California Polytechnic State University

Aerospace Engineering Department

San Luis Obispo, CA

The Effects of Damage Arrestment Devices in Composite Plate Sandwiches with Fastener Holes

Senior Project Report

Mark Anderson

Nancy Hung Choy

Lacey Jones

Rita Kourskaya

June 8, 2011

Acknowledgement:

The authors would like to thank Professor Elghandour for allowing use of the structures lab, as well as his help on experimental testing procedures and curing methods. Additionally, Michael Jacobson for aiding in the construction, and Richard Balatbat for providing FEA models.

Contents

List of Figures

List of Tables

Abstract

Composite materials such as a carbon fiber are used in a variety of new technologies including aircraft, spacecraft, and motor vehicles. Carbon fiber has a high strength to weight ratio a key advantage over other material options. This report discusses the use of composite damage arrestment devices (DADs) in composite sandwich panels with a foam core. There are three different curing cycles tested for the DADs: pressure only, vacuum only, and vacuum with 1000 lbs of pressure. Using a Tetrahedron Heat Press to cure the composite specimen and an Instron Machine to perform tensile testing, data was collected for each method. The method that can withstand the highest loads and tensile stresses is the pressure only curing process. Composite sandwich panels were comprised of a FR-6710 polyurethane closed cell foam core and two layers of carbon fiber on each side for the control group. For the specimens with DADs there were two slots milled on each side of the foam and a layer sheet resin was used to bond the surfaces. Compression testing was performed using a jig that had two blots running through the half-inch holes in the specimen. It was found that the specimens that included DADs could withstand 95% higher loads and had a Young's Modulus of around 85 ksi compared to the control group that was 55 ksi.

Chapter I Introduction

A composite material is a material constructed from matrix that serves as a binder and a reinforcement material. Composites contain two or more of these elements that macroscopically combine to form a new material. In composites, individual constitutes still remain separate, so that each constituent can still maintain its original properties. Composite materials have been in use for a long time, from medieval applications of layering sword metals to modern applications in road construction and aerospace industry.

Depending on the type of materials used to form a composite, its main advantages are high strength to weight property, advanced stiffness, corrosion resistance, thermal and acoustic advantages, and the ability to take any shape. Ideally when two or more materials are combined to form a composite, each material exhibits its best quality, or the overall material exhibits a needed quality that the individual components do not have. The disadvantage of composite materials, however, becomes the cost of combing several materials rather that one. Also, most composite matrices acquire thermo-set properties (due to curing), so if the composite breaks, it is often impossible to reshape and reuse it. These properties make it difficult to repair composite materials and most times the material has to be replaced.

Types of Composite Material

There are several types of composite materials such as fibrous, laminated, and particulate. In a fibrous composite material, the fiber is the reinforcement material embedded in some kind of a matrix material. The fibers used in this type of composite can be glass fibers, ceramic, graphite, or carbon fibers. The advantages of this composite are the fact that fibers display better strength and stiffness in a matrix than they would individually, and also the fact that they can be oriented differently to support different applications. For instance, the fibers can be arranged in a unidirectional manner, in which the fibers are uniformly arranged in the same direction; here the fibers can be continuous and aligned, or discontinuous and still aligned in the same direction. This alignment is the strongest and is used for loads in one direction. Fibers can also be arranged into a woven manner, that is, when the fiber interacts and interlaces with the other producing a large sheet of material with high strength advantage. Woven structure comes in plain weave (one fiber over/under another fiber), twill weave (two over two), or s-weave (over 3 fibers under 3 fibers). Weaves are useful in complex fiber shapes and are applicable for loads in two directions. Figure 1 demonstrates two fibrous sheets of composite materials with a unidirectional structure and woven structure.

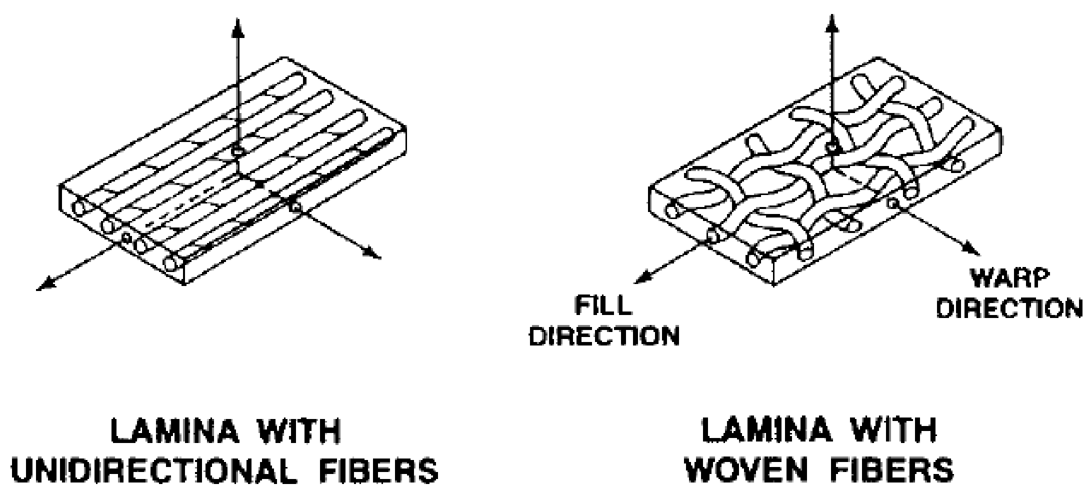

Figure 1. Directions of fibers in a matrix (courtesy of Jones, R.M.)

In a laminated composite, several sheets of the materials are layered on top of one another, forming the combined product. In this type of composite material, the sheets can be metal, glass, wood, or the previously

mentioned fibrous composite sheets. Laminated composites are fabricated by bonding fibrous composite sheets using a matrix material. They are called laminated fiber-reinforced composites. In the laminated fiber-reinforced composites, the sheets of the unidirectional fiber composites can be layered at 0-90^o angles, to produce a superior fiber structure with higher strength properties. Additionally, each individual layer of fiber composite is referred to as the lamina, and the multilayer structure is called a laminate. Figure 2 demonstrates the multi-layered structure of unidirectional sheets.

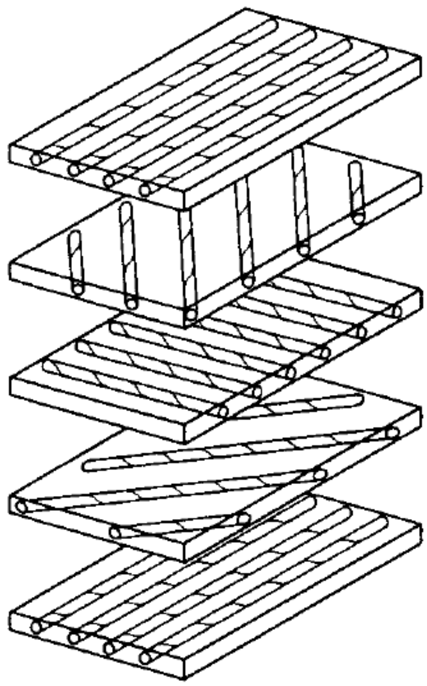

Figure 2. Laminated multilayer structure of the fibrous sheets (courtesy of Jones, R.M.)

In particulate composites, elements of one type of the material are generally suspended in a matrix material. This composite type is used in the civil engineering industry particularly for the construction of concrete. In concrete, cement powder is mixed with water, chemicals, and rocks to create a uniform composite material with superior combined properties that the individual elements do not possess.

Manufacturing Processes of Composite Materials

There are several ways to fabricate composite materials, such as a wet lay-up, a vacuum resin infusion-draw, and a pre-preg fabrication. A wet lay-up, is a process done by hand, and is generally used for small and noncommercial items or patchwork. In a wet lay-up the resin is pushed through the fibers, the soaked fibers are then placed in a vacuum sealed bag and cured. This is a simple and inexpensive process that requires no special materials, and can cure at room temperatures. However, this process is restricted by the work time; the work needs to be completed fast, and can become complicated when dealing with more complex parts, rather than patchwork, because fibers can be knocked out of alignment. Figure 3 shows the poured resin and the dry fiber sheet lay-up consolidated with a roller that works the resin into the fibers.

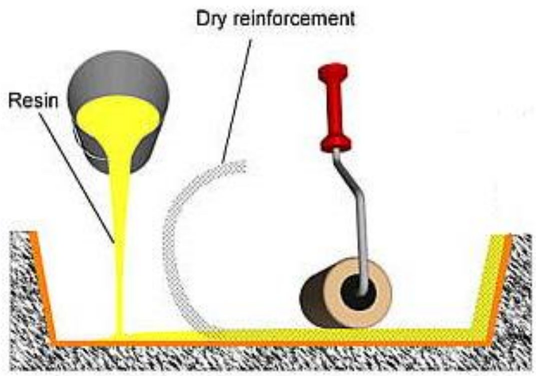

Figure 3. Demonstration of wet-lay process (courtesy of NTNU)

Another method of composite manufacturing is the vacuum resin infusion (VRI), known as the draw. This method is similar to the previous one, but is mostly used for larger applications. During this method the resin is pushed through the fiber by a vacuum. The fiber sheet is placed in a sealed bag, the resin in then introduced with the help of the vacuum pump that pushes the resin trough the fibers. This process is simple and easy, and is cleaner than wet lay-up, it does not need an oven to cure, and has more precise resin content then the above method. However, this method is more expensive because requires additional parts and types of resin to allow broader and larger applications. Figure 4 illustrates this concept.

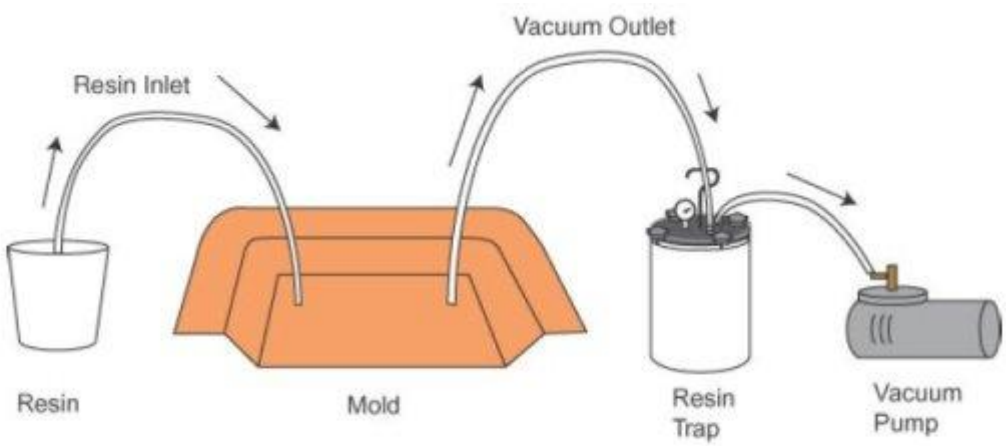

Figure 4. The vacuum resin infusion process (courtesy of NTNU)

The third type of composite fabrication is the pre-impregnated fibers (pre-preg) method that is mostly used in the aerospace industry due to its qualities. The pre-preg sheets of fiber already include the ideal resin content, mostly 60% fiber to 40% matrix or better. During manufacturing the fiber sheets are heated to cure so that they stick, and then cooled to settle. This method is clean, and has the best strength. However, it does require a head curing cycle, elongated work time, and is costly. Pre-preg sheets come in rolls, which have to be stored at certain conditions, and they have shelf life expiration dates.

Composite Plate Sandwich

The composite materials further discussed in the report, is of a sandwich type. These are laminated composite structures that are attached at both sides to a core material. Sandwich type composites are used in several industries such as automotive and aerospace; for instance, some fuselage hulls of an airplane are made from the foam surrounded by carbon fiber layers. Sandwich type composites are lightweight and their construction increases the structural strength. The composite sandwich pieces manufactured and tested for this report consists of pre-preg

composite carbon fiber laminate that have been cured and tested and a foam core with damage arrestment devices (DADs). The DADs are designed to distribute stress concentrations and reinforce the structure. The composite sandwiches are equipped with two equidistant holes that are drilled through the DADs, applying a load at these points test the concept effectiveness.

The current concept of the composite sandwich with two reinforced holes, originates from previous work done by students. In 2010, Richard Balatbat completed testing of composite sandwiches that were constructed from large fiberglass sheets, thick foam, and a central hole reinforced with a DAD. He tested his pieces under compression, and examined data such as the load, the fatigue, and interaction of bushings in the hole. The data derived from the experimental set up showed that placement of the DAD increased the failure load by as much as 109.2%, but it also showed a parabolic distribution, as he tested seven different DAD thicknesses, only the first five improved the load. Fatigue testing showed that addition of DAD only strengthened the material, but the load bearing was not improved, and bushings only allowed for better load distribution. One of the improvements Richard suggested was changing the DAD shape to lessen the stress concentration seen where the DAD and foam meet. In current experimental set up, this suggestion was adapted so that the DAD thickness is a steady three layers, and the stress concentration in the DAD channels is lessened with the use of the LTM45 sheet resin.

Additionally, in the same year, Cal Poly's master student Dominic Surano also conducted work in the area of composite panel testing with damage arrestment devices. His objective was to research delaying the skin-core delamination as well as micro-buckling and bearing stress failures resulting from fastener-hole interactions. Compression testing was performed on the composite sandwich panels with and without DADs. There was also a thermal element in the testing in which the panel was subjected to temperatures ranging from 75 to 200°F with the use of a thermal chamber. The testing was performed in an Instron machine and data was collected to find the elastic modulus and Poisson's ratio of the specimens. On the full composite sandwich with DADs the experimental elastic modulus was found to be 41,600 psi. This was a 33.6% difference from the theoretical model. Experimental Poisson's ratio was 0.214 compared to the theoretical value of 0.3, a percent difference of 28.7%. These differences were thought to be a result of the theoretical values over predicting the material properties due to assuming a perfect inter-laminar bond. Thermal testing showed that specimens without DADs, at 115°F, on average took about 12,000 cycles with a standard deviation of 80% to fail. As the temperature increased the number of cycles to failure decreased significantly. When DADs were added to the specimen and tested at 115°F, the number of cycles to failure was drastically increased to 70,000 cycles with only a 10% standard deviation. Overall, the DADs helped to increase the yield and the ultimate load the specimen could withstand in compression testing. This increase also held true in the case with increased temperature.

After adapting the previous set-ups, and the experiments, the scope of work of the current experimental set up included building the DADs, outfitting the foam to the DADs, constructing the sandwiches, placing the equidistant holes, and testing the pieces. Before the DADs were built, the ideal curing method was found by building strips of layered composite material using all available methods. Once, the method to create the strongest DADs was found, the foam core was outfitted with channels that house the DAD. The foam channels were filled with a layer of sheet resin, the DADs were then placed into the channels, and the foam was bonded to the carbon fiber face sheets. Once the sandwich plate was constructed, the pieces were cut to the specified dimensions and the holes were centered and drilled over each embedded DAD. Next, the sandwich pieces were placed in a test machine that provides a constant compressive load until the fail criteria was met. The test data was analyzed, so that material properties could be derived and compared.

The main objective of the experiment was to test the concept of the DADs, to see what happens if the fastener hole was reinforced with a DAD while placed under a compressive load. This was accomplished by manufacturing two sets of pieces that have DADs, and a set of pieces that do not have DADs. The control group used in this experiment had similar construction and equidistant holes, but it did not have the foam channels embedded with DADs. The data collected from the experimental group was compared to that of the control group, then parameters such as average load, stress, strain, elongation and Young's Modulus demonstrate that the concept of reinforcing a hole with an embedded DAD is a success. Showing the proof of concept provides ideas for future work, and shows that the performance of a piece that features a fastener hole can increase simply by placing a small light device.

Chapter II Design and Fabrication

The specimens were comprised of two major components: foam sandwiches and damage arrestment devices. The sole purpose of this experiment was to show the positive effect the DADs have. In order for the DADs to provide the optimum reinforcement, the best manufacturing process had to be used.

Manufacturing of Damage Arrestment Device

The first step in creating the test pieces was the creation of the DADs. When determining how to manufacture the DADs there were a multitude of curing processes that could be used. In order to determine the best manufacturing process for the DADs each method had to be tested. The purpose of testing the DADs was to determine the process that will be used to create the DADs for the final carbon fiber sandwiches. The DADs were cut from three, 12 inch by 12 inch laminates. These laminates were comprised of three layers of carbon pre-preg with one layer of sheet resin. The fabric was cross-ply rather than unidirectional, so the need to rotate the material to get resistance in the two primary directions was lessened. These three laminates were cured using three different methods; all three methods employed the Tetrahedron Press located in the Cal Poly Composites Laboratory. The first method that was used to cure the laminates was using the heat from the Tetrahedron Press as well as 1,000 lbs pressure force shown in Fig. 5. The second method used pressure applied by a vacuum on to the laminate while the Tetrahedron Press provided the heat for the curing process. The third and final method for creating the test DADs was a combination of the two previous processes; it used vacuum pressure as well as the heat and pressure provided by the press. The tested DADs are illustrated in Fig. 6.

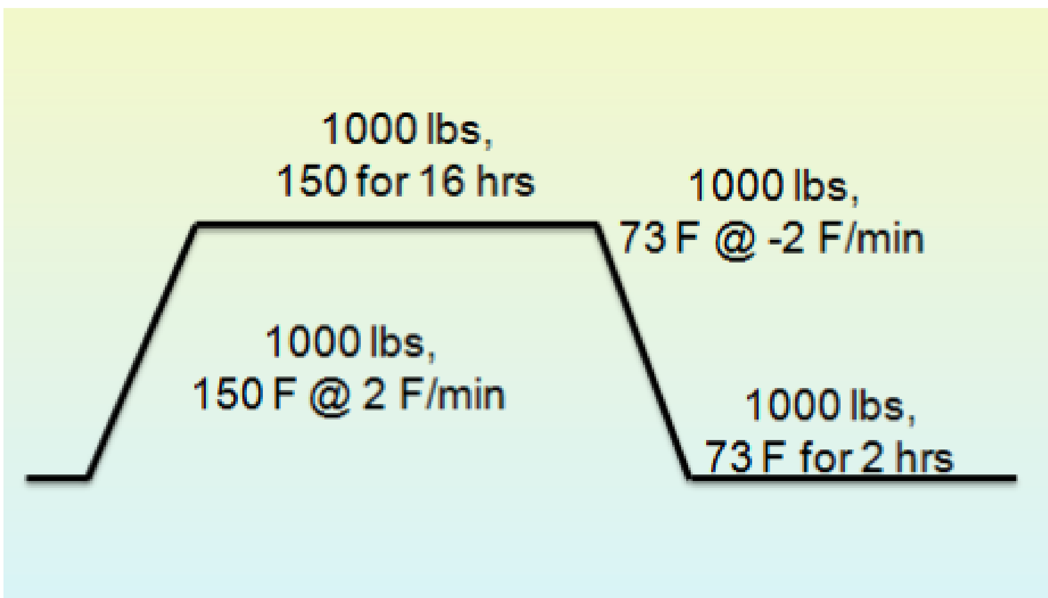

Figure 5. Cure cycle for composite specimen in Tetrahedron heat press

Figure 6. Tested specimens of three different types of DAD manufacturing methods

Manufacturing of Composite Sandwiches

Once the DADs manufacturing process had been selected, method 1, it was time to create the composite sandwiches. Two types of LTM45 sandwiches had to be created, a control group, and a group with DADs. First, the design and creation of the control group is discussed. The control group was created to be a symmetric sandwich. This sandwich used a core of foam with two layers of the LTM45 pre-preg on either side. When attempting this layup, previous research indicated this layup would be prone to delamination prior to testing. The research showed that this could be eliminated if a sheet of sheet resin was inserted between the foam and two layers of LTM45.The reason delamination is a problem is that the face sheets no longer benefit from having the core material, meaning that they will fail sooner. In order to avoid the problem of delamination in this experiment, sheet resin was also inserted into this layup. Once the layup of the control group was completed the composite plates were then cured using the same curing process as described in the previous section. Two control specimens are pictured in Fig. 7.

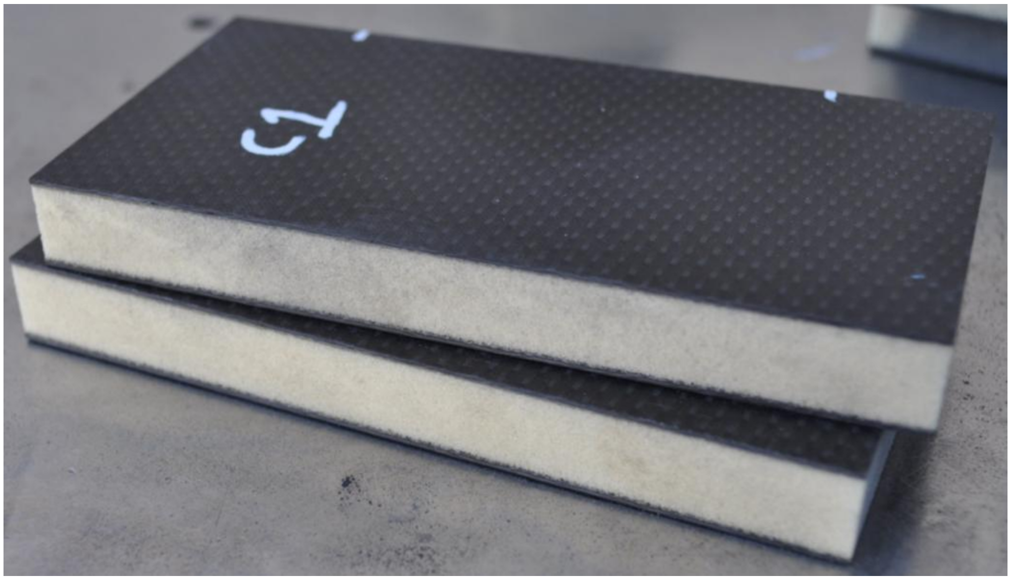

Figure 7. Control group showing the two layers of carbon fiber on each side

In order to create the sandwiches with the DADs in them, the design specifications first had to be designed. The test jig that was available for testing drove the sizing of the test specimens. Due to the fact that the specimens needed to maintain a flat exterior surface, even when DADs were present a channel had to be milled out of the foam. The depth of this channel was equal to the depth of the DADs plus the thickness of the sheet resin. For the center of the composite sandwich there was a piece of -A-Foam FR-6710, polyurethane closed cell foam, manufactured by General Plastics. It was a half-inch wide and squared to 12 inches by 12 inches. The foam was rated to have a density of 10 lbs per cubic foot and was certified by the manufacturer up to 275°F. In order to test a control group, one piece of foam did not have slots milled out. In addition, to test multiple specimens that included the DADs two foam pieces needed to be constructed. The foam had one-inch slots milled out using a CNC machine that ran the length of the piece. There were two inches between each slot and they were milled out on either side of the foam. A schematic for the specimens is shown in Fig. 8. Once the channels were milled, the layer of sheet resin was laid down and pressed onto the foam core, paying special attention to the corners of the channels. Once the sheet resin was correctly placed on the face, the DADs were inserted into the channels on top of the sheet Resin. On top, the two layers of the LTM45 were laid bonded to the surface. After on side was completed the sandwich was flipped over and the process was repeated. Once the plate of test specimens was complete, the plate was then placed into the press and allowed to cure.

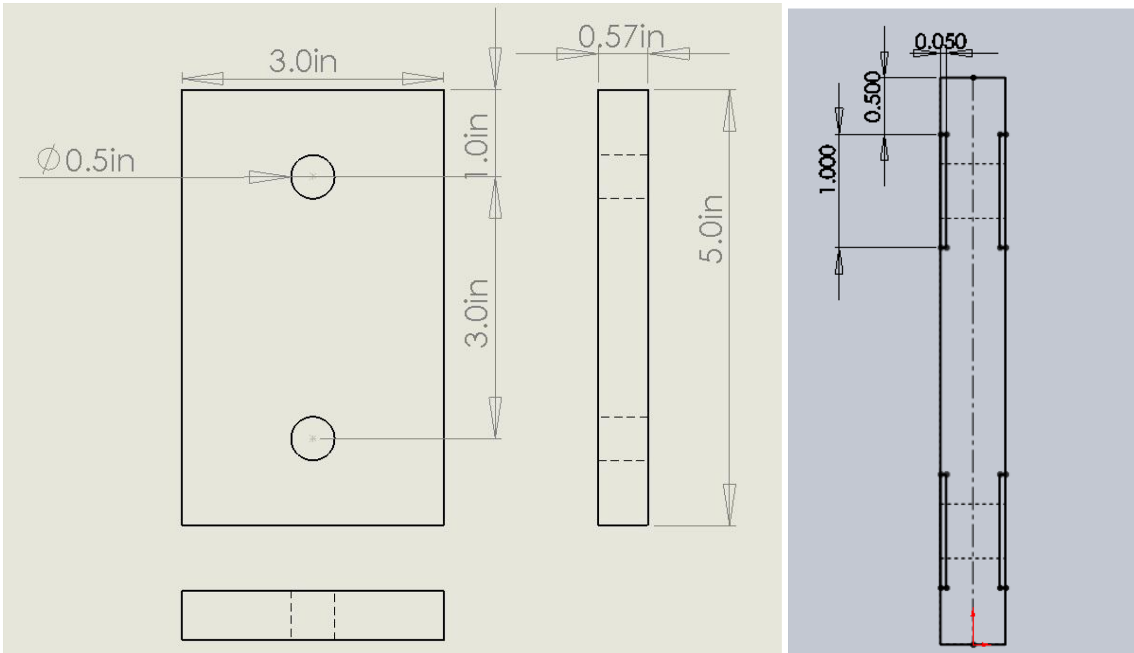

Figure 8. Shows the schematics of both the control group and DAD group

After curing was complete for both the control group and the group with DADs the plates had to be cut down into the individual test pieces. One issue that arose after the pieces were removed from the press was that the carbon did not perfectly aligned with the edge of the foam, and that some of the sheet resin spilled out over the side of the plate. In order to ensure that the test pieces were aligned with the major axes of the LTM45, the plates were squared to the direction of the fibers. In order to do this, a white paint pen was used to mark an individual strand of the carbon fiber that ran the length of the plate, and were as close as possible to the edge. A tile saw was then used to cut the specimens from the plate. The tile saw has an edge built in that is 90 degrees to the blade. Using this method each edge of the plate was squared. From here the 3 inch by 5 inch specimens were cut from the squared plate; each plate therefore yielded approximately eight pieces. When the DADs sandwiches were cut out, special care was taken in order to maintain the proper distance between the center of the hole and the end of the specimen (one inch). Figure 9 and 10 show the setup and drilling process for the sandwiches.

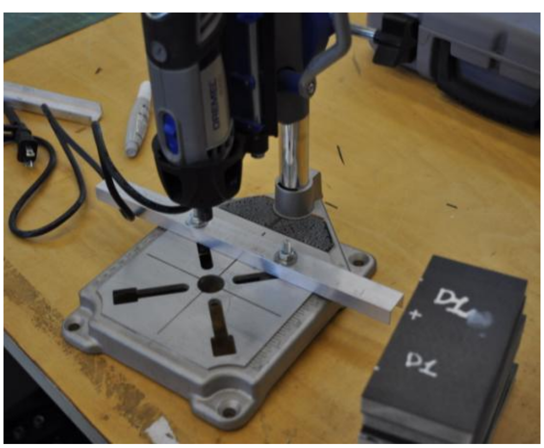

Figure 9. Shows the drilling apparatus setup

Figure 10. Holes being drilled into specimen

Also, special care was taken when drilling into the composite sandwiches. Conventional bits tear at the carbon fiber causing the fibers to fray and ruin the sandwiches. In order to alleviate this problem, a diamond dusted hole saw was used to cut out the half inch holes. Even with this much finer cut, the underside of the sandwiches tended to fray, as seen in Fig. 11. In order to try and remove these stress concentrations, the sandwiches were flipped over and the hole saw was run again through the same hole. This removed most of the burs and alleviated some of the stress concentrations.

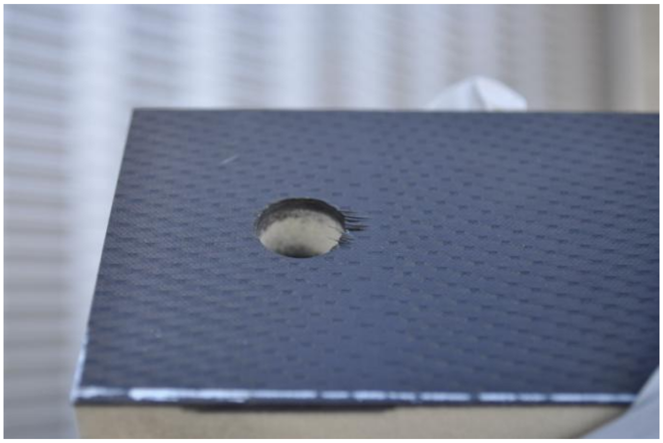

Figure 11. Shows the frayed edges around the hole

Testing Procedure

The California Polytechnic state University Instron 8801 machine was used to perform compression testing on the control group and sandwich specimens. The jig used, allowed for half inch bolts to be passed through the sandwich pieces and to be secured on both sides. First, the control group was tested and the failure criteria was determined to be either a drop of 40% of the load or half an inch deflection. A level was used to make sure the piece was aligned to a 90 degree angle to the jig. A protective Plexiglas shield was put up between the composite and the operators along with following the proper safety procedures. This process was then repeated for the test pieces that have the DAD inserts. Figure 12 shows the testing setup for the composite plate in the Instron machine.

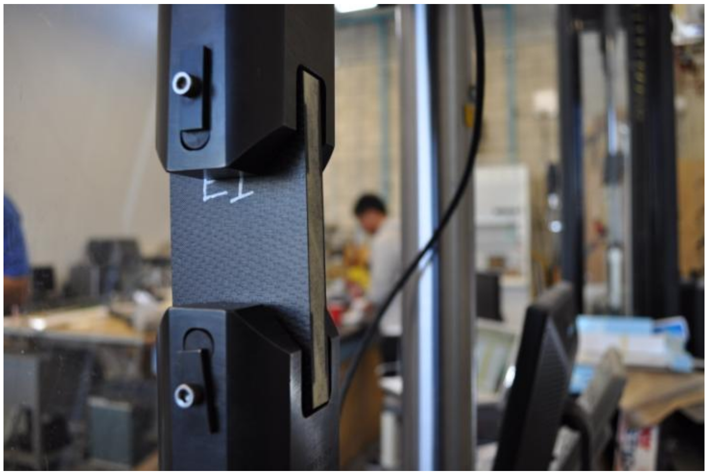

Figure 12. Shows the compression testing jig used in the Instron machine

Chapter III Data and Results

The project involves the creation and testing of damaged resistant carbon fiber sandwiches made up of foam, composite plates, and damage arrestment devices to strengthen it.

Damage Arrestment Devices Data and Results

In order to select the best damage arrestment devices (DADs), a carbon fiber plate was created, divided into three pieces, cured using one of three curing methods, and investigated through testing. Each piece was cured using either pressure at 1,000 lbs, vacuum and 1,000 lbs of pressure, or vacuum and 10 lbs of pressure. Once the smaller plates were ready, they were cut into four-5 inch by 0.5 inch strips and tested in the California Polytechnic State University's Instron machine. The testing process for all twelve strips was the same. One by one, the strips were placed in the Instron machine, put under tensile loads until the strip fractured. Figure 13 below, shows the placement of a DAD for the tensile test.

Figure 13. Instron machine with composite specimen ready for tensile test

During the tests, important properties of the material were taken for each of the four specimens: extension and load. These values were recorded until the composite strip failed. With the extension, load, and dimension values, the tensile strain, tensile stress, and Young's modulus were calculated and graphed. Figure 14 shows the stress-strain curves from the pressure only DADs. The slope of the curve represents Young's modulus. All four graphs show a very similar slope; where specimen 1 and 2 are practically aligned while specimen 3 and 4 show the same pattern. In order to reflect better results, only a percentage of the data was used. Data between 10 and 40% of the maximum load was graphed.

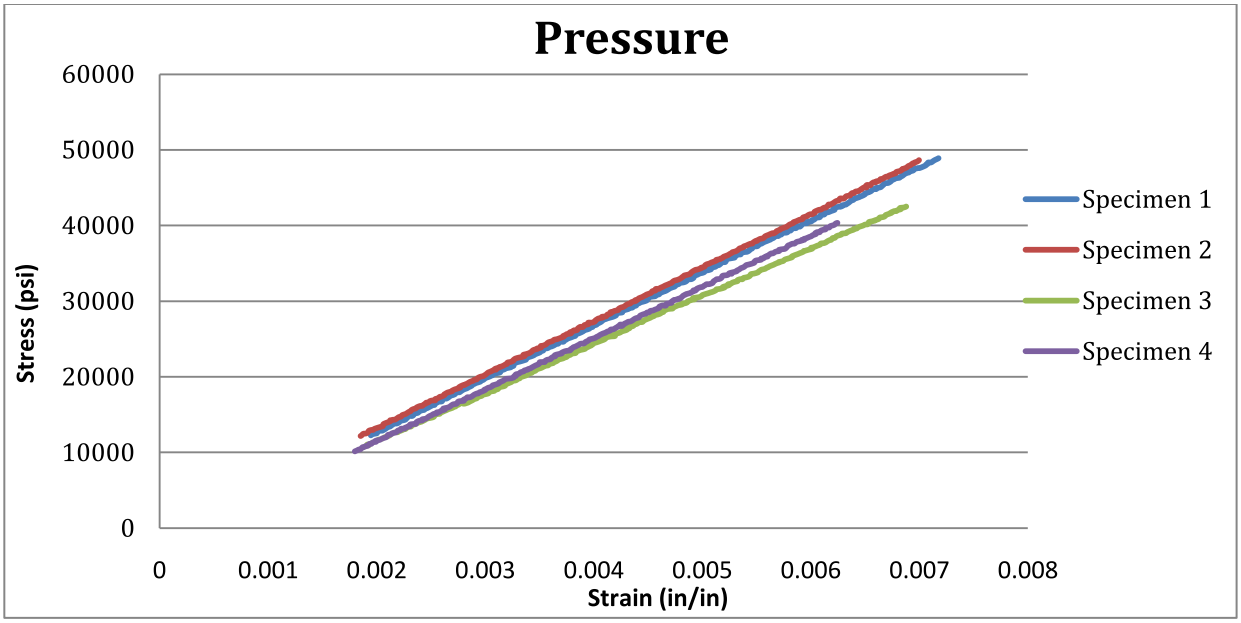

Figure 14. Stress-strain curve for the four pressure only DADs

The results show that the pressure only strips have on average an extension of 0.02 inches and can withstand loads of 698 lbs with a max load of 1223 lbs. The stress was divided by the strain and an average Young's Modulus of 6,446,476 psi was obtained. Table 1 shows a summary for the pressure only results.

Table 1. Pressure only test results summary

	Extension (in)	Load (lbf)	Strain (in/in)	Tensile Stress (psi)	Young's Modulus (psi)
AVE	0.020403	698.8464111	0.004454	29240.24	6446476
STD DEV	0.000412	19.84709748	0.000101	934.0859	50308.2
	MAX F	1223.31892			

The same properties were recorded and calculated for the four vacuum only specimens. In this case, the stress-strain curves do not align as those in the pressure only (see Fig. 15). The curves are offset due to the difference in each specimen's strain and stress; however, all four graphs are parallel to each other. In other words, when the stress is divided by the strain the slope is the same.

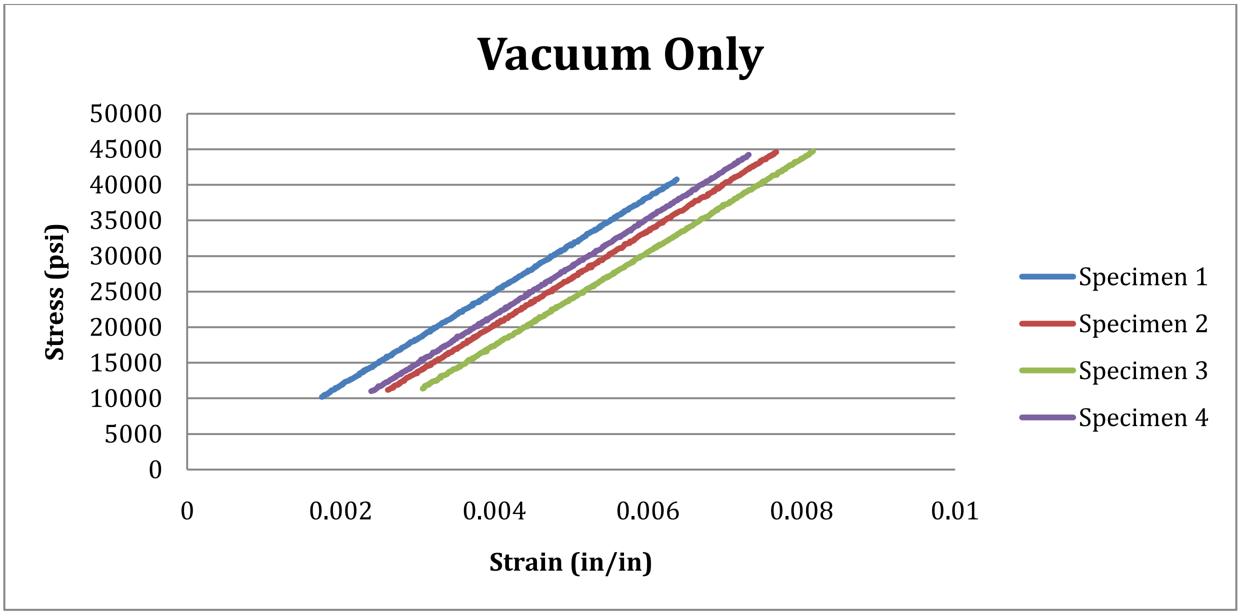

Figure 15. Stress-strain curve for the four vacuum only DADs

The data recorded for the vacuum only method showed that on average loads of 743 lbs can be withstood. The average of the Young's modulus was calculated to be approximately 5.5 million psi. Table 2 shows the averages for the different properties.

Table 2. Vacuum only test results summary

	Extension (in)	Load (lbf)	Strain (in/in)	Tensile Stress (psi)	Young's Modulus (psi)
AVE	0.024389	743.1969917	0.004922	27226.98	5485249
STD DEV	0.000303	8.192941712	6.16E-05	408.4535	146977.8
	MAX F	1134.85439			

Finally, four strips manufactured with the third method of vacuum added with 1,000 lbs of pressure were tested. Figure 16 shows the stress and strain curves calculated from the test's extension and load values.

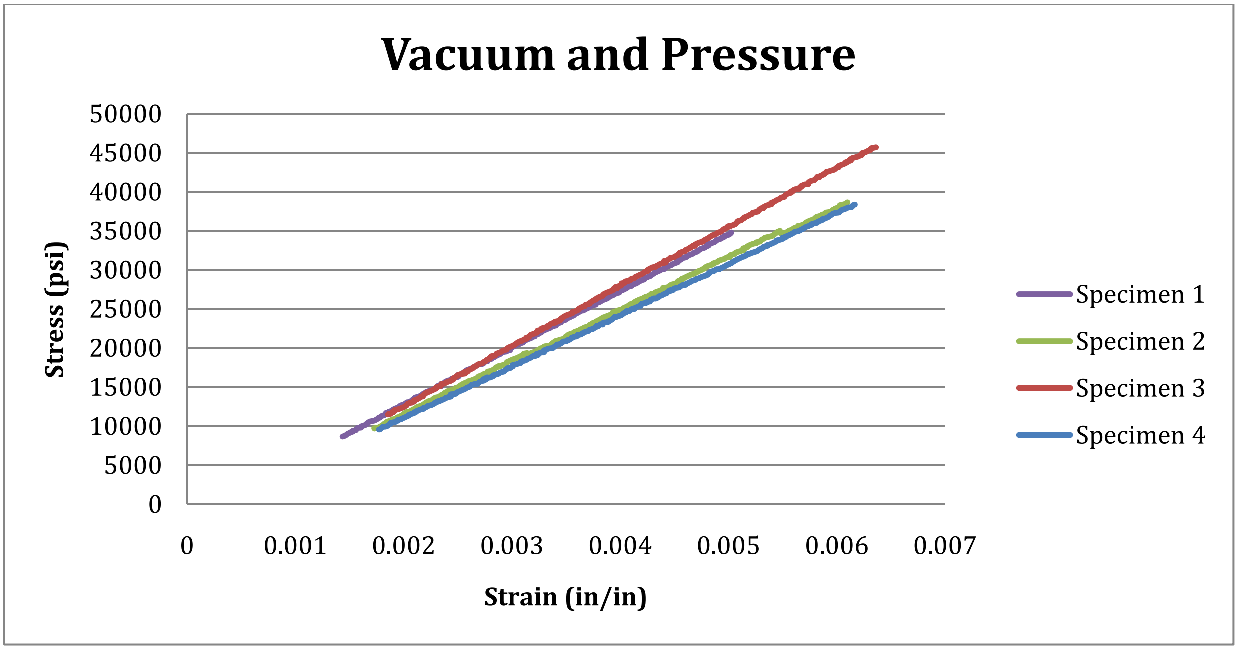

Figure 16. Stress-strain curve for the four vacuum with 1,000 lbs of pressure DADs

The third method shows that vacuum and pressure DADs can withstand on average loads of 604 lbs and a max of approximately 860 lbs. Table 3 shows these and other properties.

Table 3. Vacuum and pressure test results summary

	Extension (in)	Load (lbf)	Strain (in/in)	Tensile Stress (psi)	Young's Modulus (psi)
AVE	0.018862	604.5263454	0.003805	24689.45	6426035
STD DEV	0.000589	20.49196543	0.00012	1006.511	34901.83
	MAX F	858.17829			

Out of the three curing methods, the pressure only was concluded to be the best method to follow in the creation of the damage arrestment devices since it showed a Young's Modulus of 6.44 million psi compared to the 5.48 million and 6.42 million psi of the vacuum only and vacuum and pressure respectively. The DADs were implemented into composite sandwich pieces, tested, and the results are discussed below.

Composite Sandwiches Data and Results

Material properties are calculated, analyzed, and compared in order to determine the effects that damage arrestment devices (DAD) have on the mechanical characteristics of composite sandwiches. To do the comparison, a control group with eight specimens was contrasted to two groups with shear keys, of eight and six specimens respectively.

Control Group

As the Instron 8801 machine compressed each of the eight control specimens, the elongation changes and the applied loads were measured. These two characteristics were then used to calculate both the strain and stress values. Stress-strain curves were then created to find the Young's Modulus. Figure 17 shows the stress-strain curves for each of the eight control specimens. Note that to create the curves below, only a set of the measurements were taken (10% to 40% of the maximum load of each specimen).

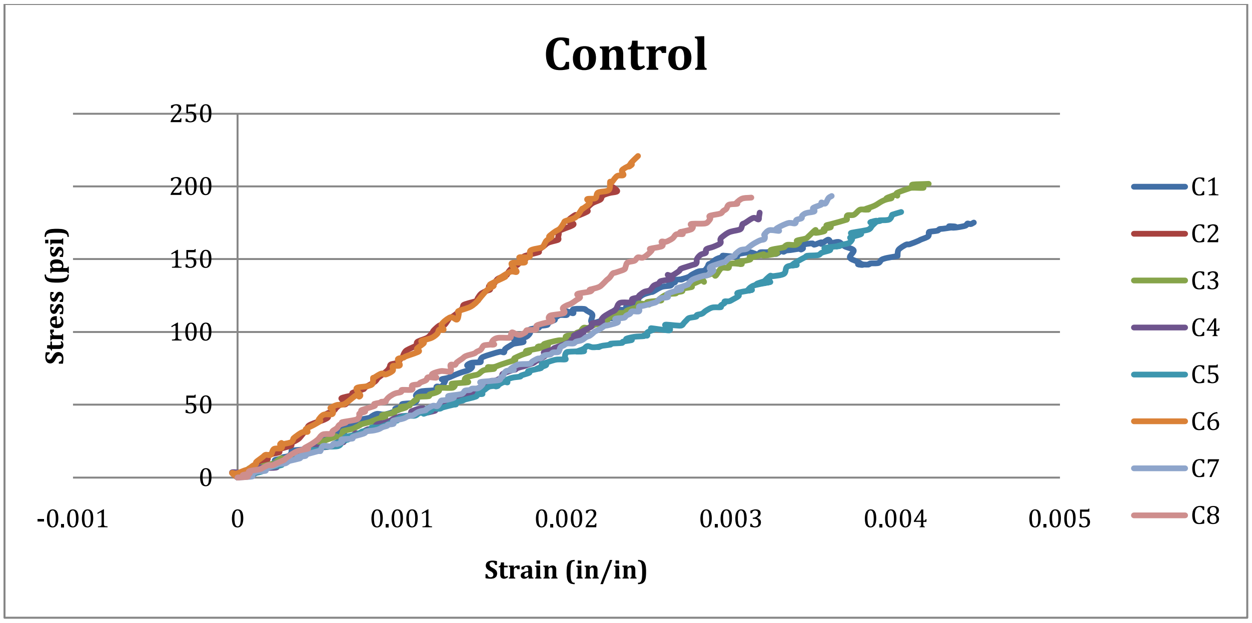

Figure 17. Stress-strain curves for the eight control specimens

Analyzing the above graph, the trends are very similar with the eight specimens having similar slopes (Young's Modulus). Specimen C1, although following the same trend, deviates past a strain of 0.0035. The reason behind the discrepancy may be due in much extent to human error. Specimen C1 was the first one to be set up and tested in the Instron machine. The test ran longer than the other specimens because the restrictions (40% drop in load or half and inch deflection) were not being reached. The test was stopped as it was noticed that the corners of the composite sandwich were resting on the jig. Further analysis on this set, shows a clear discrepancy with specimen C1, as seen in Fig. 18.

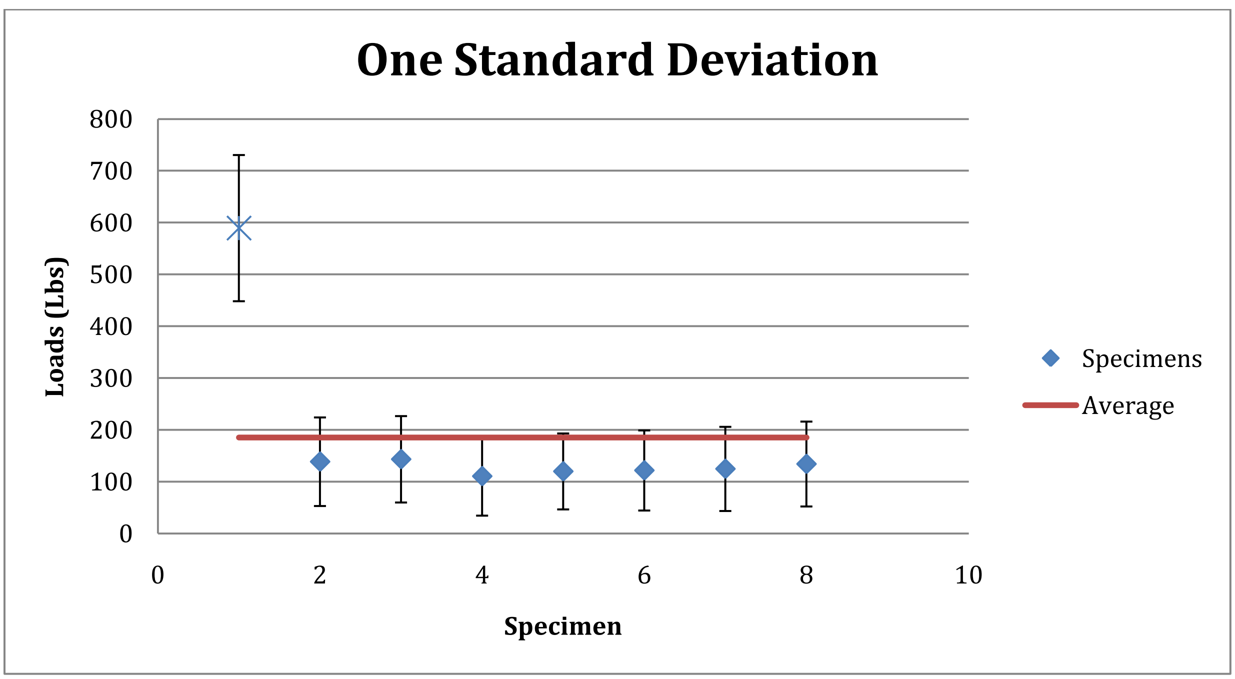

Figure 18. One standard deviation for the control group's loads with specimen C1

Although Fig. 18 shows specimen C4 as an outlier, it is due greatly to the "big pull" specimen C1 has on the average. If specimen C1 is considered as an outlier and not taken into consideration, all other data points lie within one standard deviation from the average load of 216 lbs., as seen in Fig. 19.

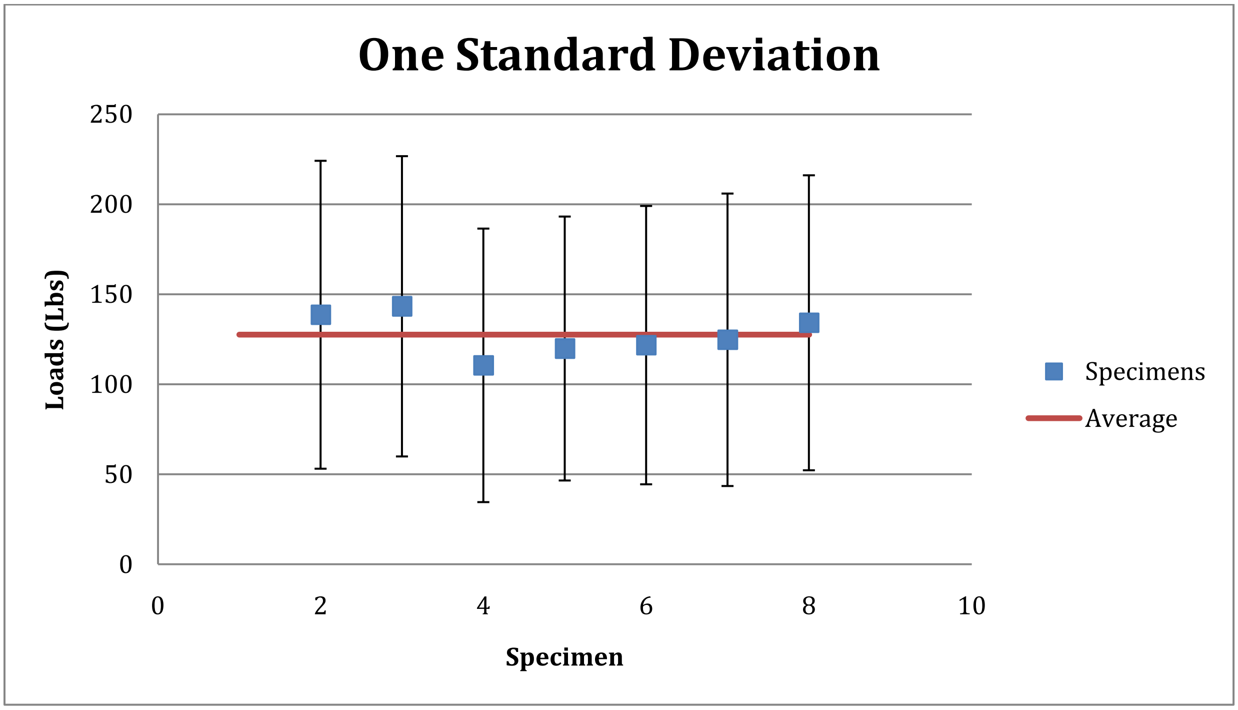

Figure 19. One standard deviation for the control group's loads without specimen C1

For better visualization of the control group's material properties the average for each of the specimens can be found in Table 4 below. The values for the outlier and its effect on the average values are highlighted.

Table 4. Control group's summary of properties

	Extension (in)	Load (lbf)	Strain (in/in)	Stress (psi)	Young's Modulus (psi)
C1	0.090689	589.4364	0.035056	404.6253	18112.29
C2	0.002922	138.6092	0.001139	96.05115	73818.05
C3	0.005364	143.2959	0.002087	100.5342	48854.44
C4	0.004125	110.5029	0.001591	77.50894	43885.19
C5	0.00518	119.851	0.002029	84.57959	40115.91
C6	0.003137	121.7312	0.001212	103.8733	77871.14
C7	0.004679	124.7049	0.001828	86.70717	43958.64
C8	0.003986	134.141	0.001555	93.24543	57008.34
AVERAGE W/C1	0.01501	185.2841	0.005812	130.8906	50453
STD DEV W/C1	0.017746	22.04388	0.006858	14.57226	22173.12
AVERAGE W/O C1	0.004199	127.548	0.001634	91.78568	55073.1
STD DEV W/O C1	0.000523	4.381643	0.000206	4.621005	23586.24

The control group shows extensions ranging from 0.0029 inches to 0.090 inches. The big difference in the elongations is due to the different critical loads, ranging from 110 lbs to 589 lbs. As already described, the values

have a large difference due to specimen C1 (outlier). If this specimen is not used in calculations, values like the average Young's Modulus improve from 50,453 psi to 55,073 psi, just over 9%. The average load that it can sustain worsens; this change is to be expected as sandwich C1 was transferring the load on to the jig.

DAD Key D Group

Group D was the second group to be tested. This group contained two strips of composite materials used to reinforce the sandwich where the holes were drilled. Figure 20 below shows the results of this group's eight specimens' test.

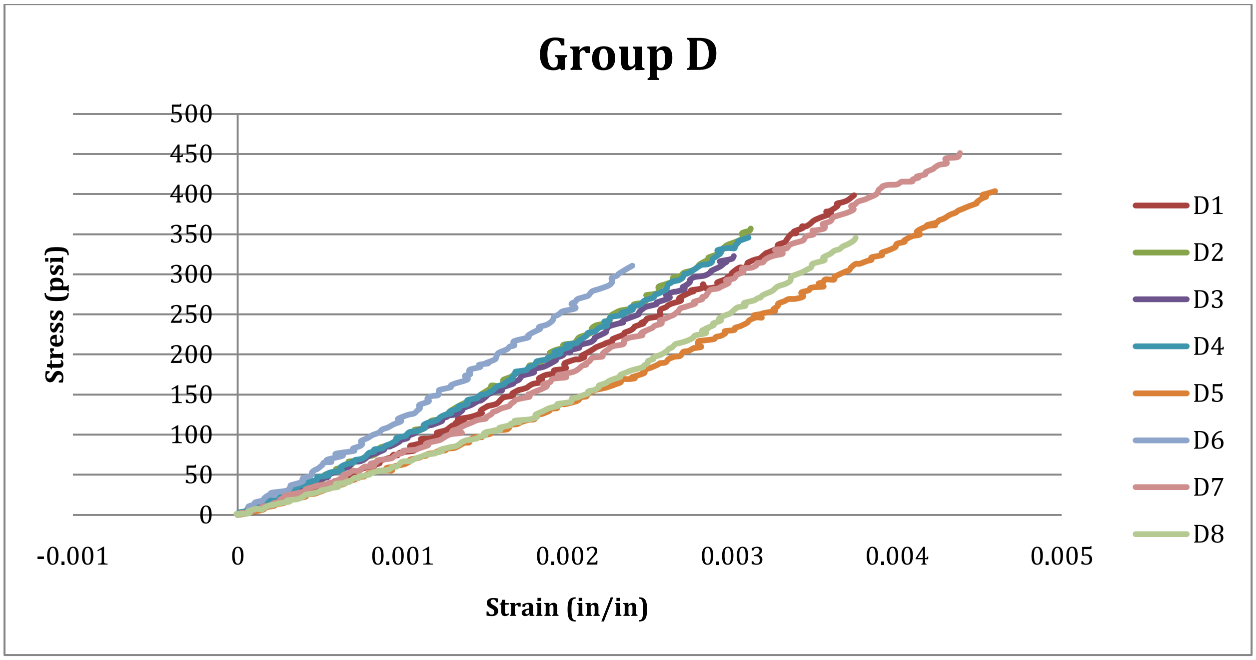

Figure 20. Stress-strain curves for the eight group D specimens

Just as for the control group, the slopes' trends are very similar although with small slope deviations. This graph, at first sight, does not show any discrepancies. Another standard deviation graph was created to confirm this. Figure 21 shows how close each specimen is to the average.

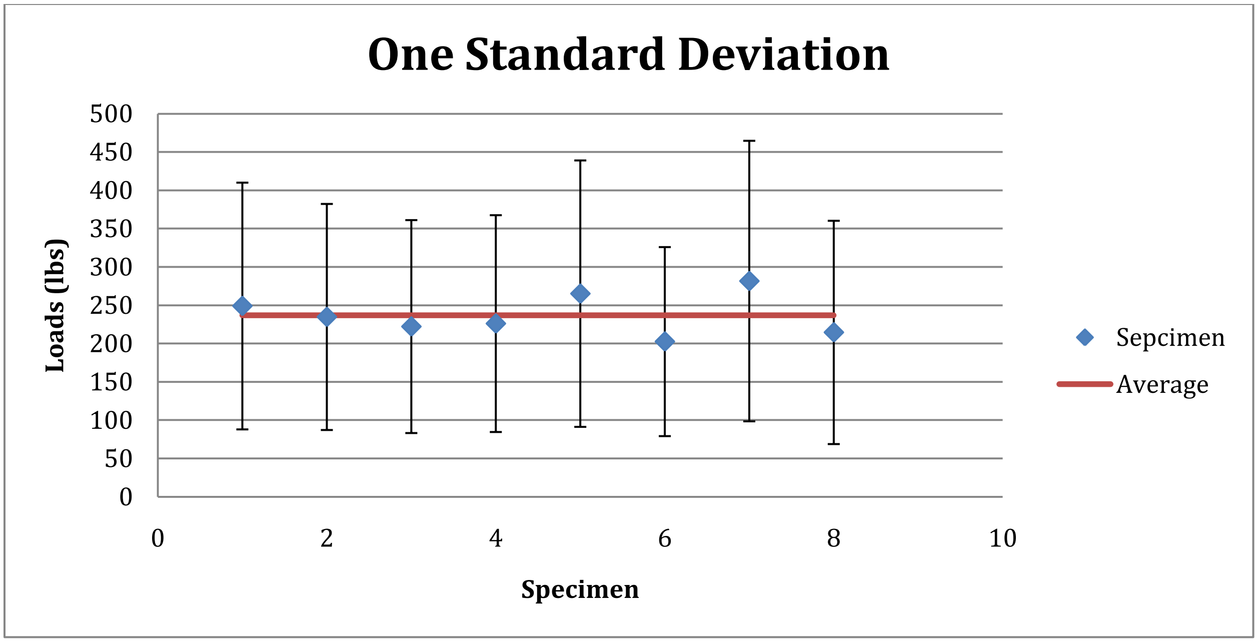

Figure 21. One standard deviation for group D loads

All eight specimens lie within one standard deviation of the average. This provides confidence on the data collected. Again, a summary of group D's mechanical properties is shown below in Table 5.

Table 5. Group D's summary of properties

	Extension (in)	Load (lbf)	Strain (in/in)	Stress (psi)	Young's Modulus (psi)
D1	0.004898	248.9598	0.001885	181.1729	88262.92
D2	0.003976	234.6565	0.001575	166.7845	99586.22
D3	0.003741	222.1276	0.001511	152.4409	97438.3
D4	0.003942	226.0198	0.001549	162.9139	103715.1
D5	0.006	265.1192	0.002321	179.9675	71562.86
D6	0.002921	202.5203	0.001188	149.1663	121967
D7	0.005636	281.5439	0.002203	209.7924	88593.21
D8	0.0048	214.5108	0.001888	147.7123	70254.55
AVERAGE	0.004489	236.9322	0.001765	168.7438	92672.51
STD DEV	0.000573	19.5819	0.000211	14.87841	6019.012

The above data shows that these sandwiches' can withstand an average of 236 lbs with a standard deviation of 19. Another very important characteristic to be noted is the Young's Modulus of 92,672 psi.

DAD Key E Group

Group E was composed of six specimens. These specimens, like the ones on group D, were reinforced with composite DADs. Once each of the six was exposed to compression, data was measured and summarized in the Fig. 22.

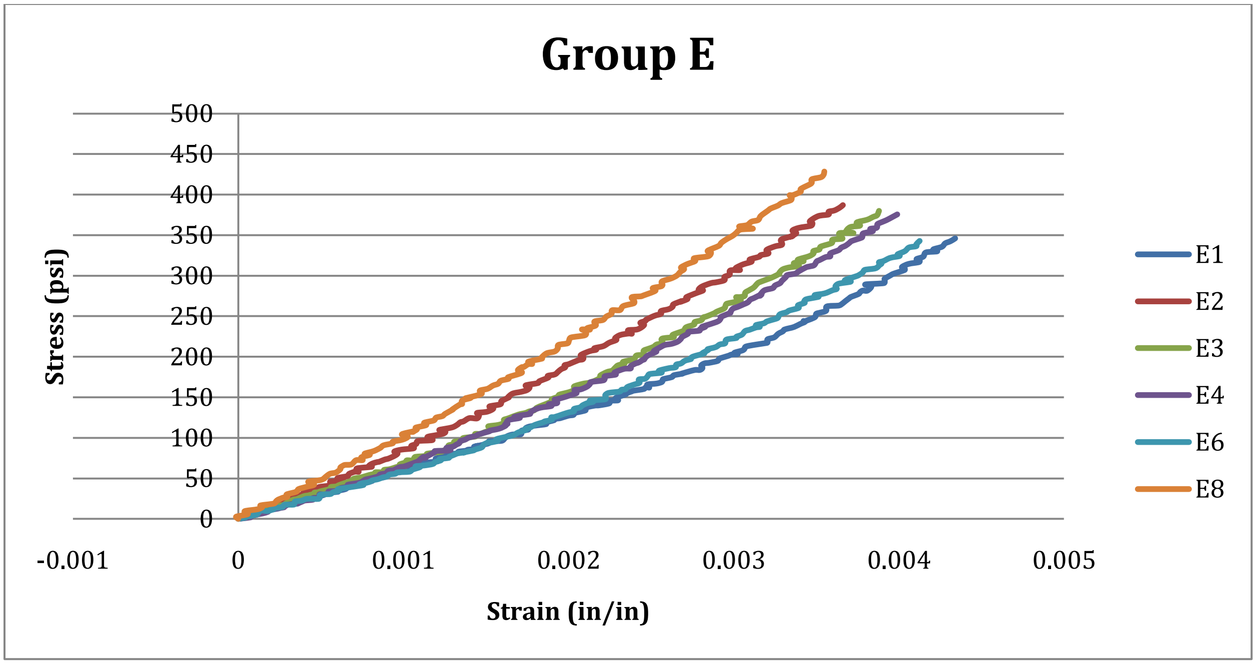

Figure 22. Stress-strain curves for the six group E specimens

The trends for these specimens are very similar to each other, following an upward tendency. By analyzing this graph no inconsistencies are apparent. Figure 23 below shows that the six samples fall inside one standard deviation as well.

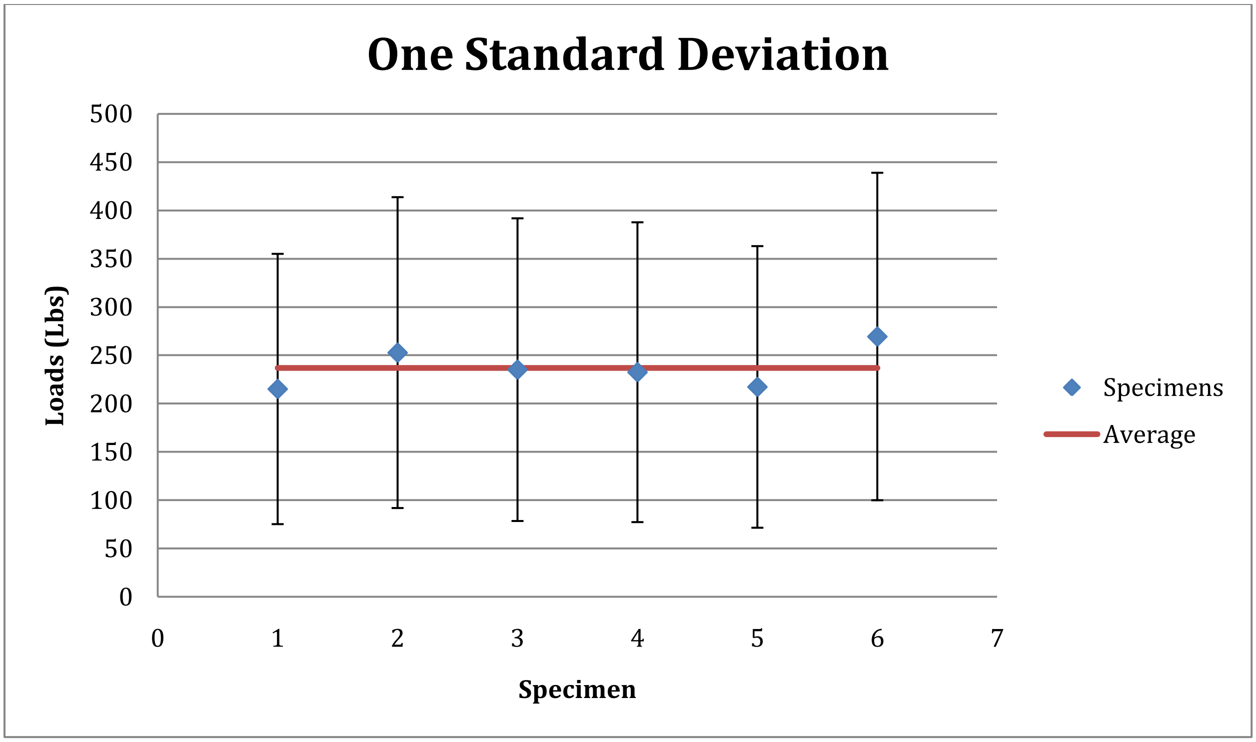

Figure 23. One standard deviation for group E loads

In fact, it is as if all the data points are on the average of 240 lbs. For a better visualization of the values, Table 6 shows a summary of Group E's properties.

Table 6. Group E's summary of properties

	Extension (in)	Load (lbf)	Strain (in/in)	Stress (psi)	Young's Modulus (psi)
E1	0.005434	215.0429	0.002188	151.4703	64781.97
E2	0.004688	252.7133	0.001838	179.014	91654.49
E3	0.004946	235.0762	0.001964	167.308	78732.01
E4	0.005166	232.4339	0.002015	165.8311	74627.55
E6	0.005118	217.1928	0.002072	149.9301	67257.7
E8	0.004493	269.3646	0.001781	200.1137	106457.1
AVERAGE	0.004974	236.9706	0.001976	168.9445	80585.14
STD DEV	0.000342	20.94448	0.00015	18.71992	15863.03

This group shows that the composite sandwiches withhold forces from 215 lbs to 269 lbs. They also show an average of 0.0049 inches in extension with a Young's Modulus of 80,585 psi.

Comparison of Control Group and Reinforced Groups

The experiment's intent is to show that the Damage Arrestment Devices (DADs) have a positive impact on composite sandwiches; that the addition of these composite strips is better than having just the foam core and the composite plates. Table 7 summarizes the average results found from the control group and the reinforced groups (D, and E) as well as an average of both reinforced groups combined.

Table 7. Average values of control and reinforced groups

	Extension	Load	Strain	Stress	Young's Modulus
CONTROL	0.004199	127.548	0.001634	91.78568	55073.1
Group D	0.004489	236.9322	0.001765	168.7438	92672.51
Group E	0.004974	236.9706	0.001976	168.9445	80585.14
REINFORCED	0.004732	236.9514	0.001871	168.8442	86628.83

From the table above, it is clear that the reinforced groups improve the mechanical characteristics of the sandwich. Comparing the control group with each of the reinforced groups (group D and group E) individually and combined, there is an improvement of 68%, 46%, and 57% respectively in the Young's Modulus. Analyzing the load, it is also evident that the amount of force that the reinforced sandwiches may withstand increases as well. The sandwiches without DADs may only take an average of 127 lbs while those that are reinforced with the strips may withstand an average of 236 lbs almost a 95% increase.

Modes of Failure

Through the three different groups and the 22 specimens there were two common modes of failure. The most common is called bearing failure, depicted in fig. 24. This kind of failure shows the load concentration on the bottom center portion of the hole and was seen in the control, D, and E groups.

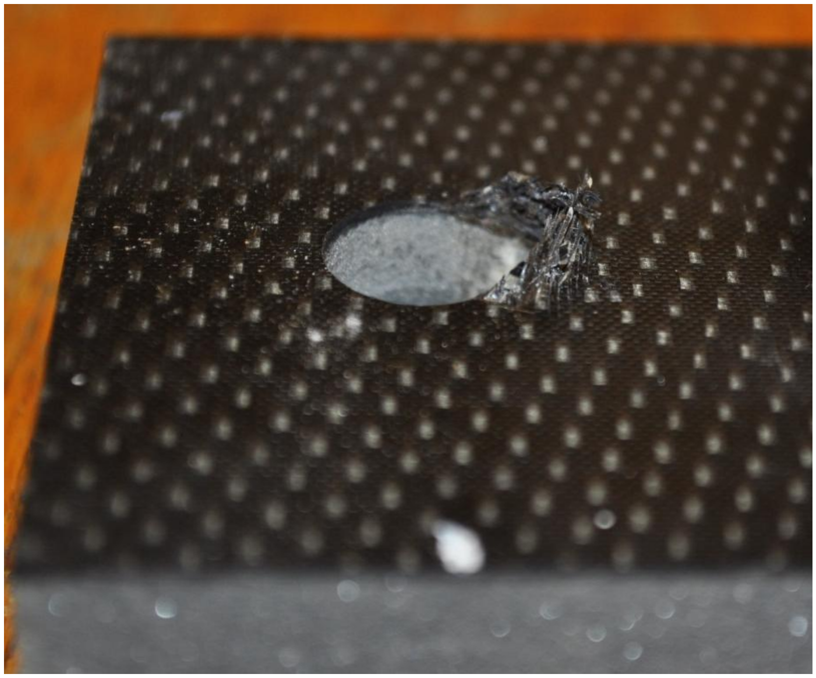

Figure 24. Bearing failure most common form of failure

Figure 25 shows the second mode of failure called face sheet buckling. This type of failure shows how the loads on the hole and sandwich are distributed along the DADs.

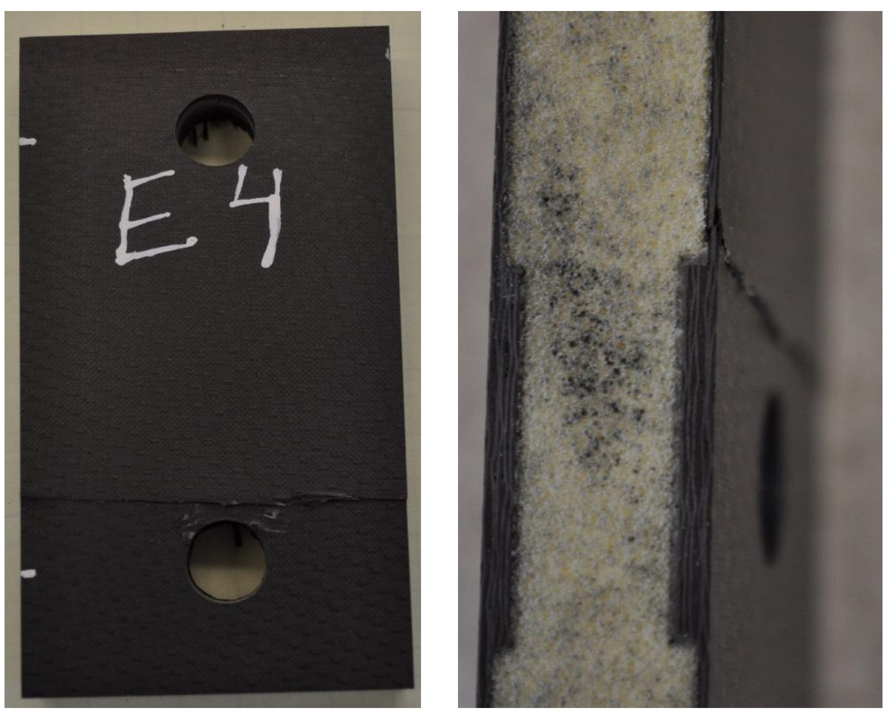

Figure 25. Front and side view of face sheet buckling

Chapter V Theoretical

COSMOS was used in an attempt to validate the results seen from the experimental data. Richard Balatbat's theoretical model was used as the basis for this theoretical model. In order to make Mr. Balatbat's theoretical model more in line with this experiment the dimensions and material properties of his model needed to be changed. COSMOS is a finite element analysis software that is able to determine, the stress, strain, and deformation of the test pieces. COSMOS uses a digital 3D model of the test piece in order to calculate the numerical results. While attempting to modify his model several errors occurred that prevented the alteration of any of his model.

Initially each of the dimensions of the model was altered in order to conform to this experiment. This produced an error that only allowed the front plane of the test piece to be created inside of COSMOS. After consulting with Dr. Elghandour it was decided to attempt just the modification of the bottom plane of the model. Even this slight adjustment caused the entire model to error out. After several attempts to fix the various errors that occurred it was determined that the modification of Mr. Balatbat's model was not feasible.

Chapter VI Conclusion

Composite sandwich plates were tested to find how much an inserted carbon fiber damage arrestment device could help to increase load capabilities. First, the curing cycle of the DADs was tested with three methods: pressure of 1000lbs. only, vacuum only, and vacuum with 1,000lbs pressure. It was found that the pressure only method produced the specimens that could withstand the highest load and tensile strength, therefore that method was used in the sandwich panels. For the sandwich panels the results showed that the presence of DADs, does increase the performance of the test pieces, as much as 95% improvement in test averages. Young's modulus for the control group was much lower at about 55 ksi compared to the specimens with DADs, which was about 85 ksi. In future work, the thickness of the DADs and their placement can be further varied, to see if that decrease piece performance. Additionally, things like load or fail criteria can also be varied so that the results can show a wider spectrum of configurations and their performance. Several problems were encountered during the construction of the experiment that could have affected the results negatively. For instance, during the placement of fastener holes, it was found that the drilling mechanism caused fraying in some faceplates, essentially destroying some of the fibers. This fraying could have caused easier propagation of shear; next time, this could be prevented by replacing the drill bit, or adjusting drilling practices so fraying is avoided. Additionally, it was found that some of the DADs were not aligned as originally intended, and that could have influenced the results as well. More careful construction and constant measuring of the sandwich components could prevent misalignment in the future. Overall, the pieces performed as expected, and the concept has been proven, however construction improvements and input variations could further improve the concept, and minimize error.

References

Balatbat, Richard. *An Investigation of Damage Arrestment Devices Applications with Fastener/Hole Interactions.* San Luis Obispo : California Polytechnic State University, 2010.

ivt.ntnu.no, 2011, Norwegian University of Science and Technology, 1 March 2011, <http://www.ivt.ntnu.no/ipm/web/?q=lab/compositelab/vi>.

Jones, Robert M. *Mechanics of Composite Materials*, 2rd Ed., Taylor & Francis Group, New York, NYMA, 1999, p. 15-17.

Surano, Dominic. *The Effectiveness of Damage Arrestment Devices in Delaying Fastener-Hole Interaction Failures in Carbon Fiber Polyurethane Foam Composite Sandwich Panels Subjected to Static and Dynamic Loading Under Increased Temperatures.* San Luis Obispo : California Polytechnic State University, 2010.