 were used to generate the results shown below in Table 11.

Table 11: Overall Material Characteristics of Manufactured Composite Sandwiches

	Elastic Modulus (psi)	Percent Difference (-)	Poisson's Ratio (-)	Percent Difference (-)
Theoretical	62,650	33.6%	0.30	28.7%
Experimental Testing	41,600		0.214	

The theoretical calculations generate an elastic modulus of 63,650 psi and a Poisson's ratio of about 0.3, whereas the experimental tests give an elastic modulus of 41,600 psi and a Poisson's ratio of 0.214. The theoretical results over predict the material properties of the composite sandwich panels most likely because they assume a perfect inter-laminar bond.

6.2.2 COEFFICIENT OF THERMAL EXPANSION RESULTS

The results from the experimental procedure described in §5.4.5 is available in this section.

These values needed to be measured to compare with manufacturer claims and to aid in constructing the numeric model described in §7.

6.2.2.1 FOAM

For the FR-6710 foam, the strain gages supplied a strain at each temperature. Table 12 details these results.

Table 12: Strain Gage Results for Foam Thermal Expansion

Temperature °C	Strain in/in
23	0
37	267
46	440
51	520
54	580
62	685
63	715
70	805
78	850
92	800

Using the regression equation found on the pamphlet inside the strain gage package, these values yielded a thermal expansion coefficient, α of $2.33\text{e-}5$. This range is relatively close to the manufacturer claims, which were $2.12\text{e-}5$. Typically, polyurethane foam has a coefficient of thermal expansion between $1\text{e-}5$ and $3\text{e-}5$, so this measured value seemed reasonable. When used in the numerical modeling, the results were also extremely close to experimental data collected.

6.2.2.2 CARBON FIBER

Unfortunately regardless of the strain gage or type of strain gage used, the LTM45 carbon fiber coefficient of thermal expansion could not be measured. For the first few temperatures, data could be recorded, but after about 100 °F, the strain gage would stop functioning. Even using strain gages that are suppose to operate up to 250 °F didn't work properly. Nevertheless, the manufacturer tested a coefficient of thermal expansion, α of $6\text{e-}7$ and this was the value used in numeric modeling.

6.3 THE EFFECT OF RATE ON STATISTICAL DEVIATION

When designing the testing procedure, it was necessary to pick a strain rate to compress the specimens. Rather than arbitrarily choosing a value, ten specimens were tested at each of the following five strain rates: 0.5, 0.75, 1.0, 1.25, and 1.5 mm/min. The primary goal was to minimize error by minimizing standard deviation. With so many other variables such as manufacturing defects, material inconsistencies, humidity, and duration of time in the thermal chamber, reducing error wherever possible was a top priority. Although all of the units used in the report are in United States customary units, it is not possible to switch the Instron machine strain rate out of Metric units. Although strain rate optimization is usually done on a log scale (i.e. tested at values of 0.1, 1.0, 10.0, 100.0 mm/min), strain rates were chosen in the order of magnitude recommended by Instron and proven in the Cal Poly Structures / Composites Laboratory previously. Figure 94 below shows the load extension curves from the ten specimens tested at 0.5 mm/min.

Figure 94: Effect of rate on statistical deviation.

Notice that the curves are extremely close together. A strain rate of 0.5 mm/min was chosen because of all the rates tested, it had the smallest standard deviation--a value of 4.21%. All of the standard deviations, maximum force, and bulk modulus values are available below in Table 13.

Table 13: Summary of strain rate results.

Rate (mm/min)	P _{cr} (lb)	Std Dev (-)	E (psi)	Std Dev (-)
0.5	1,011	4.91%	45,170	4.21%
0.75	983	9.54%	48,940	7.53%
1.0	934	36.51%	37,530	51.92%
1.25	926	12.71%	45,010	9.51%
1.5	940	7.34%	46,270	5.03%

Although 0.5 mm/min extended the length of each test, reducing the error provided more legitimacy to the results and allowed less specimens to be tested.

6.4 THE EFFECT OF INSERT THICKNESS ON ULTIMATE LOAD

Once a strain rate was chosen as described above in §6.3, and a geometry was decided on as described in §2, it was necessary to evaluate the thickness of the damage arrestment device. Ten specimens, each with 1, 2, 3, 4, 5, 6, and 7 layer carbon fiber inserts respectively, were tested. In order to accomplish this feat, the foam had to be milled at different depth as described in §4.4. Figure 95 below shows the stress-strain curves of the ten specimens with the chosen thickness of three layers of LTM45 carbon fiber.

Figure 95: Finding the optimal insert thickness.

The results of the study are summarized below in Table 14. Three layer inserts were chosen because they provided the smallest standard deviation in terms of maximum failure load while still providing a great increase in maximum failure load.

Table 14: Summary of results for insert thickness study.

Ply (# of Layers)	P_{cr} (lb)	Std Dev (-)	E (psi)	Std Dev (-)
0	1,010	4.89%	45,170	4.21%
1	1,380	9.37%	70,470	12.25%
2	1,570	8.80%	74,800	8.72%
3	1,650	2.43%	59,340	17.14%
4	1,860	6.40%	86,560	12.41%
5	2,160	6.71%	103,060	4.96%
6	2,120	10.92%	95,950	5.48%
7	2,020	9.67%	66,196	14.46%

Figure 96 below shows the average maximum load of each insert thickness. At thicknesses of six and seven layers the maximum load begins to decrease because of the relative thickness of the LTM45 carbon fiber insert compared to the foam region as explained in §0. The thicker the insert, the more difficult the

plate was to manufacture. At an insert thickness of seven layers, the plate broke multiple times because too much foam was removed making the core extremely weak.

Figure 96: Affect of ply thickness of inserts on ultimate load.

6.5 MECHANICAL BEHAVIOR OF COMPOSITE SANDWICH PANELS SUBJECTED TO MONOTONIC COMPRESSION AT ELEVATED TEMPERATURES

This section details the results of the first quarter of the major bulk of research performed for this thesis—the control specimens under monotonic compression at elevated temperatures. In order to perform the experiment designed in §2, the methods described in §5, ten specimens each were tested at six different temperatures: 75, 100, 125, 150, 175, and 200 °F. This section discusses possible problems that could have skewed the results during the tests, the results, and the significance of those results.

6.5.1 75 DEGREES (ROOM TEMPERATURE)

This section details the monotonic compression tests performed on control specimens at 75 °F.

6.5.1.1 WARM UP

Because San Luis Obispo has such temperate weather, it was not necessary to heat the specimens to 75 °F.

6.5.1.2 EXPERIMENTAL RESULTS

Ten specimens were tested at 75 °F which provided an average yield load of 747 pounds with a standard deviation of 10.1% with and an average ultimate load of 807 lb with a standard deviation of 6.1%. These results and other values of interest are shown below in Table 15.

Table 15: Summary of compression testing results at 75 °F.

Compression at 75 °F									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0409-01	FALSE	3.26	548	3.26E-02	602	6.77	605	6.77E-02	842
0409-02	FALSE	2.97	723	3.02E-02	814	3.97	510	4.04E-02	816
0409-03	TRUE	2.83	470	2.86E-02	524	6.41	537	6.48E-02	711
0409-04	FALSE	3.66	656	3.68E-02	748	6.78	638	6.81E-02	818
0409-05	FALSE	3.21	682	3.25E-02	743	4.37	611	4.41E-02	748
0409-06	FALSE	3.10	682	3.11E-02	774	4.96	592	4.97E-02	856
0409-07	FALSE	3.25	642	3.26E-02	718	6.66	584	6.68E-02	727
0409-08	FALSE	4.49	745	4.57E-02	833	5.22	614	5.31E-02	837
0409-09	TRUE	4.07	910	4.11E-02	1018	4.86	600	4.90E-02	1027
0409-10	TRUE								
W/ Outliers	Avg.	3.43	673	3.46E-02	753	5.56	588	5.60E-02	820
	% Error	15.9%	18.4%	16.2%	18.6%	19.9%	6.8%	19.6%	11.4%
	Error	0.55	124	5.59E-03	140	1.11	40	1.10E-02	94
W/O Outliers	Avg.	3.42	668	3.45E-02	747	5.53	593	5.57E-02	807
	% Error	15.2%	9.6%	15.5%	10.1%	21.6%	6.9%	21.2%	6.1%
	Error	0.52	64	5.35E-03	76	1.20	41	1.18E-02	49

Figure 97 below shows the yield and ultimate forces for each specimen, with the standard deviation error bars, all around the average value represented by a blue line. The error bars shown for each trial were calculated as the standard deviation of the entire trial data set. Specimen 3 was thrown out because the force balance on the Instron servo hydraulic machine was not properly balanced and specimen 9 was thrown out because of a manufacturing defect. Specimen 10 was not tested because it was crushed in the machine while trying to trouble shoot an instrumentation error.

Figure 97: Compressive yield and ultimate loads of all specimens tested at 75 °F.

Figure 98 shows the stress-strain and force-displacement curves of all of the specimens tested at 75 °F. The yield value for each specimen, defined as the first major drop in the stress-strain curve in which the specimen is loaded beyond the linear-elastic region and retains plastic deformation, was found manually. The noise at the beginning of each stress-strain curve was removed. This noise usually occurs prior to the bolts making contact with the inside boundary of each hole. Removing the noise allows the stress-strain curves to be lined up easily enough to make sure their bulk modulus, or E values are close. Lastly, it is important to note that although the second horizontal and vertical axes are labeled as compressive force, $F_{compressive}$, and displacement, δ , these are average values because each specimen had a slightly different cross sectional area, so an average was taken. The difference in cross section areas between specimens was so small that the force and displacement axes locations are extremely close. The values above in Table 15 are also correct.

Figure 98: Stress-strain and force-displacement curves of all specimens tested at 75 °F.

6.5.2 100 DEGREES

This section details the monotonic compression tests performed on control specimens at 100 °F.

6.5.2.1 WARM UP

Prior to testing the specimens, heat trials were conducted to measure the amount of time necessary to heat up the specimens being tested. The thermocouple part described in §4.7.4 was placed in the thermal chamber and heated as described in §5.4.1. Table 16 below shows the results.

Table 16: Time required to heat specimen to 100 °F in the thermal chamber.

Time Required to Warm to 100 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:06:13	74.8	97.3	2.1	0:04:29	0:00:45
2	0:04:34	76.4	98.7	2.2	0:04:29	0:00:45
3	0:04:47	74.9	98.1	2.0	0:04:29	0:00:45
4	0:04:32	76.1	98.5	1.9	0:04:29	0:00:45
5	0:04:32	75.8	98.5	1.9	0:04:29	0:00:45
6‡	0:04:00	77.6	99.6	2.0	0:04:29	0:00:45
With Outliers	Avg. Time	0:04:46				
	%σ	15.79%				
Without Outliers	Avg. Time	0:04:29				
	%σ	6.46%				

Date of Trials	7/2/2010	
Time of Day	1:00:00-7:00:00	PM
Room Temp.	72.8	°F
Temp. in Celsius	37.78	°C
Temp. for Chamber	37	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† Changed temperature in chamber because it ramped too fast

‡ The final measured time to temperature after all the testing was completed

The six thermal trials yielded an average time of 0:04:30 with a standard deviation of 6.46% at a room temperature of 72.8 °F. It's important to note that the average is highly dependent on the room temperature. Thus, throughout the experiment it was important to finish a set of trials within a time window when the room temperature didn't change significantly. If the tests could not be completed in a single day, the thermal trials were repeated. Figure 99 below shows the average time to temperature with each of the six trials.

Figure 99: Time required to heat specimen to 100 °F in the thermal chamber.

6.5.2.2 EXPERIMENTAL RESULTS

Once the time required to heat the specimens to temperature was determined, all ten specimens were tested—Table 17 details the results.

Table 17: Summary of compression testing results at 100 °F

Compression at 100 °F									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0410-01	TRUE	5.34	889	5.34E-02	972	5.69	584	5.69E-02	982
0410-02	TRUE	2.89	316	2.93E-02	357	4.12	278	4.19E-02	386
0410-03	FALSE	2.76	555	2.80E-02	616	5.38	473	5.46E-02	767
0410-04	FALSE	4.42	494	4.36E-02	569	9.75	487	9.62E-02	652
0410-05	FALSE	3.67	555	3.70E-02	613	6.66	561	6.70E-02	786
0410-06	FALSE	3.62	515	3.64E-02	585	5.89	508	5.91E-02	662
0410-07	TRUE	4.35	747	4.37E-02	849	4.91	576	4.93E-02	854
0410-08	FALSE	3.75	460	3.80E-02	528	6.64	560	6.72E-02	668
0410-09	FALSE	3.29	392	3.33E-02	438	7.21	558	7.31E-02	678
0410-10	FALSE	5.97	531	6.04E-02	599	8.54	499	8.65E-02	613
W/ Outliers	Avg.	4.01	545	4.03E-02	612	6.48	509	6.52E-02	705
	% Error	25.8%	30.3%	25.6%	29.4%	26.1%	17.7%	25.6%	22.5%
	Error	1.03	165	1.03E-02	180	1.69	90	1.67E-02	159
W/O Outliers	Avg.	3.93	500	3.95E-02	564	7.15	521	7.20E-02	689
	% Error	26.3%	11.7%	26.2%	11.2%	21.3%	7.3%	20.6%	9.2%
	Error	1.03	59	1.04E-02	63	1.52	38	1.48E-02	63

At 100 °F, an average yield load of 564 lb with a standard deviation of 26.2% and an ultimate load of 689 lb with a standard deviation of 9.2% were recorded. This represents a significant drop from the specimens tested at room temperature (75 °F). Specimen 1 was thrown out because it took much longer to reach

temperature than the other specimens and may have made contact with the grips. Specimen 2 was thrown out because it had a much smaller thickness than the other specimens. Specimen 7 was thrown out because it appeared to have some manufacturing damage. Figure 100 shows the average yield and ultimate forces for each specimen. Notice how tightly coupled the forces are. The specimens that were tested correctly and not found to have any manufacturing defects proved to behave nearly identically when tested.

Figure 100: Compressive yield and ultimate loads of all specimens tested at 100 °F.

Figure 101 on the next page shows the stress-strain and force-displacement curves for the specimens tested at 100 °F. Notice how the stress-strain curves of the specimens not only reduce in load compared to the specimens tested at 75 °F, but also start to get noisier in the plastic region (after the specimen has yielded). This is most likely due to the resin becoming gooier as temperature increases

Figure 101: Stress-strain and force-displacement curves of all specimens tested at 100 °F.

6.5.3 125 DEGREES

This section details the monotonic compression tests performed on control specimens at 125 °F.

6.5.3.1 WARM UP

Six thermal trials were performed at 72.8 °F to find the average time necessary to heat the control specimens to 125 °F. It was discovered that, on average, it took 0:10:25 to get to temperature, with a standard deviation of about 4%. The first trial was thrown out because it included the time to warm the inside of the thermal chamber. Table 18 details the results from the thermal trials.

Table 18: Time required to heat specimen to 125 °F in the thermal chamber.

Time Required to Warm to 125 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:12:20	73.9	123.1	2.0	0:10:25	0:00:53
2	0:10:53	76.5	122.6	2.0	0:10:25	0:00:53
3	0:10:21	75.6	122.9	1.9	0:10:25	0:00:53
4	0:10:46	75.3	122.1	2.1	0:10:25	0:00:53
5	0:10:16	76.6	122.4	2.0	0:10:25	0:00:53
6‡	0:09:47	74.2	122.5	1.9	0:10:25	0:00:53
With Outliers	Avg. Time	0:10:44				
	%σ	8.18%				
Without Outliers	Avg. Time	0:10:25				
	%σ	4.21%				

Date of Trials	7/3/2010	
Time of Day	1:00:00-7:00:00	PM
Room Temp.	72.8	°F
Temp. in Celsius	51.67	°C
Temp. for Chamber	51	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† The chamber was not pre-heated like all the other trials

‡ The final measured time to temperature after all the testing was completed

Figure 102 below plots the times from each thermal trial, as well as the average and the standard deviation. Notice that, as explained above, the first trial took longer because the thermal chamber had been sitting at room temperature.

Figure 102: Time required to heat specimen to 125 °F in the thermal chamber.

6.5.3.2 EXPERIMENTAL RESULTS

When the thermal trials were complete, monotonic testing could resume. Table 19 below details the results of monotonic testing that occurred at 125 °F. The specimens had an average yield force of 548 lb with a standard deviation of 12.1% and an ultimate force of 630 lb with a standard deviation of 7.7%.

Table 19: Summary of compression testing results at 125 °F

Compression at 125 °F									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0419-01	FALSE	4.03	526	4.03E-02	594	7.27	545	7.27E-02	689
0419-02	TRUE	4.55	684	4.40E-02	725	5.53	565	5.35E-02	727
0419-03	FALSE	3.48	438	3.53E-02	490	7.33	473	7.44E-02	574
0419-04	TRUE	4.05	654	4.10E-02	728	6.14	483	6.22E-02	735
0419-05	FALSE	4.66	562	4.70E-02	635	5.92	534	5.97E-02	665
0419-06	TRUE	3.37	300	3.41E-02	336	6.78	492	6.85E-02	553
0419-07	FALSE	3.94	530	3.93E-02	596	6.89	501	6.88E-02	650
0419-08	FALSE	3.53	479	3.57E-02	534	7.34	515	7.43E-02	581
0419-09	FALSE	4.88	483	4.95E-02	542	7.83	514	7.95E-02	586
0419-10	FALSE	3.68	405	3.69E-02	445	6.79	559	6.82E-02	668
W/ Outliers	Avg.	4.02	506	4.03E-02	563	6.78	518	6.82E-02	643
	% Error	13.2%	22.5%	12.9%	21.6%	10.6%	6.1%	11.5%	10.2%
	Error	0.53	114	5.19E-03	121	0.72	32	7.81E-03	66
W/O Outliers	Avg.	4.03	489	4.06E-02	548	7.05	520	7.11E-02	630
	% Error	13.6%	11.3%	13.8%	12.1%	8.6%	5.6%	8.9%	7.7%
	Error	0.55	55	5.61E-03	66	0.60	29	6.29E-03	48

Specimens 2 and 4 were not included in the final average because the Instron servo hydraulic machine force balance was not properly reset, which made the specimens appear to support more load. Specimen

6 was removed because it had been fractured prior to testing. Figure 103 below shows the yield and ultimate loads of each individual specimen compared to the average with standard deviation error bars.

Figure 103: Compressive yield and ultimate loads of all specimens tested at 125 °F.

Figure 104 below shows the stress-strain and force-displacement curves of each specimen. Notice, how explained in the previous section, that the stress-strain curves become more noisy in the failure / plasticity zone most likely due to the thermal effects on the resin. As before, all stress-strain curves were zero prior to plotting below in Figure 104.

Figure 104: Stress-strain and force-displacement curves of all specimens tested at 125 °F.

6.5.4 150 DEGREES

This section details the monotonic compression tests performed on control specimens at 150 °F.

6.5.4.1 WARM UP

Six thermal trials were completed to find the average time necessary to heat the specimens to 150 °F. It was found, that on average, it took 0:17:02 to heat the specimens. These trials are summarized below in Table 20. The last trial was thrown out because the stop watch was incorrectly operated. The first trial was not thrown out as it was in the previous sections because this testing was performed immediately following the testing performed at 125 °F, thus, the chamber was already much warmer than room temperature.

Table 20: Time required to heat specimen to 150 °F in the thermal chamber.

Time Required to Warm to 150 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5 σ w/ Outliers
1†	0:17:49	68	145.3	2.0	0:17:02	0:02:15
2	0:18:59	67.7	145.3	3.0	0:17:02	0:02:15
3	0:16:52	69.7	146.5	3.2	0:17:02	0:02:15
4	0:15:06	73.1	146.4	2.0	0:17:02	0:02:15
5	0:16:25	73.2	146.6	2.4	0:17:02	0:02:15
6‡	0:12:34	73.6	147.2	1.7	0:17:02	0:02:15
With Outliers	Avg. Time	0:16:18				
	% σ	13.78%				
Without Outliers	Avg. Time	0:17:02				
	% σ	8.59%				

Date of Trials	7/5/2010	
Time of Day	11:30:00-8:00:00	AM, PM
Room Temp.	65.8	°F
Temp. in Celsius	65.56	°C
Temp. for Chamber	63	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† Needed to add 15 seconds because the timer wasn't started at the right time

‡ The final measured time to temperature after all the testing was completed

Figure 105 below shows the thermal trials compared to the average with standard deviations as error bars. It is not possible to know exactly how long each individual specimen will take to get to temperature, but

Figure 105: Time required to heat specimen to 150 °F in the thermal chamber.

6.5.4.2 EXPERIMENTAL RESULTS

After the thermal trials were complete, ten specimens were tested at 150 °F. The specimens tested had an average yield force of 463 lb with a standard deviation of 21.1% and an ultimate load of 556 lb with a 5.3% standard deviation. Table 21 details these results. The standard deviation was probably much higher than the previous trials because as the temperature increased, each individual specimen reacted a little differently. It seems as if higher temperatures magnify manufacturing defects.

Table 21: Summary of compression testing results at 150 °F

Compression at 150 °F									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0410-01	FALSE	2.76	337	2.76E-02	390	5.95	482	5.95E-02	583
0410-02	FALSE	3.08	483	3.09E-02	555	6.18	481	6.20E-02	575
0410-03	TRUE	3.41	592	3.42E-02	667	4.63	480	4.64E-02	694
0410-04	FALSE	3.03	473	3.05E-02	538	4.71	421	4.73E-02	541
0410-05	FALSE	5.13	422	5.12E-02	557	7.66	393	7.65E-02	561
0410-06	FALSE	2.33	278	2.34E-02	314	6.56	432	6.57E-02	501
0410-07	TRUE	0.00	0	0.00E+00	0	9.35	0	9.38E-02	563
0410-08	FALSE	2.34	304	2.34E-02	350	6.27	471	6.28E-02	597
0410-09	FALSE	4.38	455	4.39E-02	513	9.02	486	9.05E-02	553
0410-10	FALSE	2.98	425	2.98E-02	490	5.74	427	5.76E-02	540
W/ Outliers	Avg.	2.94	377	2.95E-02	437	6.61	407	6.62E-02	571
	% Error	46.0%	43.0%	46.0%	42.8%	24.4%	36.0%	24.4%	8.9%
	Error	1.35	162	1.36E-02	187	1.61	147	1.62E-02	51
W/O Outliers	Avg.	3.25	397	3.26E-02	463	6.51	449	6.53E-02	556
	% Error	30.4%	20.1%	30.3%	21.1%	20.0%	7.8%	20.0%	5.3%
	Error	0.99	80	9.89E-03	98	1.30	35	1.30E-02	30

Figure 106 shows the yield and ultimate forces of each specimen in comparison to the average. Specimen 3 was excluded from the average because the Instron servo-hydraulic machine was not properly reset.

Specimen 7 was excluded because it seemed to have an artificial yield point early on; most likely due to a manufacturing defect.

Figure 106: Compressive yield and ultimate loads of all specimens tested at 150 °F.

Figure 107 below shows the stress-strain and force-displacement curves of all specimens tested. Although not directly visible on the chart, specimen 7's artificial yield is represented by the bottom left x.

Remember; yield is defined as the first major drop in load. In the instance of specimen 7, it occurred much earlier than anticipated.

Figure 107: Stress-strain and force-displacement curves of all specimens tested at 150 °F.

6.5.5 175 DEGREES

This section details the monotonic compression tests performed on control specimens at 175 °F.

6.5.5.1 WARM UP

Six thermal trials were performed providing an average time of 0:12:07 with a 1.61% standard deviation to heat each specimen to 175 °F. This is a shorter duration than might be expected by examining the previous thermal trial, however, the room temperature was 78.1 °F, much warmer than before. Table 22 details the results of the thermal trial. The last trial was thrown out because the thermocouple inside the part was not properly connected to the thermocouple reader.

Table 22: Time required to heat specimen to 175 °F in the thermal chamber.

Time Required to Warm to 175 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1	0:12:01	79.8	172.1	1.9	0:12:07	0:01:13
2	0:12:18	80.4	172.3	2.0	0:12:07	0:01:13
3†	0:11:54	80.8	172.2	2.0	0:12:07	0:01:13
4	0:12:21	80.2	172.4	2.1	0:12:07	0:01:13
5	0:12:02	81.3	172.1	2.1	0:12:07	0:01:13
6‡	0:09:09	78.6	172.5	2.0	0:12:07	0:01:13
With Outliers	Avg. Time	0:11:37				
	%σ	10.54%				
Without Outliers	Avg. Time	0:12:07				
	%σ	1.61%				

Date of Trials	7/13/2010	
Time of Day	12:10:00-6:30:00	PM
Room Temp.	78.1	°F
Temp. in Celsius	79.44	°C
Temp. for Chamber	78	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† Should have added 10 seconds or so and didn't, seems to be OK though

‡ The final measured time to temperature after all the testing was completed

Figure 108 shows each thermal trial in comparison to the average with standard deviation error bars.

Once the thermal trials were complete, testing could resume.

Figure 108: Time required to heat specimen to 175 °F in the thermal chamber.

6.5.5.2 EXPERIMENTAL RESULTS

Ten specimens were tested culminating in an average yield force of 374 lb with a standard deviation of 9.7% and an ultimate load of 417 lb with a standard deviation of 4.3%. The results are detailed below in Table 23. Specimens 7, 8, and 9 were thrown out because of manufacturing defects.

Table 23: Summary of compression testing results at 175 °F

Compression at 175 °F									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0420-01	FALSE	4.98	327	4.98E-02	374	10.19	309	1.02E-01	437
0420-02	FALSE	3.80	376	3.78E-02	434	8.79	368	8.74E-02	441
0420-03	FALSE	4.13	359	4.02E-02	413	8.68	332	8.45E-02	417
0420-04	FALSE	3.67	322	3.66E-02	366	8.96	332	8.92E-02	402
0420-05	FALSE	3.82	294	3.68E-02	336	11.22	354	1.08E-01	418
0420-06	FALSE	4.82	309	4.80E-02	355	13.13	353	1.31E-01	417
0420-07	TRUE	3.47	171	3.43E-02	195	13.18	318	1.30E-01	364
0420-08	TRUE	3.10	165	3.00E-02	190	13.54	338	1.31E-01	387
0420-09	TRUE	2.68	172	2.66E-02	196	13.21	350	1.31E-01	410
0420-10	FALSE	6.25	299	6.29E-02	343	11.84	317	1.19E-01	390
W/ Outliers	Avg.	4.07	280	4.03E-02	320	11.27	337	1.11E-01	408
	% Error	25.5%	28.6%	26.5%	28.8%	17.7%	5.7%	17.6%	5.7%
	Error	1.04	80	1.07E-02	92	1.99	19	1.96E-02	23
W/O Outliers	Avg.	4.50	327	4.46E-02	374	10.40	338	1.03E-01	417
	% Error	20.7%	9.4%	21.8%	9.7%	16.6%	6.3%	17.0%	4.3%
	Error	0.93	31	9.71E-03	36	1.73	21	1.76E-02	18

Figure 109 below shows the yield and ultimate force of each specimen with standard deviation error bars in comparison to the average. Notice that specimens 7, 8, and 9 all had similar yield forces. This is because

their manufacturing defects were nearly identical. They all had severe damage around one of their holes due to the use of a dull drill bit. This solidifies the claims of the important of using the correct bit to drill composite sandwiches described in §4.9.

Figure 109: Compressive yield and ultimate loads of all specimens tested at 175 °F.

Figure 110 on the next page shows all of the stress-strain and force-displacement curves. As explained before, the curves become much noisier after the yielding force is applied. As temperature increases, it also becomes much more difficult to isolate the yield portion of the curve. This is because the maximum cure temperature of the resin is 150 °F. When tested at temperature higher than 150 °F, the resin becomes much weaker, and exhibits non-linear behavior instead of the predictable linear-elastic homogenous behavior.

Figure 110: Stress-strain and force-displacement curves of all specimens tested at 175 °F.

6.5.6 200 DEGREES

This section details the monotonic compression tests performed on control specimens at 200 °F.

6.5.6.1 WARM UP

Prior to testing, six thermal trials were completed. On average, it took 0:15:15 (with a standard deviation of 8.53%) to heat the specimens from a room temperature of 78.5 °F to the target temperature of 200 °F. The results of the trials are detailed below in Table 24. The first trial was thrown out because the chamber was originally at room temperature. The last trial was pulled out because the specimen with the thermocouple inside it was not fully cooled after the fifth trial.

Table 24: Time required to heat specimen to 200 °F in the thermal chamber.

Time Required to Warm to 200 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:17:54	78.5	195.5	3.1	0:15:15	0:01:19
2	0:15:58	79.8	195.5	2.8	0:15:15	0:01:19
3τ	0:14:58	80.1	195.4	2.9	0:15:15	0:01:19
4	0:14:51	80.4	195.3	3.0	0:15:15	0:01:19
5	0:15:12	80.7	195.2	3.3	0:15:15	0:01:19
6‡	0:14:06	84.7	196.6	2.1	0:15:15	0:01:19
With Outliers	Avg. Time	0:15:30				
	%σ	8.53%				
Without Outliers	Avg. Time	0:15:15				
	%σ	8.29%				

Date of Trials	7/14/2010	
Time of Day	11:30	AM,PM
Room Temp.	78.5	°F
Temp. in Celsius	93.33	°C
Temp. for Chamber	92	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† Raised the temp from 90 to 91 because wasn't hot enough

τ Raised temperature to 92

‡ The final measured time to temperature after all the testing was completed

Figure 111 below shows all of the thermal trials compared to the average with their standard deviation error bars.

Figure 111: Time required to heat specimen to 200 °F in the thermal chamber.

6.5.6.2 EXPERIMENTAL RESULTS

After the thermal trials, ten specimens were tested. It was discovered that specimens tested at 200 °F had an average yielding load of 324 lb with a standard deviation of 8.1% and an ultimate load of 355 lb with a standard deviation of 5.0%. Table 25 below details these results.

Table 25: Summary of compression testing results at 200 °F

Compression at 200 °F									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0504-01	FALSE	3.46	244	3.46E-02	277	12.94	296	1.29E-01	340
0504-02	FALSE	3.89	268	3.90E-02	305	7.56	302	7.57E-02	354
0504-03	FALSE	2.92	305	2.93E-02	347	5.84	290	5.85E-02	351
0504-04	FALSE	3.67	287	3.67E-02	326	7.54	293	7.53E-02	344
0504-05	FALSE	3.55	302	3.56E-02	345	8.29	299	8.31E-02	351
0504-06	FALSE	3.56	283	3.57E-02	322	7.19	311	7.21E-02	355
0504-07	TRUE	2.11	203	2.11E-02	235	6.80	276	6.81E-02	329
0504-08	FALSE	4.06	305	4.08E-02	348	6.96	331	6.99E-02	394
0504-09	TRUE	/	/	/	/	/	/	/	/
0504-10	TRUE	2.11	182	2.11E-02	207	8.80	231	8.81E-02	267
W/ Outliers	Avg.	3.26	264	3.26E-02	301	7.99	292	8.00E-02	343
	% Error	22.2%	17.3%	22.2%	17.1%	25.6%	9.4%	25.5%	9.8%
	Error	0.72	46	7.26E-03	52	2.04	27	2.04E-02	34
W/O Outliers	Avg.	3.59	285	3.59E-02	324	8.05	303	8.06E-02	355
	% Error	10.1%	7.9%	10.1%	8.1%	28.4%	4.6%	28.3%	5.0%
	Error	0.36	23	3.63E-03	26	2.28	14	2.28E-02	18

Figure 112 below shows the yield and ultimate loads of all ten specimens compared to their respective average. Notice how much more inconsistent the yield data is compared to the ultimate data. This is most

likely because of the inter-laminar stress between the facesheets and the foam which are heavily dependent on the material properties of the film adhesive which vary with temperature. Specimens 7, 9, and 10 were thrown out due to manufacturing defects. Specimen 9 in particular was not even tested because the damage around the hole was so noticeable.

Figure 112: Compressive yield and ultimate loads of all specimens tested at 200 °F.

Figure 113 on the next page shows the stress-strain and force-displacement curves of all ten specimens. As explained before, as a result of the heat effect on the resin's material properties, it is to characterize the exact yielding point of each specimen. This is also visible in the inconsistencies and noise in the curves compared with the data taken at 75 °F.

Figure 113: Stress-strain and force-displacement curves of all specimens tested at 200 °F.

6.5.7 SUMMARY OF MONOTONIC COMPRESSION RESULTS

This section compares all of the different averages along with the standard deviations calculated at each temperature tested. Figure 114 below shows the relations between the averages.

Figure 114: Average ultimate load decrease of specimens tested between 75 °F and 200 °F.

This data exhibits an extremely strong linear correlation with an R^2 value, or coefficient of determination, of 0.987. The coefficient of determination is used in the context of statistical models whose main purpose is the predication of future outcomes on the basis of related information. It is the proportion of variability in a data set that is accounted for by the statistical model and provides a measure of how well future outcomes are likely to be predicted.⁽²⁰⁾ Thus, for the temperature interval between 75 °F and 200 °F, it is nearly certain that the equation above in Figure 114 will predict the average ultimate load of a set of specimens. Because no data points were taken below 75 °F or above 200 °F, it is unknown if the relationship will hold. Most likely, higher temperature will seen an even greater decrease in strength, as will extremely low temperature essentially forming more of a parabolic relationship. For other future experimental ideas, see §9.2

The difference in standard deviations is most likely explained by the amount of rigor used to manufacture the plates and prepare the specimens. A single plate was used to make the specimens at each temperature rather than using random sampling. The plate manufactured for testing 200 °F could have been better made than the plate made for manufacturing at 100 °F.

6.6 MECHANICAL BEHAVIOR OF COMPOSITE SANDWICH PANELS WITH INSERTS SUBJECTED TO MONOTONIC COMPRESSION AT ELEVATED TEMPERATURES

This section details the results of the second quarter of the major bulk of research performed for this thesis—the specimens with inserts under monotonic compression at elevated temperatures. In order to perform the experiment designed in §2, the methods described in §5, ten specimens each were tested at six different temperatures: 75, 100, 125, 150, 175, and 200 °F. This section discusses possible problems that could have skewed the results during the tests, the results, and the significance of those results.

6.6.1 75 DEGREES (ROOM TEMPERATURE)

This section details the monotonic compression tests performed on insert specimens at 75 °F.

6.6.1.1 WARM UP

No warm up was required for testing at 75 °F

6.6.1.2 EXPERIMENTAL RESULTS

Ten specimens with three layer inserts were tested at 75 °F. On average, they yielded at 1451 lbs with a standard deviation of 5.8% and failed at an ultimate load of 1548 lb with a standard deviation of 6.5%. This represents a major increase in both yield and ultimate load capacity when compared to the control specimens. These results are available below in Table 26. Specimens 1, 9, and 10 were thrown out due to manufacturing defects and thermal chamber malfunction.

Table 26: Summary of compression testing results at 75 °F with inserts.

Compression at 75 °F w/ Inserts									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0705-01	TRUE	6.94	1511	6.94E-02	1813	7.27	1154	7.27E-02	1834
0705-02	FALSE	6.46	1270	6.46E-02	1476	10.79	1355	1.08E-01	1721
0705-03	FALSE	5.28	1300	5.28E-02	1528	5.48	1129	5.48E-02	1535
0705-04	FALSE	6.61	1222	6.61E-02	1430	10.15	1283	1.01E-01	1560
0705-05	FALSE	5.94	1319	5.94E-02	1531	6.34	1111	6.34E-02	1539
0705-06	FALSE	4.73	1288	4.73E-02	1500	5.13	887	5.13E-02	1506
0705-07	FALSE	5.72	1186	5.72E-02	1390	9.40	1286	9.40E-02	1594
0705-08	FALSE	6.32	1108	6.32E-02	1299	11.15	1129	1.11E-01	1385
0705-09	TRUE	6.29	1483	6.29E-02	1780	6.86	1242	6.86E-02	1806
0705-10	TRUE	6.28	1539	6.28E-02	1806	6.81	1208	6.81E-02	1818
W/ Outliers	Avg.	6.06	1323	6.06E-02	1555	7.94	1178	7.94E-02	1630
	% Error	10.9%	10.9%	10.9%	11.7%	28.1%	11.1%	28.1%	9.5%
	Error	0.66	144	6.60E-03	182	2.23	131	2.23E-02	155
W/O Outliers	Avg.	5.87	1242	5.87E-02	1451	8.35	1169	8.35E-02	1548
	% Error	11.6%	6.0%	11.6%	5.8%	31.2%	13.4%	31.2%	6.5%
	Error	0.68	75	6.80E-03	84	2.61	157	2.61E-02	101

Figure 115 below shows the yield and ultimate load of each specimen in comparison to the average. The x's represent the specimens that were thrown out. Overall the data appear to be consistent.

Figure 115: Compressive yield and ultimate loads of all specimens tested at 75 °F with inserts.

Figure 116 on the next page shows the stress-strain and force-displacement curves of each specimen.

Notice how closely grouped the data are.

Figure 116: Stress-strain and force-displacement curves of all specimens tested at 75 °F with inserts.

6.6.2 100 DEGREES

This section details the monotonic compression tests performed on insert specimens at 100 °F.

6.6.2.1 WARM UP

Prior to testing, thermal trials were performed. A new thermocouple part was not manufactured with inserts because the inserts are so small in comparison to the entire part. In these thermal trials, it took on average 0:4:07 with a standard deviation of 4.33% to heat the specimens to 100 °F. Table 27 details the results of the thermal trials.

Table 27: Time required to heat specimen with inserts to 100 °F in the thermal chamber.

Time Required to Warm to 100 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:04:14	80.1	100.9	1.8	0:04:07	0:00:11
2	0:04:10	80.4	101.0	2.0	0:04:07	0:00:11
3	0:04:08	81.2	101.1	1.6	0:04:07	0:00:11
4	0:04:03	81.6	101.2	1.8	0:04:07	0:00:11
5	0:04:02	81.9	101.4	1.9	0:04:07	0:00:11
6‡	0:03:44	80.4	101.1	1.5	0:04:07	0:00:11
With Outliers	Avg. Time	0:04:04				
	%σ	4.33%				
Without Outliers	Avg. Time	0:04:07				
	%σ	2.01%				

Date of Trials	7/16/2010	
Time of Day	2:25	PM
Room Temp.	78.9	°F
Temp. in Celsius	37.78	°C
Temp. for Chamber	37	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† Still heating up

‡ The final measured time to temperature after all the testing was completed

Figure 117 shows the time required for each trial in comparison to the average. The first trial was thrown out because the inside of the thermal chamber began at room temperature. The last trial was thrown out because the thermocouple part was not properly cooled prior to beginning the trial.

Figure 117: Time required to heat specimen with inserts to 100 °F in the thermal chamber.

6.6.2.2 EXPERIMENTAL RESULTS

After the conclusion of the thermal trials, ten specimens with inserts were tested at 100 °F; they yielded at an average load of 1171 lb with a standard deviation of 14.7% and failed at an average load of 1352 lb with a standard deviation of 6.7%. These results are detailed below in Table 28.

Table 28: Summary of compression testing results at 100 °F with inserts.

Compression at 100 °F w/ Inserts									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0702-01	FALSE	5.77	857	5.77E-02	1022	13.01	1073	1.30E-01	1389
0702-02	FALSE	5.37	754	5.37E-02	895	12.99	1244	1.30E-01	1515
0702-03	FALSE	5.35	1056	5.35E-02	1252	6.37	1087	6.37E-02	1289
0702-04	TRUE	5.03	697	5.03E-02	822	13.01	967	1.30E-01	1142
0702-05	TRUE	4.38	593	4.38E-02	705	13.03	949	1.30E-01	1128
0702-06	FALSE	6.75	1057	6.75E-02	1258	11.97	965	1.20E-01	1264
0702-07	FALSE	7.96	1114	7.96E-02	1325	12.46	848	1.25E-01	1327
0702-08	TRUE	7.01	889	7.01E-02	1034	11.62	821	1.16E-01	1042
0702-09	FALSE	6.34	1078	6.34E-02	1278	12.33	1068	1.23E-01	1326
0702-10	TRUE								
W/ Outliers	Avg.	5.99	900	5.99E-02	1066	11.86	1002	1.19E-01	1269
	% Error	18.6%	21.0%	18.6%	21.1%	17.9%	13.0%	17.9%	11.5%
	Error	1.12	189	1.12E-02	225	2.12	131	2.12E-02	146
W/O Outliers	Avg.	6.25	986	6.25E-02	1171	11.52	1047	1.15E-01	1352
	% Error	16.0%	14.7%	16.0%	14.7%	22.2%	12.7%	22.2%	6.7%
	Error	1.00	145	9.99E-03	172	2.56	133	2.56E-02	91

Figure 118 shows the yield and ultimate load of each specimen compared to the average with standard deviation error bars. Notice how with the inserts, the standard deviation seems to be much larger.

Specimens 4, 5, and 8 were thrown out because of manufacturing defects. Specimen 10 was not testable because it was dropped on the laboratory floor.

Figure 118: Compressive yield and ultimate loads of all specimens tested at 100 °F with inserts.

Figure 119 on the next page shows the stress-strain and force-displacement curves of each specimen with inserts. Notice how just increasing the temperature a little bit made the curves much less smooth.

Figure 119: Stress-strain and force-displacement curves of all specimens tested at 100 °F with inserts.

6.6.3 125 DEGREES

This section details the monotonic compression tests performed on insert specimens at 125 °F.

6.6.3.1 WARM UP

Five thermal trials were performed to find the average time necessary to heat the specimens to 125 °F. It was found that on average, it took 0:08:58 with a standard deviation of 2.57%. These results are detailed below in Table 29.

Table 29: Time required to heat specimen with inserts to 125 °F in the thermal chamber.

Time Required to Warm to 125 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:09:32	80	123.9	2.0	0:08:58	0:00:19
2	0:08:45	80	123.8	1.9	0:08:58	0:00:19
3	0:09:02	82.1	123.8	2.0	0:08:58	0:00:19
4	0:08:50	81.2	123.6	2.0	0:08:58	0:00:19
5	0:09:16	80.4	123.4	2.0	0:08:58	0:00:19
6‡					0:08:58	0:00:19
With Outliers	Avg. Time	0:09:05				
	%σ	3.53%				
Without Outliers	Avg. Time	0:08:58				
	%σ	2.57%				

Date of Trials	7/16/2010	
Time of Day	1:25	PM
Room Temp.		°F
Temp. in Celsius	51.67	°C
Temp. for Chamber	51	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† The chamber was not pre-heated like all the other trials

‡ The trials were not finished because the machine was having an alignment issue

Figure 120 below shows all five thermal trials. The first trial was thrown out because, as usual, this trial was performed in the beginning of the day and the inside of the chamber was at room temperature.

Figure 120: Time required to heat specimen with inserts to 125 °F in the thermal chamber.

Unfortunately not all the testing could be performed in one day. So, it was necessary for thermal trials to be performed on the second day of testing specimens at 125 °F as well. In the second round, it took an average of 0:08:39 with a standard deviation of 1.08% to heat the specimens inside the chamber. These results are summarized below in Table 30.

Table 30: Time required to heat specimen with inserts to 125 °F in the thermal chamber.

Time Required to Warm to 125 °F (Retrial)						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:08:33	77.1	123.8	1.9	0:08:39	0:00:06
2	0:08:38	77.5	123.6	1.9	0:08:39	0:00:06
3	0:08:35	77.3	123.3	2.0	0:08:39	0:00:06
4	0:08:44	77.4	123.6	2.0	0:08:39	0:00:06
5	0:08:46	79.2	123.5	2.0	0:08:39	0:00:06
6‡					0:08:39	0:00:06
With Outliers	Avg. Time	0:08:39				
	%σ	1.08%				
Without Outliers	Avg. Time	0:08:39				
	%σ	1.08%				

Date of Trials	7/17/2010	
Time of Day	11:15:00-6:35:00	AM,PM
Room Temp.	74.2	°F
Temp. in Celsius	51.67	°C
Temp. for Chamber	51	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† The chamber was not pre-heated like all the other trials

‡ The trials were not finished because the machine was having an alignment issue

Figure 121 below shows the results from the thermal trials. Each individual trial is plotted and compared to the average. Although the error bars look large, it's only because the scale on the vertical axis is so small.

Figure 121: Time required to heat specimen with inserts to 125 °F in the thermal chamber (retrial).

6.6.3.2 EXPERIMENTAL RESULTS

After each subsequent day of thermal trials was finished, the specimens were tested. For this temperature, the specimens yielded at an average load of 1212 lb with a standard deviation of 13.2% and failed at an average ultimate load of 1299 lb with a standard deviation of 10.9%. These values are detailed below in Table 31.

Table 31: Summary of compression testing results at 125 °F with inserts.

Compression at 125 °F w/ Inserts									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0708-01	FALSE	5.25	846	5.25E-02	983	7.67	764	7.67E-02	987
0708-02	FALSE	6.23	1117	6.23E-02	1286	8.40	700	8.40E-02	1297
0708-03	FALSE	8.13	1087	8.13E-02	1264	11.24	1173	1.12E-01	1441
0708-04	FALSE	5.17	1167	5.17E-02	1387	6.83	1002	6.83E-02	1439
0708-05	TRUE	4.70	748	4.70E-02	884	5.82	736	5.82E-02	887
0708-06	FALSE	5.17	1087	5.17E-02	1275	6.79	993	6.79E-02	1302
0708-07	FALSE	5.21	1135	5.21E-02	1293	5.93	946	5.93E-02	1304
0708-08	FALSE	5.13	1096	5.18E-02	1270	6.10	957	6.15E-02	1274
0708-09	FALSE	4.65	811	4.69E-02	941	6.96	1160	7.02E-02	1346
0708-10	TRUE	4.03	648	4.06E-02	758	7.24	873	7.30E-02	1266
W/ Outliers	Avg.	5.37	974	5.38E-02	1134	7.30	930	7.31E-02	1254
	% Error	20.9%	19.5%	20.7%	19.3%	21.9%	17.7%	21.8%	14.3%
	Error	1.12	190	1.11E-02	219	1.60	165	1.59E-02	180
W/O Outliers	Avg.	5.62	1043	5.63E-02	1212	7.49	962	7.50E-02	1299
	% Error	19.7%	13.0%	19.5%	13.2%	22.9%	17.3%	22.7%	10.9%
	Error	1.11	135	1.10E-02	160	1.71	167	1.70E-02	141

Figure 122 below shows the yield and ultimate load of each specimen in comparison to the average with respective standard deviation error bars. In general, the data agreed well. Both specimen 5 and 10 were thrown out due to drilling damage in the holes.

Figure 122: Compressive yield and ultimate loads of all specimens tested at 125 °F with insert.

Figure 123 shows the stress-strain and force-displacement curves of all specimens tested at 125 °F. The specimens were tightly bunched in the first part of the stress-strain curve, but deviated into two groups.

Figure 123: Stress-strain and force-displacement curves of all specimens tested at 125 °F with inserts.

6.6.4 150 DEGREES

This section details the monotonic compression tests performed on insert specimens at 150 °F.

6.6.4.1 WARM UP

Prior to testing, five thermal trials were performed. On average, it took specimens 0:13:08 with a standard deviation of less than 1% to heat up to 150 °F. The first two trials were thrown out of the average because it took a while for the chamber to heat up. These results are detailed below in Table 32.

Table 32: Time required to heat specimen with inserts to 150 °F in the thermal chamber.

Time Required to Warm to 150 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1	0:15:33	76.2	143.4	3.9	0:13:08	0:01:22
2	0:15:43	78.3	143.3	3.7	0:13:08	0:01:22
3†	0:13:07	83.6	145	3.7	0:13:08	0:01:22
4	0:13:13	83.5	144.9	3.7	0:13:08	0:01:22
5	0:13:03	83.6	144.9	3.7	0:13:08	0:01:22
6‡					0:13:08	0:01:22
With Outliers	Avg. Time	0:14:08				
	%σ	9.73%				
Without Outliers	Avg. Time	0:13:08				
	%σ	0.64%				

Date of Trials	7/18/2010	
Time of Day	11:15:00-7:30:00	AM,PM
Room Temp.	76.6	°F
Temp. in Celsius	65.56	°C
Temp. for Chamber	64	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† Changed temperature from 63 to 64

‡The final temperature was not completed because it was too late in the day and the temperature changed

Figure 124 below shows the five thermal trials compared with the average with standard deviation error bars. Although the first two trials were consistent, the thermal state of the thermal chamber was changed because of the constant heat being applied. The subsequent trials showed a strong agreement.

Figure 124: Time required to heat specimen with inserts to 150 °F in the thermal chamber .

6.6.4.2 EXPERIMENTAL RESULTS

After the thermal trials, ten specimens were tested at 150 °F. On average, these specimens yielded at 1169 lb with a standard deviation of 10.3% and failed at an ultimate load of 1280 lb with a standard deviation of 10.1%. These results are detailed below in Table 33. Specimens 6, 9, and 10 were all thrown out because of the drilling damage around their holes. This testing was performed at a time when a new drill bit was needed for the drill press.

Table 33: Summary of compression testing results at 150 °F with inserts.

Compression at 150 °F w/ Inserts									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0706-01	FALSE	5.26	1030	5.26E-02	1209	7.00	922	7.00E-02	1338
0706-02	FALSE	5.23	1065	5.23E-02	1271	6.25	939	6.25E-02	1281
0706-03	FALSE	4.68	960	4.68E-02	1124	8.39	948	8.39E-02	1203
0706-04	FALSE	4.75	865	4.75E-02	1015	7.39	855	7.39E-02	1037
0706-05	FALSE	4.24	869	4.24E-02	1037	8.78	1127	8.78E-02	1433
0706-06	TRUE	3.62	678	3.62E-02	802	6.70	1018	6.70E-02	1322
0706-07	FALSE	4.98	998	4.98E-02	1174	9.25	1099	9.25E-02	1293
0706-08	FALSE	4.48	1132	4.48E-02	1349	5.01	976	5.01E-02	1370
0706-09	TRUE	3.73	602	3.73E-02	720	7.92	1112	7.92E-02	1341
0706-10	TRUE	3.52	473	3.52E-02	556	7.85	1074	7.85E-02	1318
W/ Outliers	Avg.	4.45	867	4.45E-02	1026	7.46	1007	7.46E-02	1294
	% Error	14.6%	25.0%	14.6%	25.0%	17.0%	9.2%	17.0%	8.3%
	Error	0.65	217	6.51E-03	257	1.27	93	1.27E-02	108
W/O Outliers	Avg.	4.80	988	4.80E-02	1169	7.44	981	7.44E-02	1280
	% Error	7.9%	10.0%	7.9%	10.3%	20.2%	10.0%	20.2%	10.1%
	Error	0.38	99	3.78E-03	121	1.50	98	1.50E-02	129

Figure 125 below shows the yield and ultimate load of each specimen with standard deviation error bars in comparison to the average.

Figure 125: Compressive yield and ultimate loads of all specimens tested at 150 °F with insert.

Figure 127 below shows the stress-strain and force-displacement curves of each specimen. The slopes of the curves are all extremely similar meaning the material properties of the specimens are extremely consistent. The inconsistent yield and failure loads are most likely due to the slight differences in the damage around the holes of each specimen.

Figure 126: Stress-strain and force-displacement curves of all specimens tested at 150 °F with inserts.

6.6.5 175 DEGREES

This section details the monotonic compression tests performed on insert specimens at 175 °F.

6.6.5.1 WARM UP

Prior to testing, thermal trials were performed to measure how long it would take to heat specimens to 175 °F. On average, it took 0:11:15 with a standard deviation of 2.46%. The results of the thermal trials are detailed below in Table 34.

Table 34: Time required to heat specimen with inserts to 175 °F in the thermal chamber.

Time Required to Warm to 175 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:13:13	71.7	172.6	2.3	0:11:56	0:00:35
2	0:11:39	72.9	171.7	2.2	0:11:56	0:00:35
3‡	0:12:10	73.9	172	2.1	0:11:56	0:00:35
4	0:12:09	72.9	171.8	2.3	0:11:56	0:00:35
5	0:12:08	72.5	172.1	2.1	0:11:56	0:00:35
6‡	0:11:35	73.4	173.2	2.1	0:11:56	0:00:35
With Outliers	Avg. Time	0:12:09				
	%σ	4.81%				
Without Outliers	Avg. Time	0:11:56				
	%σ	2.46%				

Date of Trials	7/20/2010	
Time of Day	1:00:00-3:30:00	PM
Room Temp.	75.4	°F
Temp. in Celsius	79.44	°C
Temp. for Chamber	78	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† Needed to warm up

‡ Heated up to 79

‡ The final measured time to temperature after all the testing was completed

Figure 127 below shows all of the thermal trials performed for this temperature. Like before, the first thermal trial was thrown out because the thermal chamber had to warm up beyond room temperature, so it took slightly longer, whereas in subsequent trials, the temperature of the metal inside the chamber was already slightly elevated.

Figure 127: Time required to heat specimen with inserts to 175 °F in the thermal chamber.

6.6.5.2 EXPERIMENTAL RESULTS

After the thermal trials were concluded, five specimens were tested at 175 °F. Five rather than ten were tested, because the manufactured plates take a week to cure, and unfortunately, two were not ready for testing at 175 °F and 200 °F. Thus, five specimens each from a single layup, at each temperature were tested. On average, the specimens yielded at 784 lb with a standard deviation of 9.0% and failed at an ultimate load of 852 lb with a standard deviation of 1.4%. These results are detailed below in Table 35.

Table 35: Summary of compression testing results at 175 °F with inserts.

Compression at 175 °F w/ Inserts									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0711-01	TRUE	5.68	589	5.68E-02	698	12.26	653	1.23E-01	855
0711-02	FALSE	3.59	607	3.59E-02	700	8.18	656	8.18E-02	840
0711-03	FALSE	3.60	652	3.60E-02	753	8.46	725	8.46E-02	867
0711-04	FALSE	4.43	718	4.43E-02	838	6.14	606	6.14E-02	847
0711-05	FALSE	3.88	727	3.88E-02	847	9.10	720	9.10E-02	853
0711-06	TRUE								
0711-07	TRUE								
0711-08	TRUE								
0711-09	TRUE								
0711-10	TRUE								
W/ Outliers	Avg.	4.24	659	4.24E-02	767	8.83	672	8.83E-02	852
	% Error	20.7%	9.5%	20.7%	9.4%	25.1%	7.5%	25.1%	1.2%
	Error	0.88	63	8.78E-03	72	2.22	50	2.22E-02	10
W/O Outliers	Avg.	3.87	676	3.87E-02	784	7.97	676	7.97E-02	852
	% Error	10.2%	8.4%	10.2%	9.0%	16.0%	8.4%	16.0%	1.4%
	Error	0.39	57	3.94E-03	70	1.28	57	1.28E-02	12

Figure 128 shows the specimen yields and ultimate loads with their standard deviation error bars compared to the average loads. Although it looks like the data are not extremely close on the ultimate load plot, the vertical axis only goes from 830 lb to 875 lb. The first specimen was thrown out because it had a delamination problem.

Figure 128: Compressive yield and ultimate loads of all specimens tested at 175 °F with insert.

Figure 129 below shows the stress-strain and force-displacement curves of each specimen tested. The bold “x” annotates the yielding value of the curve. Notice how different the first stress-strain curve is from the other specimens. This was the first indication that there might be a problem. Upon further inspection, the delamination problem was discovered.

Figure 129: Stress-strain and force-displacement curves of all specimens tested at 175 °F with inserts.

6.6.6 200 DEGREES

This section details the monotonic compression tests performed on insert specimens at 200 °F.

6.6.6.1 WARM UP

Prior to testing, six thermal trials were performed. On average, it took the thermocouple specimen 0:14:41 with a standard deviation of 1.73% to heat up to 200 °F. These results are detailed below in Table 36.

Table 36: Time required to heat specimen with inserts to 200 °F in the thermal chamber.

Time Required to Warm to 200 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:15:13	77.5	196.1	3.9	0:14:41	0:00:22
2	0:14:29	81.8	196.2	2.8	0:14:41	0:00:22
3	0:14:28	77.5	195.8	3.9	0:14:41	0:00:22
4	0:14:58	80.1	195.4	2.9	0:14:41	0:00:22
5	0:14:51	80.4	195.3	3.0	0:14:41	0:00:22
6‡	0:14:13	77.5	196.5	2.5	0:14:41	0:00:22
With Outliers	Avg. Time	0:14:42				
	%σ	2.54%				
Without Outliers	Avg. Time	0:14:41				
	%σ	1.73%				

Date of Trials	7/20/2010	
Time of Day	3:30	PM
Room Temp.	78.5	°F
Temp. in Celsius	93.33	°C
Temp. for Chamber	92	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† Raised the temp from 90 to 91 because wasn't hot enough

‡ The final measured time to temperature after all the testing was completed

Figure 130 below shows all of the thermal trials with the standard deviation error bars compared to the average. The first trial was excluded because the chamber had to heat up beyond room temperature, and the last trial was excluded because the thermocouple part was not fully cooled between the fifth and sixth trial.

Figure 130: Time required to heat specimen with inserts to 200 °F in the thermal chamber.

6.6.6.2 EXPERIMENTAL RESULTS

After the thermal trials were completed, five specimens were tested at 200 °F. On average, the specimens yielded at a load of 620 lb with a standard deviation of 10.8% and failed at an ultimate load of 765 lb with a standard deviation of 7.7%. These results are summarized below in Table 37.

Table 37: Summary of compression testing results at 200 °F with inserts.

Compression at 200 °F w/ Inserts									
Specimen	Outlier?	ϵ_y	σ_y	δ_y	F_y	ϵ_{ult}	σ_{ult}	δ_{ult}	F_{ult}
0711-06	FALSE	3.25	610	3.25E-02	705	7.58	535	7.58E-02	722
0711-07	FALSE	3.44	515	3.44E-02	596	10.38	706	1.04E-01	845
0711-08	FALSE	2.99	510	2.99E-02	593	6.60	618	6.60E-02	779
0711-09	FALSE	3.98	597	3.98E-02	689	8.84	662	8.84E-02	785
0711-10	FALSE	2.99	590	2.99E-02	680	7.11	580	7.11E-02	693
	TRUE								
	TRUE								
	TRUE								
	TRUE								
	TRUE								
W/ Outliers	Avg.	3.33	564	3.33E-02	653	8.10	620	8.10E-02	765
	% Error	12.3%	8.5%	12.3%	8.3%	18.8%	10.8%	18.8%	7.7%
	Error	0.41	48	4.09E-03	54	1.52	67	1.52E-02	59
W/O Outliers	Avg.	3.33	564	3.33E-02	653	8.10	620	8.10E-02	765
	% Error	12.3%	8.5%	12.3%	8.3%	18.8%	10.8%	18.8%	7.7%
	Error	0.41	48	4.09E-03	54	1.52	67	1.52E-02	59

Figure 131 below shows the yield and ultimate loads of each specimen with standard deviation error bars compared with the average.

Figure 131: Compressive yield and ultimate loads of all specimens tested at 200 °F with insert.

Figure 132 below shows the stress-strain and force-displacement curves of each individual specimen.

Surprisingly, there was not nearly as much noise in the region beyond yield when compared to the control specimens. All specimens exhibited extremely similar behavior.

Figure 132: Stress-strain and force-displacement curves of all specimens tested at 200 °F with inserts.

6.6.7 SUMMARY OF MONOTONIC COMPRESSION RESULTS WITH INSERTS

After all of the insert specimens were tested, the average ultimate loads with standard deviation error bars were plotted for comparison. Figure 133 shows these results.

Figure 133: Average ultimate load decrease of specimens tested between 75 °F and 200 °F with inserts.

Although there is not nearly as strong of a linear correlation as was found in the control specimens, the data were still extremely close. With a coefficient of determination, or R^2 value of 0.899, the data were overall, still very good and well explained with a linear fit. The R^2 was most likely affected by the data taken at 150 °F. It is possible that the plate manufactured for testing at 150 °F had a slightly stronger bond. Outside of that, nearly all the other data point with their respective standard deviation error bars fall within the line.

6.7 SUMMARY OF THE EFFECTIVENESS OF INSERTS IN DELAYING FAILURE IN MONOTONIC COMPRESSION AT ELEVATED TEMPERATURES

This section details the comparison between the two monotonic compression cases tested, the control specimens and the specimens with three layer of LTM45 inserts around the holes. Table 38 shows the percent improvement in average failure load between the control specimens and the specimens with inserts. In nearly all cases, the improvement was about 100% meaning that the inserts functionally doubled the load capacity of the sandwich composites while hardly adding any weight.

Table 38: Effectiveness of inserts under increased temperatures.

Temperature (°F)	% Improvement
75	92
100	96
125	106
150	130
175	104
200	115

Figure 134 below shows the average failure load at each temperature of specimens with and without inserts. The lines are mostly parallel signifying that within the temperature range of 75 °F to 200 °F, the addition of the insert doubles the load. The insert data has on average higher standard deviations most likely because the inserts did not always fit perfectly within the milled slots. If they were a little too small for example, then resin would fill in the gaps. Anytime geometry is complicated, variation will inevitably increase.

Figure 134: Comparison of average ultimate load decrease of specimens tested between 75 °F and 200 °F with and without inserts.

6.8 MECHANICAL BEHAVIOR OF COMPOSITE SANDWICH PANELS SUBJECTED TO 65% YIELD COMPRESSION-COMPRESSION FATIGUE AT ELEVATED TEMPERATURES

This section details the results of the third quarter of the major bulk of research performed for this thesis—the control specimens subjected to compression-compression fatigue at elevated temperatures. In order to perform the experiment designed in §2, the methods described in §5, specimens each were tested at six different temperatures: 75, 100, 115, 130, 145, and 160 °F for the reasons described in §5.4.3. This section discusses possible problems that could have skewed the results during the tests, the results, and the significance of those results.

6.8.1 75 DEGREES (ROOM TEMPERATURE)

This section details the compression-compression fatigue tests performed on control specimens at 75 °F.

6.8.1.1 WARM UP

No warm up was required for testing at 75 °F.

6.8.1.2 EXPERIMENTAL RESULTS

For the testing at 75 °F only two specimens were tested because the amount of time for testing was rather limited. The first specimen roughly took two days. The second specimen took about a day in a half. On average, the specimens took 425,000 cycles with a standard deviation of about 25% to fail. Table 39 details the results of the test.

Table 39: Summary of compression-compression fatigue testing results at 75 °F.

Fatigue at 75°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1	0626-09	500,000	425,000	106,066
2	0629-10	350,000	425,000	106,066
3			425,000	106,066
4			425,000	106,066
5			425,000	106,066
6			425,000	106,066
7			425,000	106,066
8			425,000	106,066
9			425,000	106,066
10			425,000	106,066
With Outliers	Avg. Cycles	425,000		
	% Error	24.96%		
Without Outliers	Avg. Cycles	425,000		
	% Error	24.96%		

Figure 135 below shows the cycles for each specimen with their standard deviation error bars in comparison to the average.

Figure 135: Number of cycles to failure of all specimens tested at 75 °F.

6.8.2 100 DEGREES

This section details the compression-compression fatigue tests performed on control specimens at 100 °F.

6.8.2.1 WARM UP

Six thermal trials were performed prior to testing at 100 °F. On average it took 0:04:29 with a standard deviation of 6.46% to heat the specimens to temperature from a room temperature of 66.5 °F. These trials are detailed below in Table 40. The first thermal trial was thrown out because, like the first trials of all the monotonic cases, the thermal chamber had to warm up beyond room temperature.

Table 40: Time required to heat specimen to 100 °F in the thermal chamber.

Time Required to Warm to 100 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:06:13	74.8	97.3	2.1	0:04:29	0:00:45
2	0:04:34	76.4	98.7	2.2	0:04:29	0:00:45
3	0:04:47	74.9	98.1	2.0	0:04:29	0:00:45
4	0:04:32	76.1	98.5	1.9	0:04:29	0:00:45
5	0:04:32	75.8	98.5	1.9	0:04:29	0:00:45
6‡	0:04:00	77.6	99.6	2.0	0:04:29	0:00:45
With Outliers	Avg. Time	0:04:46				
	%σ	15.79%				
Without Outliers	Avg. Time	0:04:29				
	%σ	6.46%				

Date of Trials	7/19/2010	
Time of Day	10:00	AM,PM
Room Temp.	66.5	°F
Temp. in Celsius	37.78	°C
Temp. for Chamber	37	°C

Note: Results taken from monotonic no inserts at 100 deg b/c room temperature is the same

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

‡The final measured time to temperature after all the testing was completed

Figure 136 below shows each thermal trial with standard deviation error bars compared to the average.

The data for this trial were very consistent.

Figure 136: Time required to heat specimen to 100 °F in the thermal chamber.

6.8.2.2 EXPERIMENTAL RESULTS

After the thermal trials were complete, seven specimens were tested to find the total number of cycles before failure. On average, it took about 37,000 cycles with a standard deviation of about 30% to fail at 100 °F. The test trial results are summarized below in Table 41. The second and fifth trials were thrown out because they didn't actually fail. The Instron servo-hydraulic machine had problems with losing hydraulic pressure meaning it applied much less than the expected load, artificially increasing the number of cycles. Specimen 3 was not actually tested because it was dropped and damaged.

Table 41: Summary of compression-compression fatigue testing results at 100 °F.

Fatigue at 100°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1	0505-01	28,901	37,083	118,694
2†	0505-02	281,966	37,083	118,694
3	0505-03		37,083	118,694
4	0505-04	45,265	37,083	118,694
5†	0505-05	172,285	37,083	118,694
6	0505-06		37,083	118,694
7	0505-07		37,083	118,694
8			37,083	118,694
9			37,083	118,694
10			37,083	118,694
With Outliers	Avg. Cycles	132,104		
	% Error	89.85%		
Without Outliers	Avg. Cycles	37,083		
	% Error	31.20%		

† Did not fail, loss of hydraulic pressure in machine

Figure 137 below shows the four tested trials with standard deviation error bars compared to the average number of cycles.

Figure 137: Number of cycles to failure of all specimens tested at 100 °F.

6.8.3 115 DEGREES

This section details the compression-compression fatigue tests performed on control specimens at 115 °F.

6.8.3.1 WARM UP

Before testing, five thermal trials were performed. On average, it took 0:10:24 with a standard deviation of about 4% to heat the thermocouple part to 115 °F. These results are detailed below in Table 42.

Table 42: Time required to heat specimen to 115 °F in the thermal chamber.

Time Required to Warm to 115 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:10:01	80.8	112.6	3.5	0:10:24	0:00:25
2	0:10:19	75.1	112.8	3.1	0:10:24	0:00:25
3	0:10:59	75.3	113.5	2.7	0:10:24	0:00:25
4	0:10:15	75.9	113.0	3.0	0:10:24	0:00:25
5					0:10:24	0:00:25
6‡	0:09:57	75.1	114.5	1.5	0:10:24	0:00:25
With Outliers	Avg. Time	0:10:18				
	%σ	3.98%				
Without Outliers	Avg. Time	0:10:24				
	%σ	3.99%				

Date of Trials	8/11/2010	
Time of Day	2:15	PM
Room Temp.	74.3	°F
Temp. in Celsius	46.11	°C
Temp. for Chamber	46	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† Still heating up

‡ The final measured time to temperature after all the testing was completed

Figure 138 below shows each thermal trial with standard deviation error bars compared to the average.

No thermal trials were thrown out in this set because they were all relatively close. The first four trials were performed before the testing of the specimens; the sixth was performed after specimen testing to ensure that specimens were not heating up faster than intended.

Figure 138: Time required to heat specimen to 115 °F in the thermal chamber.

6.8.3.2 EXPERIMENTAL RESULTS

After the thermal trials were completed, five specimens were tested at 115 °F. On average, it took the specimens about 12,000 cycles with a standard deviation of about 80% to fail. These results are detailed below in Table 43. The last specimen was thrown out because the Instron servo-hydraulic machine lost hydraulic pressure and didn't apply the correct load.

Table 43: Summary of compression-compression fatigue testing results at 115 °F.

Fatigue at 115°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5 σ w/ Outliers
1	0626-04	6,568	11,910	51,567
2	0626-05	1,299	11,910	51,567
3	0626-06	16,895	11,910	51,567
4	0626-07	22,878	11,910	51,567
5	0626-08	125,654	11,910	51,567
6			11,910	51,567
7			11,910	51,567
8			11,910	51,567
9			11,910	51,567
10			11,910	51,567
With Outliers	Avg. Cycles	34,659		
	% Error	148.78%		
Without Outliers	Avg. Cycles	11,910		
	% Error	82.02%		

Figure 139 below shows each trial with standard deviation error bars compared to the average. Specimen 5 is a great example of how losing hydraulic pressure can increase the number of cycles. If it was possible to measure the actual load applied in trials where hydraulic pressure was lost, more data could be plotted. However, the force magnitude in these instances was probably not constant.

Figure 139: Number of cycles to failure of all specimens tested at 115 °F.

6.8.4 130 DEGREES

This section details the compression-compression fatigue tests performed on control specimens at 130 °F.

6.8.4.1 WARM UP

Prior to testing, five thermal trials were performed to determine the amount of time necessary to heat specimens to 130 °F. On average, it took 0:11:15 with a standard deviation of 5.23%. Table 44 detailed these results. The first trial was thrown out because the inside of the chamber had to heat up from room temperature.

Table 44: Time required to heat specimen to 130 °F in the thermal chamber.

Time Required to Warm to 130 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:16:28	70.6	127.4	3.9	0:11:15	0:02:23
2	0:10:53	73.7	125.9	5.1	0:11:15	0:02:23
3	0:11:10	73.4	126.3	4.4	0:11:15	0:02:23
4	0:12:06	79.8	127.4	3.2	0:11:15	0:02:23
5					0:11:15	0:02:23
6‡	0:10:50	79.2	130.5	2.1	0:11:15	0:02:23
With Outliers	Avg. Time	0:12:17				
	%σ	19.44%				
Without Outliers	Avg. Time	0:11:15				
	%σ	5.23%				

Date of Trials	8/11/2010	
Time of Day	9:00-12:00	AM, PM
Room Temp.	66.2	°F
Temp. in Celsius	54.44	°C
Temp. for Chamber	54	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† The chamber was not pre-heated like all the other trials

‡ The final measured time to temperature after all the testing was completed

Figure 140 below shows the durations for each trial with standard deviation error bars compared to the average.

Figure 140: Time required to heat specimen to 130 °F in the thermal chamber.

6.8.4.2 EXPERIMENTAL RESULTS

Once the thermal trials were completed, five specimens were tested at 130 °F. On average, it took roughly 5,000 cycles with a standard deviation of nearly 90% for the specimens to fail. No specimens were thrown out. The results of testing at this temperature are summarized below in Table 45.

Table 45: Summary of compression-compression fatigue testing results at 130 °F.

Fatigue at 130°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1	0506-09	11,033	4,891	4,276
2	0506-10	1,156	4,891	4,276
3	0626-01	7,597	4,891	4,276
4	0626-02	1,602	4,891	4,276
5	0626-03	3,066	4,891	4,276
6			4,891	4,276
7			4,891	4,276
8			4,891	4,276
9			4,891	4,276
10			4,891	4,276
With Outliers	Avg. Cycles	4,891		
	% Error	87.43%		
Without Outliers	Avg. Cycles	4,891		
	% Error	87.43%		

Figure 141 shows each trials with standard deviation error bars compared to the average. Although the first specimen falls outside of the range of the average plus the standard deviation, it was not any different than the other trials—any exclusion would have been an artificial one.

Figure 141: Number of cycles to failure of all specimens tested at 130 °F.

6.8.5 145 DEGREES

This section details the compression-compression fatigue tests performed on control specimens at 145 °F.

6.8.5.1 WARM UP

Prior to testing, five thermal trials were performed. On average, it took 0:11:46 with a standard deviation of 7.59% to heat the thermocouple part to 145 °F at a room temperature of 71.7 °F. These results are summarized below in Table 46. The last trial was excluded from the average because the thermocouple part was not properly cooled after the fourth trial.

Table 46: Time required to heat specimen to 145 °F in the thermal chamber.

Time Required to Warm to 145 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:10:30	71.7	140.3	2.3	0:11:46	0:02:50
2τ	0:11:47	78.3	140	4.5	0:11:46	0:02:50
3	0:12:27	75.3	140	4.6	0:11:46	0:02:50
4	0:12:20	80.7	139.2	5.5	0:11:46	0:02:50
5					0:11:46	0:02:50
6‡	0:05:41	79.1	143.5	-1.4	0:11:46	0:02:50
With Outliers	Avg. Time	0:10:33				
	%σ	26.81%				
Without Outliers	Avg. Time	0:11:46				
	%σ	7.59%				

Date of Trials	8/10/2010	
Time of Day	11:55-6:30	AM, PM
Room Temp.	71.7	°F
Temp. in Celsius	62.78	°C
Temp. for Chamber	62	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† The chamber was pre-heated to 165 for previous testing

τ Switched temperature from 61 to 62

‡ The final measured time to temperature after all the testing was completed, thermal part on floor, too hot

Figure 142 below shows each thermal trial with standard deviation error bars compared to the average.

Figure 142: Time required to heat specimen to 145 °F in the thermal chamber.

6.8.5.2 EXPERIMENTAL RESULTS

After the thermal trials were complete, five specimens were tested at 145 °F. On average, the specimens failed after about 2,700 cycles with a standard deviation of about 40%. These results are detailed below in Table 47. The first specimen was thrown out due to loss of hydraulic pressure.

Table 47: Summary of compression-compression fatigue testing results at 145 °F.

Fatigue at 145°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1	0506-04	8,951	2,737	3,242
2	0506-05	2,206	2,737	3,242
3	0506-06	3,914	2,737	3,242
4	0506-07	2,090	2,737	3,242
5	0506-07	585	2,737	3,242
6			2,737	3,242
7			2,737	3,242
8			2,737	3,242
9			2,737	3,242
10			2,737	3,242
With Outliers	Avg. Cycles	3,549		
	% Error	91.33%		
Without Outliers	Avg. Cycles	2,737		
	% Error	37.32%		

Figure 143 below shows each trial with standard deviation error bars compared to the average number of cycles to failure.

Figure 143: Number of cycles to failure of all specimens tested at 145 °F.

6.8.6 160 DEGREES

This section details the compression-compression fatigue tests performed on control specimens at 160 °F.

6.8.6.1 WARM UP

Prior to testing, five thermal trials were performed. On average, it took 0:12:18 with a standard deviation of less than 1% to heat the specimens to 160 °F from a room temperature of 75.5 °F. These results are summarized below in Table 48. As explained before, the first thermal trial was excluded because the thermal chamber had to warm up beyond room temperature.

Table 48: Time required to heat specimen to 160 °F in the thermal chamber.

Time Required to Warm to 160 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:12:45	75.5	155.8	7.8	0:12:18	0:00:13
2τ	0:12:11	77.9	154.6	6.3	0:12:18	0:00:13
3	0:12:21	78.4	154	6.9	0:12:18	0:00:13
4	0:12:18	77.9	154.2	6.5	0:12:18	0:00:13
5					0:12:18	0:00:13
6‡	0:12:24	73.5	160.1	2.5	0:12:18	0:00:13
With Outliers	Avg. Time	0:12:24				
	%σ	1.72%				
Without Outliers	Avg. Time	0:12:18				
	%σ	0.75%				

Date of Trials	8/9-10/2010	
Time of Day	3:13-11:45	PM, AM
Room Temp.	75.5	°F
Temp. in Celsius	71.11	°C
Temp. for Chamber	70	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† The chamber was not pre-heated like all the other trials

τ Switched temperature to 70 degrees

‡ The final measured time to temperature after all the testing was completed

Figure 144 below shows each thermal trial with standard deviation error bars compared to the average time necessary to heat the specimens to temperature.

Figure 144: Time required to heat specimen to 160 °F in the thermal chamber.

6.8.6.2 EXPERIMENTAL RESULTS

After the thermal trials were complete, seven specimens were tested. On average, the specimens lasted 2,600 cycles before failure with a standard deviation of about 25%. These results are summarized below in Table 49. The first and fifth specimens were not tested because they had incurred damage during the manufacturing process. The second specimen was excluded due to lack of hydraulic pressure. The sixth specimen was excluded because the damage around the holes was observed to be much greater than that of other specimens prior to testing.

Table 49: Summary of compression-compression fatigue testing results at 160 °F.

Fatigue at 160°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1	0505-07		2,633	1,492
2	0505-08	5,042	2,633	1,492
3	0505-09	2,567	2,633	1,492
4	0505-10	2,027	2,633	1,492
5	0506-01		2,633	1,492
6	0506-02	1,076	2,633	1,492
7	0506-03	3,306	2,633	1,492
8			2,633	1,492
9			2,633	1,492
10			2,633	1,492
With Outliers	Avg. Cycles	2,804		
	% Error	53.22%		
Without Outliers	Avg. Cycles	2,633		
	% Error	24.38%		

Figure 145 below shows each trial with standard deviation error bars compared to the average.

Figure 145: Number of cycles to failure of all specimens tested at 160 °F.

6.8.7 SUMMARY OF COMPRESSION-COMPRESSION FATIGUE RESULTS

At the conclusion of testing at each temperature, the average number of cycles to failure were plotted and compared. Table 50 below summarized the average decrease in cycles with increase in temperature. The standard deviations are not uncharacteristically high for this type of testing. Military Specifications and published literature usually have standard deviations for fatigue testing between 50 and 70%.

Table 50: Average decrease in cycles with cycle differential.

Decrease in Avg. Load w/ Inc. in Temp.			
Temperature (°F)	Avg. Cycles	0.5σ w/ Outliers	Cycle Differential
75	425,000	106,066	0
100	37,083	118,694	387,917
115	11,910	51,567	25,173
130	4,891	4,276	7,019
145	2,737	3,242	2,154
160	2,633	1,492	103

Figure 145 below shows the average number of cycles at each temperature. With a coefficient of determination, or R^2 value of 0.92, the logarithmic relationship is extremely accurate. Although these type of plots usually compare number of cycles with an increase in amplitude, temperature was the independent variable for this thesis experiment.

Figure 146: Average decrease in number of cycles of specimens tested between 75 °F and 160 °F.

6.9 MECHANICAL BEHAVIOR OF COMPOSITE SANDWICH PANELS WITH INSERTS SUBJECTED TO 65% YIELD COMPRESSION-COMPRESSION FATIGUE AT ELEVATED TEMPERATURES

This section details the results of the fourth and final quarter of the major bulk of research performed for this thesis—the specimens with inserts subjected to compression-compression fatigue at elevated temperatures. In order to perform the experiment designed in §2, the methods described in §5, specimens each were tested at six different temperatures: 75, 100, 115, 130, 145, and 160 °F for the reasons described in §5.4.3. This section discusses possible problems that could have skewed the results during the tests, the results, and the significance of those results.

6.9.1 75 DEGREES (ROOM TEMPERATURE)

This section details the compression-compression fatigue tests performed on insert specimens at 75 °F.

6.9.1.1 WARM UP

No warm up was required for testing at this temperature.

6.9.1.2 EXPERIMENTAL RESULTS

Two specimens were tested at 75 °F. Unfortunately the first specimen failed prematurely due to damage incurred during manufacturing. The second specimen did not fail because the maximum number of cycles of the machine was exceeded. The first specimen failed about 130,000 cycles and the second endured 872,000 before the machine stopped. Table 51 summarizes these results.

Table 51: Summary of compression testing results at 75 °F with inserts.

Fatigue at 75°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1	0719-03	130,480	872,506	524,692
2†	0719-04	872,506	872,506	524,692
3			872,506	524,692
4			872,506	524,692
5†			872,506	524,692
6			872,506	524,692
7			872,506	524,692
8			872,506	524,692
9			872,506	524,692
10			872,506	524,692
		Avg. Cycles	501,493	
With Outliers		%σ	104.63%	
Without Outliers		Avg. Cycles	872,506	
		%σ	-	

† Did not fail

Figure 147 below shows each trial with standard deviation error bars. It is very likely that the second specimen tested could have endured more cycles as the test had to be stopped prematurely.

Figure 147: Number of cycles to failure of all specimens with inserts tested at 75 °F.

6.9.2 100 DEGREES

This section details the compression-compression fatigue tests performed on insert specimens at 100 °F.

6.9.2.1 WARM UP

Prior to testing, six thermal trials were performed. On average, it took 0:04:29 with a standard deviation of 6.46% to heat the specimens to 100 °F. The results from the thermal trials are summarized below in Table 52. The first trial was thrown out because the thermal chamber had been sitting at room temperature.

Table 52: Time required to heat specimen to 100 °F in the thermal chamber.

Time Required to Warm to 100 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:06:13	74.8	97.3	2.1	0:04:29	0:00:45
2	0:04:34	76.4	98.7	2.2	0:04:29	0:00:45
3	0:04:47	74.9	98.1	2.0	0:04:29	0:00:45
4	0:04:32	76.1	98.5	1.9	0:04:29	0:00:45
5	0:04:32	75.8	98.5	1.9	0:04:29	0:00:45
6‡	0:04:00	77.6	99.6	2.0	0:04:29	0:00:45
With Outliers	Avg. Time	0:04:46				
	%σ	15.79%				
Without Outliers	Avg. Time	0:04:29				
	%σ	6.46%				

Date of Trials	7/19/2010	
Time of Day	10:00	AM,PM
Room Temp.	66.5	°F
Temp. in Celsius	37.78	°C
Temp. for Chamber	37	°C

Note: Results taken from monotonic no inserts at 100 deg b/c room temperature is the same

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

‡The final measured time to temperature after all the testing was completed

Note: This data was taken from testing without inserts at 66.5 °F, current is 73.1 °F

Figure 148 below shows each thermal trial with standard deviation error bars compared to the average.

Figure 148: Time required to heat specimen to 100 °F in the thermal chamber.

6.9.2.2 EXPERIMENTAL RESULTS

After the thermal trials were complete, two specimens were tested at 100 °F. On average, they failed at about 300,000 cycles. The first trial was thrown out because it failed prematurely. It was

accidentally placed in compression while putting it in the machine. This had the effect of prematurely weakening the part. These results are summarized below in Table 53.

Table 53: Summary of compression testing results at 100 °F with inserts.

Fatigue at 100°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1	0719-06	1,054	297,000	209,265
2	0719-05	297,000	297,000	209,265
3			297,000	209,265
4			297,000	209,265
5			297,000	209,265
6			297,000	209,265
7			297,000	209,265
8			297,000	209,265
9			297,000	209,265
10			297,000	209,265
With Outliers	Avg. Cycles	149,027		
	% Error	140.42%		
Without Outliers	Avg. Cycles	297,000		
	% Error	-		

Figure 149 below shows the two trials with standard deviation error bars.

Figure 149: Number of cycles to failure of all specimens with inserts tested at 100 °F.

6.9.3 115 DEGREES

This section details the compression-compression fatigue tests performed on insert specimens at 115 °F.

6.9.3.1 WARM UP

Prior to testing, six thermal trials were performed to determine the time necessary to heat the specimens to 115 °F. On average, it took 0:10:24 with a standard deviation of about 4%. These results are summarized below in Table 54.

Table 54: Time required to heat specimen to 115 °F in the thermal chamber.

Time Required to Warm to 115 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:10:01	80.8	112.6	3.5	0:10:24	0:00:25
2	0:10:19	75.1	112.8	3.1	0:10:24	0:00:25
3	0:10:59	75.3	113.5	2.7	0:10:24	0:00:25
4	0:10:15	75.9	113.0	3.0	0:10:24	0:00:25
5					0:10:24	0:00:25
6‡	0:09:57	75.1	114.5	1.5	0:10:24	0:00:25
With Outliers	Avg. Time	0:10:18				
	%σ	3.98%				
Without Outliers	Avg. Time	0:10:24				
	%σ	3.99%				

Date of Trials	8/11/2010	
Time of Day	2:15	PM
Room Temp.	74.3	°F
Temp. in Celsius	46.11	°C
Temp. for Chamber	46	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† Still heating up

‡ The final measured time to temperature after all the testing was completed

Note: This data was taken from testing without inserts at 74.3 °F, current is 71.7 °F

Figure 150 below shows each thermal trial with standard deviation error bars compared to the average.

No trials were thrown out.

Figure 150: Time required to heat specimen to 115 °F in the thermal chamber.

6.9.3.2 EXPERIMENTAL RESULTS

After the thermal trials were complete, two specimens were tested at 115 °F. On average, the specimens failed after about 70,000 cycles with a standard deviation of about 10%. These results are detailed below in Table 55.

Table 55: Summary of compression testing results at 115 °F with inserts.

Fatigue at 115°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1	0719-01	65,699	70,411	6,663
2	0719-02	75,122	70,411	6,663
3	0719-03		70,411	6,663
4	0719-04		70,411	6,663
5			70,411	6,663
6			70,411	6,663
7			70,411	6,663
8			70,411	6,663
9			70,411	6,663
10			70,411	6,663
With Outliers	Avg. Cycles	70,411		
	% Error	9.46%		
Without Outliers	Avg. Cycles	70,411		
	% Error	9.46%		

Figure 151 below shows each specimen with standard deviation error bars compared to the average.

Figure 151: Number of cycles to failure of all specimens with inserts tested at 115 °F.

6.9.4 130 DEGREES

This section details the compression-compression fatigue tests performed on insert specimens at 130 °F.

6.9.4.1 WARM UP

Prior to testing, five thermal trials were performed to find the average time necessary to heat specimens to 130 °F from a room temperature of 66.2 °F. The average was determined to be 0:11:36 with a standard deviation of 5.88%. These results are summarized below in Table 56. The first trial was thrown out because the thermal chamber had been sitting at room temperature.

Table 56: Time required to heat specimen to 130 °F in the thermal chamber.

Time Required to Warm to 130 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:16:28	70.6	127.4	3.9	0:11:36	0:02:15
2	0:10:53	73.7	125.9	5.1	0:11:36	0:02:15
3	0:11:10	73.4	126.3	4.4	0:11:36	0:02:15
4	0:12:06	79.8	127.4	3.2	0:11:36	0:02:15
5					0:11:36	0:02:15
6‡	0:12:16	78.6	128.8	2.1	0:11:36	0:02:15
With Outliers	Avg. Time	0:12:35				
	%σ	17.92%				
Without Outliers	Avg. Time	0:11:36				
	%σ	5.88%				

Date of Trials	8/11-13/2010	
Time of Day	9:00-12:00	AM, PM
Room Temp.	66.2	°F
Temp. in Celsius	54.44	°C
Temp. for Chamber	54	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† The chamber was not pre-heated like all the other trials

‡ The final measured time to temperature on 8/13/2010 at a room temperature of 78.6 °F

Note: This data was taken from testing without inserts at 66.2 °F

Figure 152 below shows each thermal trial with standard deviation error bars compared to the average.

Figure 152: Time required to heat specimen to 130 °F in the thermal chamber.

6.9.4.2 EXPERIMENTAL RESULTS

After the thermal trials were complete, five specimens were tested at 130 °F. On average, the specimens lasted nearly 13,000 cycles with a standard deviation of just over 100%. These results are summarized below in Table 57.

Table 57: Summary of compression testing results at 130 °F with inserts.

Fatigue at 130°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1	0721-06	2,429	12,876	13,472
2	0721-07	10,992	12,876	13,472
3	0721-08	36,047	12,876	13,472
4	0721-09	4,484	12,876	13,472
5	0721-10	10,430	12,876	13,472
6			12,876	13,472
7			12,876	13,472
8			12,876	13,472
9			12,876	13,472
10			12,876	13,472
With Outliers	Avg. Cycles	12,876		
	% Error	104.63%		
Without Outliers	Avg. Cycles	12,876		
	% Error	104.63%		

Figure 153 shows each individual fatigue trial with standard deviation error bars compared to the average.

Although the average doesn't fall within the expected range of the third trial, there was no reason to exclude the data. Any exclusion would have been an artificial one.

Figure 153: Number of cycles to failure of all specimens with inserts tested at 130 °F.

6.9.5 145 DEGREES

This section details the compression-compression fatigue tests performed on insert specimens at 145 °F.

6.9.5.1 WARM UP

Prior to testing, six thermal trials were performed. On average, it took 0:11:26 with a standard deviation of about 9% to heat the thermocouple specimen from a room temperature of 71.7 °F to 145 °F. These results are summarized below in Table 58.

Table 58: Time required to heat specimen to 145 °F in the thermal chamber.

Time Required to Warm to 145 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:10:30	71.7	140.3	2.3	0:11:26	0:01:04
2‡	0:11:47	78.3	140	4.5	0:11:26	0:01:04
3	0:12:27	75.3	140	4.6	0:11:26	0:01:04
4	0:12:20	80.7	139.2	5.5	0:11:26	0:01:04
5					0:11:26	0:01:04
6‡	0:10:07	75.8	143.7	1.7	0:11:26	0:01:04
With Outliers	Avg. Time	0:11:26				
	%σ	9.35%				
Without Outliers	Avg. Time	0:11:26				
	%σ	9.35%				

Date of Trials	8/10-13/2010	
Time of Day	11:55-12:30	AM, PM
Room Temp.	71.7	°F
Temp. in Celsius	62.78	°C
Temp. for Chamber	62	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† The chamber was pre-heated to 165 for previous testing

‡ Switched temperature from 61 to 62

‡ The final measured time to temperature taken on 8/13/2010 to verify the parts were not too hot

Note: This data was taken from testing without inserts at 71.1 °F

Figure 154 below shows each thermal trial with standard deviation error bars compared to the average.

All of the data collected were extremely close. It's also important to note that this data was taken from testing without inserts at 71.1 °F.

Figure 154: Time required to heat specimen to 145 °F in the thermal chamber.

6.9.5.2 EXPERIMENTAL RESULTS

After the thermal trials were completed, five specimens were tested at 145 °F. On average, the specimens failed at about 3,500 cycles with a standard deviation of 182%. These results are summarized below in Table 59.

Table 59: Summary of compression testing results at 145 °F with inserts.

Fatigue at 145°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1	0721-01	14,712	3,462	6,301
2	0721-02	134	3,462	6,301
3	0721-03	1,148	3,462	6,301
4	0721-04	460	3,462	6,301
5	0721-05	856	3,462	6,301
6			3,462	6,301
7			3,462	6,301
8			3,462	6,301
9			3,462	6,301
10			3,462	6,301
With Outliers	Avg. Cycles	3,462		
	% Error	182.00%		
Without Outliers	Avg. Cycles	3,462		
	% Error	182.00%		

Figure 153 below show the number of cycles to failure of each specimen with standard deviation error bars compared to the average. Although the first specimen lasted much longer than the others, it was not excluded because there was nothing wrong with the hydraulic pressure of the machine.

Figure 155: Number of cycles to failure of all specimens with inserts tested at 145 °F.

6.9.6 160 DEGREES

This section details the compression-compression fatigue tests performed on insert specimens at 160 °F.

6.9.6.1 WARM UP

Prior to testing, six thermal trials were performed to determine the amount of time to heat the thermocouple specimen from a room temperature of 75.5 °F to the testing temperature of 160 °F. On average, it took 0:12:18 with a standard deviation of less than 1%. These results are detailed below in Table 60. The first trial was excluded because the thermal chamber had been sitting at room temperature and needed to warm up.

Table 60: Time required to heat specimen to 160 °F in the thermal chamber.

Time Required to Warm to 160 °F						
Trial #	Time to Temp	Start Temp	Final Temp	T1-T2*	Avg. Time to Temp	0.5σ w/ Outliers
1†	0:12:45	75.5	155.8	7.8	0:12:18	0:00:13
2τ	0:12:11	77.9	154.6	6.3	0:12:18	0:00:13
3	0:12:21	78.4	154	6.9	0:12:18	0:00:13
4	0:12:18	77.9	154.2	6.5	0:12:18	0:00:13
5	0:12:18	77.9	154.2	6.5	0:12:18	0:00:13
6‡	0:12:24	73.5	160.1	2.5	0:12:18	0:00:13
With Outliers	Avg. Time	0:12:24				
	%σ	1.72%				
Without Outliers	Avg. Time	0:12:18				
	%σ	0.75%				

Date of Trials	8/9-10/2010	
Time of Day	3:13-11:45	PM, AM
Room Temp.	75.5	°F
Temp. in Celsius	71.11	°C
Temp. for Chamber	70	°C

* T1 is the temperature inside the chamber, T2 is the temperature inside the part; wait until T1-T2 is around 2

† The chamber was not pre-heated like all the other trials

τ Switched temperature to 70 degrees

‡ The final measured time to temperature after all the testing was completed

Note: This data was taken from testing without inserts at 75.5 °F

Figure 156 below shows each thermal trial with standard deviation error bars compared to the average time to temperature.

Figure 156: Time required to heat specimen to 160 °F in the thermal chamber.

6.9.6.2 EXPERIMENTAL RESULTS

After the thermal trials were concluded, five specimens were tested. On average, the specimens failed after 2,350 cycles with a standard deviation of about 27%. These results are summarized below in Table 61. The first specimen was used to autotune the Instron servo-hydraulic machine prior to testing. Autotuning need to occur whenever the amplitude is changed and usually destroys the specimen.

Table 61: Summary of compression testing results at 160 °F with inserts.

Fatigue at 160°F				
Test #	Test Sample	Cycles	Avg. Cyc.	0.5σ w/ Outliers
1†	0709-06		2,344	1,019
2	0709-06	2,587	2,344	1,019
3	0709-07	1,630	2,344	1,019
4	0709-08	2,815	2,344	1,019
5	0709-09	995	2,344	1,019
6	0709-10	426	2,344	1,019
7			2,344	1,019
8			2,344	1,019
9			2,344	1,019
10			2,344	1,019
		Avg. Cycles	1,691	
With Outliers		% Error	60.28%	
Without Outliers		Avg. Cycles	2,344	
		% Error	26.82%	

† Autotune parameters: Tuning Disturbance Amplitude: 247.5
Tuning Frequency: 5 Hz, Tuning Damping Ratio: 0

Figure 157 below shows each trial with standard deviation error bars compared to the average.

Figure 157: Number of cycles to failure of all specimens with inserts tested at 160 °F.

6.9.7 SUMMARY OF COMPRESSION-COMPRESSION FATIGUE WITH RESULTS WITH INSERTS

At the conclusion of testing all the fatigue specimens with inserts, the average cycles to failure at each respective temperature were plotted as shown below in Figure 158.

Figure 158: Average decrease in number of cycles to failure in specimens with inserts tested between 75 °F and 160 °F.

Although the standard deviation error bars on lower temperature specimens are extremely high, a coefficient of determination, or R^2 value of 0.971 was found which indicates an extremely strong data correlation. The high standard deviations are most likely due to the lack of specimens tested at 75 and 100 °F. More specimens were available, but each test can take multiple days. Time was ultimately the limiting factor. In the future, those standard deviations could most likely be reduced by testing more specimens.

6.10 SUMMARY OF THE EFFECTIVENESS OF INSERTS IN DELAYING FAILURE IN COMPRESSION-COMPRESSION FATIGUE AT ELEVATED TEMPERATURES

After all the control specimens and specimens with inserts were tested, the cycles to failure at each respective temperature were compared. Table 62 below shows the percent improvement of utilizing

inserts at each temperature. It is important to realize that any percent improvement is not the same as percent improvement in the monotonic compression sense. The displacement failure criteria and force amplitude for the control specimens and insert specimens were different as explained in §5.4.3.

Table 62: Effectiveness of inserts under increased temperatures.

Temperature (°F)	% Improvement
75	105
100	701
115	491
130	163
145	27
160	-11

Figure 159 shows the two fatigue curves plotted on the same axis. Notice how the curve for the specimens with inserts is displaced positively on the horizontal axis indicating that overall it can endure more cycles. Prior to testing, it was hypothesized that there would be no improvement, meaning the fatigue curves would lie directly on top of each other. Instead, it was found that the inserts provide an even greater advantage in fatigue than monotonic. Had the insert specimens been tested with the exact same failure and load criteria as the control specimens, the curve would be displaced even further to the right with percent improvement values most likely over 200%. Future testing should probably take place to figure out what about the geometry of the added insert provides the unexpected advantage in fatigue.

Figure 159: Comparison of average number of cycle decrease of specimens tested between 75 °F and 160 °F with and without inserts.

Figure 160 below shows the same data points as Figure 159 except with a log scale on the horizontal axis. This plot is useful in planning for testing because it's easier to extrapolate a linear curve than a logarithmic one. Even though the data are relatively sparse, it still provides extremely high R^2 values indicating that it has the potential to be relatively predictive.

Figure 160: Log plot comparison of average number of cycle decrease of specimens tested between 75 °F and 160 °F with and without inserts.

6.11 FAILURE ANALYSIS

This brief section aims to characterize the failures examined during monotonic and fatigue testing at elevated temperatures. Prior to reading this section a review of §1.4 might be helpful.

6.11.1 MONOTONIC FAILURES

The three main types of failures that occurred during monotonic tests were bearing, shearing, and micro-buckling. Bearing stress failures were typically characterized by the pushing the facesheets outwards around the hole region of contact. Bearing failure was worse at 200 °F than at 75 °F. Shearing stress failures were characterized by the movement of the entire material on the inside of the holes being evenly pushed towards the center of the part without buckling outwards like the bearing failures. Micro-buckling failures only occurred in specimens with inserts and were characterized by the insert popping out of the facesheet. This was the most likely form of failure in insert specimens because of the stress concentration at the insert-foam boundary. Figure 161 shows all of the failures described above.

Figure 161: Types of failure that occurred during monotonic testing.

6.11.2 FATIGUE FAILURES

The fatigue failures were much less diverse than the monotonic compression failures, which made the failure type much more predictable. Nearly all the failures were categorized by a shearing motion that steadily grew as the bushing sawed through the holes until the displacement failure criteria was reached. This failure is shown below in Figure 162.

Figure 162: Shearing failure caused during the majority of fatigue tests.

7 NUMERIC ANALYSIS AND DISCUSSION

Two finite element models were developed to model the control specimens and the specimens with inserts. The material properties obtained from experimental testing available in §6 were used to model and simulate the failures experience that occurred at various temperatures. The modeling was performed using Abaqus/CAE 6.10, the solving was performed using Abaqus 6.10, and the post-processing was performed in Abaqus/Viewer 6.10.

7.1 GEOMETRIC DEFINITIONS

Prior to assigning material properties, it was necessary to actually model both of the specimen types. The core was modeled first based on the measurements described in §2.5.5. The facesheet thickness was based on an average of the experimental thickness obtained by just laying up a two layer plate of LTM45 carbon fiber with one layer of sheet resin. The insert thicknesses were found in a similar manner by laying up a three layer thick plate. Figure 163 shows the geometric definitions of each specimen.

Figure 163: Test specimens with and without inserts geometric definition: 2 rigid bolt instances, 2 solid deformable brass bushing instances, 1 solid deformable foam core instance, 2 solid deformable anisotropic carbon fiber weave instances.

7.2 MATERIAL PROPERTIES

The core section of both models were defined as solid isotropic materials with the properties found in §6.2.1.1. The LTM45 carbon fiber facesheets were described as a solid anisotropic material with the properties found in §6.2.1.2. The bushings were treated as a solid isotropic SAE 841 bronze with a bulk modulus of elasticity, or E , of $1.65e7$ and a Poisson's ratio of .32. The bolts were treated as analytically rigid.

The thermal expansions of the foam, carbon fiber, and bronze were $3.1e-5$, $0.54e-6$, and $1.00e-5$ respectively. The temperature property was applied to the entire assembly using the temperature predefined field in Abaqus/CAE as shown below in Figure 164. There were seven steps in the analysis, one for each temperature. At the end of each step, the temperature was set back to 75 °F and the assembly was unloaded.

Figure 164: Application of temperature to the entire assembly.

7.3 MESHING

Most literature, including the Abaqus documentation⁽²¹⁾ suggests a minimum number of elements through the thickness of thin parts such as plates. The documentation specifies no less than four linear elements, or two quadratic elements to be used through the thickness of plates. For this model, three quadratic elements were used through the thickness of the carbon facesheets, and seven were used through the thickness of the foam. The areas of most interest are located just above the bottom hole and just below the top hole. These are the areas with the maximum compressive stress. Because the most displacement occurs at these regions, it was necessary to increase the mesh density.

The meshes of the control specimen and the specimen with inserts are shown below in Figure 165. For the core and carbon sections, a structured hexahedral mesh with a seed size varying from 0.03 to 0.094 was used. For the bushing sections, a swept hex mesh with a seed size of 0.062 was used.

Figure 165: Mesh of control specimen (no DAD) and specimen with inserts (DAD).

Prior to running the analysis, the mesh was verified to have less than 1% distorted elements. This was done using the Abaqus built in mesh verify control. It was important to make sure no element distortion occurred in the regions of interest. Distorted elements have a propensity to report inaccurately

high stresses. Element distortion can be caused by high aspect ratio elements, which force the integration points (which are further apart than they should be) to interpolate over larger distances and report higher stress values.⁽²¹⁾ Having face angles that are too large or small can cause sliver shaped elements that don't deform correctly.⁽²¹⁾ Abaqus will also show warnings for elements that are too small because they might significantly increase the time the analysis takes to complete. No element distortion was found.

Although composite sandwiches are typically defined using shell elements and specifying a layup, in this particular instance, C3D20R (20-node quadratic bricks, with reduced integration and hourglass control) elements were used. Layups are modeled as shells when included in a large assembly to reduce the total number of elements (decreasing the total analysis run-time) and make the modeling easier. Shell elements are great at showing surface stresses, but lack the dimensions to accurately analyze inter-laminar forces. Because this analysis was interested in the bearing stress of the hole-bolt interaction, it was necessary to include a thickness.

Quadratic elements were picked because they provide higher accuracy than linear elements for smooth problems that do not include severe element distortion.⁽²¹⁾ They're better at capturing stress concentrations, modeling curved surfaces, and extremely effective in bending-dominated problems⁽²¹⁾ — all of which are important to this specific problem. Linear elements are over stiff and exhibit slow convergence. To solve these problems, an extremely fine mesh is necessary, which requires more time for analysis. Hour glassing, the tendency for elements to distort in such a way that the strains calculated at the integration point are all zero, is also more prone to happen with first order reduced-integration elements (such as C3D8R).

Reduced integration, which uses a lower-order integration to form element stiffness, was used in order to reduce runtime. Where normally the element type C3D20 has 27 integration points, C3D8R only has 8, and is approximately 3.5 times more computationally cost effective.⁽²¹⁾ In addition, reduced-integration elements typically yield more accurate results than fully integrated elements. Lastly, shear and volumetric locking, which causes elements to give rise to shear strains that do not really exist, making them too stiff in bending, is more likely to occur with fully integrated elements.

Hexahedral elements were used in meshing the composite sandwich because they typically provide a better stress formulation. Tetrahedral elements are good for meshing complex geometry, but were not necessary in the development of this model.

A mesh convergence study was done to make sure that the element size was not significantly affecting the stress results. The model initially had a coarse mesh to allow the analysis to run quickly for trouble shooting purposes. The mesh density was then gradually increases until the stress values didn't change more than 5%.

7.4 CONTACT DEFINITIONS

The model was constructed to meet the following criteria in order to avoid or reduce the probability of convergence problems⁽²¹⁾:

- 1) Master and slave surfaces have similar mesh density: Abaqus relies on the assumption that there are more nodes on the master surface, if there are not, converge problems surface;
- 2) Master surface is the stiffer material: Abaqus bases the contact forces on the deformation of the master nodes, if they're a softer material, convergence problems can surface, and stress values could be distorted;
- 3) Small sliding is used, which smoothed the transition from the bushing to the composite sandwich;
- 4) Mesh converges within 5 percent: A large mesh density was initially used to converge the models contact definitions and discover areas of maximum stress, which were identified as the portions of the holes that are in bearing compression. The mesh density was then increased in those areas to improve the stress formulations;
- 5) Node-to-surface contact definitions initially were used for convergence, but provided spotty stress results, and were replaced with surface-to-surface definitions which improved the surface stress formulation;

- 6) Avoid overlapping constraints: Initially over constraints were a problem, but were overcome by changing two interactions to constraints.

The contact definitions of the control specimen and the specimen with inserts are shown below in Figure 166. A tie constraint was used between the core and carbon. For the bushing and hole contact, a node to surface contact formulation was using with a smoothing of 0.2, tolerance of 0.001, and a normal / rough hard contact property.

Figure 166: Contact definitions of control specimen (no DAD) and specimen with inserts (DAD).

7.5 LOADS AND CONSTRAINTS

Especially when using rigid elements, it's important to make sure there is adequate distance between specified boundary conditions and the regions of interest. Because the rigid beam makes contact with the bushing rather than the surface of the holes in the composite sandwich, artificially high stresses were not an issue.

Because a rigid part is governed entirely by the motion and constraints of its reference node, it was only necessary to constrain one reference point on each bolt. On the top bolt, all six degrees of freedom were constrained (3 displacement— x , y , z , and three rotational— rx , ry , rz). It was necessary,

however for the bottom bolt to move to simulate the movement of the servo-hydraulic machine. Thus, the bottom bolt only had five degrees of freedom constrained (2 displacement-z, y, and three rotational- rx , ry , rz). This enabled the bolt to move freely in the vertical direction thus allowing the simulation of tension and compression. The constraints definitions are shown below in Figure 167.

Figure 167: Load applied to bottom bolt of assembly as shown on the left. All other degrees of freedom were constrained. On the top bolt, all six degrees of freedom were constrained..

A single load was applied to the entire assembly at the reference point found on the bottom bolt. This is the same as applying a load anywhere on the bolt because the bolt has a rigid formulation and all directional and rotational degrees of freedom except the vertical direction, constrained.

The experimental data were analyzed to find the average yield force and respective displacement as discussed in §8. This force was then applied to the model and analyzed. The resulting displacement of the bolt was then measured in the Abaqus/Viewer post-processor and recorded. This was done for all temperatures. The resulting comparison is shown in Figure 169 and Figure 170: Comparison of average experimental yields and FEA yields for specimens with inserts at all test conditions., the values of which are available in §8.

Table 64 and Table 65 below show the comparison between the experimental data and the finite element analysis (FEA) for the specimens with inserts. On average, all of the percent differences are less than about 10%. This means that the finite element model (FEM) was extremely predictive and a good representation of the physical system. However, as explained in the experimental section, due to the geometry of the specimens with inserts, the results vary from specimen to specimen much more than the control specimens.

7.6 RESULTS

After the model was analyzed in all seven steps, the results could be viewed in Abaqus/Viewer.

These results are shown below in Figure 168.

Figure 168: Von Mises stress results of control specimen (no DAD) and specimen with inserts (DAD).

Each model was loaded with 10 pounds. Notice how the control specimen (left) has much higher stress in the middle of the middle and much more displacement through the holes. The specimen with the insert or damage arrestment device (DAD) (right) has less of a stress concentration in the middle of the part and less overall displacement in the hole region. These results are summarized in Table 63.

Table 63: Numeric Comparison of Specimens with and without Inserts.

	Comparison of Specimens w/ and w/o Inserts			
	Temperature (°F)	Avg. δ_y (in.)	Avg. F_y (lbf.)	% Difference
No Insert	75	6.26E-04	10	-
Insert	75	4.26E-04	10	-31.85

A 32% difference in displacement was recorded, which is actually much less than was found experimentally.

In the future, it would be easy to increase the thickness of the insert, or damage arrestment device (DAD) in this model to see at which point increasing the thickness has no greater affect.

8 COMPARISON OF RESULTS

This section compares numeric and experimental results for each temperature. The average force at each temperature was known for the control specimens and the specimens with inserts. Using the experimental data, the average displacement at failure was found as well. The average forces were applied to both numeric models, and the resulting displacements were compared to the experimental displacements.

8.1 COMPARISON OF EXPERIMENTAL AND FEA RESULTS

Table 64 below shows the comparison between the experimental data and the finite element analysis (FEA) for the control specimens. On average, all of the percent differences are less than about 5%. This means that the finite element model (FEM) was extremely predictive and a good representation of the physical system.

Table 64: Comparison of experimental and FEA displacements for a given applied force.

		Comparison of Experimental Results and FEA			
		Temperature (°F)	Avg. δ_y (in.)	Avg. F_y (lbf.)	% Difference
Experimental		75	3.45E-02	747	
		100	3.95E-02	564	
		125	4.06E-02	548	
		150	3.26E-02	463	
		175	4.46E-02	374	
		200	3.59E-02	324	
FEA		75	3.32E-02	747	-3.75
		100	3.87E-02	564	-2.08
		125	4.01E-02	548	-1.18
		150	3.07E-02	463	-5.82
		175	4.32E-02	374	-3.11
		200	3.52E-02	324	-2.05

Figure 169 below shows the linear elastic (up to yield) force-displacement curves of the experimental data compared to the FEA results for the control specimens. As demonstrated above, the results are extremely close.

Figure 169: Comparison of average experimental yields and FEA yields for specimens without inserts at all test conditions.

8.2 COMPARISON OF EXPERIMENTAL AND FEA RESULTS FOR SPECIMENS WITH INSERTS

Table 65 below shows the comparison between the experimental data and the finite element analysis (FEA) for the specimens with inserts. On average, all of the percent differences are less than about 10%. This means that the finite element model (FEM) was extremely predictive and a good representation of the physical system. However, as explained in the experimental section, due to the geometry of the specimens with inserts, the results vary from specimen to specimen much more than the control specimens.

Table 65: Comparison of experimental and FEA displacements for a given applied force in specimens with inserts.

Comparison of Experimental Results and FEA (Inserts)				
	Temperature (°F)	Avg. δ_y (in.)	Avg. F_y (lbf.)	% Difference
Experimental	75	5.87E-02	1451	
	100	6.25E-02	1171	
	125	5.63E-02	1212	
	150	4.80E-02	1169	
	175	5.87E-02	1451	
	200	3.33E-02	653	
FEA	75	5.80E-02	1451	-1.05
	100	6.11E-02	1171	-2.31
	125	5.30E-02	1212	-5.82
	150	4.71E-02	1169	-1.96
	175	5.96E-02	1451	1.61
	200	3.62E-02	653	8.57

Figure 170 below shows the linear elastic (up to yield) force-displacement curves of the experimental data compared to the FEA results for the specimens with inserts. As demonstrated above, the results are extremely close.

Figure 170: Comparison of average experimental yields and FEA yields for specimens with inserts at all test conditions.

8.3 COMPARISON OF THEORETICAL, EXPERIMENTAL, AND COSMOS FEA RESULTS⁽¹³⁾

An analysis was performed using the theoretical equations described in §3.2 and the SolidWorks FEA program called COSMOS in order to compare the bulk modulus or stiffness of the composite sandwich.⁽¹³⁾ These results are shown below for comparison in Table 66.

Table 66: Comparison of theoretical, experimental, and Cosmos FEA results for control specimen at 75 °F⁽¹³⁾

	Elastic Modulus	% Difference from Theoretical	% Difference from Experimental
	(psi)	(-)	(-)
Theoretical Results	62,650	-	-
Experimental Results	45,174	-27.9%	-
Force Loading: Base Model w/ Bushing	34,573	-44.8%	-23.5%
Force Loading: Base Model w/ Bushing & Fastener	47,578	-24.1%	5.3%
Pressure Loading: Base Model	48,715	-22.2%	7.8%

Additionally, these values are plotted below for a visual comparison in Figure 171.

Figure 171: Visual comparison of results for control specimen.⁽¹³⁾

The modeling and the experimental test results are in reasonable agreement. Any discrepancy most likely results from the limitation of the developed model and/or the accuracy of the material properties obtained.

8.4 ERROR ANALYSIS

This section examines the potential areas of the experiment that contributed most to the variance between results.

8.4.1 ATMOSPHERIC PRESSURE / HUMIDITY NOT MEASURED OR RECORDED

During the experiment, the atmospheric pressure and humidity were not recorded. Although not a major effect, especially in the central coast of California, this could have contributed to variation between trials conducted on separate days. If this experiment were to be repeated, especially in a different part of the world, humidity might play a large role.

8.4.2 MANUFACTURING DEFECTS

Throughout the entire experimental section of the report, manufacturing defect were reported as the main reason specimens were excluded from the average. There are numerous types of manufacturing defects. The defects that occurred during the layup included dimples in the surface of the facesheet, unevenness of film adhesive in certain parts of the sandwich, and possible areas that didn't bond at all. During the cutting process, specimens were not always cut to the perfect 2" by 5" dimensions. The most devastating area of manufacturing defects, however, was most likely the damage initiated around the hole by incorrect drilling practices or utilizing a dull tool. Because the holes were the only loaded region of the specimen, any small differences in delamination around the hole, extra fibers, hole size, etc. could have contributed greatly to the variation in results.

8.4.3 DIRECTIONALITY OF FOAM

Apparently the FR-70 polyurethane foam used for the core has slightly different material properties in its longitudinal and lateral directions. This was not made clear to us until we contacted the manufacturer after we noticed an issue. As a result, the layups were not 100% consistent meaning that sometimes the core was compressed in the longitudinal direction, and sometimes it was compressed in the lateral direction. This was most likely the largest source of error.

8.4.4 TEMPERATURE VARIATION

Because it's impossible to get a perfect temperature reading in the thermal chamber due to poor instrumentation, and each specimen is a slightly different size, it is possible that some specimens were heated to temperature slightly longer than others which could have resulted in thermal fatigue. However

the differences in specimen size and potential time were so small that they were probably washed out in the average.

8.4.5 STRAIGHTNESS OF THE TESTING JIGS

Because the testing jigs were bent due to another group incorrectly loading the Instron machine, we had to bend the steel back using an extremely large compression machine. In doing so, it was impossible to get the jigs exactly straight. Thus, each time we tested only one side of the specimen was loaded. In the force strain curves where it looks like the specimen yielded multiple times, that's probably because one side failed and transferred the load to the other side. This is also why all of our pieces only fractured on one side. However, this was good because we could make sure that each side fractured on the side with the shear key.

8.4.6 PRECISION USING THE SAW

Because the saw is old and not exactly straight, not all of the specimens we tested were of uniform dimensions. Thus, loading each specimen was almost a unique instance. In the future, better equipment will be ordered which will allow our results to be more consistent.

9 CONCLUSION

This section concentrates on a summary of the thesis, recommendations for future work, recommendations for updated equipment, and recommendations to decrease experimental error.

9.1 SUMMARY

It was found that as the DAD thickness increases in the specimen, the overall failure load also increases. The overall failure load trend for the varying DAD thickness ended up being a parabolic shape. The failure mode of the experimental testing started from a pure bearing stress on specimens with small or no DAD thickness to a buckling failure with the facesheet delaminating for specimens with thicker DADs. The fatigue testing showed that specimens with or without a DAD have similar life cycle curves and fatigue endurance limits. This proved that the DADs only strengthen the composite sandwich panel and not prolong failure of the panels.

It was discovered that temperature linearly decreases both yield and ultimate load capacity in foam composite sandwiches. The DADs directly increase both yield and ultimate load capacity. This increase is not penalized with an increase in temperature. It was also found that the number of cycles to failure is logarithmically related to temperature and that DADs may have an additional benefit in fatigue at lower temperatures beyond just adding stiffness.

The numeric analysis showed that the type of loading on the model and the configuration of the model greatly affected the results.

Throughout this experiment a comprehensive literature review and design of experiment was performed. Much time was spent on figuring out the best method of fabrication and jig design. Throughout the testing process, rigorous, repeatable methods were developed. Finally, the experimental results were analyzed and compared to the numeric model.

The rest of this section will concentrate on future work.

9.2 RECOMMENDATION FOR FUTURE WORK

Although this thesis research investigated a wide range of concepts, there is always more potential research that can be done. Current students looking for research direction on their thesis or

senior project will benefit from this section. The list described in this section seeks to expand the scope of the research to benefit the education of graduate and undergraduate students, further the field of sandwich composite research, and aid in financial and material donations to the Cal Poly Structures / Composites Laboratory.

9.2.1 IMPACT

An interesting extension of this research would be the impact response of the manufactured composite sandwiches. Using the impact machine, shown below in Figure 172, sandwich composites could be punctured with a variety of jigs.

Figure 172: Impact machine used to test composite puncture at high velocities.

It is very possible that the insert geometry developed for this thesis could drastically improve the impact response of the sandwich composites. However, most puncture or impact problems occur in unpredictable spots. Adding an insert all the way around a wing of an aircraft would be the equivalent of increasing the skin thickness. It's very possible that even if an insert was found beneficial, the application would be very limited. Nevertheless, as an academic exercise, the experiment could yield some interesting results. Additionally, the numeric modeling for impact response of sandwich composites is extremely interesting and complex and shown below in Figure 173.

Figure 173: Experimental and numerical comparison for impact response of sandwich composite.

9.2.2 SANDWICH COMPOSITE REPAIR

Sandwich composites are typically punctured, bent, warped, crimped, or rendered useless in a variety of ways. Finding new novel ways to repair them could prove to be an interesting project. Additionally, testing the reduction in strength and the increase in weight of various sandwich composite repair techniques on the specimens used in this thesis could lead to a breakthrough.

9.2.3 DECREASED TEMPERATURES

Because this thesis was solely focused on the effect of elevated temperatures on composite sandwich panels, it would be extremely interesting to see the response under cooler temperatures. Using the same exact methods, and a slightly modified apparatus (i.e. adding liquid nitrogen to the thermal chamber), it would be possible to test at reduced temperatures. Reduced temperatures have a variety of applications, such as high altitude, safety in cold areas (such as Canada or Russia), and de-icing. The barrier to performing this research is relatively low because all of the difficult work is already done!

9.2.4 OPTIMIZING TESTING PROCEDURES

One area that all graduate students found to be of interest while working in the Structures / Composites Laboratory was the potential for laboratory procedure optimization. The majority of time in this research was spent attempting to find quicker, more effective, safer, and fully repeatable procedures that produced predictable, repeatable, quality results. This would be a great senior project or thesis for an Industrial Manufacturing Engineer (IME). The main focuses might include optimizing the layup process,

selecting proper tooling for cutting, optimizing resin content, scheduling testing, and adopting a proper method for random specimen selection.

9.2.5 DIFFERENT INSERT GEOMETRY

As explained in §2.3.2, a wide variety of insert geometries are available, but not all could be tested due to time and material constraints. Any of the described geometries could be manufactured, tested, and compared to the results in this thesis. Of primary interest might be the circular inserts because most of the specimens in this experiment that failed at the insert, failed because of the sharp corner between the insert and the foam. Utilizing circular inserts could potentially fix this issue, as long as they can be manufactured, drilled, and placed in the correct spot.

9.2.6 VIBRATION RESPONSE OF COMPOSITE SANDWICHES

Vibration is always of concern when designing any mechanical system. It would be simple enough to create a jig capable of attaching the specimens manufactured for the purposes of this thesis to the vibration machine shown below in Figure 174.

Figure 174: Vibration machine.

It's not clear what affect the inserts would have in dampening out vibration, but adding stiffness to certain spots in a support structure has the potential to change the frequency of certain dangerous modes that could potentially cause failure.

9.2.7 TESTING THE EFFECTIVENESS OF POTTED INSERTS

In the introduction, §1.5.5 described the potted insert, the typically solution to bearing stress problems. Unfortunately, there was not enough time or resources to test the potted inserts. A future

project might test their effectiveness, while holding all other variables constant. Additionally, it would be beneficial to weigh them to see how much heavier or lighter they are than specimens with inserts.

9.2.8 HUMIDITY

The equations described in §3.3 have a reference humidity term for supporting analysis for aircraft conditions such as elevated temperature wet (ETW). Certain regions of the world have drastically different humidity. It would be interesting to see the effect of humidity on the manufactured specimens.

9.2.9 PULL THROUGH

Pull through is one of the largest problems in composite design. Depending on the loading, composites are as likely to fail in pull through as they are to fail due to bearing stress. It would be relatively easy to develop an experiment in which the Instron servo-hydraulic machine was used to pull bolts through the composite sandwich designed for the purposes of this thesis.

9.3 RECOMMENDATION FOR UPGRADED LABORATORY EQUIPMENT

This section concentrates on improvements to the California Polytechnic State University, San Luis Obispo Structures / Composites Laboratory that would be extremely beneficial to further students and research projects.

9.3.1 GET MULTI-CHANNEL STRAIN GAGES TO WORK

Getting multi-channel strain gages to work in conjunction with the Instron servo-hydraulic machine would allow for the correlation of surface stress in experimental tests and finite element models. Using only one strain gage only allows the determination of stress in one area, which is not very helpful.

9.3.2 GET IMPACT MACHINE SOFTWARE

Purchasing and installing the proper software to use the Instron Impact machine would allow an impact analysis to be performed on the composite sandwiches analyzed in this thesis. Impact is a huge problem that most military customers are extremely interested in because they tend to drop tools and equipment on products and don't know if repair is required or not.

9.4 RECOMMENDATION TO DECREASE EXPERIMENTAL ERROR

This section details the two simplest ways to speed up the experiment and reduce error.

9.4.1 UTILIZE AUTOCLAVE

Getting the proper certification to utilize the autoclave would go a long way in the experimental research performed in the Structures / Composites lab because it would allow batch manufacturing. Throughout this thesis, it would take a single day to layup one plate which would yield ten specimens. If the autoclave was adopted, it would be possible to lay up twelve plates in one day. This would allow more time to be spent on testing and more interesting research to take place. Figure 175 below shows the autoclave. Utilizing the autoclave would also allow the adoption of random sampling.

Figure 175: Cal Poly Aerospace Department autoclave.

9.4.2 RANDOM SAMPLING

Using the autoclave would allow the adoption of random sampling because rather than manufacturing a plate, testing, manufacturing a plate, testing, etc., an entire batch could be manufactured, prepped, mixed up, and then tested. This would be one of the best ways to wash manufacturing defects between test conditions out of the experiment.

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