Compression Testing of Composite Laminated Foam under Thermal Loading and with Central Holes

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Abstract
A study was conducted to investigate the effect of heat on composite sandwich plates, fabricated with the vacuum resin infusion process, with center holes of varying diameters. The study involved conventional notched specimens and notched specimens with shear keys, both of which were subjected to monotonic inplane compression loading. Hole diameter was be varied from one to four inches in one inch increments. Loading rate was applied using the Instron machine at one millimeter per minute. The diameter of the shear key around the holes varied from one inch to four inches in one inch increments. The specimens were placed in a fire 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.

Nomenclature
\( \rho_f \) = density of carbon fiber
\( \rho_m \) = density of matrix
\( \sigma_{ult} \) = ultimate failure
\( \sigma_y \) = yield strength
\( E \) = elastic modulus
\( E_f \) = elastic modulus of fibers
\( E_m \) = elastic modulus of matrix

I. Introduction

A. Introduction to composite materials and applications in general
Composite materials are composed of two or more materials combined on a macroscopic scale to form a useful their material. Composites are made up of individual materials referred to as constituent materials. The two categories of constituent materials include matrix and reinforcement. At least one portion of each type is required. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties. A synergism produces material properties unavailable from the individual constituent materials, while the wide variety of matrix and strengthening materials allows the designer to choose an optimum combination. Engineered composite materials must be formed to shape. The matrix material can be introduced to the reinforcement before or after the reinforcement material is placed into the mold cavity or on the surface.

B. Advantages and Disadvantages of Composite Materials
Composite materials, if well designed, they 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, weight, fatigue life, temperature-dependent behavior, thermal insulation, thermal conductivity, and acoustical insulation. Additional cost advantages include low assembly cost, integral part design, lower maintenance cost, and high material utilization factors. Properties improved by the fabrication of composite materials. Disadvantages include the bearing strength, impact behavior, health monitoring, and moisture damage.

C. Definitions (with examples):
Composite materials: Composite materials are engineered materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct on a macroscopic level. Examples include wood, carbon-fiber reinforced plastic, and glass-reinforced plastic.
Thermoset and thermoplastic materials: Thermoset plastics are polymer materials that once cured are irreversible. They are usually liquid or malleable prior to curing and designed to be molded into their final form, or even used as adhesives. A thermoplastic is a polymer that turns to a liquid when heater and freezes to a very glassy state when cooled sufficiently. They differ from thermosetting polymers because they can be remelted and remolded. Thermoset examples include polyester fiberglass, vulcanized rubber, bakelite, epoxy resin, and polyimides. Thermoplastic examples include acrylic, celluloid, ionomers, and liquid crystal polymers.

Organic and non-organic materials: Organic material is a material that comes from a once-living organism; is capable of decay, or the product of decay. Examples include materials such as wood, minerals, or bi-products of living or dead plants or animals. Non-organic materials are considered to be of a mineral, not biological origin; many are fabricated synthetically. Examples include silicon, carbon fiber, and fiber glass.

A fiber is characterized geometrically not only by its very high length-to-diameter ration by its near-crystal-sized diameter. The types used in lab include carbon fiber, and fiberglass. The matrix material is used to hold the shape and positions of the fibers. The main matrix used in lab is epoxy.
D. Types of fabrication methods

Unlike in most processes of metal manufacturing, the relationship between design, analysis and manufacturing of composite materials is a very closely related. Fabrication of the material is in most cases part of the manufacturing of the part or the structure itself. There is still a lot of research going on in this area, and today the manufacturing process is still complicated compared to metals. The following fabrication methods are only some of a variety of possibilities.

1. Winding and Braiding:

Choosing a type of composite manufacturing consist of many different factors: part size and shape, schedule, cost, and experience with different techniques. 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. 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 performs for composite structures by robot assisted braiding. 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.

![Composite braiding](image1.png)

Figure 1: Composite braiding [Courtesy of EADS]

2. Laying

Tape laying uses pre-impregnated fibers that are unwound and laid out in the desired shape. This process is mostly automated and is used in a variety of applications, such as manufacturing of the BOEING 787 fuselage.

![Composite Laying machine](image2.png)

Figure 2: Composite Laying machine
3. RTM

Resin-transfer molding (RTM) is a process that uses dry fibers or textile sheets and resin sheets 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 used the resin-hardener mixture and varies between 15 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. It 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 and 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.

E. Introduction of composite panels and application in general, advantage and disadvantage

The common composite sandwich structure is made up of two major elements, the skin and the core. Sandwich panel skins are the outer layers and are constructed out of a variety of materials. Wood, aluminum, and plastics are commonly used. More recently though, advanced composite fibers and resins are being used to create skin material. First, picture a simple I-beam where flanges are bonded to a web to create a structural member. When stressed, the two flanges are in tension and compression. This creates the majority of strength. However, an I-beam is most effective in bending in the plane defined by the Y-Z direction.

![Figure 3: I-beam](image)

A sandwich panel is much like 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 only the Y-Z plane (like the I-beam above) but also the X-Z plane, and any plane between.

![Figure 4: Infinite I-beam](image)
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 two skins attempt to slide past each other. 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.

1. **Core**

   Flexible cores that bend easily are known to have a “low shear modulus” while very stiff cores have a “high shear modulus”. If the 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 a higher tensile/compressive strength. This skin would work in conjunction with the core. By doing this, a composite sandwich panel is constructed.

2. **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.

3. **Conclusion**

   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 the separation of different 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.

**D. Computer Numerical Control**

Computer numerical control, otherwise known as cnc, is a new age way of manufacturing parts quickly and precisely! Today cnc machines are used for many things from cutting precision parts from aluminum to plastics to even wood. They can be used to create molds and if you have a 4 axis cnc machine you can make a 3-D part from a solid block of material. The cnc machine is controlled by a computer which is running a program that gives the machine commands through coding. The coding sends single commands that represent what step the machine needs to take in order to get the desired part. Before the part can be written into code a solid model must first be created in a 3-D modeling program, such as solid works or Pro E, when entered in all the dimensions of the part are included. The cnc program then takes the solid modeling and with the dimensions turns every cut needed into a single line command that is sent to the step motors on the cnc machine. In the code the precise distance the step motor needs to turn is set. Usually a cnc machine will make passes over a solid block of material taking off only thousands of an inch each pass but cutting the part with great precision. The more precise the machines and the step motors the more precise the part.

![Figure 5: CNC machine at work.](image)

**E. Experimental Objectives**

The objectives of this experiment are to gain an understanding of the mechanical properties of a laminated composite sandwich under compression and thermal loading. Additionally the effects of various central hole diameters and shear keys will analyzed to determine their effect on the composite structure. This experiment further seeks to find a relationship between hole diameter and shear key diameter and how that effects the material under compression and thermal loading.
F. Previous Research
After a through such of peer review journals and undergraduate senior projects at the California Polytechnic State University in San Luis Obispo, CA a firm foundation was discovered for the testing of fiberglass/epoxy/foam plates. There are numerous publications on the use of fiberglass/epoxy plates on reentry craft and spacecraft in general due to their low weight to strength ratio. In addition there is a large following regarding the use of foam specimens in insulation and commercial aircraft situations. Foam composites have been used before they have only been tested with carbon fiber or Kevlar plates, and never with fiberglass/epoxy sandwich. This creates a great combination due to the extremely inexpensive nature of fiberglass/epoxy and Polyvinyl Chloride. There are numerous uses for the fiberglass/epoxy/foam plates in marine vehicles, and private/commercial airlines. The foam/fiberglass composites have an extremely low thermal conductivity, while being extremely light. Once question that must be asked is how the plates will work under thermal stress such as engine compartments or being subjected to large amounts of skin friction. This is one vacare spot in prior research that this report intends to fulfill.

II. Design, Fabrication, and Testing

A. Fabrication of the composite specimens
In this experiment a vacuum resin infusion process, VRI, layup was conducted on a sandwich laminated composite. The VRI layup procedure is as follows:
1) The material is cut to size for the layup. This consists of a foam core, and 4 pieces of each: chop strand fiberglass and woven fiberglass cloth. Also, flow media, peel ply, and vacuum bag are cut for the layup.
2) The fiberglass cloth must be weighed to ensure that the proper amount of resin used.
Figure 7: Chop strand fiberglass cloth

Figure 8: Woven fiberglass cloth
3) The vacuum bag is laid out on the table. It is cut to size so that can wrap around the entire part.
4) Then, the flow media is placed on top of the vacuum bag, followed by release cloth.
5) On top of these is placed the fiberglass cloth in the order: woven, chopped, woven, chopped.
6) Following these materials, the foam core is placed on next. And then the reverse order of fiberglass cloth. Below is a picture of the fiberglass cloth on the foam core in order.
7) Once the entire fiberglass is in place, the release cloth and flow media are folded over the entire composition. Care is taken to ensure that the material is as tight as possible with no folds or wrinkles.

8) A length of spiral tubing is cut, ensuring it is as long as the part, and a T fitting is inserted in the center. A length of plastic tubing is attached to the T fitting; this will be the hose that resin is infused through.

9) A piece of cotton material is folded and placed on the side of the core opposite to the fold. The vacuum hose is placed inside the cotton material folds. This fitting is on the opposite side of the material to the spiral tubing.

10) Sealant tape is used to border the sides of the vacuum bag. Care is taken to ensure that the bad is firmly sealed to the tape without wrinkles or creases. One side of the tape is attached at a time, and only when that side is completed is the protective plastic on the other side removed. Then the other side is sealed to the vacuum bag, ensuring an airtight seal. The sealant tape can be seen below.
11) Once the vacuum bag is sealed it is connected to the vacuum pump and pumped free of air. The vacuum bag is checked for any leakages before proceeding. If there are any, a piece of sealant tape is used to stop air from entering the bag.

12) Taking the weight that was previously recorded for the fiberglass cloth, doubling it will be the amount of resin that is required for the part. The resin to hardener ration is 5:1. Resin and hardener is pumped into a mixing cup and stirred to ensure even mixture. The resin can be seen below.

![Resin and hardener](image13.jpg)

**Figure 13: Resin and hardener**

13) The hose that is not connected to the vacuum pump is inserted into the cup of resin. The vacuum infuses the resin into the part and pulls it across the flow media. This is continued until all of the weighed resin is infused into the part.

14) Once all of the resin is infused, the hose is clamped off with vice grips, ensuring that no air enters the part.

15) The part is then left for 24 hours to cure at room temperature while under a constant vacuum. The curing part can be seen below.

![Specimen curing](image14.jpg)

**Figure 14: Specimen curing**

16) Once the part is cured, it can be cut to the specified dimensions. For this task a diamond bladed tile-jet saw is used. The saw uses water to cool and lubricate the cut, ensuring that no delamination or burning of the part occurs. The saw can be seen in the picture below.
This is the entirety of the VRI method of fabrication. It was used to make all of the test articles. However, there are additional steps to making the parts that are embedded with shear keys. Firstly the shear keys themselves are made using the mold pictured below.

The shear key mold is fabricated from a piece of aluminum and cut to specified diameters using a Computer Numerically Controlled, CNC, milling machine. To make the shear keys, strips of fiberglass are pulled from woven sheets of fiberglass and bundled into a twisted strand. This is laid into the circles on the shear key mold. This can be seen in the picture below.
Once the fiberglass is in place, the entire aluminum mold with the fiberglass ring is infused with resin using the VRI method described above. This ring will become the shear key for the parts that require them. To fabricate a part with a shear key, the CNC milling machine was used to cut a ring into the foam core. Then, the pre-fabricated shear key will be placed into this cutout on the foam core. Following this, the same VRI method previously described will be used to create the test specimens that require shear keys.

The last step of fabrication is to cut center holes in the specimens. This is done using a drill press and hole cutting bits. The bits have a central drill, for centering the hole, and an outer cutting ring. This bit in various sizes can be seen below.

To ensure that no premature delamination occurs in the part, the hole must be carefully cut from both sides. Since the centering drill is longer than the rest of the circular cutting surface, it will come through the part before the hole is cut in the fiberglass. This way, the center drill will break through the bottom layer of composite but the circular cutting disk will still be in the foam. Then, the entire piece can be turned over and the hole that made it through can be used to center the whole bit and cut through the other side of the composite. This results in minimal damage to the composite surrounding the hole itself. A picture of the hole drilling can be seen below.
Figure 19: Cutting holes in the specimens

The finished specimens can be seen below.

Figure 20: Isometric picture of completed test specimen
Additionally, shear keys are added to help further prevent delamination. For our project we require a mold for our shear keys. In order to save time we used a Computer Numerical Control milling machine (CNC) to cut out four molds all with the same pattern of four different size circles: One one inch diameter, one two inch diameter, one three inch diameter and one four inch diameter circles. With these circles we can wet lay up fiberglass strands into circles for sandwich fiberglass specimens to be used as shear keys. After the molds have been made we used the same program to cut the foam so the shear keys have a place to sit under the fiberglass layers.

B. Testing of the specimens

Each specimen was tested under compression and thermal loading. The Instron machine was used to apply the compression loading and measure the resulting deflection, stress, and strain until the material fails. A picture of the Instron machine can be seen below.

The furnace used to apply the thermal loading is large enough to house the test specimens and clamps that will support the compression loading supplied by the Instron machine. A schematic diagram and solid rendering of the completed test setup can be seen below.
Figure 23: Thermal chamber schematic

<table>
<thead>
<tr>
<th>PART NUMBER</th>
<th>PART NAME</th>
<th>QTTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>COMPOSITE LAYUP</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>STEEL CLAMP</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>HEAT FURNACE</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>SHEAR KEY</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 24: Solid rendering of thermal chamber and test article
III. Experimental Tests and Results

The following outlines the exact methods used in actually testing the individual specimens. As specified earlier in this report there are numerous testing characteristics or variables. The three criteria that will be varies are as follows: heat (temperature), hole diameter, shear key size. There must be 34 specimens created and tested in order to fulfill the 34 different, but required experimental criteria. The table below outlines the individual criteria and the amount of tests needed to complete the requirements.
Table 1. Number of Parts for Each Given Variable

<table>
<thead>
<tr>
<th>Temperature=120°F</th>
<th>Shear Key Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole Diameter</td>
<td>0in</td>
</tr>
<tr>
<td>0in</td>
<td>1</td>
</tr>
<tr>
<td>1in</td>
<td>1</td>
</tr>
<tr>
<td>2in</td>
<td>1</td>
</tr>
<tr>
<td>3in</td>
<td>1</td>
</tr>
<tr>
<td>4in</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature=160°F</th>
<th>Shear Key Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole Diameter</td>
<td>0in</td>
</tr>
<tr>
<td>0in</td>
<td>1</td>
</tr>
<tr>
<td>1in</td>
<td>1</td>
</tr>
<tr>
<td>2in</td>
<td>1</td>
</tr>
<tr>
<td>3in</td>
<td>1</td>
</tr>
<tr>
<td>4in</td>
<td>1</td>
</tr>
</tbody>
</table>

As outlined, 34 specimens were created. The individual trials are tabulated in the following report. Each specimen was inspected and was found within the acceptable limits for the VRI method that was utilized. The criteria that the specimens were judged by were any signs of delaminating, uneven resin casting, and within 5% of length, width, and surface area of the original specimen. The original specimen’s total dimensions are 8 inches by 6 inches by 1 inch as shown in the following figure.

![Figure 27: Detailed specimen geometry](image)
After successful fabrication and inspection the parts were outfitted with their required drilled hole and shear key. During the drilling process each specimen was inspected and approved to have no visible delamination and a perfectly perpendicular drilled hole with the fiberglass datum plane. The drilled holes had to be with a tolerance of no more than 0.03 inches. After approval the pieces were outfitted with their shear keys. Each shear key was inspected to have a completely coating/seal of Aeropoxy with no delamination. The foam was then machined in a CNC machine so that each specimen had the proper sized shear key diameter. This was a very accurate procedure, so each specimen was inspected with a Dial Caliper and in order to receive approval all pieces had to be accurate to within 0.05 inches. After being outfitted with the shear key grooves the specimens resembled the figure below.

![Figure 28: Solid model of specimen with shear key](image)

These specimens were then laminated with the shear keys in the proper grooves and the specimens were put through their final inspection. Once the specimens were full assembled the experimental procedure was begun. First the specimens were load into the heat furnace. Each specimen was then slow heated for 10 min until the entire composite was a uniform temperature, either 120°F or 160°F depending on the trial number. Once the composite was at a uniform temperature, the specimens were anchored into the Instron machine using the automatic mechanical clamps. The steel clamps on the Instron machine clamped down until the slope of the resistance started to plateau meaning that the composite was full “compressed” and therefore secure in the clamps. Once the specimens were securely clamped the Instron machine was calibrated to insure that the initial point was recorded as the point of zero compression. The settings were loaded on the PC interface of the Instron machine where the load rate was selected. After checking to insure that the specimen was square with the clamps and fully secure the test was started. The Instron machine slowly and evenly applied pressure by compressing the specimen by moving the steel clamps closer and closer together at a rate of .05mm/min. The PC interface of the machine than real time recorded the amount of stress and strain (along with several other data types that will ignored due to the scope of the experiment) for each specimen as the load was applied. Once the specimen had visibly fractured past the point of the ultimate failure (the specimen was either splintered or fractured into two pieces) the Instron machine was turned off saving the results and releasing the specimen. This process was repeated for all 34 specimens.
IV. Results and Discussion

A. Quantitative Results

All 34 specimens were tested; however Instron data was only acquired for 32 specimens. As seen in appendix 1, data does not exist for specimen number 24. It was the first specimen to be tested and literally cooked because the thermometer was not correctly assembled. This was a fortunate mistake however because it provided very interesting results that will be covered in the qualitative results below.

Two types of force/strain curves were assembled. The first type plots all four (in cases without shear keys, 2) a specimen at each temperature in order to examine the effect temperature has on maximum buckling force. The second type plots all specimens per temperature to see the effect of hole size and shear key diameter in comparison to one another.

Figure 29: Force/Strain curves for most specimens
Figures 29 and 30 show the force/strain relations for all specimens we were able to collect data from. It should immediately be noted that the last figure (Fig. 30 bottom) was not zeroed when data was collected. This is also the reason that it was smashed when the machine finished testing. Zeroing is extremely important to collect accurate data and preventing the specimens from being ruined. In almost every case, the specimens placed as 160 degrees Fahrenheit buckled between 20 and 60 percent the maximum yielding force of the same specimens at 120 degrees Fahrenheit. The cases at which this didn’t happen could easily be attributed to experimental error which is covered below. This decrease in maximum buckling force can be attributed to thermal fatigue. For the specimens that were tested at 120 degrees, the oven was opened, cooled to about 105 degrees, the specimen was added, the oven was brought to 130 degrees, turned off, cooled to 120 degrees, and then tested. By the end of the test, the oven was about 115 degrees. For the specimens that were tested at 160 degrees, the oven was opened, cooled to about 125 degrees, the specimen was added, the oven was brought to 170 degrees, turned off, cooled to 160 degrees, and then tested. By the end of the test, the oven was about 145 degrees. Because the 160 degree specimens were tested as a higher temperature, it took longer for them to reach that temperature and cool down, thus more thermal damage was done.

Additionally, in order to actually examine the effect of hole size and shear key, we had to plot all specimens to together at each temperature.
Figure 31: All specimens tested at 120 degrees Fahrenheit.

Figure 31 shows that the specimens with the largest buckling force were the ones that had the largest shear keys and the smallest holes. Thus, it can be extrapolated that the larger the shear key and the smaller the hole, the larger the maximum buckling force will be. This was experimentally shown by another group who tested various shear key sizes with delamination patches. Their specimens that had no delamination sheet went to the maximum possible loading of the Instron machine. This actually broke the gig, which we had to fix.

Figure 32: All specimens tested at 160 degrees Fahrenheit.

Figure 32 shows once again, even at a higher temperature, that the maximum force is obtained when the largest shear key with the smallest hole is employed. Comparing Fig. 31 and Fig. 32 shows that the higher temperature causes more thermal fatigue, greatly weakening the specimens.

In conclusions, optimal resistance to buckling and compression is achieved when the shear key is maximized and the hole is minimized.
B. Comparison to No Heat
Another group did all of our testing but at room temperature. This appears in Fig. 33 below.

Figure 33: Maximum compression load with no heat

Exchanging Fig. 33 shows that they obtained similar results, with higher maximum compression results, as expected. Thus, thermal loading at 120 degrees reduces the maximum compression load by 20 to 60 percent.

C. Qualitative Results
In addition to the qualitative results obtained from the Instron machine, it would be foolish to ignore the qualitative effects, mainly the location of cracks in the specimens. At this point it’s important to note that each specimen was notched all the way across the center of the hole, 1/10 of an inch on each side. This was to start the crack propagation in the correct place each time. Figure 34 shows specimen number 24 which was subjected to nothing but thermal fatigue for about two hours.

Figure 34: Pure thermal loading.

As you can see, this led to cracks in the same places that would be expected under compression. Additionally, this led to delamination on the back side. The foam also expanded, showing the temperature profile of the thermal chamber. This is also one of the potential sources of error which could easily be corrected with a high temperature fan.

Figure 35 shows all of the specimens lined up after testing was completed.
In almost all cases, the cracks started where the initial notches were created and traveled across the part. In the shear key specimens, the shear keys stopped the crack from propagating, but then delaminated on the outside of the shear key causing failure. There were also numerous instances in which the specimens failed at the boundary conditions, which can be blamed on the lack of precision in the loading jigs.

D. Possible Error

There were numerous sources of potential error which were realized including, but not limited to lack of (1) straightness in the testing jigs, (2) precision using the saw, (3) precision in the VRI process, (4) uniform temperature in the thermal chamber, and (5) regulation of the thermal chamber.

1. 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.

2. Precision using the saw

   Because our 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.

3. Precision in the VRI process

   Due to our lack of experience with the VRI method, consistency in manufacturing was not always possible. At time, the resin would start to harden before arriving at the other side of the piece causing dry fibers in various areas. Because the resin to fiber ratio was not always consistent, our results may have suffered.

4. Uniform temperature in the thermal temperature

   As Fig. 31 shows, the temperature distribution in the thermal temperature was not consistent and actually had more of a parabolic shape. Thus, the specimen was never actually heated to the correct temperatures. However, this is not so much of a problem because the maximum heat was in the same vertical location of the notches which allowed us to control where failure occurred.

5. Regulation of the thermal chamber

   Because the group before us functionally broke the regulator of the temperature, the only way we could regulate the temperature in the chamber was by using a thermal blanket and unplugging the thermal pads at the correct time. Although we did this pretty consistently, there is no guarantee that it actually worked as anticipated.
E. Safety and Environmental Concerns

As stated prior in this report the composite test pieces were mainly compromised fiberglass sheets and epoxy resin sandwiching polyvinyl chloride foam rectangular blocks. While the testing procedure was fairly straightforward there are many safety and environmental aspects that need to be addressed before future studies are completed.

I. Mechanical Safety Hazards

The initial testing period has several key sections that have a high level of danger. The layups procedure has virtually no mechanical safety concerns. The testing procedure on the other hand has inherit risks involved.

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

The heating chamber was also a large source of safety concern due to its homemade design and high temperature. The high temperature was easily regulated by the use of certified heat resistant welding gloves. As a result of these gloves the insertion and removal of the test specimens lead 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.

II. Health Hazards

In terms of health hazards three main concerns were identified and analyzed. The first of these was the cutting and drilling of the specimens, the epoxy/hardener combination, and the heating of the specimens.

In the cutting and drilling procedural steps the fully cured fiberglass/epoxy foam blocks were timed, squared off, and drilled as required in the problem statement. This introduced all the researchers to extremely fine and heated fiberglass/epoxy dust. This dust was mixture of two parts: particulates and fumes. The particulates were almost entire room temperature fiberglass/epoxy fragments that were free floating in the air. Cal Poly’s Composite Lab’s standard safety procedure was adequate in limiting exposure. The standard safety procedure required the user to wear long sleeves, closed toed shoes, eye protection, and a NIOSH N95 approved respirator. Minor fiberglass inhalation can lead to breathing and respiratory issue such as coughing, wheezing, and increased amounts of phlegm, but the majority of these symptoms dissipate without any long-term damage over a few days. Long term inhalation of fiberglass has been proven to lead to pulmonary fibrosis and other respiratory conditions such as scarring of lung tissue, damage to lung alveoli (air sacs in lungs), sinusitis, bloody phlegm. Though the resultant dust did cause some minor discomfort in the form of itching and painful patches on the skin, a simple hot shower was able to quell most of the safety concerns. In the future the above safety procedure should be more firmly enforced in order to keep students and faculty safe from possible respirator or optical injuries. Also it should be noted that the composites lab failed to have the required safety equipment in adequate numbers given the larger size of the class. This problem needs to be remedied before any further testing or research is begun.

The safety concern regarding the epoxy/hardener combination and test specimen thermal testing can be classified as fume inhalation and the resulting conditions that are derived from that. According to the CDC’s NIOSH division the epoxy resin releases toxic fumes during and after its curing process. These fumes can be classified as organic fumes and can be filtered safely by any NIOSH approved R/P95 organic vapor respirator. The recommended respirators are of utmost importance because the fumes from the epoxy resin mixture have been shown to lead to myoclonic limb jerks, seizures, comas, and liver, central nervous system, kidney and skin cancers. In addition lung, liver, thyroid, and adrenal cancers have been seen in animals exposed to epoxy fumes.

The thermal testing of the specimens resulted in the largest safety concerns. The epoxy/fiberglass ‘shell’ around the polyvinyl chloride (PVC) foam shares the same concerns as stated in the preceding paragraph along with sharing the same safety requirements and recommendations. The amount of epoxy fumes during the curing process was comparable to the fumes released during the thermal testing. The PVC foam blocks though proved to be far more dangerous when thermally loaded. Polyvinyl chloride is an extremely versatile and widespread material. It is used in thousands of household and industrial applications, such as pipes, silverware, Tupperware, molds, children’s toys, etc… PVC is the third largest thermal plastic used in the world. While extremely useful PVC is also extremely toxic during its creation, life, and during disposal. The manufacturing industry has been plagued for the past 50 years with law suits and cover ups from government and industrial sectors regarding the safety concerns of PVC production and use.

During the creation of PVC the several chemicals are released which can cause devastating health effects to factory workers. The three main concerns from creating PVC items are the creation of dissononyl phthalate and vinyl chloride monomers. In the early 1970s Dr. John Creech and Dr. Maurice Johnson published a report proving that vinyl chloride monomers were indeed carcinogenic. Their study was based on the lung and liver cancers rates from B.F. Goodrich plants throughout the United States. Shortly after this report was published the Center for Disease Control put a regulation on the exposure and safety standards that need to be enforced in PVC factories, this lead to the elimination of vinyl chloride monomer exposure in factory workers.

Throughout the life of all PVC products a small amount of Polychlorinated dibenzodioxins (dioxins) are released. In 1994 the United States Environmental Protection Agency reported that dioxins are most likely cancerous in addition to proving that the dioxins can lead to immune and reproduction system conditions or failures. Dioxins are especially dangerous
because they are stored in the fat cells of humans and animals and can neither be excreted or removed.\textsuperscript{13} The half life of the majority of harmful dioxins is 8 years in human fat cells making it very likely that it will lead to health effects before it safely degraded. It was shown that even extremely low levels (4.2 fg/m\textsuperscript{3}) of dioxins can lead to sarcomas and other cancers, and that as the exposure level and time period is increased the risk of tumors is greatly increased. Other effects that dioxins have been proven to cause in humans are diabetes, thyroid disorders, endometriosis, child development issues, and neural and motor functions (specifically a decrease in learning ability). As of June 2009 the State of California is deliberating a ban on the use of PVC of any form in the state.

For most end-consumers the levels of toxic chemicals secreted by PVCs in minimal in their daily lives, unfortunately when PVC of any kind (ex. PVC foam plates) is heated is releases many of the same toxic chemicals that were generated for the use of creating the PVC. The release of these chemicals is believed to be one reason why PVC fails so quickly under large load when heated. When PVC foam is heated it release dissononyl phthalate, vinyl chloride monomers, dioxins, chlorine gas, and vaporized hydrochloric acid. While the levels of dissononyl phthalate and vinyl chloride monomers are comparable to levels released during the manufacturing process the levels of dioxins released in the initial heating of PVC materials is greatly increased from its initial level. Hydrochloric acid (HCl acid) is extremely toxic in high quantities, especially in a gaseous form. HCl acid is the same acid group as the ones found in the human stomach. In addition to dioxins, dissononyl phthalate, vinyl chloride monomers and HCl acids chlorine gas is released in small quantities when PVC foam is heated.

Chlorine is extremely toxic.\textsuperscript{12,13,15,16,17} It was used as an extremely effective weaponized chemical nerve agent in World War 1. Unless levels of PVC exposure are enormously high the dangerous of the small amount of chlorine gas is far smaller than the dangerous posed from the HCl acids, dioxins and vinyl chloride monomers.\textsuperscript{16,12} As stated by the CDC and The National Institute for Occupational Safety and Health (NIOSH) and International Agency for Research on Cancer (IARC) exposure to heated PVC can lead to following conditions and diseases: brain, liver, lung, skin, sarcoma, testicular, pancreatic, breast, and prostate cancers; respiratory and pulmonary conditions (asthma, bronchitis); thyroid, liver, and lung failure; seizures; obesity; neural regeneration conditions; reproductive conditions (testicular atrophy, and impotence) and birth defects; giddiness; dizziness (loss of balance, vertigo); and drowsiness.\textsuperscript{15,16,17}

While the melting point of PVC foam is approximately 450 °F and fiberglass/epoxy’s melting point is ~1000°F, the experimental temperature was at a maximum of 160°F meaning it was well below the specimens melting temperature. On a whole the temperature was low enough as to not cause the Fiberglass/epoxy layers to release toxic fumes, but it was high enough to cause the PVC foam centers to release the aforementioned toxins. Using the NIOSH estimation technique the testing room was subjected to approximately 25ppm to 250ppm of Vinyl Chloride gas, which is well above the unprotected exposure limit.\textsuperscript{17} This is simply an estimation, in order to achieve a more accurate result a certified Haz Mat or Industrial Hygienist would need test Cal Poly’s Composite Laboratory for harmful and dangerous gases.

NIOSH has very strict regulations for business and institutions on what safety equipment is required to for individuals exposed to the aforementioned toxins.\textsuperscript{7,14,15,17} See Appendix 2 for NIOSH exact recommendation for safety equipment. Due to budget constraints and the lack of safety precautions and regulations only NIOSH N95 approved masks were used for the testing of the experiment meaning that all persons who entered the lab during the experimental procedure were exposed to toxic levels of the above gases. Of the three authors all three showed minor to moderate respiratory and epidermal symptoms, and one author was admitted to the Emergency Room of Sierra Vista Hospital in San Luis Obispo, CA where he was diagnosed with balance disorder, and temporary bronchial asthma from “…inhalation of a foreign and possibly toxic substance.”

Due to the extreme nature of the aforesaid safety concerns, a repeat of this experiment is strongly advised against without a complete upgrade and overall haul of Cal Poly’s Composite Lab’s safety equipment and regulations.

### III. Environmental Concerns

While PVC is widely used throughout the world the problems generated by it’s disposal and manufacturing have yet to be fully addressed. The manufacturing processes release hundreds of harmful chemicals into the atmosphere in addition to tons of toxic chemicals that are required to be contained and regulated. This leads to problems of where to dispose of these toxic chemicals and how much companies are allowed to vent into the atmosphere. In addition PVC plastics have a decomposition life from hundreds to thousands of years. Though there are some recycling programs in the Unites States of America centered around the recycling of PVC plastics, no efficient or cost effective way has been discovered. The majority of PVC recycling experiments have resulted in, many thousands of dollars later, producing more pollution than they have saved. This leads to the filling of landfills with unusable plastics that will never effectively decompose.\textsuperscript{8,9,11,13}

While extremely useful the manufacturing hurdles, implementation problems, and environmental concerns of PVC plastics and foams demand a more efficient, healthier, and more environmentally friendly plastic to be widely utilized. As a result we feel that the lack of safety precautions and health risks far outweigh the scientific advantages of the experimental testing of PVC foam composite plates and the Aerospace Department of the California Polytechnic State University in San Luis Obispo, CA needs to reassess the safety and health concerns in it’s Aerospace Composite Laboratory.
V. Conclusion

A study was conducted to investigate the effect of heat on composite sandwich plates, fabricated with the vacuum resin infusion process, with center holes of different diameters. The study involved conventional specimens and specimens with shear keys, both of which will be subjected to monotonic inplane compression loading. Hole diameter was varied from one to four inches in one inch increments. The diameter of the shear keys around the holes was varied from one inch to four inches in one inch increments. The specimens were placed in a fire chamber at temperatures of 120 and 160 degrees Fahrenheit and tested under compression loading. It was discovered that the specimens under no thermal loading with maximum shear keys and minimum holes are the strongest. Higher temperatures cause each specimen type under 120 degrees to yield at anywhere between 20 and 60 percent of the maximum compression load under no thermal loading, each specimen under 160 degrees to yield anywhere between 20 and 60 percent of the maximum compression load under 120 degrees. Additionally, it was discovered that there are extremely dangerous health consequences to heating poly vinyl chloride foam and epoxy resin. It the future, proper attire should be worn in the lab at all time.

References


## Appendix 1: Specimen Rates

### Table 2: Specimen criteria and trial number

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### Appendix E (Continued)
OSHA Respirator Requirements for Selected Chemicals

**Vinyl Chloride (1910.1017)**

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<th>Airborne Concentration or Condition of Use</th>
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<td>( \leq 10 \text{ ppm (parts per million)} )</td>
<td>(1) Combination Type C supplied-air respirator [see below], demand type, with half facepiece, and auxiliary self-contained air supply; (2) Type C supplied-air respirator [see below], demand type, with half facepiece; or (3) Any chemical cartridge respirator with an organic vapor cartridge which provides a service life of at least 1 hour for concentrations of vinyl chloride up to 10 ppm.</td>
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<td>( \leq 25 \text{ ppm} )</td>
<td>(1) Powered air-purifying respirator with hood, helmet, full or half facepiece, and a canister which provides a service life of at least 4 hours for concentrations of vinyl chloride up to 25 ppm; or (2) Gas mask with front- or back-mounted canister which provides a service life of at least 4 hours for concentrations of vinyl chloride up to 25 ppm.</td>
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<td>( \leq 100 \text{ ppm} )</td>
<td>(1) Combination Type C supplied-air respirator [see below], demand type, with full facepiece, and auxiliary self-contained air supply; or (2) Open-circuit self-contained breathing apparatus with full facepiece, in demand mode; or (3) Type C supplied-air respirator [see below], demand type, with full facepiece.</td>
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<tr>
<td>( \leq 1,000 \text{ ppm} )</td>
<td>Type C supplied-air respirator [see below], continuous-flow type, with full or half facepiece, helmet, or hood.</td>
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<tr>
<td>( \leq 3,600 \text{ ppm} )</td>
<td>(1) Combination Type C supplied-air respirator [see below], pressure demand type, with full or half facepiece, and auxiliary self-contained air supply; or (2) Combination type continuous-flow supplied-air respirator with full or half facepiece and auxiliary self-contained air supply.</td>
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<tr>
<td>( &gt; 3,600 \text{ ppm or unknown concentration} )</td>
<td>Open-circuit self-contained breathing apparatus, pressure-demand type, with full facepiece.</td>
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**Definitions for Type C and Type CE Respirators**

The definitions below were obtained from the NIOSH Certified Equipment List, which is available on the NIOSH Web site (http://www.cdc.gov/niosh/nptl/topics/respirators/cel).

**Type C Respirator:** An airline respirator, for entry into and escape from atmospheres not immediately dangerous to life or health, which consists of a source of respirable breathing air, a hose, a detachable coupling, a control valve, orifice, a demand valve or pressure demand valve, and arrangement for attaching the hose to the wearer and a facepiece, hood, or helmet.

**Type CE Respirator:** A Type C supplied-air respirator equipped with additional devices designed to protect the wearer’s head and neck against impact and abrasion from rebounding abrasive material, and with shielding material such as plastic, glass, woven wire, sheet metal, or other suitable material to protect the window(s) of facepieces, hoods, and helmets which do not unduly interfere with the wearer’s vision and permit easy access to the external surface of such window(s) for cleaning.