Abstract

The use of shear keys to help stop or inhibit the face-sheet core delamination of sandwich composite beams under monotonic loading was analyzed in Cal Poly’s structural design lab. The composite beams were treated with the same boundary conditions as the ASTM D5528 double cantilever beam bending in which both faces of the beam remain free; one of the faces would have a debonded side and the other would not. An aluminum tab is attached to the top of the specimens and the load is applied there. Each specimen has piezoelectric sensors that are utilized in the detection of delamination propagation. All the analysis is to be carried out with and without the shear keys. The effects of initial delamination lengths of 25mm, 50mm, and 75mm were tested with shear keys located at 0.5, 1.0, and 2.0 inches from the start of the delamination. The results found that the closer the shear keys were to the initial delamination, the better they were able to help prevent crack growth and failure. Also, the use of shear keys increased the maximum monotonic load the beam could withstand until it failed compared to samples with no shear keys.

I. Introduction

Broadly speaking, composite materials are any materials that are made from two or more significantly different materials both physically and chemically. Composites are very common in everyday life and can be seen in many forms such as concrete and asphalt, which pave our roads and walkways. Another common form of composites is fiberglass, which is the material that shower stalls and bathtubs are made out of. Kevlar is another greatly used type of composite material used in body armor for the armed forces, car tires, and clothes. These composites are special because they are not isotropic like many metals such as steel, copper, or aluminum; meaning that they do not have the same characteristics in every direction. Composites are engineered to conform to specific design criteria so that the direction of the fibers is the strongest in whichever direction needs the most strength. In the aerospace industry, composites have an ever growing importance. The advantages of composites are that they are far stiffer than metals and have a far superior stiffness-to-weight ratio. They can withstand high operating temperatures unlike many other materials that would just melt under the same conditions. Composites also are highly resistant to corrosion, which makes them ideal for aqueous and outdoor conditions. As composites have many great uses, they still have a few detrimental characteristics associated with them. Composites are much more expensive than metal materials such as steel which makes using them for large applications very costly. Also, when creating the composites such as carbon fiber, the fumes emitted in the chemical reaction of the resin can sometimes be hazardous to the health of the engineers creating the material. Lastly, the time it takes to make anything out of composites far surpasses the time it would take to make the same part out of another material.
Composite material has the properties of being a thermoplastic and thermoset. A thermoplastic, unlike a thermoset, can be melted and remolded once the original set has already been made. This means that once the composite is made it is stuck that way and cannot be changed. Thermosets like steel, once made can be heated to its melting temperature and reworked into a different desired shape. When we relate these properties to composites it is usually in the metal matrix that is thermoset; the matrix such as epoxy, phenol, vinlyester, and polyester are always thermoset because once the chemical reaction takes place and the substance hardens, the filler is stuck in that position. Thermoplastic matrix materials include, PPS, PEEK, and PEI. In addition to thermoset and thermoplastic materials, there is a classification called organic and inorganic materials.

Strictly speaking, organic material is any material that is either alive or was at one time living. However, many people now classify organic material as any material that contains carbon, where non-organic material is the antitheses. Not all composites are made of organic material because our definition of composites is just any two different materials bound together into one. However, in our case, and in most cases, composites are almost always organic. Many types of composites that have organic compounds in them include: carbon fiber, asphalt (steel), Kevlar etc. Now having discussed the different characteristic properties of composites, we can now talk about the types of fibers and matrices.

The two main components of most composites include the matrix and the fibers. The matrix is the component that clings the filler together to form the mass of the material. The matrix normally is made of various epoxy type polymers although there are many other materials that may be used. Metal matrix composites and thermoplastic matrix composites, as discussed above, are some of the possibilities. The fiber is the material that is infused in the matrix to provide a structural advantage to the composite which is usually strength. The fibers can be of any material such as sand, carbon fiber, glass bead, or ceramic. The different types of fiber types include short and long fibers, particulate, and laminate. To determine whether a fiber is short or long, depends on the length to diameter ratio; if this ratio is around 100 then typically we have a short fiber; if the length to diameter ratio is in the millions or on a very high level, then we have a long fiber. Examples of long and short fibers include Kevlar and fiberglass respectively. Particulate composites consist of the composite material in which the fiber materials are round. An example of this form of composite would be the unreinforced concrete where the cement is the matrix and the sand acts as the fiber. Laminate is the type of composite that utilizes the fiber substance in form of sheet as an alternative to round particles or fibers. The matrix material is usually phenolic type thermoset polymer.

There are many types of composite fibers including unidirectional as seen in figure 3, woven as seen in figure 2 and many more. Unidirectional is a lightweight, strong composite that can be used with polyester or epoxy. This composite material can strengthen any project while adding minimal weight. The way that this type is created is that it has graphite running the warp and a cloth thread securing it. Unidirectional fibers are good for areas requiring carbon strength in only one direction, or can be overlapped with itself to achieve two-directional strength. Woven fibers have multiple directions of strength, but mainly in one direction, the woven direction. In addition to adding strength in different directions, woven fibers also help to add stability.

Figure 2. This is an example of woven twill carbon fibers. This adds strength in multiple directions

Figure 3. This is an example of unidirectional carbon fibers. This adds strength in only one direction.
There are many types of fabrication methods in composites, some having advantages over others in certain conditions. The first method is perhaps the most well-known and used method called the hand lay-up method as illustrated in figure 4. The hand lay-up is the simplest and oldest method of the composite fabrication processes. It is a labor demanding method suited particularly for large components, such as aircraft fuselages and boat hulls. Glass or other reinforcing sheets or woven material is positioned by hand in the open mold; resin is poured or sprayed over and into the glass plies. Air is removed manually by machine or rollers to complete the laminates structure. Room temperature curing polyesters and epoxies are the most commonly used matrix resins as discussed above. The next method is the spray-up method, illustrated in figure 5, which is an open mold method that can produce exceedingly complicated parts easier than the hand lay-up method. Chopped fiberglass reinforcement and catalyzed resin, and in some cases, filler materials, are put on the mold surface from a combination spray gun. Injection molding is another very common way to fabricate composites and is a manufacturing process for creating parts from both thermoplastic and thermosetting plastic materials. Molten plastic is injected at high pressure into a mold, which is the opposite of the product's shape. There are many more types of fabrication methods such as cold-press and pultrusion, but these two are the most commonly used fabrication methods. These methods are used in many types of composites; but we used the hand lay-up method and vacuum resin infusion method to create specimens.

Figure 4. Hand lay-up is well matched for low volume fabrication of a product. This method can be used for both a corrosion barrier and the structural portion.

Figure 5. Spray-up is a faster process and is less labor intensive than hand lay-up. Several drawbacks include possibility of more air entrapment and a difficulty in controlling thickness and resin-to-glass ratios.

Composite panels are a very common and perhaps the most popular use of composites. A composite panel is just a regular flat, rectangular sheet of a finished composite piece. These panels are used in many things such as car bodies, some computer parts, body armor, and the aerospace industry. The panels are very strong in two dimensions and relatively weak in others. A flat panel of composite is very strong in the two different tensile directions; however it is very weak to shearing stresses which are its largest drawback. This being said makes the implementation of flat panels great for any part of a structure under tension or compression (to an extent). Using flat panels in a structure to hold shearing stress would be a bad idea to any engineer considering that they are so weak under shearing loads.

A sandwich composite as seen in figure 1 is when two stiff composite panels that are generally stiff and light in weight are attached to a lightweight but thick core. The main reason for the fabrication of composite sandwiches is to provide a composite with high bending stiffness with overall low density. These composites are a very good
material for aircraft structures such as wings, fuselages, and empennages where structures must be lightweight and strong. A test of a sandwich composite can be seen above in Figure 6. In this figure the sandwich composite is under the loading of two point loads where the bending is shown with respect to the neutral axis to show the effects of tension and compression in the cross section view.

![Figure 6. The bending of a composite sandwich structure.](image)

Static and vibration tests are perhaps the best way to get a structural analysis of a composite. In a static test the material is placed in a type of tensile or compression testing machine and either elongated or compressed. The computer software that is attached to the machine can gather data on the stress-strain relationship and generate a stress-strain diagram. From these graphs one can find the Poisson's ratio and the modulus of elasticity of the material in addition to the ultimate yielding point. Another great aspect of the static testing is that one can find the maximum stress a material can take in the linear range, then how well it endures in plastic deformation. Vibration tests are a way to do a structural analysis on a piece of material dynamically. In a vibration test, the material is put into a shaker and salt or some easily seen lightweight material is put onto the specimen to see where the natural frequencies are to help analyze the structures ability to endure a dynamic load.

The intention of this experiment is to create composite sandwich structures and perform static and dynamic tests to generate stress, strain, and load curves based on the data gathered. From this data we can find out the different vital characteristics on our sandwiches and find how shear keys affect, which supposedly help stop the propagation of delamination, actually do in fact help arrest the delamination.

II. Design and Fabrication of Composite Sandwiches

Numerous composite specimens of four main categories are made according to design specifications. All composite specimens are made of fiber glass woven roving, fiber glass chopped strand mat, epoxy, and PVC foam. The first category of specimens has no initial delamination and no shear keys in between the PVC foam core and the fiber glass epoxy surface layer. The second category of specimens has initial delamination but no shear keys. The third category of specimens has shear keys but no initial delamination. The fourth category of specimens has both initial delamination and shear keys. The initial delaminations are fabricated to be 25 mm, 50 mm, and 75 mm long measuring from the testing edge of the specimens. The shear keys are fabricated to be at 0.5 inch, 1 inch, and 2 inch away from the initial delamination or the testing edge of specimens. Each specimen should measure about 2 inches wide and 6 inches long. Refer to Figure 7 for schematics of a specimen with 50 mm initial delamination and shear keys starting at 1 inch away from the initial delaminantion.
The composite sandwich panels are fabricated by using Vacuum Resin Infusion (VRI) process instead of the wet lay-up in order to produce cleaner and lighter finished product. VRI is a process that utilizes a vacuum pump to pull resin or the matrix material across dry fibers.

Step 1: The PVC foam core is cut to the correct size for the lay-up. It is desirable to keep the sandwich panel within 14 inches by 26 inches in order to keep the fiber glass evenly saturated by epoxy. It is best to cut the foam piece bigger than it needed to be. This is for trimming and post layup cutting purposes.

Step 2: The chopped strand mat is cut to the same size as the foam core. Four pieces are needed. A little bigger or smaller will not have a major effect on the part.

Step 3: 4 pieces of woven roving is cut to the same size as the foam core as done in step 2. It is best to cut the material in between the strands. This reduces the chances of separation and will help the final part come out with cleaner edges.

Step 4: A piece of release cloth is cut so that it is large enough to fold around the core materials and have a couple inches extra on all sides.

Step 5: A piece of green flow media is cut so that it will wrap around the core and be a little longer, but not wider.

Step 6: A piece of vacuum bagging is cut so that it is at least 2 inches wider on all sides.

Step 7: All the cut materials are laid out in the following order. The vacuum bagging on the bottom, then flow media, release cloth, woven roving, chopped strand mat, woven roving, chopped strand mat, then finishing with the foam core.

Step 8: Four more layers of fiber glass material are placed on top of the foam core in the order of chopped strand mat, woven roving, chopped strand mat, and ending with woven roving on the very top. The fiber glass and foam core should be placed on one side of the bagging materials as shown in figure 8.
Figure 8. Lay up of composite sandwich with bagging materials

Step 9: The top four layers of fabric are weighed with electric balance and replace to their original position. The weight is recorded for determining the amount of the resin to be used in the later steps.

Step 10: The release cloth and flow media is then folded over the core and fiber glass fabric. The release cloth and flow media should be as smooth over the surface of fiber glass fabric as possible.

Step 11: A piece of spiral tubing with length as long as the width of the green flow media is cut out. Then a T-fitting is inserted at approximately the midsection of the spiral tubing. Figure 9 shows the junction between the spiral tubing and the T-fitting. A length of cotton material was long as the spiral tubing is cut out.

Figure 9. Spiral Tube with T-Fitting

Step 12: All extra fibers and cloth are cleared off the edges of the vacuum bagging. Sealant tape was placed on three sides of the vacuum bagging as shown in Figure 8. A length of tube is connected to the open end of the T-fitting. Then the spiral tube part of the T-shape tubing system is placed next to the folded side of the green flow material. A small length of sealant tape is placed over the tube near the edge of the vacuum bagging. The cotton material is placed near the edge of the release cloth opposite of the T-shape tubing system. A second length of tube is cut out and one of its openings is placed against the mid section of the cotton material. A length of sealant tape is placed over the tube near the edge of the vacuum bagging. Refer to Figure 10 for pictorial representation.
The free end of the vacuum bagging is folded over the green flow media; then the vacuum bagging is sealed with the sealant tape. The tube on the end of the cotton material is connected to the vacuum. The other tube’s open end is temporally sealed and the vacuum is turned on to check for possible leaks in the vacuum bagging. Sealant tape is used to seal leaks. Vacuum is turned off after all leaks are repaired.

Step 13: The epoxy mixture is prepared by using West Systems epoxy systems. The resin to hardener ratio is 5:1. After the epoxy is well mixed, the tube that is not connected to the vacuum is put into a cup full of epoxy; then the vacuum is turned on. The glass fiber sandwich would turn darker when it’s fully saturated by epoxy. Once the glass fiber is fully saturated, the epoxy tube is clamped shut with vice grips.

Step 14: The sandwich panel is left to cure over night. Figure 11 shows the sandwich composite that is fully cured.
Step 15: After the sandwich panel is fully cured, the release cloth, green flow media, and vacuum bagging was removed, then the sandwich composite is cut by a tile saw into two inch by six inch test specimens. Figure 12 shows different finish specimens.

![Figure 12. Testing specimens](image)

**Design and Fabrication of Composite Shear Keys**

In the tests where shear keys are used to help stop or reduce delamination, a special procedure was utilized to make the shear keys. There are many different types of shear keys. Some, as made by other groups, are circular in shape as others are straight. The geometry of the shear keys depends on the design specifications of the project. Because the project requires two inch by six inch sandwich composites to be tested in the Instron machine for delamination, the best type of shear keys for this project are straight shear keys.

Step 1: The aluminum mold must be machined to design specifications to fit the shear keys. The mold must be large enough to hold a substantial number of shear keys because multiple keys are needed for each test specimen. The shear key fabrication method is a tedious one, so the more shear keys made in each trail the better.

Step 2: The fiberglass fibers are then cut from the large roll so that each of the fibers can be unwoven to create the shear keys. There are between 25-30 fibers used for each shear key so that they are of uniform mechanical properties. The fiberglass should be cut carefully so that no fibers are wasted and so that each fiber gets used in the shear keys.

Step 3: The aluminum mold mentioned in step 1 is then coated with a special fluid so that the shear keys will peel off the mold once the fabrication of the shear keys are done. This step is very crucial because if the fluid is not used then the shear keys stick in the mold and can be very hard to peel off from the aluminum and the mold can easily break.

Step 4: Each of the fibers that are bundled together are then dipped in resign just before they are put into the mold so that we are completely sure that the fibers are totally saturated with epoxy. Also, the wet fibers are easier to put into the aluminum mold because they tend to stick together. When the fibers are dry before they are put into the mold they tend to want to pop out, which results in a poor quality shear key. If dry spots in the shear keys occur then concentrations of stress will arise at those points when the specimen is loaded.
Step 5: The wet fibers are now put into the mold and prepared to be laid up in a VRI technique. VRI does not work as the best technique for all shear key layups because not all shear keys are straight. If the shear keys are anything but straight, the epoxy is not allowed to flow through the mold so a different layup method must be utilized. An illustration of this technique can be seen in figure 13 on the next page.

Step 6: After the shear keys are laid up, they must be cut to the correct size and deburred using the wet saw.

Step 7: The PVC foam is then milled and cut to the correct size to fit the shear keys.

Step 8: The newly made shear keys are put into the pre-cut foam and the entire specimen is fabricated using the same VRI technique as used in the fabrication of the regular test specimens.

**Figure 13:** The vacuum resin infusion of shear keys.

**Design and Fabrication of Aluminum Test Tabs**

The aluminum tabs that are used to test the sandwich composites in the Instron machine are easy to fabricate themselves; however, connecting the tabs to the specimen is very tedious and critical. If the tabs are not perpendicular to the sandwich composite then the Instron machine can easily shear off the tabs and ruin the entire part. Aluminum was chosen as the metal of choice for the tabs because it is more than strong enough to withstand the force of the Instron machine, it is easy to machine because of its softness (compared to a metal like steel), it is
inexpensive, and available. The hardest part of this fabrication method is the fact that students need access to a mill which is hard if the student is not enrolled in the machine shop course. If no one in the group is enrolled in the machining course, then the milling of the tabs must be done by someone else in the class. A picture of how the tabs are connected to the sandwich composites is shown in figure 14 below.

**Figure 14.** The aluminum tabs connected to the sandwich specimens.
Step 1: Student who is fabricating the tabs must have access to a mill to cut the aluminum to design specifications. A vertical mill\textsuperscript{1} as used to machine the aluminum tabs is shown in figure 15 below.

![Figure 15. A vertical mill as used to machine the aluminum tabs.](image)

Step 2: The tabs are cut two inches wide by about three inches long so that the Instron machine\textsuperscript{2} can have a lot of room to grab the part.

Step 3: After the tabs have been cut, they must be attached to the specimens. This part of the procedure is the most important because many hours of laying up parts and fabricating shear keys can be gone to waste if the tabs are attached wrong. Note that because this is an imperfect process that the following procedure can be modified or totally changed if a better method is found. Start with the epoxy and hardening mixture gun, the specimens, the tabs, and a large area to work.

Step 4: Layout all the specimens that will be having tabs attached and get one tab for every specimen. With the epoxy glue gun, make a small bead of the adhesive on the aluminum tab so that it is enough to cover the entire tab, but so much that it runs off the side and gets on the test specimen. This is very important because if the adhesive material gets in the delamination part of the specimen then the delamination will not be uniform throughout the part and the test results will vary drastically. This is illustrated in figure 16.
Step 5: Once all the tabs have been attached on one side of all the parts then C-clamps must be used to keep the tabs perpendicular to the part because the epoxy takes eight hours to cure.

Step 6: After all the tabs are cured on the first side, the remaining side can then have the tabs attached. At this point follow steps 3-5 on the remaining side. The reason that only one side is done at a time is because each specimen must be moved too much to get the tab exactly perpendicular that it would be nearly impossible to do this simultaneously for two tabs at once and get both sides perfect for ideal testing.

**Strain Gage Setup**

Step 1: To attach the strain gages to the test samples first the location of where the strain gage will go must be determined. This is done by drawing a line in pencil along the edge of the delam and then drawing another line down the center of the sample. A third line is then drawn parallel to the first line at the location of the shear key. The strain gage will be placed perpendicular to the third line at the shear key, with the line going down the center of the sample going through the center of the strain gage. The placement of the strain gage is important because if it is placed on the delaminated section of the specimen, the readings will be inaccurate so precise positioning of the strain gage is highly imperative. As can be seen in figure 17, the strain gage is placed directly over the shear key on the centerline of the specimen.
Step 2: The strain gage has a shiny side and a non-shiny side. The shiny side is to face up while the non-shiny will go on the surface of the sample.

Step 3: Check the resistance of the strain gage to make sure it is within the manufactures specifications. The gage should read around 120 ohms. The proper technique of measure the resistance of the gage is shown in figure 18 below.

Step 4: Take a long strip of tape and attack the shiny side of the strain gage to it. Use the tape to apply the strain gage to the sample. Align the strain gage perpendicular to the line at the shear key, with the line going down the center of the sample going through the center of the strain gage. Fold back the tape and strain gage but allow the back part of the tape to remain attacked to sample. Put the catalyst on the non-shiny side of the strain gage and let dry. Then put the glue on the sample where the strain gage will be attached. Place strain gage on the sample and apply pressure of one minute. Then peel the tape off and test the resistance again to make sure the strain gage was not damage during attachment.
Hooking up the Strain Gages for the Experiment

Step 1: For the test the strain gage will be attached to a computer through a box that makes a digital bridge.

Step 2: Test the wiring to make sure the wires are attached correctly. The voltage should be relatively constant with no large jumps in voltage. Open up mat lab on the computer. For the test start the Matlab once the tare is done start up the Instron. Figure 19 below shows the three wires of the strain gage. Take any of the two outer wires and connect them with any of the two leads of the strain gage that is connected to the computer with Matlab.

![Figure 19: Hook any of the two outer wires to the strain leads of the computer.](image)

Step 3: Once the voltage has been tared by Matlab, the test can be started and the computer will automatically sync the data from the Instron machine with the data accumulated from Matlab.

Testing of the Sandwich Specimens

Step 1: Both the Instron computer and the Matlab computer must be on and ready to take data.

Step 2: Connection that holds the specimens while being tested must be attached to the Instron machine so that specimen does not move vertically or laterally during testing.

Step 3: Place the sandwich composite in the Instron machine such that the strain gage is facing the floor because only the lower jaw of the machine pulls on the specimen. Refer to figure 14 to see a visual of the process.

Step 4: Start the data collecting process for the strain in Matlab and then start the pulling of the Instron machine.

Step 5: After specimen has failed, save the data and repeat steps 3-5 for each sample.
III. Results and Discussion

Experimental testing was performed to investigate the effects of initial delamination and the use of shear keys for arresting delamination failure. Of the trials conducted, several of the tests were limited in success because of apparatus failure due to the bond between the tabs and the specimen. The test cases run include several types of specimens:

1. No initial delamination with no shear key
2. 25 mm of initial delamination with no shear key
3. 50 mm of initial delamination with no shear key
4. 25 mm of initial delamination with shear key 0.5” from initial delamination
5. 50 mm of initial delamination with shear key 0.5” from initial delamination

The trials are summarized in Table 1 below.

Table 1: Summary of test specimens and results

<table>
<thead>
<tr>
<th>Specimen Type (Specimen Name)</th>
<th>Maximum Strain (inches)</th>
<th>Maximum Load (lb)</th>
<th>Notes</th>
<th>Loading Rate (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Initial Delamination (ID), No Shear Key (SK) (A1)</td>
<td></td>
<td>615.4</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>No ID (A4)</td>
<td></td>
<td>637.6</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>25mm ID, No SK (d5)</td>
<td>-0.0159</td>
<td>81.5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>25mm ID, No SK (d7)</td>
<td>-0.0174</td>
<td>98.5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>25mm ID, No SK (d8)</td>
<td>73.6</td>
<td>Tab Failure</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>50mm ID, No SK (b10)</td>
<td>-0.0137</td>
<td>52.8</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>50mm ID, No SK (b11)</td>
<td>-0.0156</td>
<td>46.5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>50mm ID, No SK (b12)</td>
<td>33.0</td>
<td>Tab Failure</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>25mm ID, SK 0.5” behind delamination (e1)</td>
<td></td>
<td>107.5</td>
<td>Tab Failure</td>
<td>2</td>
</tr>
<tr>
<td>25mm ID, SK 0.5” behind delamination (e2)</td>
<td></td>
<td>316.2</td>
<td>Tab Failure</td>
<td>2</td>
</tr>
<tr>
<td>25mm ID, SK 0.5” behind delamination (e3)</td>
<td></td>
<td>286.6</td>
<td>Tab Failure</td>
<td>2</td>
</tr>
<tr>
<td>50mm ID, SK 0.5” behind delamination (e4)</td>
<td>-0.0033</td>
<td>114.0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>50mm ID, SK 0.5” behind delamination (e5)</td>
<td></td>
<td>87.4</td>
<td>Tab Failure</td>
<td>3</td>
</tr>
<tr>
<td>50mm ID, SK 0.5” behind delamination (e6)</td>
<td></td>
<td>62.9</td>
<td>Tab Failure</td>
<td>3</td>
</tr>
</tbody>
</table>

The two variables between the test cases are amount of delamination and the presence of a shear key. As these variables are changed, the trends are clear.

Initial Delamination

The most apparent trend as initial delamination length is increased is that the maximum load before delamination failure is decreased. Figure 20 shows the maximum load applied before fiber glass delaminates from a foam core for various specimens with different initial delamination. For each delamination size, the results are fairly consistent, showing that the results are repeatable. When no initial delamination is present, it takes a very large force to break the initial bond between the outer laminate layers and the core. A 25mm initial delamination from the
foam core decreases the maximum load the specimen can handle by a factor of six. When the delamination length is doubled to 50 mm, the maximum load before failure is reduced again by a factor of two.

This trend is significant for any sandwich composite subjected to delaminating forces. The initial bond takes a large force to overcome, once the delamination exists; the structure becomes more fragile and susceptible to complete failure. Therefore, a method to arrest delamination must be implemented. Utilization of shear keys is one technique used to achieve this goal.

![Graph](image)

**Figure 20:** *Effect of initial delamination length on maximum load before delamination failure.*

**Implementation of a Shear Key**

For both the specimens with 25mm of delamination and 50mm of delamination, the presence of a shear key increases the maximum force the sample can withstand. Measurements were taken with respect to the applied load, the total deflection of the fiberglass laminate from the foam core, and the strain the fiberglass laminate is subjected to. As is called out in Table 1, many of the test specimens experienced limited success in data acquisition because the apparatus failed before strain measurements could be recorded. Although strain measurements will not be shown for these cases, load and deflected data was recorded and will be presented.
Figure 1 shows the displacements of the fiberglass laminate from a foam core due to an applied load perpendicular to the core orientation for specimens with 25 mm of initial delamination for configurations with and without shear keys. Of the six cases plotted, a clear difference can be seen between the cases with shear keys and those without shear keys with the exception of the trial of specimens ‘d8’ and ‘e1’ which resulted in apparatus malfunction early in the tests, these cases will be excluded from further discussion. Although several of the other tests resulted in apparatus malfunctions, meaningful load data was able to be first collected. In all relevant cases, linear-elastic behavior was first exhibited before a ‘knee’ in the load-extension curve exists. Cases ‘d5’ and ‘d7’ were able to withstand a load of approximately 100 pounds before they could not handle a larger load. For these trials, the initial delamination expanded into cracking within the foam core and compromised strength. The curves for these cases suggest the delamination behavior between the initial imposed case, and that caused by the load were fairly continuous and only able to withstand a small load.

Specimens ‘e2’ and ‘e3’ have shear keys implemented 0.5 inches from the initial delamination. These trials also show a kneeing behavior, however, very different from the cases without shear keys. First, the initial linear behavior is much steeper. A much higher load is applied with a very small amount of deflection of the laminate. The kneeing then occurs which represents the initiation of delamination due to the applied load. The shear key helps to hinder the propagation of delamination and withstand the increasing load until the apparatus malfunctions and the tabs are peeled away from the fiberglass laminate. The malfunction of the apparatus is represented by the discontinuous sharp decrease in load.

![Figure 21: Displacement of a fiberglass laminate from a foam core due to an applied load for specimens with 25 mm of initial delamination with and without shear keys.](image)

The trends exhibited for the cases with 25 mm of initial delamination are confirmed by the cases with 50 mm of initial delamination seen in Figure 22. Because the delamination is twice as much as the previous set of trials discussed, the fiberglass laminate is able to deflect much more with less force. This is due to the flexibility of the laminate. It is also the flexibility of the laminate which allows the tabs to stay attached to the laminate until a larger displacement is achieved. Of the six trials of specimens with 50 mm of initial delamination, cases ‘b11’, ‘e5’ and ‘e6’ experienced apparatus malfunctions after the maximum load had been applied to the specimens. This suggests the cause of the malfunction is the displacement of the laminate which causes a peeling effect on the bond, not the applied force.

Cases ‘b10’, ‘b11’ and ‘b12’ have 50 mm of initial delamination with no shear keys. These trials show linear behavior until a force between 30 and 40 pounds is applied as which point further delamination occurs due to...
the applied load. This linear behavior seems to be much steeper than the previous 25 mm cases, however, that is because the scale on the extension has been greatly expanded because the free delaminated surface is much longer for these cases, allowing the displacement to be much larger. After this initial linear trend, the kneeing behavior occurs, representing delamination caused by the load. The load and displacement are then increased until a maximum load is applied and the structure is no longer able to withstand an increased delaminating force which signifies total failure.

Cases ‘e4’, ‘e5’ and ‘e6’ have 50 mm of delamination and shear keys 0.5 inches behind the initial delamination. The trial on specimen ‘e4’ is the most significant because no apparatus malfunction occurred during this trial. For this case, linear behavior was exhibited until approximately 80 pounds of force was applied. This is much higher than the specimens without shear keys. This serves to confirm that shear keys prevent the onset of delamination due to an applied load. After this linear portion, the specimen begins to experience delamination due to the applied load. The shear key help to withstand the applied load even after the onset of induced delamination until the point at which the structure can no longer handle an increased load, representing the ultimate load. The ultimate load for the case with the shear key where no apparatus malfunction occurred is over double that of the cases with no shear keys.

Figure 22. Displacement of a fiberglass laminate from a foam core due to an applied load for specimens with 50 mm of initial delamination with and without shear keys

Figure 23 and Figure 24 show the strain on the delamination surface due to the applied load for cases without and with a shear key, respectively. The strain guages are in compression for these trials, starting at zero and then registering negative values. The maximum load for the case with the shear key is over 20 pounds greater, but the important metric to note is the maximum magnitude of strain. The case without a shear key is strained to -0.0136, the implementation of a shear key reduces this strain to -0.0033 which is a 75% reduction in strain. The reduction in strain with an increase in load is significant because it shows a shear key not only benefits the sandwich structure by hindering delamination, it also reduces the strain on the material which extends part life.
Figure 23. Strain of the delaminated surface of a specimen with 50 mm of delamination and no shear key.

Figure 24. Strain of the delaminated surface of a specimen with 50 mm of delamination and a shear key 0.5 inches from the initial delamination.
Issues

The number of successful cases able to be run was limited due to flaws in the experimental apparatus. Metal tabs were used as grips for the Instron machine to apply a delaminating force to the test specimens. The glue used to secure the metal tabs to the specimens can withstand many thousands of pounds of force in pure tension, far exceeding the requirements for the test. However, when a torque is applied to the glued interface, the bond is essentially peeled away. Initially it was hypothesized that an increase in bonding area would strengthen the bond sufficiently. Initially, the tabs were shaped like extruded rectangles. To increase the bond area, the bottom surface of the tab was extended to make a bracket shape, or an extruded “L”. The rectangular and “L” shaped tabs can be seen in Figure 25 and Figure 26 respectively.

![Figure 25. Sandwich structure with rectangular tabs.](image)

![Figure 26. Sandwich structure with “L” shaped tabs.](image)

Regardless of the tab shape, the bond between the tab and the specimen was susceptible to failure. This failure occurred later for cases with larger initial delamination, although this may be counter intuitive, it is because the bending moment was relieved by shape deformation of the delaminated layers. Figure 27 and Figure 28 show the deformed laminate shape due to the applied load of the Instron machine which caused the tabs to peel away from the fiberglass laminate for the 25mm and 50mm of initial delamination.
The peeling effect due to the moment applied to the bonding surface could be mitigated with a system allowing the bonding surface to rotate independent of the direction of applied force. Any such system would increase the manufacturing time for the apparatus required for each specimen. Improving the experimental apparatus is an area which requires further consideration.

Figure 27: Deformation shape of fiberglass laminate for 25mm initial delamination which causes apparatus malfunction.

Figure 28: Deformation shape of fiberglass laminate for 50mm initial delamination which causes apparatus malfunction

IV. Conclusion

There are three primary conclusions which were drawn from the experiments run. First, a larger initial delamination length results in failure due to a smaller maximum load. Second, the use of a shear key increases the maximum load the specimen can withstand before further delamination and failure. Finally, for future experiments to be run, the experimental apparatus must be improved so that the full load can be applied to the specimen resulting in material failure, not apparatus failure. A flexible or hinged tab mechanism is one option for this. Improvement of the experimental set up is an area which requires further attention.
Appendix A: Matlab code

clc
clear all
close all

% [data, time] = daqread('b10_test.daq'); plot (time, data)
% hold on;
% [data, time] = daqread('b11_test.daq'); plot (time, data, 'g') % error
% hold on;
% [data, time] = daqread('b12_test.daq'); plot (time, data, 'r')

xlabel('Time (sec)')
ylabel('Voltage (V)')

b10tare = max(daqread('b10_tare.daq'));
b12tare = max(daqread('b12_tare.daq'));
b10test = daqread('b10_test.daq');
b12test = daqread('b12_test.daq');

d5tare = max(daqread('d5_tare.daq'));
d7tare = max(daqread('d7_tare.daq'));
d5test = daqread('d5_test.daq');
d7test = daqread('d7_test.daq');

e4tare = max(daqread('e4_tare.daq'));
e4test = daqread('e4_test.daq');

% Strains of specimens that experienced deformation past the shear key location
strain_d5 = Voltage2Strain(1,d5test,d5tare,2.5,1,0.3,0,120);
strain_d7 = Voltage2Strain(1,d7test,d7tare,2.5,1,0.3,0,120);
strain_b10 = Voltage2Strain(1,b10test,b10tare,2.5,1,0.3,0,120);
strain_b12 = Voltage2Strain(1,b12test,b12tare,2.5,1,0.3,0,120);
strain_e4 = Voltage2Strain(1,e4test,e4tare,2.5,1,0.3,0,120);

% Stress from
stress_b10 = xlsread('F:\DelamTesting\CompiledDelamData.xlsx','50mm','B3:B232');
stress_b12 = xlsread('F:\DelamTesting\CompiledDelamData.xlsx','50mm','F42:F232');
stress_d5 = xlsread('F:\DelamTesting\CompiledDelamData.xlsx','25mm','B3:B113');
stress_d7 = xlsread('F:\DelamTesting\CompiledDelamData.xlsx','25mm','D3:D113');
stress_e4 = xlsread('F:\DelamTesting\CompiledDelamData.xlsx','50mm','H3:H232');

j=1;
for i=1:round(15000/length(stress_b10)):15000
    reduced_strain_b10 (j) = strain_b10(i);
    j= j+1;
end

length(reduced_strain_b10)
length(stress_b10)

plot(reduced_strain_b10(2:end), stress_b10)
xlabel ('Strain (inches)')
ylabel ('Load (lbf)')
title('b10, 50mm ID - No Shear Key')

figure
j1=1;
for i=1:round(15000/length(stress_b12)):15000
    reduced_strain_b12 (j1) = strain_b12(i);
    j1= j1+1;
end

length(reduced_strain_b12)
length(stress_b12)

plot(reduced_strain_b12, stress_b12(2:end))
xlabel ('Strain (inches)')
ylabel ('Load (lbf)')
title('b12, 50mm ID - No Shear Key')

figure
j2=1;
for i=1:round(15000/length(stress_d5)):15000
    reduced_strain_d5 (j2) = strain_d5(i);
    j2= j2+1;
end

length(reduced_strain_d5)
length(stress_d5)

plot(reduced_strain_d5(2:end), stress_d5)
xlabel ('Strain (inches)')
ylabel ('Load (lbf)')
title('d5, 25mm ID - No Shear Key')

figure
j3=1;
for i=1:round(15000/length(stress_d7)):15000
    reduced_strain_d7 (j3) = strain_d7(i);
    j3= j3+1;
end

length(reduced_strain_d7)
length(stress_d7)

plot(reduced_strain_d7(2:end), stress_d7)
xlabel ('Strain (inches)')
ylabel ('Load (lbf)')
title('d7, 25mm ID - No Shear Key')
%%
figure
j4=1;
for i=1:round(15000/length(stress_e4)):15000
    %lower from 15000 to length of the excel file cells
    reduced_strain_e4 (j4) = strain_e4(i);
    j4= j4+1;
end

length(reduced_strain_e4)
length(stress_e4)

plot(reduced_strain_e4(2:end), stress_e4)
xlabel ('Strain (inches)')
ylabel ('Load (lbf)')
title('e4, 25mm ID - Shear Key 0.5" from Delamination')
%%

d5tare = max(daqread('d5_tare.daq'));
d7tare = max(daqread('d7_tare.daq'));
d5test = daqread('d5_test.daq');
d7test = daqread('d7_test.daq');

strain_d5 = Voltage2Strain(1,d5test,d5tare,2.5,1,0.3,0,120);
strain_d7 = Voltage2Strain(1,d7test,d7tare,2.5,1,0.3,0,120);
e4tare = max(daqread('e4_tare.daq'));
e4test = daqread('e4_test.daq');
strain_max_e4 = Voltage2Strain(1,e4test,e4tare,2.5,1,0.3,0,120);

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References