PERFORMANCE OF BOLTED JOINTS IN
DISCONTINUOUS CERAMIC CORED SANDWICH STRUCTURES

by

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ABSTRACT

Thick section composites that consist of discontinuous ceramic tile arrays as a core represent a unique class of sandwich structures. They have been developed to provide a balance of structural and impact performance at minimum weight. Bolted joints are often used to fasten the Discontinuous Ceramic Cored Sandwich Structures (DCCS structures) to the primary frame. Extensive experimental testing has been completed in order to better understand the performance of bolted joints in DCCS Structures. In this study specimens with 0.5 inch pins are subjected to in-plane tensile loading statically to establish the sequence and severity of failure modes that occur in the tiles, face sheets and the bonding interlayer. Static testing was completed on various geometric ratios such as pin spacing and edge distance as well as the influence of tile gaps that exist in the discontinuous tile array. Specimens were also subjected to in-plane tensile fatigue loading to determine the fatigue sensitivity of the joints in the DCCS structure. This study provides a better understanding of load paths from the pin into the face sheets and ceramic tiles, the material’s failure modes, and the sequence and load levels at which these failures occur for both static and fatigue loading conditions. The compilation of data determined from this study will result in design guidelines assisting engineers in future design of bolted joints in DCCS structures.
Chapter 1

INTRODUCTION

1.1 **Background:**

Discontinuous Ceramic Cored Sandwich Structures (DCCS Structures) are a unique composite material. DCCS Structures consist of three main parts making it a multifunctional hybrid composite. These constitutive parts help to maximize impact and structural performance while minimizing weight. The face sheet is a composite laminate comprised of S2-Glass reinforcement and infused with FCS-2 epoxy resin. The core of the DCCS Structure is an array of square alumina ceramic tiles. The interlayer acts as an adhesive bonding the ceramic tiles to the face sheet material.

![Discontinuous Ceramic Cored Sandwich Structure](image)

**Figure 1.1:** Discontinuous Ceramic Cored Sandwich Structure
In order to better understand how a complex composite such as the DCCS Structure behaves under bolted joint loading conditions it is first important to understand how bolted joints behave in standard composite laminates. Mechanically fastened joints in composite laminates are often the most common method for connecting structures despite the fact that bonded joints are more weight efficient. Mechanically fastened joints are often cheaper and require minimal preparation which allows for easy installation, inspection, and repair. Despite the many benefits that bolted joints provide, they also cause large stress concentrations that are the catalyst for failure modes. The failure modes for bolted joints in advanced composites are bearing failure, net-tension failure, and shear-out failure. (DOD/NASA Advanced Composites Design Guide) These can be seen in Figure 1.2(b, c, and d).
Figure 1.2: Common Failure Modes for Thin Laminates.
(a) net-tension failure, (b) shear-out failure, (c) bearing failure
Based on failure modes that may occur and the fact that bolted joints in composites may fail at loads that cannot be predicted by either perfectly elastic or perfectly plastic assumptions, it is imperative that the load capacity and failure modes of these joints are known and understood before being used for structural applications. (Thoppul et al 301 - 329)

A review written by Thoppul et al has proven that the mechanics of mechanically fastened joints in thin polymer-matrix composite structures has been studied extensively. Detailed reports exist describing many factors relevant to bolted joint experimentation and analysis, however a majority of these papers relate to thin laminates, which is directly addressed in the ASTM Standard D5961. (Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates) The use of this ASTM standard and other standards for bolted joint testing is discussed. (Thoppul et al 301 – 329). Despite having a large knowledge base about thin laminates, the Discontinuous Ceramic Cored Sandwich Structures (DCCS Structures) are far more complicated and extensive research must be completed to better understand their behavior under conditions that are present in mechanically fastened joints. Various bolting parameters have been discussed in the literature that directly relate to issues included in DCCS Structures. These parameters include joint configuration, loading conditions, material parameters, joint geometry, and fastening parameters.

The material properties of each constituent part in the DCCS Structure are very different. The ceramic tile is very stiff in comparison to composites, strong in compression, but very weak in tension. The face sheet material is significantly more compliant (compared to the tile), strong in tension, but not as strong in compression. The interlayer (which is the most compliant of the three constituents) has many
variables that can affect the overall performance of the DCCS Structure such as the thickness and stiffness of the interlayer. According to Huang et al. a stiff and/or thin interlayer will allow more load to be transferred to the ceramic tiles while a less stiff and/or thicker interlayer will have a lower load transfer from the face sheet to the ceramic tile. (Huang et al 81 – 90) Fatigue studies by Gawandi (personal communications), it was determined that the addition of the interlayer also reduces the fatigue sensitivity of the DCCS Structure to interlaminar stresses that exist at stiffness discontinuities (e.g. tile gaps shown in Figure 1.1). This is a result of the decoupling between the stiff ceramic core and a not so stiff face sheet with the use of an interlayer. Being able to control the amount of load transferred to the ceramic tiles by changing the interlayer properties is an important design tool. While the performance of DCCS Structures under in plane tensile loading and shear is understood from studies by Huang et al, Mahdi et al, and Alfredsson et al.

The performance of bolted joints in this material is not well understood. In past studies, the load was being applied to the structures uniformly across the specimen width as a force resultant or bending (tension) or moment (line load applied to a beam in bending). However, a bolted joint introduces the load in a localized region where the pin bears on the hole in contact and creates a stress concentration. As a result of the pin directly bearing on all three constitutive parts simultaneously, the role that the interlayer, ceramic tile, and face sheet has in load sharing under bolted joint conditions compared to in-plane tension is unknown. In order to determine the performance of bolted joints in DCCS Structures a series of tests must be completed for varying geometries. Each specimen tested has a width (w), edge distance (e), and hole diameter (D). Figure 1.3 graphically represents the geometry measurements.
Figure 1.3: DCCS Structure Dimensions

Multiple joint configurations have been discussed and tested throughout the literature. (Thoppul et al 301 – 329) Each configuration has separate issues that need to be addressed. The configurations that have been most significantly discussed are single-overlap and double overlap joints. Each of these could utilize a single bolt configuration or a configuration with multiple bolt rows. Each configuration is better suited for a specific type of testing scenario. The joint configuration directly affects how load is transferred into the composite material being tested. A single-overlap joint is unsymmetrical in nature. When loaded the unsymmetrical fixture introduces
eccentricities that often cause additional failure modes related to bending. These two joint configurations are shown in Figure 1.4.

Figure 1.4: Test Configurations
(Left – Single Overlap, Right – Double Overlap)
The single lap configuration has been used extensively for thin laminates due to the fact that as the thickness of the laminate increases the eccentricities become larger. Therefore, there are often issues when testing thick section composites in such a manner. Even though this configuration is more complicated, it simulates many conditions in the field and is important to understand the behavior of composites in such situations. Double-lap joints are the simplest scenario for experimental testing due to the symmetric setup as seen in Figure 1.4. Load is theoretically distributed evenly throughout the joint making thicker composite testing far less complicated. Despite the symmetric distribution of load in the double-lap joint, as the specimen’s thickness becomes large the potential for pin or bolt bending also increases. This bending causes stress concentrations near the edges of the joint and can potentially cause premature failure. In most cases, however, laminates are thin enough that pin or bolt bending is usually not a concern. Bolt bending in DCCS Structures may also create stress concentrations in the ceramic tile. Since DCCS Structures are relatively thick, 0.94 inches, the double lap joint is considered the best choice for experimentation. This will reduce extra eccentricity complications caused by a single lap joint. Unlike the single-lap configuration, double-lap joints can be tested using pins with zero clamping pressure. This is also due to the inherent nature of the symmetric design of the joint.

Since clamping pressure can affect the stiffness and strength of a mechanically fastened joint (Cooper and Turvey 217 - 226), initial testing using pins is conducted in this study to minimize clamping effect. Our pin testing results will be needed to quantify the benefits of clamping effects in future studies. Both of these joint configurations can use either a single bolt joint or a multi-hole joint. Single bolt
joints are the most common for experimental testing and very straightforward, but multi-bolt joints are very commonly used in the field, especially in the aerospace industry. Multi-bolt configurations induce many complications into the joint such as load sharing. This makes failure modes of the multi-hole joint a main topic of concern. There are many factors that must be considered when deciding which joint configuration to use for experimental testing. In our study the effects of bolted joints in DCCS Structure is unknown and therefore the simplest single pin joint configuration has been chosen. Multiple bolts bearing on different tiles within the discontinuous tile array adds another level of complexity that could be pursued in the future.

Loading conditions can greatly affect the results of an experiment. Mechanically fastened joints can be loaded in various ways including inplane and transverse loading. In this study, we are focusing on inplane loading. The most common scenarios for inplane loading of joints include static and fatigue loading in tension or compression. Tension and compression tests can both provide the structural response of the joint in terms of load capacity (i.e. strength) and deformation (i.e. stiffness) of mechanically fastened joints. The direction of applied load is an important consideration. When far-field tension is applied and reacted through the pin, the edge distance between the pin and the specimen free edge is an important failure mode to consider (e.g. possible shear-out shown in Figure 1.2 (b) is possible). Conversely, when the far-field load is compressive, the shear-out failure mode is largely eliminated. For this reason static tests in tension are the most common and will be used in this study as well. Furthermore, compression tests require robust
fixtures to remove the possibility of global buckling, making them much more complicated to perform.

Another loading condition that is common is fatigue. This helps to determine a joint’s durability under cyclic loading conditions. Within a fatigue test you can have a tension-tension, compression-compression, or a tension-compression test. Each condition affects how the load is distributed through the joint. Tension-tension and compression-compression only apply a cyclic load on one side of the bolt hole, while a tension-compression loading condition applies load to the bolt hole on both opposing sides. In this study, tension-tension fatigue testing is conducted over the range of tensile loads that caused the first failure mode to occur in static tests. An important benefit of fatigue testing is that it offers more opportunities to quantify the sequence and evolution of damage modes that is very helpful in establishing design guidelines.

Material parameters can affect the failure modes of the joint consisting of composite adherents. These parameters fiber and matrix type, fiber volume fraction, fiber architecture and stacking sequence. The face sheet material used in this study is a 3D woven fabric. It is a 3TEX 3Weave 100oz ZZ S-2 glass fabric. This is stacked in a specific order along with the interlayer and alumina ceramic tiles. Fabrication is controlled in an environmentally controlled room and the process is monitored until resin is fully infused. The specific fabrication process can be found in Chapter 3.

According to Thoppul et al, the design of bolted joints in composite materials requires a higher level of complexity than in metals, due to the almost unlimited combinations of composite materials and fiber patterns. The failure modes that occur in composite materials are also far more complex than in their metallic counterparts. (Thoppul et al,
This being said the strength and durability of a composite joint can be designed directly. This is not only by the external geometries of the joint, but by the internal individual layers of the laminate.

Quality of the joint during fabrication and the machining process also has a large effect on the performance of the mechanically fastened joint. This makes quality control extremely important. Fiber volume fraction is the measure of the percent or fraction of the composite material that the fiber encompasses. This can have a direct effect on the strength of the composite. The presence of any voids in the material that are induced during the infusion process can also be detrimental to the properties of a composite. The fiber volume fraction in the face sheets of the DCCS Panel is 47%. The void content for the face sheet is .75 % and was calculated using image analysis. Below in Figure 1.5 is an image of the microstructure of the face sheet.
The VARTM (Vacuum Assisted Resin Transfer Molding) Process is used to fabricate the panels. To make the DCCS Structure Panels the vacuum is monitored to ensure a low void content. Proper care must be taken during the fabrication and machining process to minimize any unnecessary flaws within the test specimens. Flaws during machining can cause premature delamination around the boundary of the bolt hole, which may ultimately result in premature failure of the joint. DCCS Structures are complicated to machine due to the fact that they have varies parts with different properties. The face sheet and ceramic tile are very abrasive and damaging to tools, but cut different due to the stiffness and hardness differences. To help with this problem water cooled diamond tipped saw blades and drill bits were used. The interlayer causes these machining tools to become glazed over and was dressed frequently to ensure a quality cut.
Joint geometry relates to the specimen width, edge distance, thickness, and bolt hole diameter. Each of these factors can greatly affect the bearing strength and stiffness of the joint being studied. The width and edge distance are some of the most common parameters studied to determine the structural performance of mechanically fastened joints. According to Cooper and Turvey, as the w/D ratio increases, assuming the e/D ratio is large, the failure mode will change from net-tension to bearing. Similarly, as the e/D ratio increases, assuming that the w/D ratio is large, the failure mode will change from shear-out to bearing. (Cooper and Turvey 217 – 226) The effect joint geometry can have on the performance of a mechanically fastened joint has resulted in the extensive research in the subject, specifically for thin laminates. ASTM Standard D 5961/D 5961 m – 05 gives detailed procedures to tested mechanically fasted joints in thin laminate materials. Following standardized procedures greatly increases the accuracy and repeatability of experiments for thin laminates. This is not the case, however, for thick section composites or sandwich structures. There is no guide to standardize the effects of testing mechanically fasted joints in these complicated structures. Therefore, minimal research has been completed on the performance of bolted joints in thick section composites or sandwich structures. The DCCS Structure adds another level of complexity. The presence of the discontinuous tile array in the region of the gap complicates the performance of the bolted joint. While joint geometry is the most widely tested and one of the most important properties of mechanically fastened joints, in many cases the fastening parameters can have drastic effects on the performance of bolted joints. The most common fastening parameters studied that have an effect on the performance of bolted joints include bolt/hole clearance, bolt and washer clearance, tightening torque or clamping force,
washer size, and the presence of countersink. Each of these parameters has varying effects on the failure modes and strength of the joint.

The variability of the bolt to hole clearance can have an effect on the ultimate load capacity of the joint. According to McCarthy et al, most studies have shown that the bolt-hole contact area reduces significantly with small amounts of hole oversize, resulting in increased peak bearing or radial stress. It has also been determined that the peak circumferential stress varies with the change in clearance. The joint tested in McCarthy’s experiment was a single lap single bolt joint and had the highest allowable thickness provided in the D 5961/D 5961 M ASTM Standard. The importance of the thickness is that the purpose of the study was to investigate the 3D effects within the composite. The clearances used in McCarthy’s experiment were neat-fit, 80, 160, and 240 μm, which represent percentage clearances of 0, 1, 2, and 3%. Results show that 2% offset strength shows a relatively small dependency on clearance for finger tight protruding head bolts, while countersunk joints show no sign of that dependency. (McCarthy et al 1415 – 1431) The measure of strength at a given percentage loss of stiffness showed a dependency in the protruding head bolts, but the countersunk again did not. According to Lawlor et al., several previous analytical and numerical studies of single-bolt or pin-loaded joints have shown that clearance can significantly affect bolt hole contact area and peak stresses at the hole, leading to a prediction that the joints strength could be affected. In multi-bolt joints with large clearance issues, the load initially tends to be distributed to the neat-fit holes, but eventually as long as the test is not interrupted by failure the load will distribute evenly throughout all the bolt holes after the neat fit holes begin to deform. As a result of this load redistribution the quasi static strength is not necessarily affected by the clearance.
effects in a multi-bolt joint, but the failure modes are often affected. During fatigue loading, hole elongation and failure initiation tended to occur sooner due to increase clearance. (Lawlor, McCarthy, and Stanley 176 – 190) In the present study on DCCS, hole tolerances are equally important. It is challenging to machine through materials with such wide range in hardness, sensitivity of ceramic to cracking under tensile stress concentrations and maintain tight tolerances. In order to keep the tolerance constant the diamond cored drill bit had to be properly cared for. A clearance of .007 inches was maintained for test specimens throughout this study. According to McCarthy et al for a clearance of of 240 micrometers (.009 inches) a 10% loss of joint stiffness occurs and a decrease in 2% offset bearing strength by 7.5%. This was for specimens with a nominal bolt diameter of 8mm (.31 inches) and a diameter to thickness ratio of 1.6. (McCarthy et al 1415 – 1431) The DCCS Structure is about four times as thick as the specimens McCarthy et al’s experimentation and uses a range of materials and the pin diameter is much larger. It is unclear how the clearance size affects the strength and stiffness of the DCCS Structure, but should be studied in future work.

Tightening torque or clamping torque of a bolt can greatly affect the bearing strength of a composite joint. Having different torque levels on a bolt depending on the washer size will apply various pressures laterally to a joint that otherwise would not be present. The main explanation for the affected bearing strength is that the lateral pressure suppresses local delamination and out-of-plane deformations associated with bearing failure. Un-torqued bolts will most commonly fail in bearing as long as the geometric ratios are properly dimensioned. Torqued bolts behave differently by commonly failing catastrophically instead of a gradual bearing
failure. These catastrophic failures often result in net-tension or shear-out failures as bearing failures are suppressed. Catastrophic failures normally show no advanced warning of imminent failure. In many cases bolt torque and washer size work together to affect the performance of a bolted joint. According to Khashaba et al., the stiffness of the joint increases with a decreasing washer size. Note that at constant tightening torque (i.e. constant bolt axial force), the contact pressure of the washer decreases with increasing the contact area, \( A = \frac{\pi}{4} \cdot (D_{wo} - D_{wi})^2 \), and the latter increases by increasing the washer outer diameter \( D_{wo} \). (Khashaba et al 310 – 317) This shows that the bolt bearing strength not only depends on the contact pressure that the bolt applies but also on the constrained area that the washer is providing. It was also determined that as the tightening torque increased, the stiffness of the joint increased. In the range tested, Khashaba et al. was able to determine that the bolt bearing strength increases with increasing tightening torque. Understanding how the bolt tightening torque affects the joints strength, it was determined that pinned joints would be used for the purposes of experimentation in this study. Future work will utilize the pinned joint performance to quantify the benefits provided by various levels of torque with various washer sizes will have on the strength and stiffness of the joint. From a design guideline perspective, pin bearing results should provide a conservative lower bound on joint performance.

DCCS Structures are very complex composite materials. Having an understanding of how they behave under various loading conditions is important to understanding the performance of bolted joints in these materials. Based on the literature review, our experiments will be conducted using a double lap single pin joint to simplify experimentation. Pinned joints will be utilized to provide a baseline for
future bolted joint studies. Proper fabrication and machining processes will be carried out when creating DCCS Structure test specimens. Machining the various specimen geometries will be closely monitored and cut to a consistent and as tight a tolerance as possible. The effect that joint geometry has on the performance of the bolted joint will be established. Static tests will be performed on specimens with varying widths, edge distances, and distance to ceramic tile gap. The pin diameter can directly relate to the geometric ratios and therefore will be held constant at half an inch. This material is designed to be used in conditions that may encounter cyclic loading, therefore a series of fatigue tests will be performed to determine fatigue sensitivity. Combining all the features discussed above will provide the necessary information to accurately determine the performance of bolted joints in DCCS Structures.

1.2 Objectives:

Discontinuous Ceramic Cored Sandwich Structures (DCCS Structures) are a new type of advanced composite material that provides both excellent impact and structural properties. The performance of this structure under bearing load conditions is not currently understood. Therefore it is the goal of this project to gather a better understanding of the failure modes, location, and order in which the failure modes occur. Advanced Composites, such as the DCCS Structures, can have extremely complicated failure modes due to the addition of the discontinuous ceramic core. The discontinuity, while excellent for minimizing damage during impact, causes structural issues when designing mechanically fastened joints. The ceramic core has many properties that are structurally positive, such as a high modulus of elasticity; however it is also extremely brittle. This results in fast damage propagation. It is extremely
imperative that damage is minimized to allow for proper performance of the DCCS Structure. Therefore, design methodologies must be created in order to prevent failure modes and allow the DCCS Structures to perform optimally in bearing load situations. Since this material is likely to undergo cyclic loading conditions, fatigue of the mechanically fastened joints is a major issue. Therefore a fatigue program is necessary to determine long term durability for such a material. The brittleness of the ceramic tile, even under small loads has the potential to fail, thus reducing its beneficial properties. This fatigue criterion must be taken into account during design to prevent unnecessary fatigue failure throughout the composites lifetime.

Throughout this thesis the experimental procedures, test results, failure modes, and design guidelines for bolted joints in DCCS Structures will be described in detail. Chapter 2 will discuss the process necessary to fabricate and machine the specimens for bolted joint testing. It is extremely important that it is performed consistently to ensure accurate test results. The test procedures utilized for both static and fatigue testing are discussed in Chapter 3. This Chapter also describes the fixture design for the in-plane tensile static and fatigue tests. Two test fixtures were made to be able to test all joint geometries. Since the joint geometries were one of the only variables to change during testing it was discussed thoroughly in Chapter 3. In order to better understand how the DCCS Structure behaves static testing was performed on the face sheet material individually. This is discussed in detail in Chapter 4. Design Charts were created describing the failure modes that occur at varying edge distance to diameter and width to diameter ratios. This helps to have an understanding of what might occur during DCCS Structure static testing. Static testing the DCCS Structure is more complicated than the face sheet due to the increased thickness and the
constitutive parts. These complications are discussed in Chapter 5. Within this Chapter the effects of geometric ratios are discussed. The increase in strength of the joint by adding the ceramic tile is quantified and how the loads are transferred between those parts are discussed. To get a better understanding in the load transfer, software called Bolted Joint Stress Field Model (BJSFM) and Finite Element Analysis was used.

Based on the results in Chapter 5 a fatigue testing matrix was completed in Chapter 6. The reason for this is to determine how sensitive the DCCS Structure is to cyclic loading. The stiff and brittle core has the potential to be very fatigue sensitive. After fatiguing for one million cycles the residual strength of each specimen was tested to determine if the cyclic loading had any effect on the strength of the joint. The same procedures are used and discussed in Chapter 7 for a very unique case. This Chapter describes the static and fatigue performance of bolted joints with the pin located directly over a region of discontinuity in the ceramic tile. The gap between ceramic tiles provides an even more complex bolted joint scenario that can drastically affect the joints performance. To better understand how the load is transferred across the gap between tiles a finite element analysis model was created for both the baseline geometry (w/D = 8 and e/D = 4) and the pin on gap scenario (w/D = 8 and e/D = 8). This provides detailed stress analysis as to how the different pin placement affects the strength of joints within the DCCS Structure. The results from the various Chapters above are discussed and recommendations are made in Chapter 8. Many ideas for future work are discussed in Chapter 9. These ideas include variations in torque, joints with inserts and transverse loading of DCCS Structures.
Chapter 2
MATERIALS, FABRICATION, AND MACHINING

2.1 Materials:

Discontinuous Ceramic Cored Sandwich Structures are a very unique type of structure that utilizes a variety of materials to take advantage of their beneficial properties. Each material serves a particular purpose making it into a highly efficient structure when compositely combined. DCCS Structures are fabricated from three separate parts. The constitutive parts are the face sheet, the adhesive interlayer, and the discontinuous ceramic tile core. The part is then infused with FCS-2 epoxy resin using the VARTM (Vacuum Assisted Resin Transfer Molding) process at room temperature. For the purpose of experimental testing mechanically fastened joints, the DCCS structure being used contains two equal sized face sheets. This allows for a symmetric design, simplifying the experimental process. See Figure 1.1 for cross section of DCCS Structure.
Each face sheet consists of two layers of 3-TEX 3Weave S-2 Glass 100oz ZZ fabric. This fabric is considered a 3D woven structure that has fibers woven in the x, y, and z directions. This can be seen in Figure 2.1 above. Fabric in the z direction helps to suppress delamination while increasing its impact toughness. (3TEX Incorporated) The face sheets fabric is supplied by 3TEX Incorporated and they are infused with FCS-2 resin from Applied Polymeric Inc. After infusion each face sheet is 0.25 inches thick. Properties for the face sheet can be seen in Table 2.1 below.
Table 2.1  Face Sheet Material Properties

<table>
<thead>
<tr>
<th></th>
<th>Inplane Tension</th>
<th>Interlaminar Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E1T (Msi)</strong></td>
<td>3.25</td>
<td>E3T (Msi) 1.70</td>
</tr>
<tr>
<td><strong>E2T (Msi)</strong></td>
<td>3.34</td>
<td>S3T (ksi) 1.21</td>
</tr>
<tr>
<td><strong>υ12T</strong></td>
<td>0.11</td>
<td>ϵ3T (%) 0.07</td>
</tr>
<tr>
<td><strong>υ21T</strong></td>
<td>0.10</td>
<td>υ31T 0.13</td>
</tr>
<tr>
<td><strong>X1T (Ksi)</strong></td>
<td>69.6</td>
<td>υ32T 0.18</td>
</tr>
<tr>
<td><strong>X2T (Ksi)</strong></td>
<td>87.2</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>ε1T (%)</strong></td>
<td>2.56</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>ε2T (%)</strong></td>
<td>2.84</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Compression</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E1C (Msi)</strong></td>
<td>3.66</td>
<td>E3C (Msi) 1.79</td>
</tr>
<tr>
<td><strong>E2C (Msi)</strong></td>
<td>4.19</td>
<td>S3C (ksi) 43.5</td>
</tr>
<tr>
<td><strong>X1C (Ksi)</strong></td>
<td>39.2</td>
<td>ϵ3C (%) 2.44</td>
</tr>
<tr>
<td><strong>X2C (Ksi)</strong></td>
<td>30.8</td>
<td>υ31C 0.19</td>
</tr>
<tr>
<td><strong>ε1C (%)</strong></td>
<td>1.02</td>
<td>υ32C 0.21</td>
</tr>
<tr>
<td><strong>ε2C (%)</strong></td>
<td>0.74</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Shear (1-2) (2 Rail)</th>
<th>V-Notch (1-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>G12 (Msi)</strong></td>
<td>0.42</td>
<td>G13 (Msi) 0.43</td>
</tr>
<tr>
<td><strong>S12 (Ksi)</strong></td>
<td>5.47</td>
<td>S13 (Ksi) 5.03</td>
</tr>
<tr>
<td><strong>γ12 (%)</strong></td>
<td>4.89</td>
<td>γ13 (%) &gt;5.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>V-Notch (2-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>G23 (Msi)</strong></td>
<td>0.44</td>
</tr>
<tr>
<td><strong>S23 (Ksi)</strong></td>
<td>5.16</td>
</tr>
<tr>
<td><strong>γ23 (%)</strong></td>
<td>4.58</td>
</tr>
</tbody>
</table>
The discontinuous tile core is comprised of thirty six 101.6 mm wide by 101.6 mm long by 10.16 mm thick (4 inch wide by 4 inch long by 0.4 inch thick) square alumina ceramic tiles supplied by Coorstek. Mechanical properties of this isotropic material are given can in Table 2.2. The ceramic tiles are placed in an aligned array for each of the panels created. An adhesive interlayer is applied between the ceramic tiles and the face sheets. The interlayer is grade 8150 Surlyn provided by DuPont. The material properties for this material can be seen below in Table 2.2. Each interlayer has a thickness of .508 mm (0.02 inches). The stiffness of the interlayer adhesive greatly affects the load distribution within the composite. A stiff interlayer will allow more load sharing between the ceramic tile and face sheet, whereas a less stiff interlayer prevents load from being distributed to the ceramic. Each panel that is created is approximately 609.6 mm by 609.6 mm (24 inches by 24 inches) with a total thickness of 23.876 mm (0.94 inches) at the center.

**Table 2.2 Mechanical Properties of Ceramic Tile and Interlayer**

<table>
<thead>
<tr>
<th>Material</th>
<th>Units</th>
<th>Modulus</th>
<th>Poisson Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic Tile</td>
<td>metric</td>
<td>344.7 GPa</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>US</td>
<td>50.0 Msi</td>
<td>0.22</td>
</tr>
<tr>
<td>Interlayer</td>
<td>metric</td>
<td>.489 GPa</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>US</td>
<td>71 Kxi</td>
<td>0.35</td>
</tr>
</tbody>
</table>

The discontinuous ceramic core provides excellent impact properties due to the high energy absorption properties of the overall ceramic composite sandwich structure. Upon impact the materials absorb energy very efficiently. The discontinuity of the structure prevents damage from propagating throughout the entire structure, therefore only the initially damaged tile remains damaged after impact. The high
stiffness of the ceramic tile also provides increased structural stiffness, but it is also extremely brittle. This stiff, but brittle material provides excellent compressive strength, however it is extremely weak in tension. The face sheet’s main purpose is to hold the discontinuous tile array in place, thus providing increased tensile strength and overall joint capacity. The interlayer provides separation between the extremely stiff tiles and the face sheet material. This helps to prevent damage and determines the amount of load sharing between the face sheet and ceramic tile. Compositely combining the constitutive parts of the DCCS Structure greatly improves the properties of the structure compared to the individual parts.

2.2 Fabrication Process:

Establishing consistent and effective fabrication techniques for composites is imperative to the quality of the part being created. In the fabrication process everything from temperature to fiber-layup can be a variable. The most seemingly insignificant changes from part to part can drastically affect the material properties, making comparisons between specimens difficult. A consistent fabrication process will ensure similar void, resin and fiber content, and a consistent geometric thickness. By maintaining these, the material properties will be similar and experimental results will be comparable. Fabrication of the face sheet panels is a simple layup utilizing the VARTM process. However, the process of fabricating the DCCS Structures is far more complicated. The increased complications allow for an increased probability that the fabricated panels may have variations in microstructure. Therefore each step of the fabrication process was documented and followed for all panels to ensure consistency between each fabricated structure. A traveler is created for each DCCS Structure
panel that was fabricated followed standard operating procedures established at UD-CCM over the past decades. Each traveler provides detailed information about the composite parts, the resin, mold preparation, and the environmental conditions at the time of infusion. Everything is weighed, measured, and recorded precisely. After the first panel was created successfully, each following DCCS Structure panel is fabricated keeping measurements accurate to the first panel.

Table 2.3  Panel Dimensions and Weights

<table>
<thead>
<tr>
<th>Panel Number</th>
<th>Weight</th>
<th>Thickness (Edge)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg</td>
<td>lbs</td>
</tr>
<tr>
<td>1</td>
<td>23.36</td>
<td>51.49</td>
</tr>
<tr>
<td>2</td>
<td>23.58</td>
<td>51.99</td>
</tr>
<tr>
<td>3</td>
<td>23.46</td>
<td>51.72</td>
</tr>
<tr>
<td>4</td>
<td>23.41</td>
<td>51.60</td>
</tr>
</tbody>
</table>

In order to get a better understanding about the behavior of DCCS Structures, the face sheets were independently fabricated and tested starting with simple material layups and geometries. This allows for test procedures to be standardized. Each face sheet panel consists of 2 layers of 3TEX 3Weave S2 Glass 100oz ZZ fabric. The orientation of this fabric is mainly 0/90, but it also has tows woven in the z direction. (3TEX Incorporated) This 3D fabric orientation helps to reduce delamination. Each panel fabricated is 24 inches by 24 inches and is infused with FCS-2 epoxy resin. The VARTM process is used for resin infusion. This process uses a vacuum to draw the resin into the fabric being infused. The vacuum also provides a source of pressure to help compress the fabric, nesting it together more efficiently. The process to complete the fabrication of the DCCS structure is very
similar to that of the face sheet individually. However, the infusion process in DCCS Structures is much more complicated, due to the increased thickness and the many constitutive parts involved.

Fabrication of the DCCS structure panel needs to be conducted very precisely to keep the quality consistent. 609.6 mm by 609.6 mm (24 inch by 24 inch) aluminum molds are used to provide lateral restraint necessary when adding ceramic tiles. Using the mold keeps the external dimension consistent from panel to panel. The mold and table surface must be waxed before use to ensure proper separation from the panel after curing. Three layers of the 3TEX 3 Weave S2 glass 100oz ZZ fabric were 609.6 mm by 609.6 mm (24 inches by 24 inches) in dimension and the fourth (bottom) layer of the 3TEX 3 Weave S2 glass 100oz ZZ fabric is larger in dimension and called a wrap ply. The purpose of the wrap ply is to support around the edges of the panel and hold the constitutive layers together. Tile pre-preparations were conducted using an acetone wipe followed by a silane bath. After the silane bath each tile was cured at room temperature overnight, followed by a 12 hour post cure at 82.2 degrees Celsius (180 degrees Fahrenheit). Pre-preparation is necessary to ensure a proper chemical bond with the interlayer. This chemical bond provides a strong adhesion between the interlayer and ceramic tile. 120 spacers .508 mm (.02 inches) thick were applied on all 36 of the ceramic tiles. Spacers keep the discontinuity between the ceramic tiles equidistant and allow for even resin flow throughout the entire panel. Since the ceramic tiles are relatively non-porous, proper resin flow through the discontinuous ceramic tiles is extremely important.

The order that the individual materials must be placed in the aluminum mold is very important. This includes materials necessary to assist the VARTM
process. Before any structural material can be placed in the mold, distribution media and peel ply must be laid. The distribution media ensures that resin flows completely through the top and bottom of the panel, wetting the entire part evenly. Peel ply ensures that after the panel has cured at room temperature, it can be separated from the aluminum mold, the Table that it was infused on, and any additional parts necessary during the infusion process such as the distribution media. On top of the peel ply two layers of the face sheet material are placed into the mold. The bottom of the two is the wrap layer and the second layer is one of the 609.6 mm by 609.6 mm (24 inch by 24 inch) 3TEX layers. The interlayer material is placed next to ensure adhesion between the tiles and face sheet material. For the purposes of experimental testing the tiles are placed in an aligned array, which allows for easier machining and for a maximum number of tests specimens to be cut from each panel. On top of the alumina ceramic tiles another interlayer is placed and on top of this the remaining two 609.6 mm by 609.6 mm (24 inch by 24 inch) layers of 3TEX 100oz ZZ S-2 glass fabric. Each panel is infused with resin using the VARTM process. A waxed caul plate is placed on top of this media to keep a smooth top surface. From this the remainder of the peel plies and distribution media was wrapped on the top of the caul plate. Tubing for resin infusion and the vacuum bag was laid and secured with tacky tape. The tacky tape allows for an airtight seal between the vacuum bag and the infusion Table.

The thick mold necessary to create DCCS Structure panels makes infusion by VARTM more difficult than thinner layups, therefore leaks are more probable. To ensure that there are no leaks in the vacuum seal, a leak check must be performed. A machine draws up vacuum in the part and measures the rate the panel is losing vacuum in Hg/min. If this is the case, the seal between the vacuum bag and the Table must be
repaired until the leak rate for each panel being fabricated is at a rate less than -.02 Hg/min. The vacuum leak rate shall not be recorded until 5 minutes after vacuum has been applied. Leaks in the VARTM process can cause race tracking and a high void content. Large quantities of voids can cause decreased strength and in many cases the panel has to be discarded. If the leak check is passed, each panel is infused with CCM FCS-2 epoxy resin. Panel wet out is usually achieved in approximately one hour and fifteen minutes and is followed by a room temperature cure for two days before de-molding. After de-molding the panel is post cured for a total of 10 hours. 8 hours at 149 degrees C (300 degrees F) with an hour to ramp up to temperature and an hour to ramp back down. The panel dimensions that have consistently been met are a center thickness of approximately 23.876 mm (0.94 inches) and a width of 609.6 mm by 609.6 mm (24 inches and a length of 24 inches).
Figure 2.2: Apply spacers to Ceramic Tiles

Figure 2.3: Apply Distribution Media
Figure 2.4: Apply Peel Ply

Figure 2.5: Apply first two layers of fabric and interlayer
Figure 2.6: Insert Alumina Ceramic Tiles in Aligned Array

Figure 2.7: Insert interlayer and last two layers of fabric
Figure 2.8: Wrap in vacuum bag for VARTM process infusion

Figure 2.9: Cure at room temperature for 48 hours and de-mold
2.3 Machining Process:

Machining composites is often a delicate process and must be carried out correctly to prevent damage from occurring to the specimen. Using improper tools and machining speeds can often result in delamination on the cut edge. This local damage can often alter the results of an experimental test. It is imperative that each specimen is machined using the proper tools and procedures. Using proper tooling also ensures that the dimensions of the cut specimens are going to be consistent.

Machining abrasive materials such as the 3TEX 100oz ZZ S-2 glass and very stiff, brittle materials like the alumina ceramic tiles is a delicate process. Machining them at the same time is even more so. Therefore a water cooled table saw with a diamond tipped blade must be used for machining DCCS Structure panels.
This tool prevents the material from overheating and ensures that the diamond tipped blade cuts smoothly and cleanly through the material. It is important that the blade be inspected before each use to determine whether it is in proper condition to cut cleanly. The carriage speed of the saw blade can be controlled, so clean consistent cuts can be maintained throughout the part. Blade motor amps should not exceed 5. This minimizes the pressure being applied to the part from the blade and reduces ceramic tile cracking and chipping. The low blade motor amps also help to reduce overheating, and face sheet delamination during the cutting process.

Drilling holes in this material is also a very difficult procedure, but is conducted using water cooled diamond tipped half inch core drill bits, purchased from Starlite Industries, Inc. The interlayer within the panels cause the diamond tipped bits and saw blades to become “glazed over”. Therefore the core drill bits were dressed after each pass through the interlayer to ensure the bit cutting cleanly with fresh, sharp, diamond bits every time. Optimum speed for a half in drill bit is 2400 to 1800 R.P.M.‘s and oil should not be used as a coolant, water is best for this purpose. An aluminum oxide dressing stick was used to ensure proper dressing. To dress a drill bit 3 short contacts with the aluminum oxide dressing stick with water coolant running are necessary Properly dressing the drill bits extends the life of the tool by preventing damage and deformation of the drill bit. Otherwise slight deformations in the drill bit can cause increased clearances or elliptical hole shapes in the specimen that is being drilled. Having proper clearance is extremely important since it can affect the bearing contact between the sample and the bolt during testing. An increase in clearance causes an increase in stress concentrations that may result in premature failure of the joint. Therefore the holes being drilled must be as tight fit to half inch as possible.
The average tolerance with a new diamond tipped drill bit is +.127 mm (+.005 inches). In order to ensure that face sheet delamination is prevented a plate of face sheet panel was placed under the DCCS Structure during drilling. This provides a stiff backing for the drill bit to drill into. If the tools are properly cleaned and cooled with water there should be no sign of ceramic tile cracking or debonding between the tile and face sheet. When the drill bit is properly dressed the interlayer should look clean and not burned or discolored. If the drill bit is properly dressed the hole diameter should be constant throughout the thickness of the DCCS Structure. On average the surface hole diameter is 12.8 mm (.504 inches) and the average hole diameter through the thickness is 12.8 mm (.504 inches) as well. This shows that the tools were properly maintained throughout their life and the holes were drilled to proper specification.

Additional machining was required to ensure compatibility with test fixtures. During setup the specimen on one end is attached to the fixture using a double lap joint with a single pin. The other end is attached the Instron machine using hydraulic grips. The fixed thickness of each panel and the test machine grip constraints were incompatible. The DCCS Structure being a thickness of .94 inches is thicker than the clearance in the grips of .85 inches. Therefore, the DCCS structure was milled to a tolerable thickness in the location the grips would be applied. Machining was completed using a surface mill blade and a milling machine. Each DCCS Structure was milled to a thickness of 0.84 inches, tapering from the actual thickness to the milled thickness. The tapering helps to reduce any stress concentrations that may form as a result of an abrupt change in thickness near the grips.
Figure 2.11: Wet saw with diamond tipped blade

Figure 2.12: Diamond Core Drill Bit
Ensuring that the DCCS Structure is fabricated and machined to the proper specifications is absolutely important. This keeps the parts material properties consistent. Realize that in our pin testing we are loading the machined surfaces directly. Maintaining consistent properties along with consistent test procedures will ensure for accurate and repeatable data. Rigorous procedures are set in place to make certain that each test specimen is fabricated and machined as perfect as possible. The target value for the bolt holes was 12.7 mm (0.5 inches). However, the bolt holes that were machined have an average diameter of 12.800 mm (0.504 inches). The maximum value machined was 12.880 mm (.507 inches) and the minimum value was 12.725 mm (.501 inches). The specimen width also varies due to the 3.175 mm (.125 inch) wide blade and the ability to center the blade over the cut line. The target width for the baseline specimens was 101.6 mm (4 inches). The average width measured for that target value was 98.061 mm (3.861 inches) with the maximum value measured at 99.669 mm (3.924 inches) and the minimum value measured at 96.672 mm (3.806 inches). Another form of machining that varied from its target dimension was the location of the bolt hole within the specimen. Centering the drill bit to the proper location is difficult since it is lined up with the human eye. Getting the hole centered from both the side end and the top edge was extremely difficult. Each specimen’s bolt hole varied from the side edge by distance due to human error. The most accurate hole was .102 mm (.004 inches) off center and the most inaccurate hole drilled was .813 mm (.032 inches) off center. The targeted edge distance for the baseline specimens was 50.800 mm (2.000 inches), however the average edge distance that was actually drilled was 50.803 mm (1.970 inches). The most accurate edge distance to the targeted value was 50.368 mm (1.983 inches) and the most inaccurate edge distance
was 49.149 mm (1.935 inches). Images of the machined edge and hole diameter can be seen below in Figures 2.13 and 2.14. In much the same way there must be rigorous test procedures to control each experiment. Each experiment and its conditions must be able to be repeated exactly.

Figure 2.13: Machined Side Edge of Specimen
It is imperative that fabrication and machining specifications are maintained. However, even if the specifications are followed exactly the experimental testing must also follow an accurate set of procedures. These procedures will ensure that each test is run exactly the same under similar loading and environmental conditions. Following test procedures along with accurate fabrication and machining will ensure accurate and repeatable data.

Figure 2.14: Machined Bolt Hole in Specimen (Pin on Gap Specimen)
Chapter 3

TEST PROCEDURE

Throughout all experimental work proper test procedures were followed to ensure consistent experimentation, resulting in accurate data. Following a procedure allows for data to be compared to directly, but can also be compared and contrasted against other test scenarios as well. Two main test procedures were used throughout experimental testing in this work. In each of the testing procedures a hole diameter target value was 12.7 mm (0.5 inches). However, the bolt holes that were machined have an average diameter of 12.800 mm (0.504 inches). The maximum value machined was 12.880 mm (.507 inches) and the minimum value was 12.725 mm (.501 inches). The bolt holes drilled were only oversized and never undersized. The pin diameter has some variation has a mean diameter of 12.680 mm (0.499 inches) with a standard deviation of 0.022 mm (0.001 inches) and a coefficient of variation of 0.002. A slightly oversized hole is necessary to insert the pin properly without damaging the internal integrity of the bolt hole. An identical procedure was used for all static tests, since the bolt diameter was held constant; the specimen geometry is the primary variable. The second procedure used was for all fatigue tests completed during experimentation. The only variable that changed during fatigue tests are the loads that were being applied. Throughout this thesis different terms will be used. Table 3.1 will describe the terms that will be necessary to understand throughout the remainder of the report.
Table 3.1  Terms used throughout document

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition and Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>Width of Specimen</td>
</tr>
<tr>
<td>e</td>
<td>Edge distance of Specimen</td>
</tr>
<tr>
<td>L</td>
<td>Length of specimen</td>
</tr>
<tr>
<td>h</td>
<td>Thickness of specimen</td>
</tr>
<tr>
<td>dG</td>
<td>Distance to gap</td>
</tr>
<tr>
<td>D</td>
<td>Bolt hole diameter</td>
</tr>
<tr>
<td>w/D</td>
<td>Specimen width to hole diameter ratio</td>
</tr>
<tr>
<td>e/D</td>
<td>Specimen edge distance to hole diameter ratio</td>
</tr>
<tr>
<td>h/D</td>
<td>Specimen thickness to hole diameter ratio</td>
</tr>
<tr>
<td>P_{max}</td>
<td>Maximum load prior to failure</td>
</tr>
<tr>
<td>P_i</td>
<td>Load at i-th data point</td>
</tr>
<tr>
<td>\sigma_{i br}</td>
<td>Bearing stress at i-th data point</td>
</tr>
<tr>
<td>\sigma_{i br}</td>
<td>= P_{max}/(D*h)</td>
</tr>
<tr>
<td>F_{bru}</td>
<td>Ultimate Bearing Strength</td>
</tr>
<tr>
<td>\delta_{1i}</td>
<td>LVDT – 1 displacement at i-th data point</td>
</tr>
<tr>
<td>\delta_{2i}</td>
<td>LVDT – 2 displacement at i-th data point</td>
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<td>Baseline</td>
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<td>PG</td>
<td>Pin on Gap</td>
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</tbody>
</table>

3.1 Static Tests:

Multiple test scenarios completed in this experimental work fall under the static test category. Any specimen that was tested statically used the same procedure so results could be directly compared. The load rate and methods of obtaining deflection and load data were all consistent from one test to another. The only variables that changed during testing were directly related to the specimens being tested. In many cases the purpose of the test was to determine whether variations in the test specimens altered the outcome of an experiment. It was therefore imperative that all other aspects of the test procedure were held constant.
The joint type being analyzed is considered a modified double-lap joint with a single pin. ASTM standard D 5961/ D 5981M – 05 was used only as a guide for conducting static bearing tests. The thickness of the test specimen was predefined and therefore could not be changed to the thicknesses suggested in the ASTM standard. The standard mentioned above is mainly related to thin section composites and does not discuss testing sandwich panels. Therefore many of the ideas mentioned in the standard were adopted and adapted to better suit the needs of the experiments in this study. The basic procedures used for testing all the various geometries are very similar. This provides each specimen tested, despite the geometry, to be able to be directly compared to the baseline geometry. The baseline dimensions were originally determined by the dimensions of the ceramic tile that the DCCS structure is made of. Each tile is 101.6 mm x 101.6 mm x 10.16 mm (4 in. x 4 in. x .4 in.) in dimension. Therefore, each baseline specimen is 4 inches wide and 12 inches in length. For the baseline geometry the pin was located 2 inches in from the edge. Since each pin is half an inch the edge distance to diameter ratio (e/D ratio) for the baseline specimen is 4 and the width to diameter ratio (w/D ratio) for the baseline specimen is 8. In order to get more detail about the role geometries plays in DCCS structures, variations in the e/D and w/D ratios are to be tested as suggested by the ASTM standard and an extensive literature review on the topic was complete. In order to systematically label each specimen a naming sequence was devised. For example when the face sheet specimens were named it looks like (FSW4E2-1). The FS stands for face sheet, naming the type of material or special geometry that was used. The W4 stands for a width of 4 inches and the E2 stands for an edge distance of 2 inches. The -1 means that this specimen was the first tested out of this specific dimension. Table 3.2 below
is a test matrix of all the dimensions for each type of test specimen that was statically tested. In the column specimen # the DC stands for discontinuous ceramic cored sandwich structure.

Due to the brittle nature of the ceramic tile a slow loading rate of 2.54 mm (.01 inches) per minute is used. This loading rate was utilized for all specimens statically tested, including the face sheet specimens themselves, to make sure all data was comparable. Loading rate can directly affect the material properties in certain materials and is therefore imperative that it is held constant for all experimental testing. The slow loading rate allows for thorough inspection of failure mode progression during testing. Throughout testing the specimens were visually monitored to determine the different failure modes that occurred, their locations, and at what load they occurred. Cracks were located using a blue die and the progression at which they formed was noted. Having an understanding of how the failure modes behave in the baseline experiment provides an insight as to how varying geometries will behave under the same loading conditions.
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<th>Sample #</th>
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<th>Distance to Gap</th>
<th>Hole Diam. (D)</th>
<th>Thickness (t)</th>
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<th>e/D</th>
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<td>12.7</td>
<td>23.876</td>
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</table>
3.2 Fatigue Tests:

ASTM D6873 – 03 was used as a guideline for fatigue testing. Baseline DCCS structure dimensions (w/D = 8, e/D = 4) were used for all fatigue testing. (Standard Practice for Bearing Fatigue response of Polymer Matrix Composite Laminates) This allows for all failure modes detected during fatigue to be directly and easily compared to the static baseline tests. In order to have an understanding as to how many cycles it takes for failure to occur at varying stress levels a total of five stress levels were tested. Below in Table 3.3 the ideal dimensions for the test specimens are listed. In Table 3.4 the loads that correspond to each of the 5 stress levels are listed. Each specimen was fatigued at these loads to one million cycles.

<table>
<thead>
<tr>
<th></th>
<th>Width (w)</th>
<th>Length (L)</th>
<th>Edge Distance (e)</th>
<th>Distance to Gap</th>
<th>Hole Diam. (D)</th>
<th>Thick. (t)</th>
<th>w/D</th>
<th>e/D</th>
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<td>304.8</td>
<td>50.8</td>
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<td>4</td>
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<td>0.5</td>
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Table 3.3  Test Matrix for Fatigue Specimens (nominal dimensions given)

45
Table 3.4  Loads and bearing stresses associated with varying stress levels for fatigue loading

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<td>1120 lbs</td>
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<td>% of 2800 lbs</td>
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</tbody>
</table>

An R value (min load/max load) of .1 was used for each stress level. Any failure modes that occurred during cyclic loading were visibly detected using blue dye at incremental cycles. In order to expedite the testing process the experiments were each tested at a rate of 3 Hertz. It can be seen from Figure 3.1 below that a proper sinusoidal wave was created as output.
Each stress level was monitored for overheating using a thermal couple on the pin and an Infrared Camera. No signs of overheating in the joint or the pin were detected at the cyclic rate of 3 Hz. This can be seen in the infrared image below in Figure 3.2. The fact that a sinusoidal curve was output and that the specimen did not show signs of overheating proves that the input equals the output at 3 Hz.
Each specimen was tested to one million cycles. No catastrophic failures occurred during fatigue testing. Upon the completion of the 1 million cycles specimen tested undergoes a detailed inspection. Dye is applied to the interior of the bolt hole and the exterior of the test specimen to visually check for any damage not otherwise visible to the naked eye.

3.3 **Fixture Design:**

Designing a fixture that can be used effectively for a wide range of tests is extremely important for experimental testing. In many cases ASTM has recommended fixtures to use since they have been extensively tested and are known to work effectively. Since the DCCS structures being tested are not directly supported by any
ASTM standard a test fixture had to be designed. Since the experiment procedures are based on the ASTM D5961 “Bearing response of polymer matrix composite laminates”, the test fixture they suggest was adapted and redesigned for the purposes of this experiment. It is constructed of 17-4PH stainless steel. 17-4PH stainless steel has high yield strength and is also very durable under cyclic loading. The material and basic design were both recommended for both static and fatigue loading. The design is a double–lap joint with a single pin, which allows for the specimen to be loaded symmetrically and evenly across the bolt hole. It consists of 3 plates, two side lap plates and a spacer plate. Two spacer plates have been designed to accommodate the grips on the hydraulic Instron testing machine necessary to perform experimental tests. The larger spacer plate will accommodate DCCS Structure testing while the thinner, tapered spacer plate is designed to accommodate face sheet testing.
Figure 3.3:  Test Fixture Parts
LVDT’s are attached using external blade clamps that allows measurement of the hole displacement relative to the fixture, thus negating any play in the Instron testing machine or its grips. During loading, the side lap plates of the fixture will have a tendency to pull apart. This is mainly due to bearing failure in the face sheets and pin bending that occurs at higher load levels. Bearing failure causes the composite material to locally buckle and forces the plates outward. In addition the natural deflected shape of the pin under these loading conditions causes the side plates to deflect outward. Therefore a set of lateral restraints are attached to the side lap plates.
to help reduce this lateral movement. Since clamping pressures can affect the bearing strength of a joint, the restraining plates were only hand tightened. Clamping pressures can have a major effect on the bearing strength of composite materials by reducing the local bucking of fibers and in turn increasing the strength of the structure, however this often results in more catastrophic failure modes.

A second test fixture was created in order to be able to test specimens that have a larger edge distance. It can accommodate specimens that have a pin located on the region of discontinuity. This is an e/D = 8. The length of the fixture was redesigned to accommodate the new length, but all other dimensions are identical. Inserts were also added to the fixture to increase the stiffness of the fixture locally. The inserts also provide a barrier to local bearing damage in the fixture due to the very hard ceramic tile. If the insert gets damaged due to high loads, it can be replaced, keeping the fixture in excellent condition.
Figure 3.5: Test Fixture and LVDT Setup for 8” (left) and 10” (right) fixtures cropped again
Figure 3.6: Test Fixture and DCCS Specimen in Instron Grips


3.4 Specimen Geometries:

Specimen geometries are a major influence in failure modes and their locations within a structure. During previous studies it has been shown that varying the width to diameter and edge distance to diameter ratios can greatly affect how the material will behave upon failure. This behavior can influence whether a specimen will fail catastrophically in net tension or shear-out, or it can determine whether it has a more gradual bearing failure. Cooper and Turvey state that generally as the width to bolt diameter w/D ratio increases, assuming that the edge distance to bolt diameter e/D ratio is large, and the failure mode changes from net-tension to bearing. Similarly, as the e/D ratio increases, assuming that w/D is large, the failure mode changes from shear-out to bearing. (Cooper and Turvey 217 – 226) Having a good understanding of this relationship provided the background knowledge to create a test matrix for varying e/D and w/D ratios. Since the specimens being tested have a core of discontinuous ceramic tiles it was determined that the baseline width would be four inches, the width of one ceramic tile within a panel. Therefore the failure modes would be well understood for a simple one tile wide specimen. Varying the e/D and w/D ratios in a DCCS Structure is more complicated than in a standard thin laminate for the reason that as you increase the edge distance you approach the discontinuity regions in the tile. Increasing the w/D ratio to more than 8 also adds complexities due to the fact that each ceramic tile is only 4 inches wide.

Face sheet testing was completed to better understand the strength and stiffness of joints in the face sheet material individually. A large variation in the w/D and e/D ratios has been completed for face sheet testing. These variations provide the information necessary to understand how varying geometric ratios affect the failure
modes in the face sheet material specifically. Based on the large number of geometric ratio variations that were tested, design Tables were created. These design Tables graphically show the loads at which each geometric ratio fails and additionally the ratios that cause the failure modes to change. The face sheets utilized 8 different e/D ratios and 7 different w/D ratios in the creation of the design Tables. See Table 3.2 for a detailed test matrix of the face sheet specimens that underwent static testing. Five replicates were tested for each different geometric ratio.

Since the DCCS specimens are far more complex, only 2 ratios including the baseline geometry, for w/D and e/D were used to verify the effect that they have on the failure modes. The baseline geometry uses ratios of w/D = 8 and e/D = 4. See Table 3.2 for detailed test matrix of DCCS Structures that underwent static testing. The baseline geometry and reduced width geometry had 4 replicates and the reduced edge distance geometry had 3 replicates that the data was valid. For specimens where the edge distance was reduced the ratios are as follows, w/D = 8 and e/D = 3. For the specimens where the width was reduced the ratios are as follows, w/D = 6, e/D = 4. Changing the geometric ratios provides detailed information on the behavior of joints in DCCS structures under these circumstances. Understanding how joints behave in these scenarios is extremely important towards the overall goal of determining the performance of joints in DCCS Structures.

The geometries used for the fatigue testing of DCCS structures were all w/D = 8 and e/D = 4. This is the same dimension as the baseline geometry for static testing. Using this ratio allowed for direct comparison to the baseline static testing, which the failure modes and their locations were already determined and understood.
This also helped to directly compare the residual strength data back to the baseline static test data that was previously determined.

A very important aspect of testing DCCS Structures is how the discontinuous array affects the performance of bolted joints within this structure. Understanding how the strength of the joint is affected when it is moved away or towards a discontinuity provides critical information necessary in designing a highly efficient joint. The final geometry tested has a bolt hole located on the horizontal gap region between discontinuous ceramic tiles. This geometry is meant to determine whether this initial gap will change failure modes that occurred when the pin was located in the center of the tile. It will also be crucial in determining whether the increased edge distance will affect the overall strength of the structure, or if it will fail similarly to the baseline specimens. Unfortunately the four inch edge distance that is part of this geometry was too large for the current test fixture. Therefore a larger test fixture had to be created as described above. It followed the same design, however longer side plates were created to accommodate for the increased edge distance. Using this fixture it is able to be determined whether the pin on gap and/or the increased edge distance has an effect on the bearing strength and stiffness of the joint.

Test procedures created to ensure repeatable experiments. Each experiment has to be prepared and carried out exactly the same way each time. Maintaining accurate dimensions for test specimens, environmental conditions, and loading rates are imperative to gathering accurate data. Accurate fixturing is also very important to the precision of the experiment. Maintaining tight tolerances prevents play between the fixture and the specimen. When testing multiple replicates the ability
to have repeatable data is extremely important. This is evident in the face sheet static testing discussed in Chapter 4 below.
Chapter 4  

BEARING TEST IN FACE SHEET

Understanding the behavior of each constituent part is vital in understanding the performance of DCCS Structures as a whole. In order to accomplish this task bearing tests were completed for the 3TEX S2 glass face sheet material infused with FCS-2 resin for varying e/D and w/D ratios. Test specimen dimensions can be seen in Table 3.2. ASTM Standard D5961 was used as a guideline to ensure a standardized test method was followed during experimentation. This kept consistent and comparable results between each specimen. In order to ensure proper data comparison a loading rate of .254 mm (.01 inches) per minute was used for both the individual face sheet experimentation and the DCCS Structures. The understanding of face sheet behavior provides an indication of the load carrying capacity of mechanically fastened joints provided by the face sheet material. This gives an insight into the additional load carrying capacity of DCCS Structure after the ceramic tile fails.

Design Charts were created based on the variations in the e/D and w/D ratios. The design curves provide bearing stress vs. geometric ratio. The different types of failure modes that occurred during testing are also labeled on each graph. There were seven different geometric ratios tested for the w/D, which consisted for w/D = 1.25, 1.5, 1.75, 2, 4, 6, and 8. Extremely small w/D ratios were necessary to force net tension failure to occur while all other failures were bearing failures. Eight different e/D ratios were tested, which include e/D = 2, 2.5, 3, 3.5, 4, 4.5, 5, and 6.
These ratios can be seen in Table 3.2. Ratios below 3.5 showed signs of shear-out failure, while ratios above 3.5 showed signs of bearing failure. Bearing stresses shown on the design charts were selected by either the peak or 2% offset bearing strengths. These were discussed in ASTM Standard D5961/D5961 M–05. Whichever strength was lowest is considered to be the determining factor. The plots for each ratio tested can be seen from the plots provided in Appendix A. See Appendix B for pictures of failures at each ratio for the face sheet design Charts. Below in Figures 4.1 and 4.2 are the design charts and Figure 4.3, 4.4, and 4.5 are examples of bearing failure, shear-out failure, and net tension failure in the face sheet specimen respectively.

Figure 4.1:  Face sheet Design Chart (e/D ratio)
Figure 4.2:  Face Sheet Design Chart (w/D ratio)

Figure 4.3:  Bearing Failure in Face Sheet (w/D = 8, e/D = 4)
Figure 4.4: Shear-out Failure in Face Sheet (w/D = 8, e/D = 2)

Figure 4.5: Net Tension Failure (w/D = 1.5, e/D = 4)
The bearing strength at failure for face test specimens is $47.5 \pm 4.5/-3.5$ ksi. This can clearly be seen on the design charts in Figures 4.1 and 4.2. An example of a bearing stress vs. displacement curve can be seen in Figure 4.6 below. The additional bearing stress vs. displacement curves can be found in Appendix A. It can be seen that as the $e/D$ ratio increases the failure modes shift. At an $e/D = 3.5$ the failure mode transitions from shear-out failure to bearing failure. Similarly, as the $w/D$ ratio increases the failure modes transitions from net tension to bearing failure. This transition occurs at a $w/D = 2.1$. This can be compared to a study completed by Cooper and Turvey. 6.35 mm (0.25 inch) thick specimens fabricated out of EXTREN™ 500 Series by the Morrison Molded Fiber Glass company. This material consists of E-Glass fibers in a polyester epoxy resin. 10 mm (0.393 in) diameter holes were drilled and double lap single pinned joints were tested. It was determined for pinned joints that for $e/D > 3$ bearing failure would occur and $e/D < 3$ shear-out would occur. This transition geometry is similar to the transition value of 3.5 determined in our testing. Bearing failure also occurs at a $w/D > 4$ while net tension failures occurred at a $w/D < 4$. The bearing failures occurred at an average of 36.5 ksi. (Cooper and Turvey 217-225) These results are similar to what was determined for the face sheet tested in this study. The face sheet is made out of S2-Glass exhibit a higher bearing strength compared to E-glass data partly due to the higher performance fiber being used. Our laminate also has a higher percentage of fibers in the bearing direction while the E-glass has fibers in the+$/-$ 45 layers. The results also show that the transition from bearing to net-tension failure occurs at lower $w/D$ ratios. This means that the bolts can be more closely spaced in the 3D fabric than in the E-glass materials and this is likely due to the higher tensile strength provided by the higher percentage of fibers
in the load direction. Being able to design joints with low w/D and e/D ratios while still failing in bearing is optimal.

![Bearing Stress vs Displacement (FSW4E2)](image)

**Figure 4.6: Bearing Stress vs. Displacement Curve (FSW4E2)**

Software called “Bolted Joint Stress Field Model (BJSFM)” was used to get a better understanding of stresses being developed in the bearing region. This model was designed by J.M. Ogonowski for use by the McDonnell Aircraft Company/McDonnell Douglas Corporation in St. Louis, Missouri and was approved for public release. It enables the user to input material properties and its coinciding strength
properties, to calculate stresses and strains on a lamina level. This model also has the ability to model open and closed bolt hole laminates. This software was developed to structurally evaluate mechanically fastened composite joints. It utilizes a closed-form analytic solution to predict stress distributions and perform strength and failure analysis for isotropic and anisotropic materials for single loaded or unloaded fastener holes. The close-form analytic approach is based on elastic anisotropic theory of elasticity, laminate plate theory, and one of the several failure criteria. This program has the capability to analyze hybrid laminates, strength and stiffness anisotropy, and general in-plane loadings. In addition to the in-plane loading case it can also analyze bearing load cases in multiple load angles. (Ogonowski 1 - 46) BJSFM uses plane stress assumptions in the interlaminar direction normal to the plane of the layers and the principal of superposition to solve for the laminate stress and strain distributions for loaded or unloaded hole cases. Loaded (bolt bearing) holes are the prominent case being studied for this project. The bearing stresses have been characterized as a cosine radial stress distribution \( P_R = -P \cos(\theta) \). Free edge stresses are not captured using BJSFM due to the fact that the analytical model assumes homogeneous properties. This is not a major concern in the present study since all layers in the face sheet have the same orientation. Interlaminar stress will develop at the interface between the face sheet and the tile and the properties of the interlayer will become important. BJSFM also cannot calculate the effects of varying edge distances, however it can calculated the differences based on varying width.
According to Zhang it is believed that actual distribution depends on the fastener head type, lap materials, and the clearance and friction of the bolt, but it is usually assumed that the radial stress distribution over half of the hole varies as a cosine function. (Zhang, 431 - 441) Bolt hole clearance not only affects the joint in a computational sense, but it also affects the strength of the joint during experimentation. Increased clearances usually have an increase in stress concentrations, which can often result in premature failure. This is why machining the bolt holes properly in both face sheet and DCCS Structure specimens are important. BJSFM assumes a tight pin to bolt hole fit. The additional .1778 mm (.007 inch) clearance may cause some additional stress concentrations in actual experimental work, but cannot be avoided.

BJSFM software is an excellent tool to determine the stress distribution on bolted joints in laminate structures. It also has the ability to predict failure using numerous failure criteria such as Maximum Stress, Maximum Strain, Tsai Hill, Modified Tsai-Wu, and Hoffman. The BJSFM software was compared to an identical model using finite element analysis to validate the finite element software used for modeling of the DCCS Structure. The finite element model was made in CATIA and
run using its built-in Elfini solver. The results between the finite element model and the BJSFM were almost identical. Figure 4.8 is a plot showing the match between the BJSFM face sheet material and the finite element analysis face sheet model. The stress on the top edge of the finite model in the face sheet was extracted and compared to the average stress that is provided with the BJSFM. Having a working finite element analysis mode is important because it will provide detail into the stress distribution across the bolt boundary in the DCCS Structure. Tables 2.1 and 2.2 list all material properties used for calculations throughout this thesis.

![Laminate Stress (Catia vs BJSFM)](image)

**Figure 4.8:** Comparison between BJSFM and CATIA Finite Model Bearing Stresses for face sheet only (10000 psi applied bearing stress)
BJSFM is an excellent tool to calculate the stress distribution over the bolt hole region very quickly. For certain geometries it can be used to predict failure modes. Failure mode prediction is important so designers can accurately understand what to design for and how to prevent failure. In the face sheet only models when a bearing stress of 45000 psi (i.e. failure load/Dt) applied to the BJSFM software on a specimen with a w/D = 8 and an e/D = 4 it can be clearly seen that the specimen is failing in compression and not tension. This can graphically be seen on Figure 4.9.

Figure 4.9: Face sheet only Finite Element Analysis Model in CATIA.
As mentioned above material properties and strengths for the face sheet are given in Table 2.1.

![BJSFM Facesheet (Bearing Failure)](image)

**Figure 4.10:** Evidence for Bearing Failure in Face sheet at an applied 45000 psi bearing stress

Bearing stress of 45 ksi applied to the face sheet only is defined as an average force in the load direction associate with an equivalent cosine pressure.
distribution. For example, a bearing stress of 45 ksi corresponds to an applied load of 5.625 kips (= 45 ksi * 0.5 * 0.94). This distribution results in a peak compression stress at 0 degrees (58 ksi), a peak tensile stress (60 ksi) at 90 degrees and a peak inplane shear stress (25 ksi) at 30 degrees (see Figure 4.11).

It is well known that the inplane shear stress-strain curve is highly nonlinear as shown in Figure 4.12. This curve was provided by John W. Gillespie, Jr. in the report “Mechanical Properties of S-2 glass 3WEAVE fabric (100 oz/yd²) 8084 Vinyl Ester Composites”. To study the effects on nonlinear shear response on peak shear stresses in our linear stress analysis, the inplane shear modulus is defined as a secant modulus. The modulus ranges from the initial modulus of 0.42 Msi at low strain to a reduced modulus of 0.118 Msi at the failure strain of 5.0 %. The effects of reduced shear modulus affect both the magnitude and location of the peak stresses. As seen in Figure 4.13, the high modulus peaks at 30 degrees with a peak bearing stress of 25 ksi. Reducing the modulus to the secant modulus changes the failure angle to 10 degrees with a peak bearing stress of 18 ksi. This shows that the non-linearity of the inplane shear stress vs. strain curve can have drastic effects on the stress analysis and failure prediction of the DCCS Structure. Therefore further study must be performed in this topic using finite element analysis.

According to the stress plots, we can predict the failure loads for each mode of failure. This was completed using a safety factor (SF) to predict the applied load at failure (or equivalently the bearing stress at failure). If one defines SF = Max Strength/Peak Stress than the predicted failure load is equal to the Applied Load (or bearing stress) * SF. For example, according to BJSFM and the max stress failure criteria, the initial failure occurs in compression at an applied bearing stress of 30 ksi.
To get this value it was calculated using the safety factor (SF = 38 ksi/58 ksi = 0.65 and the predicted failure stress is 45 ksi x 0.65 = 30 ksi). This same method was used to predict failure loads for tension and shear failure loads. The results are shown below.

- **Inplane shear**: 10.7 ksi (30 degrees) to 14.8 ksi (10 degrees)
- **Compression**: Failure at 30ksi (0 degrees)
- **Tension**: Failure at 52 ksi (90 degrees)

In can be concluded from these results that the inplane shear and compression are both critical and tension is not a factor. It cannot be concluded from these results that the bearing failure observed in experimentation is purely compression. It is most likely that the bearing failure is a combination of shear and compression that are working together throughout progressive failure and material nonlinear response. It is hard to determine which occurs first and should be studied in more detail using FEA with nonlinear material properties. The addition of the ceramic core will limit the degree of inplane shear deformations due to the high shear stiffness of the overall composite that will limit the overall inplane shear strain.
Figure 4.11: Evidence for In-plane Shear Failure in Face Sheet at an applied 45000 psi bearing stress
Figure 4.12: Inplane Shear Stress vs. Strain Curve
(Mechanical Properties of S-2 glass 3WEAVE fabric (100 oz/yd²)
8084 Vinyl Ester Composites – John W. Gillespie, Jr.)
Understanding the bearing strength in the face sheet individually provides excellent insight into the behavior of the DCCS Structure as a whole. The creation of design charts can directly be applied to failure mode prevention in designs. This can also be extended to the DCCS Structures. Varying geometric rations may have similar effects in the DCCS Structure as it does in the face sheet individually. The understanding of the face sheets strength and stiffness also provides the ability to understand the structural benefits of adding the ceramic tile to the composite. The addition of the stiff ceramic core will increase the bearing strength compared to the

**Figure 4.13: Shear Stress Values with varying Shear Modulus**
*(Bearing Stress = 45000 psi)*
face individually. After further study in the DCCS Structure testing it will be better understood if this increase in bearing strength is due to the increase in thickness alone, or is the addition of the stiff ceramic core adding additional benefits to the structure? Knowing the failure modes and the stress distribution around the bolt hole will provide valuable information to better understanding the stress distribution throughout the DCCS Structures thickness. Applying the BJSFM and FEA techniques to the DCCS Structure will increase the understanding of the load distribution throughout the structure as it is being loaded.
Chapter 5

BEARING TEST IN DISCONTINUOUS CERAMIC CORED SANDWICH STRUCTURES

Discontinuous Ceramic Cored Sandwich Structures are an extremely complex composite material. Mechanically fastened joints in DCCS Structures have numerous and unique failure modes compared to traditional materials. These failure modes are further complicated due to the discontinuous ceramic cored tile array. Static tensile bearing tests are performed to better understand the bearing performance of the DCCS Structures. Testing provides insight to the strength and stiffness of mechanically fastened joints. Testing joints in DCCS Structures allows for the many different types of failure modes to be classified. Providing details on when and where they are. These details are presented in this Chapter.

5.1 Geometric Ratios

There are many factors that can affect the results of a bearing test, many of which were discussed in the introduction. One of these factors is the geometric ratios between the diameter of the bolt hole, the edge distance, and the width. Multiple scenarios were tested to determine whether varying the w/D and e/D ratio would have any effect on the joint capacity (i.e. bearing strength) and/or failure modes. At least 3 specimens were tested per scenario at a rate of 0.254 mm (.01 inches) per minute. All of the bolt holes were drilled at 1.27 + .1778 mm (0.5 +.007 inch) diameters and were
loaded using pins. Therefore the ratios were changed by varying the width and the edge distance of the specimens being tested.

The first test scenario was the baseline scenario with a w/D ratio of 8 and an e/D ratio of 4. This test specimen was the widest possible due to the fact that the ceramic tiles used as the core material come in 101.6 mm x 101.6 mm x 10.6 mm (4 in. x4 in. x.4 in.) sections. The bolt hole was drilled directly in the center of the ceramic tile, (- 2” from the top edge and 2” from the side edges). In this configuration, the face sheets alone fail in bearing (see Chapter 4 design charts). The second specimen configuration that was tested had a w/D ratio of 6 and an e/D ratio of 4. The width was reduced by 1 inch from the first test to determine whether varying the width has a large affect on the bearing strength and or the failure modes. In traditional bolted joints this promotes net tension failure. However, the face sheet results presented in Chapter 4 shows that this configuration will still fail in bearing. The final test that was completed in the DCCS structures was a w/D ratio of 8 and an e/D ratio of 3. This specimen had a reduction in edge distance by a half an inch. This configuration can promote shear out failure of the face sheets where the transition to bearing failure occurs at e/D of 3.5. It will be interesting to quantify how the presence and influence of the ceramic tile alter the failure modes of the DCCS Structure compared to the face sheets alone. Each of the specimens was loaded until failure at a rate of .01 inches per minute. The load rate was kept slow due to the fact that the ceramic tile fails in net tension at relatively low loads since failure is visually detected. LVDT’s clamped to the fixture and the specimen were used to measure the deflection of the joint, thus negating any play in the fixturing or the specimen. Each specimen was loaded until failure and the failure modes in the order in which they occurred were recorded.
The first DCCS geometry that was tested can be seen in Figure 5.1 above. This geometry is considered the baseline specimen due to the bolt hole being in the center of one of the discontinuous ceramic tiles. This is considered a W4E2 specimen with a width of 101.6 mm (4 inches) and an edge distance of 50.8 mm (2 inches). The w/D = 8 and the e/D = 4 for this specimen geometry. As can be seen in the Figure above the edge distance and the distance to the gap are both identically 50.8 mm (2
As a specimen with this geometry is loaded, failure modes occur in succession. The first failure mode that occurs is net tension failure in the ceramic tile. This can be seen in Figure 5.1 above. This failure mode is caused by the low tensile strength in the ceramic tiles. The second failure mode to occur is the bending/shear failure mode, also in the ceramic tile. After the tile fails in net tension, the ceramic tile above the pin acts like a beam and undergoes bending. After the tile deflects a certain amount the bending causes the bending/shear crack to form. A schematic of this bending behavior can be seen below in Figure 5.2. The red arrows represent the resistance by the interlayer between the ceramic tile and the face sheet. The face sheet has not yet failed, and therefore it transfers the load over the gap produced by the tension failure in the tile. The blue arrows represent the bearing load by the pin. The black dotted lines represent an exaggerated deflected shape of the ceramic tile to cause the bending/shear failure mode to occur. The black colored in section represents the location the bending/shear failure mode will occur. The gap that runs between the bolt hole is the crack after net tension failure in the ceramic tile has occurred. These interactions provide multiple load paths between the tile and face sheet enabled by the presence of a compliant high strain to failure interlayer. As a result the tile cracking (net tension and the bending/shear failure mode) do not cause catastrophic failure to occur. An image of the bending/shear failure mode viewed from the bottom cross-section of the sample normal to the direction of pin loading can be seen in Figure 5.3. This figure shows excellent bonding between the tile and the face sheets where debonding is largely cohesive failure in the face sheets comprised of 3D fabrics. The next failure mode to occur is bearing failure in the face sheet. After the failure ceramic tile failures in bending/shear more of the load is transferred to the face sheet.
This results in increased bearing stresses on the bearing region of the face sheet. As discussed in Chapter 4, a specimen with $w/D = 8$ and $e/D = 4$ will result in a bearing failure mode. An example of the bearing failure mode in the face sheet can be seen in Figure 5.4. As the load applied to the joint continues to increase the eventual failure of the interlayer occurs at the ultimate failure. The sudden debonding between the face sheet and the ceramic tile causes ultimate failure. The interlayer debonding can be seen in Figure 5.3 as well.

**Figure 5.2: Bending/Shear Failure Mode Schematic**
**Figure 5.3:** Bending/Shear Crack in Tile and Ceramic Tile/Face sheet debonding  (looking at edge cross section of specimen; pin load normal to this view)

**Figure 5.4:** Bearing Failure in Face Sheet
Figure 5.5: Reduced Width DCCS Structure Specimen (W3E2)

It is known that varying geometric ratios can alter the performance of bolted joints in composites. The second DCCS Structure specimen geometry was the reduced width geometry. These specimens had a width of 76.2 mm (3 inches) and an...
edge distance of 50.8 mm (2 inches). The gap distance is also 50.8 mm (2 inches). Since the bolt diameter is held constant at 12.7 mm (0.5 inches) the w/D = 6 and the e/D = 4. When load was increased the first failure mode was net tension. This was expected due to the decrease in width. Due to the changes in geometry, the far field load/unit width changes and therefore cannot be used to compare failure modes and the loads that caused them. Therefore whenever failure loads are discussed for any geometry the accompanied bearing stress will also be written. The bearing stress is the applied stress no matter the change in geometry. It also normalizes the thickness, taking that out of effect as well. The main difference that was noted with this specimen geometry was that the bending/shear failure mode did not occur. As a result of the reduced width the bending of the ceramic tile, as discussed above and shown in Figure 5.2, was not as extreme. Instead of the ceramic tile cracking it was pushed up out of the face sheet material. While this occurred bearing failure in the face sheet was induced. This failure in the reduced width geometry looks very similar to that seen in Figure 5.4. Just like the baseline geometry, the final failure mode to occur is the interlayer bond line. When this fails ultimate failure is initiated. Despite the reduced width, ultimate failure occurred at similar load levels as the baseline. An image of the ceramic tile being pushed out of the face sheet can be seen below in Figure 5.6. It can be seen in this Figure that as the tile is pushed out the original net tension cracks displace, leaving a large open gap.
Figure 5.6: DCCS Structure W3E2 Ceramic Tile Push Out
(Net tension cracks also visible)
The final geometric configuration that was tested is the reduced edge distance scenario. This geometry has a width of 101.6 mm (4 inches) and an edge distance of 38.1 mm (1.5 inches). The distance to the gap between ceramic tiles is 63.5 mm (2.5 inches). The reduced edge distance has potential to reduce the bearing strength of a joint in a DCCS Structure Joint. Similarly to the previous two geometries that were discussed the first failure mode was net tension in the ceramic tile.

**Figure 5.7: Reduced Edge Distance DCCS Structure Specimen (W3E2)**
Bending/Shear failure was the second failure mode to occur in this geometry. The reduced edge distance forced this failure mode to occur much sooner than in the baseline specimen. This can be related to the schematic in Figure 5.2. Since the edge distance is reduced the ceramic tile has a lower resistance to shear/bending and thus cracks in the bending/shear failure mode sooner. After this failure the joint continues to take on load resulting in bearing failure in the face sheet. This failure mode is also similar to the image in Figure 5.4. The final failure mode is the bond line failure between the ceramic tile and the face sheet. The failure of the interlayer in this way also causes a catastrophic failure resulting in ultimate failure of the joint. The decrease in edge distance adversely affects the bearing strength of the joint.

Each of the bearing stress verse bearing strain curves for the previous 3 geometries discussed can be found in Appendix C.
5.2 Results (w/D = 8, e/D = 4):

![Load vs. Displacement (W4E2)](image)

**Figure 5.8: Baseline DCCS Structure Load vs. Displacement (W4E2)**

The location of failure modes were constantly recorded during testing using the LVDT’s as discussed in Chapter 3. The net tension failure mode occurred first in all 3 of the geometric ratios. Multiple net tension cracks formed in the ceramic tile before the second failure mode occurred. For specimens with a w/D = 8 and an e/D = 4 the first net tension crack formed at an average of 4000 lbs (bearing stress of 8510 psi) and a standard deviation of 800 lbs (1702 psi). Additional net tension cracks that formed depended on the individual specimen being tested. On average the cracks formed at load levels of 4600 lbs (9787 psi), 6800 lbs (14468 psi), 9400 lbs (20000 psi), and 15000 lbs (31914 psi). The net tension cracks do not form in the region of the gap between ceramic tiles.
The second failure mode for the baseline specimens with the ratio of w/D = 8 and e/D = 4 was the bending/shear-out failure mode. This was discussed earlier in the Chapter. The average load at which these specimens failed due to this mode was 24000 lbs (51063 psi) with a standard deviation of approximately 3000 lbs (6383 psi). This failure mode during testing can be seen in Figure 5.10 below.

Figure 5.9: Baseline DCCS Structure first failure mode (Net Tension)
Figure 5.10: Baseline DCCS Structure second failure mode  
(Bending/Shear Failure Mode)

Despite the ceramic tile being fully cracked in net tension and the bending/shear failure mode being present the intact interlayer between the face sheet and the ceramic tile still allows some load to be carried by the ceramic tile. Ultimate failure occurs when the interlayer de-bonds from either the ceramic tile or the face sheet material. This failure is very catastrophic, causing the ceramic tile to crack and shatter in many additional locations. The average ultimate failure load of the DCCS
Structure in the current geometric constraints is 33300 lbs (70850 psi). An image of the baseline geometry at ultimate failure can be seen below in Figure 5.11. See Appendix D for a complete set of pictures of failure modes in the baseline DCCS Structure during testing and after Ultimate Failure.

For this geometry the displacements to cause bearing failure in the face sheet material individually and the bearing failure in the face sheets in the DCCS Structure can be compared. It can be seen in Figure 5.11 below that the bearing failure in the face sheet individually initiates at lower displacements than in the DCCS Structure. This comparison shows that that the addition of the interlayer and ceramic tile delay the bearing failure mode in the face sheet. Perhaps the presence of the stiff ceramic offers similar benefits to bolted joints with applied torque where washers suppress local buckling and associated out-of-plane deformation. In the DCCS specimen using pin loading, this interaction occurs only on the ceramic side of the face sheet. It can also be seen that once bearing failure in the face sheet individually initiates it can no longer carry load, however in the DCCS Structure when bearing failure initiates it continues to support a substantial amount of load. From purely a structural perspective the load-deflection curve exhibits quite a bit of apparent ductility due to the complex interactions between layers that are failing in different modes. Note that a significant amount of energy is absorbed when considering the energy within the load-unload curve. Furthermore, ultimate failure is significantly higher than loads at first failure which is an important consideration when establishing design guidelines for bolted joints in DCCS Structures.
Figure 5.11: Bearing failure comparison in face sheet between face sheet individually and DCCS Structure (W4E2/FSW4E2)
### 5.3 Results (w/D = 6, e/D = 4):

![Load vs. Displacement (W3E2)](image)

**Figure 5.12: Reduced Width DCCS Structure Load vs. Displacement Graph (W3E2)**

Reducing the width of the specimen by one inch affected the development of failure modes compared to the wider four inch sample. The initial net tension failure mode in the tile remained close to an average of 4000 lbs (8510 psi) and a standard deviation of 960 lbs (2042 psi). This is surprisingly similar to the w/D = 8 results. The change in width did not have a drastic effect on the net tension failure mode. The change in local tensile stresses in the ceramic tile caused by a variation in width will be studied later in Section 5.5. The reduction in width did affect the bending/shear failure mode. In all four specimens tested with a geometric ratio of w/D = 6 and e/D = 4 none of them displayed a bending/shear failure mode. The reduced
width reduces the moment being applied by the pin on the rest of the structure. After the net tension cracks form, the ceramic tile that is intact above the pin acts like a beam. Since the width is reduced the “beams” span length is shorter and as a result the moment in the center of the ceramic tile is reduced. This prevents the bending/shear crack from forming until ultimate failure. In many cases the bending/shear failure occurred at ultimate failure, resulting in a very catastrophic failure, with minimal warning signs. Ultimate failure for this geometric ratio averaged at approximately 34000 lbs (72340 psi) with a standard deviation of 560 lbs (1191 psi). Ultimate failure in this ratio was on average a little less than 1000 lbs (2128 psi) higher in this geometric ratio than in the w/D = 8 case.

Comparing the displacements necessary to cause bearing failure in the face sheet for both the individual face sheet and the DCCS Structure face sheet can done with this geometric ratio as well. This can be seen on the graph below in Figure 5.13. The displacement to cause bearing failure in the individual face sheet material is less than the displacement to cause bearing failure in the DCCS Structure. This result is similar to the baseline geometry discussed in the previous section. The presence of the ceramic tile and the interlayer also allows for additional load to be carried after bearing failure in the face sheet has occurred. This provides the DCCS Structure with additional bearing strength, when compared to the face sheet individually.

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Figure 5.13: Bearing failure comparison in face sheet between face sheet individually and DCCS Structure (W3E2/FSW3E2)
5.4 Results (w/D = 8, e/D = 3):

Figure 5.14: Load vs. Displacement for Reduced Edge Distance Geometry (W4E1.5)

The net tension failure mode in the tile occurred at an average of 4800 lbs (10213 psi). This is within the standard deviation of the net tension failures for the baseline and reduced width geometric ratios. Much fewer net tension cracks occurred as a result of the bending/shear crack occurring much sooner than the previously tested geometries. The bending/shear failure mode occurred second just like the first geometry tested and it occurred at an average load of 10800 lbs (22980 psi). The bending/shear failure mode occurred at 10000 lbs less load (21280 psi) than the
baseline. As a result of the early bending/shear failure mode, ultimate failure also occurred much sooner than previous geometries have shown. The average ultimate failure load was 23600 lbs (50213 psi). Approximately 10000 lbs (21280 psi) less than the other 2 geometries tested. This proves that reducing the edge distance has a drastic effect on the strength of the joint, due to the early failure in the bending/shear mode. Ultimate failure in this geometry can still be considered a catastrophic failure, but it was not as “explosive” as the previous geometries mainly due to the fact that failure was at a much lower load level and the failure was not a release of nearly as much stored energy.

As discussed in the previous two sections, the deflections to cause bearing failure in the face sheet individually and the DCCS Structure face sheet can be compared. This can be seen graphically below in Figure 5.15. Unlike the previous two sections the reduced edge distance geometry shows that the bearing failure occurs at approximately the same displacement in both the individual face sheet and DCCS Structure face sheet scenarios. This is caused by the early bearing/shear failure in the ceramic tile. Similarly to the previous two sections, the presence of the ceramic tile and interlayer allows for additional load to be carried, despite bearing failure occurring at the same time.
It can be determined that the net tension failure in the ceramic tile always occurs before bearing failure in the face sheet for DCCS Structures. Therefore designing the joint for first failure mode, the designer does not have to worry about bearing failure in the face sheets. There are also ways to design, which minimize the net tension failure by utilizing the gaps present between the ceramic tiles. This will be further discussed in chapter 7.
5.5 **Comparison between Face sheet and DCCS Structure**

Each individual part (face sheet, interlayer, and ceramic tile) that makes up the Discontinuous Ceramic Cored Sandwich Structure has its own individual material properties. Having the ability to compositely combine the aforementioned materials provides beneficial increases in the material performance and properties. The addition of the ceramic tile increases the amount of load that can be supported by the composite structure. Despite the brittle nature of the ceramic tile, even after the initial net tension failure mode, the increase in load carrying capacity with the inclusion of the ceramic tile is substantial. It is easy to see in Figure 5.16 how much more load for a given displacement the DCCS structure as a whole can support when compared to the load carrying capacity of 2 individual face sheets. The face sheet load was multiplied by 2 to mimic the fact that DCCS Structures have 2 face sheets. The green line shows the difference between the DCCS Structure and the face sheet material, providing an estimate as to how much load is being supported by the ceramic tile. This also shows that after the individual face sheet fails in bearing it plateaus. The DCCS structure, however, continues to carry additional load until ultimate failure. This is caused by redundant load paths in the DCCS Structure that the individual face sheet does not have. This is an excellent attribute because it helps to increase the ultimate bearing strength of the joint. The DCCS Structure also seems to have a significant amount of ductility, despite the stiff and brittle ceramic tile core.
Figure 5.16: Difference between W4E2 and 2*Load for FSW4E2

It is clear that the DCCS structure carries higher loads than the two FS because it is approximately 50% thicker. A good way to compare the DCCS Structure and the face sheet individually is by comparing bearing stresses. Bearing stresses are normalized by the thickness and hole diameter and therefore the thickness of the specimen being tested is accounted for. In the case of the DCCS structure, applied loads to the pin are normalized by the diameter and the total thickness (nominally 23.7363 mm or 0.9345 inches). One question is whether the DCCS structure with multiple failure modes is more efficient than an equivalent composite of the same thickness (i.e. would a 0.9345 inch thick composite made of the same material as the face sheet carry more load than the DCCS structure of equivalent thickness)? This can be answered by directly comparing the bearing stresses at failure.
In Figure 5.17 below it can be seen that the bearing failure in the individual face sheet material occurs at the same bearing stress as the bending/shear failure mode in the DCCS Structure. Since the bending/shear failure mode is the initiation for bearing failure in the DCCS Structure at this geometric ratio, bearing failure occurs in both the individual face sheet and the DCCS Structure face sheet at similar bearing stresses. However, the DCCS Structure’s first failure mode (Net Tension = 10 ksi) occurs at a lower bearing stress than the face sheet’s first failure mode (bearing failure – 40 ksi). It can also be observed from this graph that the addition of the ceramic tile provides additional benefits after bearing failure is initiated in the face sheet. This plot proves that having a ceramic core is structurally more beneficial (a 50% increase in bearing strength) than just increasing the thickness of the individual face sheet. It can be concluded that there is an improvement at ultimate failure with the addition of the ceramic tile, however if we design for the first failure mode, the ceramic tile limits the bearing stress that can be carried without cracking occurring. As mentioned before there are methods that will be discussed in Chapter 7 that will minimize ceramic tile cracking due to net tension. If during design ultimate failure is the only worry, then the DCCS Structure is more beneficial structurally. Earlier in this thesis it was discussed how the varying e/D and w/D ratios affected the bearing strength of the joint. After comparing the face sheet bearing stress and the DCCS bearing stress it was concluded that the reduced edge distance and reduced width specimens showed that the addition of the ceramic tile proved to have a similar benefit as the previously discussed geometry. These comparisons can be seen below in Figures 18 and 19.
Figure 5.17: Bearing Stress vs. Displacement for Face Sheet and DCCS Structure (FSW4E2, W4E2) of Equivalent Thickness
Figure 5.18: Bearing Stress vs. Displacement (Reduced Edge Distance) Compared to Face sheets of Equivalent Thickness
Figure 5.19: Bearing Stress vs. Displacement (Reduced Width) Compared to Face sheets of Equivalent Thickness

Clearly the ceramic tile is playing a major role in altering load paths. To gain insight into how loads are being distributed throughout the joints within the DCCS Structure. The stress distributions caused by the alterations in load paths can be determined using the BJSFM software and Finite Element Analysis.

In order to determine the stress distribution between each of the constituent parts in the DCCS Structure, BJSFM software was used as a starting point. A laminate was constructed consisting of both face sheet layers and the ceramic tile core. The interlayer was not included due to its low stiffness and therefore low load...
carrying capacity. In addition, the ceramic tile is considered a continuous layer with no gaps. Recall that BJSFM uses effective homogeneous properties which are largely unaffected by a compliant thin interlayer. BJSFM calculates effective inplane properties as input to the stress analysis. These effective properties can be seen below in Table 5.1.

<table>
<thead>
<tr>
<th></th>
<th>$E_x$</th>
<th>$E_y$</th>
<th>$G_{xy}$</th>
<th>$v_{xy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>US</strong></td>
<td>Metric</td>
<td><strong>US</strong></td>
<td>Metric</td>
<td></td>
</tr>
<tr>
<td>BJSFM Effective Properties</td>
<td>24.0 x 10^6 psi</td>
<td>16.5 x 10^3 MPa</td>
<td>24.1 x 10^6 psi</td>
<td>16.6 x 10^3 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9.34 x 10^6 psi</td>
<td>6.43 x 10^4 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.212</td>
</tr>
<tr>
<td>Face Sheet Only Properties</td>
<td>3.25 x 10^6 psi</td>
<td>2.24 x 10^4 MPa</td>
<td>3.34 x 10^6 psi</td>
<td>2.30 x 10^4 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.42 x 10^6 psi</td>
<td>.289 x 10^4 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td>Ceramic Tile Only</td>
<td>50.0 x 10^6 psi</td>
<td>34.5 x 10^4 MPa</td>
<td>50.0 x 10^6 psi</td>
<td>34.5 x 10^4 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20.5 x 10^6 psi</td>
<td>14.1 x 10^4 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.22</td>
</tr>
</tbody>
</table>

In this analytical solution, an applied cosine pressure distribution is applied to a laminate with homogenous properties. The inplane strain fields (all layers are subjected to constant strain at the point of interest, which mimics the pin as a rigid body) are calculated and the layer to layer stresses are determined. Due to the stiffness mismatch between layers, the stresses are discontinuous. This allows the relative loads in the composite and tile layers to be estimated. The role of the interlayer in
DCCS was studied later using Finite Element Analysis. A bearing stress of 1000 psi (i.e. a total far field load of 450 lbs) was applied over the hole bearing surface to match the equivalent cosine pressure in the BJSFM software. Figure 5.20 shows the direction that the bearing stress is applied to the hole within the DCCS structure. This unit pressure was selected due to the linear nature of the BJSFM software. Based on Figure 5.21 below, any applied pressure for the base line geometry can be scaled to determine the actual stress distribution. Figure 5.21 shows the average x stresses for the entire laminate based on effective properties for both the baseline (w/D= 8, e/D = 4) and the reduced width (w/D = 6, e/D = 4) specimens. Since the edge distance cannot be changed as mentioned previously, reduced edge distance geometry could not be modeled using BJSFM. These Figures prove that the decreased width does not change the stress field applied on the boundary of the bolt hole. The results are almost identical for both cases with only slightly increased tensile stresses in the reduced width specimen.

In contrast to the stresses averaged through the thickness at each point in the joint, one can also calculate the stresses in each individual layer. Figure 5.23 shows how the stress is distributed between the ceramic tile and the face sheet. The stress present in the ceramic tile is 13 times higher than in the face sheet. So for an applied 1000 psi/450 lbs the ceramic tile has an x stress of 2000 psi while the face sheet has a x stress of 150 psi.
Pressures are input into BJSFM using a bearing stress \((P/D\times t)\). BJSFM then converts the bearing stress into a cosine radial stress distribution to apply the load as shown above in Figure 5.20. The distribution from the BJSFM user manual is \(P_R = -P\cos(\theta)\). Since BJSFM provides a linear-elastic solution, when the applied bearing stress is altered but everything else remains the same, the peak compressive and tensile stresses vary linearly with that change in applied stress. This can be proven below in Figure 5.22. For average stresses over the entire laminate the ratio between each of the peak tensile and compressive stress concentration and the applied bearing stress is 1.363 and -1.273 respectively. This also shows that the peak stresses are always higher than the applied bearing stress when the stresses are averaged. While Figure 5.22 helps to understand the linear nature of the BJSFM software failure depends on
individual layers. It is important to understand how the stresses are distributed between layers within the DCCS Structure. Study of this which is similar to that studied for the individual face sheet material can be seen below.

Figure 5.21: X Stress Distribution in Ceramic Tile of DCCS Structure (W3E2 and W4E2 - 1000 psi applied pressure)
Figure 5.22: Linear Relationship between variations in applied bearing stress and compressive and tensile stress concentrations (Effective Average Stress in Laminate)
Understanding the stress distribution around the hole boundary in the DCCS Structure is important for failure analysis. It allows engineers to predict which failure modes will occur first and will provide adequate knowledge to design for them. Using the distribution charts and the material strengths the failure modes are predicted and compared to experimental data. The material strengths used for this study can be seen below in Table 5.2.
Table 5.2  Ceramic Tile and Face Sheet Material Strengths

<table>
<thead>
<tr>
<th>Material</th>
<th>Units</th>
<th>X1 T</th>
<th>X1 C</th>
<th>X2 T</th>
<th>X2 C</th>
<th>S12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face Sheet</td>
<td>MPa</td>
<td>3.33</td>
<td>1.87</td>
<td>4.17</td>
<td>1.47</td>
<td>37.7</td>
</tr>
<tr>
<td></td>
<td>ksi</td>
<td>69.6</td>
<td>39.2</td>
<td>87.2</td>
<td>30.8</td>
<td>5.47</td>
</tr>
<tr>
<td>Ceramic Tile</td>
<td>MPa</td>
<td>1.72</td>
<td>17.4</td>
<td>1.72</td>
<td>17.4</td>
<td>124.1</td>
</tr>
<tr>
<td></td>
<td>ksi</td>
<td>36.0</td>
<td>363.0</td>
<td>36.0</td>
<td>363.0</td>
<td>18.0</td>
</tr>
</tbody>
</table>

BJSFM software has been run to try and predict which failure modes will occur and in what order for the baseline geometry. Due to the limitations of BJSFM (not being able to calculate with varying edge distance) only net tension failure in the ceramic tile, bearing failure in the face sheet, and in-plane shear failure in the face sheet can be predicted. Material properties from Tables 2.1 and 2.2 were used and material strengths from Table 5.2 were used for this study. The interlayer was not included in this model due to its extremely low modulus of elasticity.

Plots were created using an applied bearing stress of 1000 psi showing layer stresses in a DCCS Structure. Knowing the tensile and compressive strength of the ceramic tile and the face sheet, the first failure can be determined. Based off the applied load you can calculate the factor to increase loading until failure occurs. For instance to calculate the factor to divide the material strength by the x stress at whatever angle the max stress is occurring. This process is identical to the SF in the above chapter. According to BJSFM the first failure is max principal tensile failure in the ceramic tile. Based on the applied bearing stress of 1000 psi the factor to scale to shear failure was 17.167. This corresponds to an applied bearing stress to cause tensile failure of 17167 psi or a far field failure load of 7725 lbs. This failure occurred at 40 degrees around the bolt hole according to BJSFM. According to BJSFM the Max principal and inplane tensile stress occurred at the same bearing stress and 90
degrees around the bolt hole. Therefore the factor to cause tensile failure and the loads at which failure is predicted are identical to the max principal tensile stress results above. This an also be seen below in Table 5.3. The compression strength which is ten times higher in the ceramic tile than tension requires a very high applied bearing stress of 137.2 ksi or far field load of 61740 lbs to cause failure. This failure occurs at 0 degrees around the bolt hole. Failures predicted using BJSFM software for the face sheet was also predicted in the same way as for the ceramic tile layer. The results can be seen below in Table 5.3.

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>BJSFM Ceramic Tile</th>
<th></th>
<th>Experimental Ceramic Tile</th>
<th></th>
<th>BJSFM Face Sheet</th>
<th></th>
<th>Experimental Face Sheet</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bearing Stress</td>
<td>Load</td>
<td>Bearing Stress</td>
<td>Load</td>
<td>Bearing Stress</td>
<td>Load</td>
<td>Bearing Stress</td>
<td>Load</td>
</tr>
<tr>
<td>Max Principal Tension/Inplane Shear</td>
<td>17.2 ksi</td>
<td>7725 lbs</td>
<td>6.8 ksi to 23.4 ksi</td>
<td>3200 lbs to 11000 lbs</td>
<td>164 ksi</td>
<td>73800 lbs</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Net Tension</td>
<td>17.2 ksi</td>
<td>7725 lbs</td>
<td>6.8 ksi to 23.4 ksi</td>
<td>3200 lbs to 11000 lbs</td>
<td>260 ksi</td>
<td>122000 lbs</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Compression</td>
<td>137.2 ksi</td>
<td>61740 lbs</td>
<td>n/a</td>
<td>n/a</td>
<td>175.3 ksi</td>
<td>78900 lbs</td>
<td>43.8 ksi</td>
<td>20600 lbs</td>
</tr>
</tbody>
</table>

All failure modes that can be predicted by BJSFM in the ceramic tile occurred before any failure modes were predicted in the face sheet. When comparing this to experimental data this result is identical. It can be seen from Table 5.3 that that the order of predicted failure modes using BJSFM is max principal tension, net
tension, compression in the ceramic tile followed by inplane shear, compression, and tensile failure in the face sheet. The max principal tension and net tension failure modes both occurred at the same stress and angle around the bolt hole. Proving that tensile failure is the first failure mode to be predicted, matching the experimental results. Since BJSFM does not predict failure progression the net tension failure in the face sheets was calculated using the material strength and the area of only two face sheets. This simulates the presence of a net tension crack in the ceramic tile where all tensile load is being transferred through the face sheet. Experimentally the failure modes were net tension in the ceramic tile and then compression failure in the face sheet. Some of the failure modes cannot easily be determined during experimentation (i.e. inplane shear) and is therefore not applicable for comparison as seen above in Table 5.3. It can be concluded from this that BJSFM is accurate in predicting the sequence of failure modes. However, the loads at which failure occurs is not accurate. It can be determined from these results that further finite element analysis needs to be completed to use more detailed material properties and progressive damage during analysis. BJSFM over simplifies the problem and therefore failure bearing stress/loads are not accurate. The non-linear nature of many constitutive parts within the DCCS Structures should be addressed in this future work as well. The plots used to predict failure modes can be seen below in Figures 5.24, 5.25, 5.26, and 5.27. It can also be determined using Finite Element Analysis how the presence of the gap within the joint affects the location of the Max Principal Tensile Stress. It can be seen in the plot in Figure 5.28 below that within the ceramic tile the principal stress is no longer max at 90 degrees around the bolt hole. Instead the max tensile stress increases as it approaches 0 degrees around the bolt hole. The magnitude of this stress at that
location is also 2.03 times lower than DCCS Structure specimens without the gap present. This explains why pin on gap specimens do not fail in net tension until higher loads. Experimentally the first failure mode for pin on gap specimens with and e/D = 4 was a crack zero degrees around the bolt hole edge at an average of 21 kips. However for pin on gap specimens with an e/D = 8 the first failure mode is net tension between 40 and 47 kips. More information on pin on gap specimens is presented in Chapter 7.

![Face Sheet X Stress (Applied 1000 psi)](image)

**Figure 5.24:** Face Sheet X Stress with an applied bearing stress of 1000 psi (used for failure mode prediction)
Figure 5.25: Face Sheet Inplane Shear Stress with an applied bearing stress of 1000 psi (used for failure mode prediction)
Figure 5.26: Ceramic Tile Max Tensile Principal Stress with an applied bearing stress of 1000 psi (used for failure mode prediction)
Figure 5.27: Ceramic Tile X Stress with an applied bearing stress of 1000 psi (used for failure mode prediction)
Figure 5.28: Max Principal Tensile Stress in Pin on Gap Ceramic Tile

Understanding the strength of bolted joints under static conditions is extremely important for design. This includes understanding the different failure modes that occur. Determining the failure modes allows engineers to design joints in prevention of these failure modes. Using analysis aids such as BJSFM and FEA to determine how load is distributed throughout the DCCS Structure provides detailed information that can be applied during design. In many situations materials such as DCCS Structures are used in environments that undergo varying loading conditions such as cyclic loading. Having an understanding of the materials long term durability is extremely important to designers who are designing to accommodate for cyclic
conditions. Fatigue durability is an extremely important performance factor. Chapter 6 discusses the performance of bolted joints in DCCS Structures under cyclic loading.
Chapter 6
FATIGUE TESTING ON DISCONTINUOUS CERAMIC CORED SANDWICH STRUCTURES

Understanding the behavior of DCCS Structures under fatigue loading is essential in design. Due to the applications of DCCS Structures they will be subject to cyclic loading conditions throughout the materials lifetime. It is imperative to understand the behavior of this material under such conditions. Understanding the DCCS Structures fatigue resistance will provide engineers with the necessary information to design joints for long term durability and to optimize their performance. In many cases fatigue damage is detected visually, and the progression of that damage can be monitored throughout the life of a structure and repaired when necessary. However, fatigue damage cannot always be detected and must initially be prevented in order to ensure a safe and durable structure. Fatigue damage propagates over time and can result in the reduction of strength in many structures, including joints. Due to the natural complexity of composites fatigue damage is not always visible to the naked eye, but can still result in reduced strength. DCCS Structures consist of multiple materials and each has extremely different properties. As shown in Chapter 5 there are many failure modes that occur during static testing of DCCS Structures. In this Chapter, we intend to study the sensitivity of these failure modes to cyclic loading.
6.1 Fatigue Testing Setup

The same fixture used for static testing was used to properly test DCCS Structural Specimens under cyclic loading. Each specimen tested has the same geometric dimensions as the baseline specimens tested under static loading. The geometric ratios are \( w/D = 8 \) and \( e/D = 4 \). The loading sequences and stress levels used to categorize the cyclic loading was based on results from static testing the baseline geometry. Based on these results the first failure mode formed within the ceramic tile, due to its weakness in tension and its brittle nature. Therefore the intent of this fatigue loading was to determine, at differing stress levels, how many cycles would cause failure to occur in the ceramic tile. See Tables 3.3 and 3.4 for test matrix and stress levels. In order to accurately test the fatigue resistance of the DCCS Structure the specimens were loaded at five different stress levels. Based on the data from static testing the minimum load to cause cracking in the ceramic tile was approximately 3200 lbs (6808 psi). This load is approximately 9 percent of the ultimate failure load or bearing stress at failure. Stress level 5 is approximately 90 percent of that load and each remaining stress level is a percentage of Stress Level 5. Stress Level 5 is out of the standard deviation of loads to cause net tension failure under static conditions. Typical inspection intervals were at cycle numbers 10, 100, 1000, 10000, 100000 cycles and then every additional 100000 cycles if possible until the one million cycles was complete. The minimum and maximum applied stresses per stress level were determined by referencing the ASTM standard. According to the ASTM D 6873 – 03 the force (stress) ratio is the ratio of the minimum applied force (stress) to the maximum applied force (stress). A force (stress) ratio = .1 was used. Therefore the minimum and maximum forces/stresses applied to the tests specimens for the different stress levels are seen in Table 3.4 as mentioned above.
Each test specimen was run to one million cycles and inspected for damage at incremental cycles throughout the fatigue loading. Every test was cycled at a loading rate of three hertz. The fast loading rate was necessary to minimize the time necessary to complete one million cycles. Throughout testing the input of the cycle rate and minimum and maximum stress levels were output exactly. The 3Hz sine wave input was also output exactly as can be seen in Figure 3.1. The consistent maximum and minimum stresses can be seen below in Figure 6.1.

The first specimen for each stress level was monitored using an infrared camera. This ensured that overheating was not occurring due to the fast cyclic rates which were being used in the fatigue process. Overheating can drastically affect the performance of the joint and therefore must be minimized. All five stress levels showed no signs of overheating during the entirety of cyclic loading. This can be seen in Figure 3.2 which represents the highest stress level that specimens have been fatigued. After determining that there was a consistent sine wave at 3 Hz and no overheating occurred it can be determined that the parameters input to the machine were output exactly for all stress levels.
Damage was inspected visually by utilizing blue dye, which was wiped on the edges of the specimens at varying cycles throughout the test. Blue dye allows for cracks to be easily detected in the DCCS Structure. Photographs were taken during each check to compare whether new damaged formed or whether existing damage propagated since the previous check. Despite rigorous efforts to detect damage in the DCCS Structure specimens, there were no signs of damage externally visible on any of the specimens in stress levels one through five. Despite the lack of external damage hairline cracks were visible on the interior of the bolt hole after removing the
specimen from fixturing and carefully removing the pin. The hairline crack damage on the inside of the bolt hole was located on the ceramic tile within the pin bearing region. There is not significant pin bending within this load range. Hairline cracks were detected in stress levels two through five only and can be seen in Figure 6.2. The cracks formed approximately 30 degrees each direction from zero. The load was also applied as seen in Figure 6.2. The location of the damage made it impossible to detect until after the completion of the one million cycles, therefore the cycle number at which hairline crack initiation began is unknown for each of the stress levels. The damage is visible as cracks in blue dye within the ceramic tile. The dye in the surrounded area on the face sheet is not damage; it stained the face sheet when the dye was filled inside the hole. There were no signs of drastic failure modes within the test specimens; however the hairline cracks could be initiation points for crack propagation and future failure modes, especially under an increase in loading. These cracks also have the potential to reduce the residual strength of joints in DCCS Structure material after fatigue testing. In order to determine how the cyclic loading and hairline crack failure modes affect the overall strength of the joint, residual strength tests are performed. The residual strength of the specimen can provide information to determine whether cyclic loading at low loads can have a detrimental effect on the strength of the joint and the sequence of damage. In addition, damage can affect the structural stiffness of the joint. Stiffness was also monitored as a function of fatigue cycles. From a design guideline perspective, stress levels should be limited to levels that do not exhibit stiffness or bearing strength loss.
6.2 Residual Stiffness and Strength

Residual strength is the amount of load or force a structure can carry after damage has occurred. In this case, the amount of load a joint in DCCS Structural material can carry after fatigue damage. Residual strength testing provides a better understanding as to how cyclic loading affects the strength and/or the failure modes of a joint in DCCS Structures. In order to determine whether damage induced by cyclic loading has any detrimental effect on the strength of the joint static testing has been performed on the previously fatigued samples. Even if visible damage cannot be detected, loss of strength in the DCCS structure could still have occurred, especially since DCCS structures consist of layers with very different properties.

The test procedures followed for residual strength tests were identical to the baseline static test procedures. This ensures accuracy when comparing data between the fatigued scenarios and the baseline scenarios. To comply to this
procedure the residual strength tests were conducted at a loading rate of .01 inches per minute until failure. Deflection data was measured continuously using LVDT’s on opposing sides of the specimen. The specimen geometries used for the fatigue/residual strength testing were identical to the baseline specimens, which allow the load vs. deflection data to be accurately compared between them. Having a strong comparison between the two tests provides verification to determine whether any additional failure modes or changes in failure modes may have occurred. Figure 6.3 below shows the stiffness vs. number of cycles for each of the stress levels that underwent fatigue loading. Stiffness was defined by the maximum applied load divided by the displacement (lbs/in) at each cycle. Each stiffness curve was normalized by its initial stiffness so each curve starts at 1. This graphically represents whether the stiffness is decreasing or staying constant. It can be seen that the stiffness for stress levels 1 – 4 remains failure constant. However, stress level 5 showed signs of a significant decrease in stiffness (30% reduction). This decrease in stiffness throughout the test is a sign that damage is accumulating in the specimen during fatigue.
Figure 6.3: Normalized Fatigued Stiffness vs. Number of Cycles

It is known that the specimens fatigued at the first stress level with a max load of 560 lbs had no signs of hairline cracks or exterior damage. After completing residual strength tests for this stress level, it was observed that the load versus displacement plots shown in Figure 6.4 between the residual strength and baseline specimens matched excellently. This can be seen in Figure 6.4 below.
The type and order in which the failure modes occurred were identical between the residual strength and baseline scenarios. The slope of the linear region of the curves was identical between the residual strength specimens and the baseline specimens as well. Strength and displacement comparisons between the stress level 1 residual strength specimens and the baseline specimens can be seen in Table 6.1 below.
Table 6.1  **Strength and Displacement Comparisons**  
*(Stress Level 1 Residual Strength vs. Baseline)*

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Ultimate Strength (kips)</th>
<th>Displacement at Bending/Shear Failure (in)</th>
<th>Displacement at Ultimate Failure (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual Strength</td>
<td>29.5 – 32.4</td>
<td>.055 -.086</td>
<td>.149 -.165</td>
</tr>
<tr>
<td>Baseline</td>
<td>32.6 – 34.7</td>
<td>.040 -.070</td>
<td>.164 -.180</td>
</tr>
</tbody>
</table>

Based on Table 6.1 and Figure 6.4 it can be seen that the failure modes and their locations are very similar. This suggests that no serious damage has occurred during fatiguing at stress level 1.

Stress level 2 was fatigued with a max load of 1120 lbs and had very similar results to stress level 1. It can be seen in Figure 6.5 that the slopes of both the residual strength and baseline curves were identical within the linear portion of the curve. This shows that there was no loss of stiffness. Much like stress level 1, stress level 2’s failure modes occurred in the same order as the baseline specimen. Table 6.2 shows the ultimate strength and displacement comparisons between stress level 2 residual strength and the baseline specimens.
Figure 6.5: Fatigued vs. Non-Fatigued Specimens at Stress Level 2

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Ultimate Strength (kips)</th>
<th>Displacement at Bending/Shear Failure (in)</th>
<th>Displacement at Ultimate Failure (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual Strength</td>
<td>31.4 – 32.0</td>
<td>.045 - .094</td>
<td>.146 - .162</td>
</tr>
<tr>
<td>Baseline</td>
<td>32.6 – 34.7</td>
<td>.040 - .070</td>
<td>.164 - .180</td>
</tr>
</tbody>
</table>

Based on Figure 6.5 and Table 6.2 it can be concluded that the damage caused by fatigue at the second stress level did not cause detrimental damage to drastically cause reduced strength or stiffness in the joint. Some changes in
displacement can be noticed at the bending/shear failure mode, however the change in displacement is not large or entirely consistent between specimens.

Stress Level 3 is the first specimen tested for residual strength that showed a change in behavior when comparing it to the baseline specimen. As usual the slope within the linear region of the curve between the baseline and residual strength specimen is identical. This can show that the ceramic tile has no direct damage during fatiguing. Only after normal damage caused by static testing occurs can effects from fatiguing be noticed. The strength and displacement comparisons between the stress level 3 residual strength and baseline specimens can be seen below in Table 6.3.

![Fatigued vs. Non-Fatigued (Stress Level 3)](image)

**Figure 6.6:** Fatigued vs. Non-Fatigued Specimens at Stress Level 3
Table 6.3  **Strength and Displacement Comparisons**  
*Stress Level 3 Residual Strength vs. Baseline*

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Ultimate Strength (kips)</th>
<th>Displacement at Bending/Shear Failure (in)</th>
<th>Displacement at Ultimate Failure (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual Strength</td>
<td>28.6 – 29.3</td>
<td>.070 - .097</td>
<td>.106 - .152</td>
</tr>
<tr>
<td>Baseline</td>
<td>32.6 – 34.7</td>
<td>.040 - .070</td>
<td>.164 - .180</td>
</tr>
</tbody>
</table>

Based on Figure 6.6 and Table 6.3 it can be concluded that the failure mode comparisons between both the residual strength and baseline specimens are starting to show differences. These specimens showed signs of some decrease in failure at ultimate failure however the displacements to cause bending/shear failure are very similar to the residual strength specimens in stress level 2.

Stress level 4 was the first stress level to show considerably noticeable changes in failure mode progression. Despite this the slope of the linear portion of the curve of the residual strength specimens and the baseline specimens were identical. This behavior can be seen below in Figure 6.7. Much like stress level 3 the effects of fatiguing are not directly noticed until normal static damage has occurred within the ceramic tile. The net tension failure mode occurred at the same time for both the residual strength and baseline specimens that were tested. The second failure mode, bending/shear, began to show signs that damage during fatiguing was influencing the damage progression within the DCCS Structure. This directly affected how and at what displacement the bending/shear failure mode occurred. The failure loads and displacements at which failures occurred can be seen below in Table 6.4.
Table 6.4  
**Strength and Displacement Comparisons**  
(Stress Level 4 Residual Strength vs. Baseline)

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Ultimate Strength (kips)</th>
<th>Displacement at Bending/Shear Failure (in)</th>
<th>Displacement at Ultimate Failure (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual Strength</td>
<td>30.3 – 32.5</td>
<td>.113 - .122</td>
<td>.122 - .159</td>
</tr>
<tr>
<td>Baseline</td>
<td>32.6 – 34.7</td>
<td>.040 - .070</td>
<td>.164 - .180</td>
</tr>
</tbody>
</table>

Based on Figure 6.7 and Table 6.4 it can be clearly determined that fatiguing specimens at stress level 4 (2240 lbs) for one million cycles affects the structural integrity of the specimen. Despite the not change in slope within the linear
portion of the curve, the displacements at which bending/shear failure mode occurred based on the previous stress levels increased a lot. In many specimens the bending/shear failure mode occurred simultaneously with ultimate failure. Therefore the displacement at which ultimate failure occurred was reduced compared to the baseline geometry.

Stress Level 5 (2800 lbs) was the highest stress level tested during this entire fatigue matrix. As discussed previously stress level 5 did show a constant decrease in stiffness during fatigue, which is a sign of damage within the composite. Similarly to stress level 4 the failure mode progression was altered by the fatigue process. The bending/shear failure mode and ultimate failure were the only failure modes that were affected by this change. The ultimate loads at failure and displacements at failure and the bending/shear failure mode can be seen below in Table 6.5.
**Figure 6.8:** Fatigued vs. Non-Fatigued Specimens at Stress Level 5

**Table 6.5** Strength and Displacement Comparisons  
(Stress Level 5 Residual Strength vs. Baseline)

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Ultimate Strength (kips)</th>
<th>Displacement at Bending/Shear Failure (in)</th>
<th>Displacement at Ultimate Failure (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual Strength</td>
<td>31.1 – 34.9</td>
<td>.123 - .160</td>
<td>.140 - .169</td>
</tr>
<tr>
<td>Baseline</td>
<td>32.6 – 34.7</td>
<td>.040 - .070</td>
<td>.164 - .180</td>
</tr>
</tbody>
</table>
Stress level 5 showed a 100% increase in deflection to cause bending/shear failure compared to the baseline specimens. However, in some cases this failure mode did not occur at all and the pin deflected pushing the ceramic tile out of the top of the specimen until bearing failure occurred. While the fatigue damage did not drastically reduce the ultimate strength of the specimen, it did cause ultimate failure to occur at lower displacements.

The additional deflection shifting of the second failure mode along the increased non-linear section of the load vs. displacement curve is due to the damage and weakening of the many constitutive parts in the DCCS Structure. In most cases the ceramic tile, despite the hairline cracks, is not cracking in bending/shear until higher loads or not at all. The shift is large enough that bearing failure is occurring before bending/shear failure and/or before ultimate failure. This changes the sequence of failure modes at this stress level 4 and 5. The increased deflection has resulted in a change in how load is being transferred through the constitutive layers. The face sheet has a low strain to failure (2-3%) compared to the interlayer which has an extremely high strain to failure (200-300%). This high strain to failure could explain the extra deflection causing the cracks that formed during the net-tension failure modes to open further without debonding. This can be seen in Figure 6.9 below.
Figure 6.9: Increased Deflection in Net Tension Cracks at Stress Level 5 Residual Strength Testing

This deflection results in the ceramic tile being pushed out of the top edge of the face sheet. The shift in the failure mode sequence is likely the result of the interlayer yielding in shear over the entire shear area connecting the tile and face sheet. After net tension cracks form and interlayer yielding occurs the load transferred from the pin to the ceramic tile cannot as efficiently transfer to the face sheet. Therefore the ceramic tile gets pushed out through the face sheet.

It has been determined that at stress levels below first failure mode, the fatigue resistance of the DCCS Structure is high. There were no signs of damage on the external boundary of the test specimen and could only visibly detect hairline
cracks within the bole hole on the ceramic tile for stress levels 2 through 5. During fatigue loading stress level 5 showed signs of an overall stiffness reduction. During residual strength testing it was determined that specimens fatigued at stress levels 1 through 3 resulted in identical failure mode progression when compared to static loading. Stress level 3 showed signs of early failure as compared to the static baseline testing. Stress levels 4 and 5 had changes in failure mode progression. This change resulted in bearing failure in the face sheet to occur before bending/shear failure mode. In some cases the bending/shear failure mode did not occur at all. This can be directly related to the loss of stiffness during fatiguing. According to Gawandi et al, reducing the stiffness of the adhesive will decouple the face sheet from the tile layer and the sandwich structure will behave more like a soft core, where, the effective modulus is governed by the face sheets. (Gawandi et al 164 – 172) After net tension failure the loss of stiffness is eventually caused by yielding in the interlayer which results in higher ceramic tile displacement. The properties of the interlayer are clearly important and for interlayers that undergo extensive yielding before failure increase the interlayer shear area may also improve ultimate load capacity of the joints. The increased shear area will provide increased resistance to fatigue and static loading. This will be discussed in the next Chapter along with the effects of the pin located on the gap between ceramic tiles. The goal of the pin on gap location combined with the increased shear area is to decrease failure modes while increasing the strength and fatigue resistance of the structural joints in DCCS Structures.
Chapter 7

BEARING TEST WITH PIN ON DISCONTINUITY IN TILE ARRAY

Discontinuous Ceramic Cored Sandwich Structures are a complex structure made up of many different constituents. One of the most important parts of this structure is the discontinuous ceramic tile array. The tiles provide excellent energy absorption properties as well as high stiffness and structural strength. Despite the many benefits that the DCCS structures include, the discontinuous tile array is a catalyst for many issues. Stress concentrations form along the gaps between the tiles within the array and directly reflect that on the interlayer and face sheet materials. As a result, these stress concentrations often cause failure of the interlayer in areas where the discontinuity regions are present. In the later stages of failure, the ceramic is pushed out the end of the sample. Here the yield stress and shear area of the interlayer are expected to be a major factor in the ultimate capacity of the joint. Consequently understanding how the discontinuous tile array can affect bolted joints is extremely important to the structural design using this type of material.

It was determined in Chapter 5 that reducing the edge distance had a drastic detrimental effect on the failure modes and the strength of the joint. The reduction of the shear area caused the bending/shear crack to form on the edge sooner than in the baseline tests. This failure occurred at 10,800 lbs (22980 psi) and the ultimate failure occurred at 23600 lbs (50212 psi), approximately 10000 lbs (21276 psi) less than the baseline static tests that were already performed. These results raised the question that if the reduction of shear area caused a drastic reduction in strength,
would an increase in shear area compared to the baseline cause a drastic increase in strength? In order to test whether the increase in edge distance would positively affect the strength of the joint, the bolt hole would have to be placed increasingly closer to the discontinuity between ceramic tiles. The effect that the discontinuity region will have on a pinned joint is currently unknown. In order to test these two scenarios, two pin on gap tests were conducted. It was possible that placement of the pin on gap would eliminate the net tension failure mode in the ceramic and the increase in shear area would further increase joint capacity.

7.1 Pin on Discontinuity Testing (w/D = 8, e/D = 4)

The first scenario involved the geometric ratios of w/d = 8 and e/D = 4. These ratios are identical to the baseline geometric ratios; the only difference was that a discontinuity region was present at the location of the pin. In order to preserve similar geometric ratios while bearing directly on the discontinuity region, the baseline specimens were machined to leave only a half tile at the top. This allowed for the gap between ceramic tiles to be 2 inches from the edge and after the hole was drilled the exact e/D ratio as the baseline specimens. A schematic of the pin on gap specimen with an e/D = 4 can be seen below in Figure 7.1.
Figure 7.1: Pin on Gap Specimen (e/D = 4 w/D = 8)

Testing samples in this way allows for an excellent understanding how the presence of the discontinuity affects the failure modes and strength without any other changes in geometry. In order to accurately compare this data to the baseline specimen data an identical testing procedure was used. Each specimen was tested at a load rate of .01 inches per minute to allow for accurate detection of failure modes. Displacements were measured using a set of two LVDT’s measuring displacement on each side of the specimen. Displacements were then averaged to determine the average displacement across the entire specimen. Five specimens were tested to failure in this scenario. All bearing stress verse Displacement plots can be found in Appendix F. A representative load-deflection curve is presented in Figure 7.2.
Figure 7.2: Load vs. Displacement of Pin on Gap Specimen (e/D = 4 w/D = 8)

Figure 7.3: Load vs. Displacement Curve for Baseline Specimen (W4E2)
Net tension failure is the first failure mode to form in a standard bearing tests for DCCS Structures. The net tension failure always occurs within the ceramic tile. Pin on gap specimens are specimens where the pin is directly loading on a discontinuity region. After performing static tests it was determined that the discontinuity acts as if a net tension crack has already occurred. Designing a “net tension crack” into the specimen at the location of pin bearing will provide additional resistance to the formation of net tension cracks from forming by altering the local stress fields. Our rationale is based on the fact that a DCCS structure contains many tiles and a gap that will fail in net tension (albeit with a lower stress concentration and higher associated failure modes). Our question is whether we can raise the joint capacity to levels equivalent to the far field response.

Maintaining an undamaged core is important not only for the structural performance, but the impact performance as well. Having an undamaged core will increase the performance of the specimen as a whole. After testing specimens that had the pin located on a discontinuity region it became apparent that the presence of the gap directly over the bearing location drastically reduces the presence of net tension cracks. In fact, failure modes of any kind did not form until the bending/shear failure mode occurred. When this failure mode occurred, it also caused the net tension cracks to initiate. Until this failure, most of the noticeable displacement was present in the discontinuity between ceramic tiles. This gap displacement was very noticeable in the region of discontinuity that the pin was bearing upon. After these failure modes became present, the process of failure for the remainder of the experimental test was identical to the baseline test results. As the experiment continued deflections became noticeable at all failure mode locations.
Figures 7.2 and 7.3 show the different failure modes and when they occur for the pin on gap and static case. It can be observed that the tile gap fails at 4000 lbs over a width of 3.5 inches (4 in width – bolt diameter = 3.5 in.). This is a value of 1140 lbs per inch. According to Anis Gawandi, a researcher at the Center for Composite Materials, one inch wide specimens undergoing uniform in plane tension loading (no holes or pins), gap failure occurs at 1500 lbs per inch. The reason gap failure in the pin on gap specimens is a lower load per inch is a result of the pin directly bearing on the ceramic tile that induces local stress concentrations. However, the efficiency of this joint configuration is approximately 76% of the far-field tension capacity which is quite good for bolted joints.

Allowing the pin to bear directly on the gap prevents the ceramic tile from showing any signs of failure modes until higher load levels causing the second failure mode (bending/shear) to occur. After these failure modes occurred the ceramic tile was pushed out the top edge of the face sheet and the pin began to fail the face sheet in bearing. Designing joints with the pin located at the discontinuity between ceramic tiles helps the integrity of the ceramic tile to remain intact longer than it would in the baseline geometries. Preventing the ceramic tile from failing at low load levels increases the performance of the structure as a whole by maintaining the integrity of the material constituents.

Comparing the linear portion of the curve for both the baseline and the pin on gap specimens discussed above show that the slope is identical between the two. As discussed above the introduction of the gap to the specimen geometry changes the failure mode progression in a positive way. Comparisons between the baseline and the pin on gap specimen can be seen below in Table 7.1.
Table 7.1  **Baseline and Pin on Gap (W4E2) specimen comparison.**

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Initial Gap Failure</th>
<th>Initial Net Tension Failure</th>
<th>Bending/Shear Failure</th>
<th>Ultimate Failure</th>
<th>Displacement at Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin on Gap (W4E2)</td>
<td>4.0 – 5.0</td>
<td>20.0 – 25.0</td>
<td>20.0 – 25.0</td>
<td>31.5 – 32.2</td>
<td>.171 - .175</td>
</tr>
<tr>
<td>Baseline</td>
<td>n/a</td>
<td>3.2 – 5.4</td>
<td>20.6 – 27.0</td>
<td>32.6 – 34.7</td>
<td>.164 - .180</td>
</tr>
</tbody>
</table>

It can be clearly determined from Table 7.1 above that the failure modes from bending/shear to ultimate failure are all similar. The benefit to having the pin on gap with this geometry is that the net tension failure in the ceramic tile occurs approximately at 4 times higher loads than the baseline specimen. This keeps the structurally important, impact resistant, core intact as long as possible. The initial gap failure shown above is when the resin bonding the two ceramic tiles together fails, however this does not affect the strength or stiffness of the joint. This failure is what prevents damage from propagating to the ceramic tile.

**7.2 Pin on Discontinuity Testing (w/D = 8, e/D = 8)**

Similarly to the pin on gap specimens with an e/D = 4, the pin on gap specimens with an e/D = 8 have the same width and bolt hole diameter. Despite the specimens having an identical width as the baseline geometry, the bolt hole location is different. Increasing the edge distance to an e/D = 8 places the bolt hole directly over a region of discontinuity in the ceramic tile and it also increases the shear area so that an entire tile must be pushed out from the pin location at the latter stages of failure. Figure 7.4 can be seen below visualizing the geometry. The shear area increases as the
bolt hole location moves further away from the edge. This provides more area for the interlayer to adhere to the ceramic tile and face sheet together. In the case where the edge distance was decreased, the strength of the joint dropped drastically. Increasing the shear area increases the strength of the joint. How much strength and how it affects the failure modes are difficult issue because the nature of the discontinuous tile array is the cause for many complications. To help minimize these complications the same experimental procedure was used and setup for data gathering was used. Since this test requires that the bolt hole must be placed directly over the discontinuity within the tile array, while having an edge distance of 4 inches (e/D = 8) the current test fixture that has been used for all previous tests is too small. Therefore a new test fixture had to be designed and fabricated for these purposes. The first test fixture had an overall length of 8 inches, while the new test fixture was designed to have an overall length of 10 inches and can easily accommodate an edge distance of 4 inches (e/D = 8). As discovered in the previous section, placing the pin on the region of discontinuity provides many additional benefits to the structure, mainly the ability to increase the load levels that cause the first failure modes occur. However, it is beneficial to understand how increasing the edge distance affects the overall performance of the joint. The absolute extreme edge distance that can occur due to the discontinuous tile array is an edge distance of 4 inches (e/D = 8).
The combination of increased edge distance and the pin on the gap region provides many benefits to the joint. The presence of the gap allows for an increased resistance to the initiation of failure modes. This prevents damage from occurring in the joint until higher load levels. The increased shear area provides the resistance necessary to increase the ultimate strength of the joint. After running multiple experiments on the pin on discontinuity specimens with an e/D = 8 it was apparent that increasing the edge distance provided a large increase in load carrying capacity. This can be clearly seen in Figure 7.6. Unfortunately the specimens tested were not able to
be tested until catastrophic failure. At the highest failure loads the pins underwent significant plastic deformation and failure. The significant plastic deformations can be seen below in Figure 7.5. In addition, the strength of hardened steel fixture inserts were exceeded and failure loads were exceeding the maximum load cell capacity of the Instron (50 kip frame). The travel limitations of the LVDT’s used for testing were also overcome and therefore load displacements above 5.08 mm (0.2 inches) could not be recorded. After fixing the inserts and stiffening the fixture the joints were able to be loaded until 53,000 lbs (112760 psi). Due to the limitations discussed above the displacement could not be recorded all the way to the 53000 lbs and testing had to be halted.

Figure 7.5: Broken Insert and Deformed Pin from PGW4E4 Testing
For the pin on gap specimens with W4E4 (w/D = 8 and e/D = 8) the first failure mode to be detected was gap failure in the region of the pin. This occurred at similar loads to the pin on gap specimens with a W4E2 (w/D = 8 and an e/D = 4). The second failure mode to occur during static testing for the pin on gap specimens W4E4 (w/D = 8 and e/D = 8) was net tension failure in the ceramic tile. Due to limitations discussed above bending/shear and ultimate failure modes were not able to be achieved. A comparison between a baseline specimen (W4E2), a pin on gap specimen (W4E2), and the pin on gap specimen (W4E4) can be seen below in Table 7.2. This table will compare initial gap failure, initial net tension failure, bending/shear failure, ultimate failure, and displacement at failure for all three specimen geometries and configurations.
Figure 7.6  Load vs. Displacement (PGW4E4 [e/D = 8], W4E2 [e/D = 4], W4E1.5 [e/D = 3])

Table 7.2  Baseline, Pin on Gap (W4E2), and Pin on Gap (W4E4) specimen comparison.

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Initial Gap Failure</th>
<th>Initial Net Tension Failure</th>
<th>Bending/Shear Failure</th>
<th>Ultimate Failure</th>
<th>Displacement at Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kips</td>
<td>kips</td>
<td>kips</td>
<td>kips</td>
<td>inches</td>
</tr>
<tr>
<td>Pin on Gap (W4E4)</td>
<td>5.0 – 6.0</td>
<td>40.0 – 47.0</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Pin on Gap (W4E2)</td>
<td>4.0 – 5.0</td>
<td>20.0 – 25.0</td>
<td>20.0 – 25.0</td>
<td>31.5 – 32.2</td>
<td>.171 – .175</td>
</tr>
<tr>
<td>Baseline</td>
<td>n/a</td>
<td>3.2 – 5.4</td>
<td>20.6 – 27.0</td>
<td>32.6 – 34.7</td>
<td>.164 – .180</td>
</tr>
</tbody>
</table>
Based on Figure 7.6 and Table 7.2 it can be determined, even without knowing the ultimate capacity of the joint, that the increase in shear area provides many benefits to the joint. Comparing the slopes in Figure 7.6 for the reduced edge distance (W4E3), baseline (W4E2), and pin on gap (W4E4) specimens shows that within the linear region, the pin on gap specimen with a 4 inch edge distance has a slightly increased stiffness. This, compared with the results in Table 7.2 proves that the pin on gap (W4E4) geometry is very efficient. Including a increase load at which failure modes occur and a higher damage resistance due to static loading. In fact, the pin on gap (W4E4) represented a 900% increase in load to cause net tension failure compared to the baseline configuration (W4E2). As mentioned previously since extremely high loads were necessary to cause the first failure mode, other failure modes did not occur before the experimental test had to be halted. Pin bending was a major problem at increased loads and it was determined that the only way to ultimately fail a specimen with this geometry is to either use larger pin diameters or multiple pins. This will be a recommendation for future work. Despite not ultimately failing the e/D = 8 specimens the data recorded still shows that increasing the edge distance and in turn the shear area positively affects the load carrying capacity. Failure modes that occurred during this test can be seen in Figure 7.7 below.
Figure 7.7: Pin on Gap (W4E4) Failure modes at 53000 lbs of applied load.
(Gap Failure: 5.0 – 6.0 kips, Net Tension Cracks: 40.0 – 47.0 kips)
Various load vs. displacement curves can be seen in Figure 7.6. The orange lines are test specimens that have an e/D ratio = 3 (W4E1.5) and a shear area equal to 11.8 inches squared. The purple lines are the baseline specimens with an e/D ratio = 4 (W4E2) and a shear area of 15.8 inches squared. The blue lines represent the pin on gap specimens with an e/D ratio = 8 (PGW4E4) with a shear area of 31.8 inches squared. The shear area is defined as the area in contact with the interlayer and both sides of the ceramic tile. When comparing the ratio of the shear area to the ultimate failure load for the baseline geometry and the e/D = 3 geometry the results were very consistent. Understanding that the shear area to failure load ratio was consistent a linear trend line can be made between the W4E1.5 and W4E2 specimen geometries in Figure 7.8 below.
Figure 7.8: Failure Load vs. Shear Area (W4E1.5, W4E2, and PGW4E4)

The plot in Figure 7.7 represents the behavior of the change in shear area to ultimate load very well. Overall and increase in shear area increase the ultimate failure load. It is assumed this is a linear behavior, but only up to a certain point. It can be seen that the PGW4E4 specimen starts to deviate from the linear path established with the W4E1.5 and W4E2 specimens. It is expected that this linear path will plateau when the shear area is large enough. This shear area to initiate this plateau is currently unknown and further study is needed to determine this. However, it can be see with the pin on gap W4E4 specimen that it is deviating from the linear region.
Even though ultimate failure was unable to be achieved it is unlikely that it will reach the failure load projected by the linear trend line. This plateau is most likely due to the fact that a portion of the interlayer is not yielding like the lower shear areas. This lack of yielding is the reason the ceramic tile is not pushed out of the top of the face sheets.

It has been determined that combining the pin on gap and increased edge distance, not only reduces initial failure modes from occurring, but also greatly increases the strength of the joint, which are both are important design aspects. Based on the loads gathered from experimentation the increase in load carrying capacity from the baseline (W4E2) to the pin on gap (PGW4E4) is 32000 lbs to 53000 lbs. This results in an increase in bearing strength of 68085 psi to 112765 psi, an increase of 66 percent. Discussion with Gawandi showed that the ultimate load for the Gawandi’s tension test coupons was estimated at an in-plane tensile load of 30000 lbs/inch. The baseline DCCS Structure specimens tested ultimately failed at 32000 lbs/4inches = 8000 lbs/in. The pin on gap specimen with c/D = 8 was able to be loaded at 53000 lbs/4 inches = 13250 lbs/inch. This means that the joints in the baseline geometry are 26.6% as efficient as the DCCS Structure without a joint at ultimate failure. The pin on gap specimen is 44% as efficient as the DCCS Structure without a joint at ultimate load. These static testing results of this geometry are very promising, however it is very beneficial to have a better understanding of the fatigue performance of the pin on gap (W4E4) as well.
7.4 Fatigue Testing of Pin on Discontinuity Region in DCCS Structures

Changes in geometry can have drastic effects on the performance of bolted joints in Discontinuous Ceramic Cored Sandwich Structures. We know that the location of the pin improves the performance of bolted joints under static conditions, but the understanding of whether this affects the performance under fatigue conditions is also important. Fatigue tests have been completed on specimens that have the pin on the discontinuity region for geometric ratios of w/D = 8 and e/D = 8. The procedure used is identical to the baseline geometry which has been previously tested under fatigue conditions. These samples are cycled at a rate of 3 Hz up to 1 million cycles. This specimen started fatiguing at stress level 5, which was a maximum load of 2800 lbs and a minimum load of 280 lbs. This was the only stress level that this specimen was fatigued at. Failures in the ceramic tile were being detected visually during fatiguing using, similarly to the baseline fatigue specimens. During the fatigue cycling, there was no sign of damage propagation on the external boundary of the specimen. After removing the specimen from the test fixture, the inside of the bolt hole was inspected for hairline cracks. Unlike the baseline scenario previously tested under cyclic loading there was no sign of hairline cracks present for the pin on gap (W4E4) specimens. This lack of hairline cracks in the specimen is most likely due to the pin being located on the discontinuity region. One concludes that this configuration and load level is less sensitive to fatigue loading than the baseline geometry (W4E2). Fatigue testing at higher load levels is recommended in future studies. It is likely that in the pin on gap specimen the gap allowed some deflections, which minimized stress concentrations from the pin to the ceramic tile. Residual strength testing was not conducted with this specimen geometry due to the strength...
limitations of the fixture and test machine. It is recommended that these specimens be tested for residual strength in future study.

7.5 Finite Element Analysis of Bolted Joints in DCCS Structures

Two finite element models have been created in order to compare the stress distribution in the baseline specimens to the stress distribution in the specimens with the pin located in the region of ceramic tile discontinuity. From experimentation it is known that the presence of the gap helps to prevent the first failure modes from initiating, but it is currently unknown how the stresses are distributed around that region in detail. It is important to understand why the failure modes are not occurring at load levels that cause failure in the baseline specimen. Each model was created using the CATIA and the built-in Elfini solver. To save computational time, ¼ symmetric models were used for both specimen geometries. This is possible due to the thru-thickness and in-plane symmetry of the DCCS Structure that was used for experimentation. Each constituent part of the DCCS Structure was created separately and combined within the model. The face sheet and the ceramic tile both have 8 3D solid elements through the thickness. The interlayer has 3 3D solid elements through the thickness and resin gaps have 12 elements through the thickness. Interlayer material properties were used for both the interlayer between the face sheet and the ceramic tile and the resin gaps between ceramic tiles. The steel pin has 15 elements through its thickness. The face sheet is modeled to be 6.35 mm (0.25 inches), the interlayer is .508 mm (.02 inches), the ceramic tiles are 5.08 mm (.2 inches) thick, and the resin gaps are 5.08 mm (.2 inches) deep and .508 mm (.02 inches) thick. Interfaces between the face sheet and interlayer, interlayer and ceramic tiles, interlayer and resin gaps, and resin gaps and ceramic tiles were joined using a fastened mesh connection.
The parts that are in contact with the pin were connected using a frictionless contact mesh. Each part was meshed using a quad mesh. This mesh is applied to a surface and extruded through the part. A rigid pin was used to ensure an even stress distribution across the bolt hole. This pin was clamped on one edge and restrained in the dimension to provide symmetry. Restraints were also used on the bottom and inside surfaces to create symmetry to the part. A pressure load was applied to the face sheet material at far field, causing load to be distributed through the interlayer to the ceramic tile. This is comparative to the conditions during experimental testing. An example of the FEA mesh and restraints can be seen in Figure 7.9 below.

Figure 7.9: Restraints used for quarter symmetric FEA Model
This model was compared to the analysis performed using the BJSFM software to determine whether it is accurate and that the results converged. In an analysis using a rigid pin it can be seen in Figure 7.10 and 7.11 that the stress distribution on the hole boundary is almost identical between the FEA and BJSFM at a pressure of 500 psi or a far field load of 1000 lbs. This proves that the results are accurate. These elastic results also indicates that the presence of the interlayer and tile gap (not included in BJSFM) has minimal impact on the load instruction A Table of material properties used for modeling can be seen below in Table 7.3 and 7.4. Table 7.3 shows the material properties for the ceramic tile, interlayer, resin gaps, and the steel pin used during analysis. Table 7.4 shows the full 3D properties that were used for the face sheet during analysis. The work determining the material properties for the face sheet was performed and submitted by Dr. John W. Gillespie Jr. and Chris Arvanitelis at the Center for Composite Materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Units</th>
<th>Modulus (E)</th>
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</tr>
<tr>
<td></td>
<td>GPa</td>
<td>334.7</td>
<td></td>
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<tr>
<td>Interlayer</td>
<td>ksi</td>
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<tr>
<td></td>
<td>GPa</td>
<td>0.489</td>
<td></td>
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<tr>
<td>Resin Gap</td>
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<tr>
<td></td>
<td>GPa</td>
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<td></td>
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<tr>
<td>Steel Pin</td>
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<tr>
<td></td>
<td>GPa</td>
<td>Rigid</td>
<td></td>
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Table 7.4  Material Properties for FEA Modeling (Face Sheet Only)

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<thead>
<tr>
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<tr>
<td>$E_{2T}$ (Msi)</td>
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<td>$\nu_{12T}$</td>
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<tr>
<td>$\nu_{21T}$</td>
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<td>$X_{1T}$ (Ksi)</td>
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<tr>
<td>$\epsilon_{1T}$ (%)</td>
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<tr>
<td>$\epsilon_{2T}$ (%)</td>
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<tr>
<td><strong>Compression</strong></td>
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<tr>
<td>$E_{1C}$ (Msi)</td>
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<tr>
<td>$E_{2C}$ (Msi)</td>
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<tr>
<td>$\epsilon_{2C}$ (%)</td>
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<td><strong>V-Notch (1-3)</strong></td>
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<tr>
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</tr>
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</tr>
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<td>$\gamma_{23}$ (%)</td>
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Figure 7.10: Comparison of hole boundary x stresses between BJSFM and FEA for the Face Sheet in DCCS Structure Modeling (Applied 1000 lb far field load/500 psi pressure)

Figure 7.11: Comparison of hole boundary x stresses between BJSFM and FEA for the Ceramic Tile in DCCS Structure Modeling (Applied 1000 lb far field load/500 psi pressure)
A pressure of 500 psi was applied to the face sheet for both the baseline (pin located in center of tile) geometry and the pin on gap (e/D = 8) geometry. This pressure simulates a far field load of 1000 lbs applied to the DCCS Structure. Since the models used are linear elastic the stress distributions calculated can be easily scaled from the 1000 lbs far field load. The rigid pin applied to the structure ensures that the stress distribution across the thickness of the ceramic tile and face sheet is constant (but very different between layers based on stiffness differences) and additional local stress concentrations do not form. It can be seen in Figure 7.12 below that there are stress concentrations the ceramic tile (also see Figure 7.11). The blue region is the compressive stress concentrations caused by the pin bearing while the red region is the tensile stress concentrations. Similar stress concentrations exist in the face sheet and interlayer but are an order of magnitude lower amplitudes (see Figure 7.10). This image shows the composite face sheet layer on the top, followed by the interlayer, and the bottom is the half thickness ceramic tile.
The pin located at the gap filled with adhesive is shown in Figure 7.13. The addition of the gap to the bolt hole boundary affects the overall stress distribution. Similarly to the baseline model the ceramic tile is carrying a majority of the load. This is shown through the compressive stress concentration caused by the pin bearing on the ceramic tile (blue region). The presence of the gap introduces an area of low stiffness (71 ksi for the resin gap versus 51.0 msi for the ceramic tile) within the bolt hole region at the 90 degree location. This greatly reduces the stress concentration that exists in the tensile region of the ceramic tile without a gap. The FEA model for the baseline geometry in Figure 7.13 shows a 94% decrease in tensile stress at 90 degrees.
from the hole location compared to Figure 7.12. This reduction in tensile stress reduces the possibility that net tension failure will occur. This is directly comparable to the results from experimental testing. As mentioned before this FEA analysis is only good in the linear elastic range, however it would be valuable for non-linear analysis to be performed in the future.

Figure 7.13: Pin on Gap finite element model
It is known that the interlayer is subject to shear between the face sheet and ceramic tiles. Ultimate failure in DCCS Structural Specimens tested often results in failure in the bond line between ceramic tiles and the face sheet. The yield strength for the interlayer in shear is approximately 2.25 ksi. It was determined through finite element analysis that the interlayer is predicted to reach that failure stress at the region directly above the gap between the ceramic tiles. The maximum load achieved for each specimen geometry was applied to determine area that yielding is occurring in the interlayer. For the pin on gap specimens with an applied far field pressure of 26500 psi (i.e. 53000 lbs) the yielding can be seen below in red in Figure 7.14. A similar failure occurs in the baseline specimen at an applied far field pressure of 16000 psi (i.e. 32000 lbs), which can be seen below in Figure 7.15. However, the gap region in the baseline geometric ratio is not present in the pin bearing region. Despite this yielding is predicted to occur in the region of the gap for both the baseline and the pin on gap specimens. If failure progression was introduced into the FEA model the yielding within the baseline specimen would be more accurate. This is because the ceramic tile fails in net tension at low loads, which would create a gap region much like the pin on gap specimen.
Figure 7.14: Shear Yielding in Interlayer above gap region with 26500 psi pressure or 53000 lb far field force (Pin on Gap Specimen). Red contours correspond to regions exceeding yield stress of interlayer.
Figure 7.15: Shear Failure in Interlayer above gap region with 16000 psi pressure or 32000 lb far field force (Baseline Specimen). Red contours correspond to regions exceeding yield stress of interlayer.

The interlayer has a non-linear nature which has not been represented in this finite element model. Further study needs to be completed utilizing an elastic-plastic interlayer to grasp the non-linear nature of the interlayer. The analysis function, Abaqus for Catia, should be used for this purpose. It is also recommended that the progressive failure of the ceramic, non-linear shear of the face sheet and the elastic-plastic nature of the interlayer should be considered for future work. Having a detailed and accurate study utilizing the actual material behavior will provide a better understanding of the performance of bolted joints in Discontinuous Ceramic Cored Sandwich Structures.
Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

Mechanically fastened joints are an extremely important fastening technique for composite materials due to their easy installation, inspection and repair. However they are a catalyst for failure modes and behave differently in different types of materials. Understanding the performance of mechanically fastened joints in Discontinuous Ceramic Cored Sandwich structures has been the focal point of this study. The understanding of how joints in DCCS Structures behave has grown through numerous experimental methods which have provided an insight into the performance in failure modes, joint strength, and joint durability.

8.1 Bearing in Individual Face sheet Material

Experimental work has been performed on the face sheet material individually. This was completed to be able to provide insight into the benefits of adding the ceramic tile as a structural material. In order to complete this experimentation a large test matrix of varying e/D and w/D ratios, while holding the pin diameter constant, was made. Each geometric ratio was tested to determine the different failure modes that occur. Based on information discussed in Chapter 1, three main failure modes occur due to static loading under bearing conditions in thin laminates, such as the face sheet material. These include bearing failure, shear-out failure, and net tension failure and can be seen in Figure 1.2. These failure modes are highly dependent on the joints geometry. Therefore, geometric dimensions can be
utilized during design to ensure that specific failure modes do or do not occur. In most cases it is optimal to ensure the only failure mode to occur is bearing failure due to its slow failure propagation. This will provide additional time to detect failures if necessary. The other two failure modes, net tension and shear-out, are considered catastrophic failure modes and are less likely to be detected before a serious failure.

BJSFM software was used as a method to determine the stress distribution on the hole boundary within a linear-elastic range. This analysis tool can be valuable for design by being able use it for failure mode prediction. This can be seen in Figure 4.6. Design charts were made based on the experimental data that was received. These design charts can be found in Figure 4.1 and Figure 4.2 and it can be easily determined what geometric ratios result in specific failure modes. It is recommended for design of the face sheet material individually that an e/D ≥ 3.5 and a w/D ≥ 2.4 should be used to ensure bearing failure. It can be seen in these design charts that the bearing strengths eventually plateau despite increasing e/D or w/D ratios. This is due to a combination of inplane shear and compression failure at the bolt hole boundary.

8.2 Bearing in Discontinuous Ceramic Cored Sandwich Structures

Due to the composite nature of the DCCS Structure each of the individual layers have very different properties, but when they work together it makes a highly efficient structural and impact resistant material. Up until now the performance of bolted joints in DCCS Structures has been unknown. Through experimentation the failure modes for multiple geometric ratios have been determined. Similarly to the face sheet in the previous section, design charts have been created to help aid in the design process. The baseline geometric dimensions that have been used throughout testing have a width of 101.6 mm (4 inches) and an edge distance of 50.8 mm (2
inches). Since the bolt diameter is held constant the geometric ratios for this scenario are $w/D = 8$ and $e/D = 4$. The failure modes and order in which the failure modes occur for the baseline geometry in DCCS Structures were very consistent and are used to compare to the remaining geometric ratios tested. The failure modes that occur during static testing in order of failure are net tension in the ceramic tile, bending/shear in the ceramic tile, bearing failure in the face sheet material, and face sheet – ceramic bond line failure which occurs at ultimate failure. The other geometric ratios had similar failure mode results, but there were some differences. When the width of the joint is reduced from 101.6 mm (4 inches) to 76.2 mm (3 inches) the only difference in failure modes is the fact that the bending/shear failure mode does not occur or occurs at ultimate failure. Instead, due to the reduced shear area, the ceramic tile is pushed through the edge of the face sheets. Despite this, the first failure mode remains the same and occurs at the same bearing stress of 8510 psi. The last geometry tested is the reduced width scenario. If the width stays at 101.6 mm (4 inches) wide but the edge distance is reduced to 38.1 (1.5 inches) for an $e/D = 3$ the only failure mode to change is the bending/shear failure mode. In this case the reduced edge distance causes the bending/shear failure mode to occur at a lower bearing stress than the baseline geometry. This results in an overall lower ultimate bearing strength.

Comparing the DCCS Structure under bearing load conditions to the face sheet under similar conditions it has been determined that the addition of the ceramic tile and the interlayer has beneficial properties. The individual face sheet and the face sheet on the DCCS Structure reach bearing failure at the same bearing stress (albeit DCCS achieves this level of bearing stress at much higher loads). However, the DCCS Structure can continue to carry increasing load, unlike the individual face sheet
that exhibits a plateau. This is due to the redundant load paths that the DCCS Structure has and is very beneficial to designers. Figures 8.1 through 8.6 represent design charts that were created to aid designers in varying situations. Each design chart is bearing stress vs. either e/D or w/D ratios. Understanding the affect that variations in edge distance and the width has on the bearing strength and failure modes of the joint is extremely important.

Figure 8.1: DCCS Structure Design Chart with pin on solid ceramic tile (Baseline Specimen, has a varying w/D and constant e/D = 4)

Figure 8.1 represents the effect that variations in width has on the different failure modes and ultimate strength for the baseline DCCS structure (W4E2). Based
on this design chart it can be seen that the reduction in width did not have a great effect on the overall strength of the joint, however the reduced width joint does not have the bending/shear failure mode like the baseline specimen does. The changes in width also did not affect the stiffness of the joint. Despite the fact that changes in width did not have a drastic effect on the strength or stiffness, it is recommended that joints be designed at widths greater than or equal to 3 inches wide. Smaller joints become impractical due to the fact that all joints tested used 0.5 inch bolts.

Fatigue testing was also performed on the baseline test specimens (W4E2) to determine the sensitivity of this structure to cyclic loading. Each stress level tested was under the net tension failure mode. It is important that the ceramic tile stays intact as long as possible. Based on residual strength testing stress levels 1 to 3 showed no sign of damage within the joint and the ultimate strength was very similar to that of the baseline specimen. It is recommended that if integrity of the ceramic tile is extremely important that joints be designed for stress levels under 3.
Figure 8.2:  DCCS Structure Design Chart with pin on solid ceramic tile (Baseline Specimen, has a varying e/D and constant w/D = 8)

Figure 8.2 represents the bearing stress at different failure modes for specimens with varying edge distance. It can be determined from this design chart that variations in the e/D ratio have a larger effect on the ultimate bearing strength and failure modes of DCCS Structure. Reducing the edge distance drastically reduces the ultimate strength of DCCS structures. Despite the reduction in strength the stiffness of the linear portion of the curve between both test specimens is the same. Therefore, based on this chart it is recommended that the edge distance in DCCS Structures be greater than or equal to 2 inches. This prevents premature bending/shear and eventually ultimate failure from occurring. As previously mentioned fatigue testing was only performed on the baseline geometry. In the case of Figure 8.2 that represents the specimens with and e/D = 4. It is recommended that if the sensitivity of the
ceramic tile is of upmost importance that the joint should be designed for stress levels at least 3 or below.

8.3 Pin on Discontinuity Region in DCCS Structure

The last geometric ratio that has been tested is the pin on the region of discontinuity within the ceramic tile. The addition of the gap to the bolt hole boundary affects the overall stress distribution. In many cases the integrity of the ceramic tile is extremely important. This is for both structural and impact resistance purposes. It was therefore important to find a way to increase the load to cause net tension failure in the ceramic tile. In a standard baseline specimen after the net tension cracks form, those cracks behave as if a gap was in the region of the pin. Therefore by designing the pin to be initially in the discontinuity region the gap prevents initial net tension failure from occurring until much higher stresses. The addition of the gap in the ceramic tile reduces the tensile stress by 8.6 times. The Figures below represent design charts comparing the reduced edge and/or width specimens, baseline specimens, and the pin on gap specimens. Therefore the designer can make educated decisions as to which geometry will be used for varying circumstances.
Table 8.1  Symbol and line definitions for design charts

<table>
<thead>
<tr>
<th>Symbol and line definitions for design charts</th>
</tr>
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<tbody>
<tr>
<td>Individual Face Sheet Material Testing</td>
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<tr>
<td>DCCS Solid Ceramic Net Tension</td>
</tr>
<tr>
<td>DCCS Solid Ceramic Bending/Shear</td>
</tr>
<tr>
<td>DCCS Solid Ceramic Ultimate Failure</td>
</tr>
<tr>
<td>DCCS Pin on Gap Net Tension Failure</td>
</tr>
<tr>
<td>DCCS Pin on Gap Bending/Shear Failure</td>
</tr>
<tr>
<td>DCCS Pin on Gap Ultimate Failure</td>
</tr>
<tr>
<td>((e/D = 4 \text{ – ultimate, } e/D = 8 \text{ – max achieved load}))</td>
</tr>
</tbody>
</table>

Figure 8.3:  DCCS Structure Design Chart
(Baseline and Pin on Gap, has a varying \(w/D\) and a constant \(e/D = 4\))
Figure 8.3 represents pins bearing on a solid ceramic tile (i.e. any specimen without the gap present in the bolt hole) and the pin on gap specimens that were tested. For this design chart the e/D was help constant at 4 and therefore the only pin on gap specimens represented are those with a w/D = 8 and e/D = 4. Based on the previous chapter it is known that the ultimate bearing stress of this pin on gap specimen and the baseline specimen at failure are very similar. Therefore designing for the ultimate strength of the joint only, either geometry would be fine. If the integrity of the ceramic tile is important it is recommended to use the pin on gap configuration. This configuration allows for additional load to be carried before damage to the tile occurs. This is a direct result of the presence of the gap material in the region of the bolt hole.
Figure 8.4 represents the comparison between pins bearing on solid ceramic tile (i.e. any specimen without the gap present in the bolt hole) and the pin on gap specimens for varying edge distance geometries. Since edge distance variations are sensitive to the strength of the joint, this is one of the most important design charts represented in this thesis. It clearly shows the increase in strength based on the increase in edge distance. As discussed in the previous chapter, pin on gap joints also have many benefits such as increasing the load to cause different failure modes. This design chart directly shows this benefit. An example would be if the designer were very concerned about a high ultimate strength, but also needs the tile to stay intact as
long as possible for impact purposes. In this case the designer would choose the pin on gap joint configuration with an e/D = 8 and a w/D = 8. This configuration has a high tolerance to failure modes and a high ultimate strength. This configuration also underwent fatigue testing conditions and was determined to be highly resistant to cyclic loading, showing no sign of damage in the ceramic tile at stress level 5. Based on these results this joint configuration is the most efficient. It is recommended to use this configuration unless there are confining geometric limitations.

It is important to be able to directly compare the design charts for DCCS structures directly to the Design Charts for the face sheet material given in in Figures 4.1 and 4.2. The combined design charts seen below in Figures 8.5 and 8.6. These charts visually display the benefits of the addition of ceramic tile and the benefits given by increasing the e/D ratio. Every design situation is different and these combined design charts provides engineers with the ability to choose what failure mode to design for. These charts provide the face sheet failure mode data in black dashed lines. The DCCS Structure failure mode lines are exactly the same as the above four Figures (Figures 8.1, 8.2, 8.3, and 8.4).
Comparing Face Sheet and DCCS Structure Design Charts

Figure 8.5: Combined Design Chart with varying w/D and c/D = 4 (Individual Face Sheet (dashed lines) and DCCS Structure under static conditions pin on solid tile (solid lines))

Figure 8.5 shows how the bearing stress for individual face sheet material and DCCS structure compare at varying w/D ratios. It can be seen that the dashed black line representing the individual face sheet material bearing failure and the DCCS Structure bending/shear failure are at similar bearing stresses. The ultimate failure of the DCCS structure is much higher than the ultimate failure of the individual face sheet material. This proves that the DCCS structure has a higher bearing strength than the individual face sheet material, which is extremely important for engineers designing for ultimate strength of a joint. It can be determined that structurally the
DCCS Structure is more efficient than the individual face sheet material and is recommended to be used.

Figure 8.6: Combined Design Chart with varying e/D and w/D = 8 (Individual Face Sheet, Solid Ceramic, and Pin on Gap DCCS Structure)

Figure 8.6 compares the bearing stress for varying e/D ratios for the individual face sheet material and DCCS Structures. It is known that varying this ratio can drastically affect the failure modes and ultimate strength of the joint. Introducing the pin on gap specimens to this further complicates this issue. It can clearly be determined that the reduced width DCCS structure is by far the least efficient
specimen from a structural standpoint. Its ultimate failure is similar to the bearing failure of the individual face sheet material. The most efficient joint configuration is the pin on gap specimen with an e/D = 8 and a w/D = 8. This clearly shows that it has the highest strength and reduced failure modes. The designer must remember that the ultimate strength of this joint has not yet been determined due to limitations discussed in the previous chapter. Therefore designing to this load level is conservative, but it is unknown to what factor of safety. It is recommended to use this joint configuration to increase the overall structural and impact resistance efficiency of the bolted joint.

8.4 Fatigue Testing in DCCS Structure

Discontinuous Ceramic Cored Sandwich Structures will be heavily used in conditions that are subject to cyclic loading. Therefore having an understanding of their fatigue performance is a necessary requirement. The baseline geometry was tested under cyclic conditions for 5 different stress levels. The stress levels were selected by using percentages under lowest static load that caused net tension failure. Stress levels 2 through 5 showed signs of hairline cracks which formed on the inside of the bolt hole on the ceramic tile. It could be determined from stiffness vs. number of cycle plots in Figure 6.3 that stress level 5 showed signs of stiffness reduction with time. This is a sign of damage occurring within the structure. This was validated as stress levels 4 and 5 were the only levels during the residual strength tests that showed any adverse affect to the cyclic loading. It was determined that at these levels, the second failure mode (bending/shear) occurred at larger displacements than usual or occurred at ultimate failure. The damage occurred within the interlayer as yielding in shear. This yielding allowed additional displacement during residual strength testing which altered the failure mode progression. Despite the change in failure modes, the
ultimate strength of the joint was not affected, however the decrease in stiffness during cyclic loading is a sign that damage has occurred and should be avoided if possible. The redundancy of the DCCS Structure is what allowed the ultimate failure load to remain constant despite damage. Despite this it can be determined that DCCS Structures have a good fatigue resistance due to the fact that severe damage did not occur to the specimen during fatigue cycling. Despite a good fatigue resistance at the loads tested, it is recommended to ensure minimal forces in each joint under cyclic loading conditions. Minimizing this will help to prevent any long term damage that could adversely affect the structural integrity of the joint. For up to one million cycles maintaining the stress levels below stress level 3 (1680 lbs or 3574 psi) for each joint would be ideal. This will minimize the amount of damage to the interlayer. However, if larger stresses are necessary understand that damage may slowly propagate causing failure modes to change or cause other forms of failure. Future fatigue testing at higher stress levels may be necessary. Since the residual strength test results under stress level 3 were similar to that of the baseline geometry the previous design charts can be used. It is recommended that engineers do not design in the range of stress level 4 or 5 unless only designing for ultimate failure.

Much like the baseline geometry, in order to truly have an understanding on the performance of bolted joints in the pin on gap region with an e/D = 8, fatigue testing was performed. Fatigue testing on this specimen geometry was completed using an identical test procedure to the baseline (W4E2) testing scenario. The pin on gap specimens with an e/D = 8 were fatigued at stress level 5 (2800 lbs). Having an understanding of how the presence of the discontinuity affects the fatigue resistance of the joint is extremely important for the design. After completing fatigue it was
determined that no damage occurred on the exterior or interior of the joint. Unlike the baseline scenario which had hairline cracks form at stress level’s 2 - 5, no hairline cracks of any kind were detected at the highest stress level for this scenario. The more compliant interlayer changes the stress distribution around the bolt hole. Specimens with an edge distance of 4 inches (e/D = 8) and the pin located on a region of discontinuity had an increased resistance to damage within the joint under cyclic loading.

8.5 Directions Toward Future Work

This work has been performed specifically on double lap joints with a single pin. As a result there is a lot of room for further work on this subject. In real life scenarios mechanically fastened joints will not use pinned joints to attach DCCS Structural Material to a structural frame. Despite the fact that pinned joints are an excellent baseline for experimental tested, the interaction between torque load levels and the performance of the bolted joint in the DCCS Structure needs to be verified. Various bolt torque levels and washer sizes all play a role in determining the most efficient joint.

Despite the durability this material has against failure modes, they are still present and can be improved upon. Inserts can be utilized to ensure that there is a larger bearing area on the DCCS Structural material. The addition of inserts can also help to absorb energy and reduce vibrations caused by cyclic loading or impact. There are various options for insert design, which can be used in the joint. These options should be investigated and eventually a design should be selected for optimal performance. The insert design can work together with the data recovered from torque bolt experiments to ensure the most optimally designed joint.
In many cases the loading conditions that are applied in direct double lap tension tests are not realistic in the field. Different loading cases, such as bending, should be investigated to determine the failure modes that occur as a result of bolted joints in these cases. Bending using a simply supported fixture in this case is already thoroughly understood, however the inclusion of bolted joints into this scenario has never been studied. Understanding the failure modes and the performance of joints for transverse loading/bending conditions would provide insight to the performance of bolted joints in DCCS Structures from a completely different design standpoint. Including the various torque and insert techniques would help to improve mechanically fastened joints in DCCS Structures.

Continuing work on this subject will ensure optimization for design loads and methodologies. Having a better understanding of how this material behaves and discovering ways to minimize failure modes is imperative to creating a safe and efficient joint in Discontinuous Ceramic Cored Sandwich Structures.
Appendix A

FACE SHEET BEARING TEST GRAPHS

Figure A.1: Bearing Stress vs. Displacement (FSW4E3)
Figure A.2: Bearing Stress vs. Displacement (FSW4E2.5)
Figure A.3: Bearing Stress vs. Displacement (FSW4E2.25)
Figure A.4: Bearing Stress vs. Displacement (FSW4E2)
Figure A.5: Bearing Stress vs. Displacement (FSW4E1.75)
Figure A.6: Bearing Stress vs. Displacement (FSW4E1.5)
Figure A.7: Bearing Stress vs. Displacement (FSW4E1.25)
Figure A.8: Bearing Stress vs. Displacement (FSW4E1)
Figure A.9: Bearing Stress vs. Displacement (FSW3E2)
Figure A.10: Bearing Stress vs. Displacement (FSW2E2)
**Figure A.11: Bearing Stress vs. Displacement (FSW1E2)**
Figure A.12: Bearing Stress vs. Displacement (FSW.875E2)
Figure A.13: Bearing Stress vs. Displacement (FSW.75E2)
Figure A.14: Bearing Stress vs. Displacement (FSW.625E2)
Appendix B

FACE SHEET FAILURES IN DESIGN CHARTS

Figure B1: Shear-out failure in face sheet (e/D = 2)
Figure B.2: Shear out failure in face sheet (e/D = 2.5)

Figure B.3: Shear out failure in face sheet (e/D = 3)
Figure B.4: Bearing failure in face sheet (e/D = 3.5)

Figure B.5: Bearing failure in face sheet (e/D = 4)
Figure B.6: Bearing failure in face sheet (e/D = 4.5)

Figure B.7: Bearing failure in face sheet (e/D = 5)
Figure B.8: Bearing Failure in face sheet (e/D = 6)

Figure B.9: Net Tension failure in face sheet (w/D = 1.25)
Figure B.10: Net Tension failure in face sheet (w/D = 1.5)

Figure B.11: Bearing failure in face sheet (w/D = 1.75)
Figure B.12: Bearing failure in face sheet (w/D = 2)

Figure B.13: Bearing failure in face sheet (w/D = 4)
Figure B.14: Bearing failure in face sheet (w/D = 6)

Figure B.15: Bearing failure in face sheet (w/D = 8)
Appendix C

DCCS BEARING TEST GRAPHS

Bearing Stress vs Displacement (W4E2)

![Graph showing Bearing Stress vs Displacement (W4E2)](image)

Figure C.1: Bearing Stress vs. Displacement (W4E2)
Figure C.2: Bearing Stress vs. Displacement (W3E2)
Figure C.3: Bearing Stress vs. Displacement (W4E1.5)
Appendix D

DCCS STRUCTURE BASELINE FAILURE MODES

Figure D.1: DCCS Structure Net Tension Failure Mode on Edge
Figure D.2: DCCS Structure Bending/Shear Failure and Face sheet Ceramic Tile Debonding
Figure D.3: DCCS Structure Bearing Failure in Face Sheet
Figure D.4: Sequence of Failure modes in DCCS Structure for Baseline Geometry
Appendix E

DCCS RESIDUAL STRENGTH BEARING TEST GRAPHS

Figure E.1: Residual Strength (Stress Level 1)
Figure E.2: Residual Strength (Stress Level 2)
Figure E.3: Residual Strength (Stress Level 3)
Figure E.4: Residual Strength (Stress Level 4)
Figure E.5: Residual Strength (Stress Level 5)
Appendix F

PIN ON DISCONTINUITY IN CERAMIC TILE SPECIMENS

Figure F.1: Bearing Stress vs. Displacement (PGW4E2)
Figure F.2: Bearing Stress vs. Displacement (PGW4E4)
REFERENCES


