CHARACTERIZATION OF DELAMINATION IN 3D WOVEN COMPOSITES UNDER STATIC AND DYNAMIC LOADING

By

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# TABLE OF CONTENTS

ACKNOWLEDGMENTS .................................................................................................................................................. 3

LIST OF TABLES ............................................................................................................................................................ 6

LIST OF FIGURES ............................................................................................................................................................ 7

ABSTRACT ........................................................................................................................................................................ 11

CHAPTER

1 INTRODUCTION .......................................................................................................................................................... 13

2 DAMAGE EVOLUTION IN 3D WOVEN COMPOSITES ......................................................................................... 22
   Materials and Microstructure .................................................................................................................................. 23
   Ballistic Impact ....................................................................................................................................................... 24
   Indentation Experiments ....................................................................................................................................... 25
   Discussion and Results ........................................................................................................................................ 25
      Ballistic Impact .................................................................................................................................................. 25
      Indentation Experiments ................................................................................................................................ 27
   Summary .................................................................................................................................................................. 28

3 STATIC SHORT BEAM SHEAR TESTS .................................................................................................................. 33
   Materials ................................................................................................................................................................. 33
   Experimental Procedure ..................................................................................................................................... 35
      Interlaminar Shear Testing ............................................................................................................................... 36
      Multi-Step Loading ........................................................................................................................................ 36
      Cyclic Loading ................................................................................................................................................ 37
   Results .................................................................................................................................................................... 38
      Interlaminar Shear Tests ................................................................................................................................. 38
      Optical Micrographs ....................................................................................................................................... 39
      Multi-Step Loading ........................................................................................................................................ 42
      Cyclic Loading ................................................................................................................................................ 44
   Summary .................................................................................................................................................................. 45

4 DEVELOPMENT OF DYNAMIC SHORT BEAM SHEAR TEST ..................................................................... 52
   Experimental Procedure ..................................................................................................................................... 52
   Materials ................................................................................................................................................................. 53
   Static Short Beam Shear .................................................................................................................................... 53
   Dynamic Short Beam Shear ............................................................................................................................... 54
   High Speed Photography .................................................................................................................................... 59
   Results .................................................................................................................................................................... 60
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>Summary of the composite specifications as well as ILSS from SBS tests.</td>
<td>51</td>
</tr>
<tr>
<td>4-1</td>
<td>Apparent ILSS and initial stiffness determined from short beam shear tests</td>
<td>69</td>
</tr>
<tr>
<td>5-1</td>
<td>Summary of the composite panels tested including average thickness (d) Z-</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>yarn fiber volume fraction ($V_{Z-yarn}$) and total fiber volume fraction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>($V_{Fiber}$)</td>
<td></td>
</tr>
<tr>
<td>5-2</td>
<td>Summary of short beam shear test results</td>
<td>93</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1-1</td>
<td>Examples composites used in aerospace and marine industries</td>
<td>20</td>
</tr>
<tr>
<td>1-2</td>
<td>Schematics of double cantilever beam test and end notch flexure test.</td>
<td>20</td>
</tr>
<tr>
<td>1-3</td>
<td>Schematic of short beam shear test</td>
<td>21</td>
</tr>
<tr>
<td>2-1</td>
<td>Schematic of 3D woven composite</td>
<td>29</td>
</tr>
<tr>
<td>2-2</td>
<td>Microscopy images of a specimen sectioned along y-z plane.</td>
<td>29</td>
</tr>
<tr>
<td>2-3</td>
<td>Schematic of the dynamic indentation test set up</td>
<td>30</td>
</tr>
<tr>
<td>2-4</td>
<td>Cross sectional images of the Induced-damage due to projectile impact on 3D woven composite</td>
<td>30</td>
</tr>
<tr>
<td>2-5</td>
<td>Cross-section along y-z plane showing low depth indentation damage</td>
<td>31</td>
</tr>
<tr>
<td>2-6</td>
<td>Cross-section along y-z plane showing damage due to intermediate indentation depth</td>
<td>31</td>
</tr>
<tr>
<td>2-7</td>
<td>Cross-section along y-z plane showing high amplitude indentation damage</td>
<td>32</td>
</tr>
<tr>
<td>3-1</td>
<td>Schematic of SBS test configuration</td>
<td>47</td>
</tr>
<tr>
<td>3-2</td>
<td>Microstructure of 3D woven composites</td>
<td>47</td>
</tr>
<tr>
<td>3-3</td>
<td>Representative load-displacement curves for all the composites</td>
<td>47</td>
</tr>
<tr>
<td>3-4</td>
<td>Optical micrographs detailing the observed damage in each of the four composite architectures</td>
<td>48</td>
</tr>
<tr>
<td>3-5</td>
<td>Multi-step load-displacement curves for each composite architecture</td>
<td>49</td>
</tr>
<tr>
<td>3-6</td>
<td>Residual stiffness vs. energy from multi-step loading test results</td>
<td>50</td>
</tr>
<tr>
<td>3-7</td>
<td>Comparison of load-displacement curves for monotonic and cyclic testing</td>
<td>50</td>
</tr>
<tr>
<td>3-8</td>
<td>Normalized stiffness vs. number of cycles</td>
<td>51</td>
</tr>
<tr>
<td>4-1</td>
<td>Schematic and optical micrograph of 3D woven angle interlock composite specimen</td>
<td>65</td>
</tr>
<tr>
<td>4-2</td>
<td>Dynamic short beam shear test fixture using a modified Hopkinson bar apparatus</td>
<td>65</td>
</tr>
</tbody>
</table>
Typical data acquired from dynamic short beam shear test ........................................ 66
Representative load-displacement response of angle interlock 3D woven composite .......................................................... 67
High speed images of quasi-static SBS test at 0.01 m/s ........................................ 68
High speed images of dSBS test at 10 m/s ........................................................... 69
Schematic of quasi-static short beam shear test .................................................... 85
Image of dynamic short beam shear test using modified Hopkinson bar apparatus ........................................................................... 85
Load and strain signals from dynamic short beam shear test ................................ 86
Load-deflection response of composites subjected to quasi-static and dynamic short beam shear tests .......................................................... 87
Summary of SBS test results for various composites as a function of loading rate ........................................................................... 88
Images of damage development in each composite architecture tested at 10 m/s ............................................................................. 89
Damage initiation and propagation in a OW-10 specimen .................................. 90
Selected load displacement curves for quasi-static SBS tests and residual stiffness tests ........................................................................ 91
Plot of normalized initial SBS stiffness residual, blunt impact stiffness, and residual dSBS stiffness .......................................................... 92
Quasi-static short beam shear tests of 2DPW at a rate of 0.1 mm/s .................... 98
Quasi-static short beam shear tests of 2DPW at a rate of 1.0 mm/s .................... 98
Quasi-static short beam shear tests of 2DPW at a rate of 10 mm/s .................... 99
Quasi-static short beam shear tests of OW-3 at a rate of 0.1 mm/s ................. 99
Quasi-static short beam shear tests of OW-3 at a rate of 1.0 mm/s ................. 100
Quasi-static short beam shear tests of OW-3 at a rate of 10 mm/s ................. 100
Quasi-static short beam shear tests of OW-6 at a rate of 0.1 mm/s ............... 101
Quasi-static short beam shear tests of OW-6 at a rate of 1.0 mm/s ............... 101
A-9  Quasi-static short beam shear tests of OW-6 at a rate of 10 mm/s .................. 102
A-10 Quasi-static short beam shear tests of OW-10 at a rate of 0.1 mm/s .......... 102
A-11 Quasi-static short beam shear tests of OW-10 at a rate of 1.0 mm/s .......... 103
A-12 Quasi-static short beam shear tests of OW-10 at a rate of 10 mm/s .......... 103
A-13 Quasi-static short beam shear tests of D1BL at a rate of 0.1 mm/s .......... 104
A-14 Quasi-static short beam shear tests of D1BL at a rate of 1.0 mm/s .......... 104
A-15 Quasi-static short beam shear tests of D1BL at a rate of 10 mm/s .......... 105
A-16 Quasi-static short beam shear tests of OW-X at a rate of 0.1 mm/s .......... 105
A-17 Quasi-static short beam shear tests of OW-X at a rate of 1.0 mm/s .......... 106
A-18 Quasi-static short beam shear tests of OW-X at a rate of 10 mm/s .......... 106
A-19 Quasi-static short beam shear tests of AI-TT at a rate of 0.1 mm/s .......... 107
A-20 Quasi-static short beam shear tests of AI-TT at a rate of 1.0 mm/s .......... 107
A-21 Quasi-static short beam shear tests of AI-TT at a rate of 10 mm/s .......... 108
A-22 Quasi-static short beam shear tests of L2L at a rate of 0.1 mm/s .......... 108
A-23 Quasi-static short beam shear tests of AI-L2L at a rate of 1.0 mm/s ......... 109
A-24 Quasi-static short beam shear tests of AI-L2L at a rate of 10 mm/s .......... 109
A-25 Quasi-static short beam shear tests of AI-20 at a rate of 0.1 mm/s .......... 110
A-26 Quasi-static short beam shear tests of AI-20 at a rate of 1.0 mm/s .......... 110
A-27 Quasi-static short beam shear tests of AI-20 at a rate of 10 mm/s .......... 111
A-28 Quasi-static short beam shear tests of AI-60 at a rate of 0.1 mm/s .......... 111
A-29 Quasi-static short beam shear tests of AI-60 at a rate of 1.0 mm/s .......... 112
A-30 Quasi-static short beam shear tests of AI-60 at a rate of 10 mm/s .......... 112
B-1  Dynamic short beam shear tests of 2DPW at a rate of 10 m/s .................. 113
B-2  Dynamic short beam shear tests of OW-3 at a rate of 10 m/s .................. 113
B-3  Dynamic short beam shear tests of OW-6 at a rate of 10 m/s .................. 114
B-4  Dynamic short beam shear tests of OW-10 at a rate of 10 m/s ..................... 114
B-5  Dynamic short beam shear tests of D1BL at a rate of 10 m/s ....................... 115
B-6  Dynamic short beam shear tests of OW-X at a rate of 10 m/s ....................... 115
B-7  Dynamic short beam shear tests of Al-L2L at a rate of 10 m/s ...................... 116
B-8  Dynamic short beam shear tests of Al-TT at a rate of 10 m/s ....................... 116
B-9  Dynamic short beam shear tests of Al-20 at a rate of 10 m/s ....................... 117
B-10 Dynamic short beam shear tests of Al-60 at a rate of 10 m/s ....................... 117
CHARACTERIZATION OF DELAMINATION IN 3D WOVEN COMPOSITES UNDER STATIC AND DYNAMIC LOADING

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Recent years have shown an increase in the use of structural composites in many industries. This increase is a response to the need for lightweight high strength materials to reduce weight and increase performance. Many structures are often subjected to impact loading events. Due to the susceptibility to delamination damage caused by such impacts the characterization of delamination damage in laminated composites becomes critical to creating safe designs. 3D woven composites are one method in reducing or mitigating delamination damage. In this study several 3D woven composites were tested at a variety of loading rates to gains insight into the effect of weaving architecture on the delamination resistance and damage tolerance of a woven composite. Preliminary impact tests were performed to examine the damage mechanisms during high velocity and low velocity impact of a 3D woven composite. Tests are performed using the short beam shear test. This test method was used to examine several designs of composites through monotonic and cyclical static testing. A new method for performing dynamic short beam shear tests was developed and results will be presented detailing the effect of loading rate on the performance of these
materials. This test method was modified to perform blunt impact tests on small test coupons. Beam specimens were cut from these coupons which include the damaged region and bend tests were performed on these specimens to determine the effect of damage by examining the residual stiffness of the samples. The results from these tests show unanimous agreement that 3D woven composites have lower damage resistance but higher damage tolerance when compared to traditional 2D woven composites.
CHAPTER 1
INTRODUCTION

Composite materials are known to exhibit very high strength and stiffness to weight ratios which allow them to be utilized in designs which require high performance. In addition, laminated composites may be specifically engineered for a given application to maximize strength and reduce weight making them useful in the design of structures. For this reason composite materials have been used in the design and construction of vehicles for many years (Figure 1-1). It is not uncommon to find composites used in the construction of small boats such as canoes and kayaks as well as in the construction of large watercraft. In recent years, Naval vessels have been developed which utilize advanced composites in the hulls and superstructures such as the Finnish Hamina class missile boat and Swedish Visby class corvette. The automotive industry has had limited use of composites over the years. Examples of large scale use of composite in the automotive industry are mostly limited to high end sports cars and racing vehicles. Examples of such applications include the Chevrolet Corvette and the McLaren F1. These vehicles represent only a small percentage of the vehicles used today. However commercial transportation has benefited from the advantages of composite materials especially in the areas of high speed railways and commercial airliners. Interestingly early flight greatly benefited from the use of low weight materials such as sandwich composites and primitive fiber reinforced composite materials. However these materials were quickly replaced with light alloys such as aluminum and magnesium. Today the aerospace industry has shifted back to advanced composite materials as seen in the construction of the Boeing 787 Dreamliner. The reason for this shift is the necessity to
further reduce weight and increase performance in order to counter the ever increasing price of fuel.

Vehicles used in transportation are often subjected to impact loading due to collisions with other vehicles and objects. While large impacts or collisions often necessitate major repairs, damage due to small impacts are often overlooked. While small impulse (or impact) loading is not a concern for many materials (in fact impact on metals may be used to increase strength, e.g., shot peening), this type of loading may lead to catastrophic failure in laminated composites due to potential delamination and subsequent damage propagation during service. In metallic materials impact damage in the form of plastic deformation remains mostly confined to the region of impact, however in laminated composites delamination due to impact may slowly propagate during normal service conditions leading to further damage, loss in stiffness and ultimately failure. For this reason it becomes necessary, to understand the nature of damage resistance and damage tolerance of composite materials.

Numerous attempts have been made to strengthen or increase the damage resistance and damage tolerance of laminated composites. Toughened matrices, such as rubber toughened epoxies [1, 2], or the addition of through-thickness reinforcements (e.g., z-pinning, stitching, tufting or 3D weaving) [1-3] have often been used to increase the toughness of laminates. 3D weaving can be utilized to enhance the through-thickness strength of a laminate [4] while also allowing the production of complex pre-form shapes with continuous fiber reinforcement [2]. While 3D composites have been around for some time, their use has often been limited due to high cost of manufacturing. Also, manufacture of parts from such composites with repeatable
properties is nontrivial. However, recently there has been a growing interest in these materials as the cost of their manufacture has decreased dramatically and the demand for strong and damage-tolerant lightweight materials has increased.

A number of studies have been conducted to determine the tensile properties of 3D reinforced composites. Tensile tests at low loads revealed crack initiation even in the elastic regime [5]. The crack formation was associated with the resin rich areas near the z-yarn reinforcement [6]. Compressive tests performed on both stitched and woven 3D composites revealed that the geometric flaws created by the weaving process significantly reduce the yield strength when compared to stitched composites [7]. However the woven composites showed larger strain to failure whereas the stitched composites failed catastrophically at low levels of strain. Also composites are reported have very good fatigue performance, however tests on various types of composites revealed that reinforcements, in general, show a decrease in the fatigue life [8-10].

To determine the effectiveness of 3D weaving on inter-laminar strength, several test methods have been utilized. The double cantilever beam (DCB) test [11] has been used to determine the mode I fracture toughness of composites whereas the end-notch flexure (ENF) test [12] has been used to determine mode II fracture toughness. Schematics of DCB and ENF are shown in Figure 1-2. Both methods require a pre-crack either produced during manufacture using Teflon® tape or by cutting a crack into the edge of a sample. When performing DCB tests on high strength composites (such as stitched or 3D woven composites), premature failure often occurs due to the compressive stress caused by bending. To ensure proper failure, a test method has been developed [13] in which a combination of axial and transverse loads are applied
to the test specimen. The axial tensile force prohibits the compressive bending failure
while the transverse load produces mode I fracture. Other methods have also been
developed to produce mixed-mode loading [14]. Studies using these methods have
shown a significant increase in the mode-I fracture toughness and a moderate increase
in the mode-II fracture toughness was noted in reinforced composites [1, 15, 16].

Another method of determining delamination resistance is the short beam shear
(SBS) test [17-19] which is used to determine the interlaminar shear strength (ILSS).
While DCB and ENF tests require pre-cracks SBS test specimens do not and therefore
may be easily prepared from a composite plate by sectioning the plate into the desired
dimensions. The SBS test uses a three-point bending fixture to apply load to the
composite specimen with a large height to length ratio. A schematic of the SBS test
fixture is shown in Figure 1-3. On either side of the central load a large shear stress is
generated just beneath the top surface. Due to the short span relative to the thickness
of the composite, the bending moment generated in the specimen is limited thus
reducing the level of tensile and compressive bending stresses. The central punch
creates a large contact stress which can cause local damage and lead to crushing of
the specimen if the delamination strength is significantly high. To reduce this contact
stress and create a more uniform load distribution, 4-point [17] bending and 5-point [20]
bending fixtures have been adopted. Other limitations to the use of SBS testing include
a greatly underestimated ILSS of the material [17, 21, 22] due to the simplified
assumption of shear flow equations which neglect the effect of concentrated load.
Despite these disadvantages, SBS continues to be a useful test for qualitative
comparison of the behavior of different material architectures as well as for quality 
control [17, 21].

Short beam shear testing may also be used in the study of impact behavior of 
composites. The large contact stresses created by the punch during SBS testing 
mimics the localized stresses generated during impact. Studies into the impact 
behavior of composites have shown that the large compressive and transverse shear 
stresses created beneath a projectile dominate the failure of the material [25, 26]. Since 
the SBS test creates a similar state of stress, the results from these tests may be used 
to establish a baseline in which dynamic test results can be compared or to gain a 
fundamental understanding of damage evolution during impact.

Indentation or “punch” test is another type of test method for determining the 
mechanical response of composite materials. This method is particularly effective in 
examining the delamination strength of the composite as well as for understanding the 
evolution of damage mechanisms during low velocity impact. A variety of methods are 
used to perform this test including static indentation using universal testing machine 
[23], low velocity impact with instrumented drop tower [24, 25] and dynamic indentation 
using the split Hopkinson pressure bar (SHPB) technique [26, 27]. In these studies, 3D 
woven composites were found to absorb more energy and survive more repeated 
impacts before perforation compared to 2D woven composites. Low velocity drop tests 
on 2D plain woven, 3D stitched, and 3D pinned composites revealed that at low energy 
impacts, both pinned and stitched composites enhanced the inter-laminar shear 
strength [28]. However at higher loads the 3D pinned composite did not show any 
improvement over the 2D woven specimen, while the 3D stitched composite revealed
much better strength. On the other hand, experimental studies by Grogan et al. [29] have also clearly shown that 3D woven composites provide better resistance to delamination under ballistic conditions than 2D woven composites. Clearly, all these results point to the fact that 3D stitching and weaving may not always be beneficial.

Since delamination is a primary mode of failure in composites during impact or impulse loading, it is important to characterize the response under dynamic loading conditions. Several techniques exist to perform low velocity impact tests. As mentioned above, the most common technique is the drop tower test where a given impact energy is imparted to a composite specimen. A variety of composite structures including stitched and 3D woven composites have been tested using this method [24, 25, 30] at various impact velocities. The disadvantage with this method is the rate of loading is not uniform throughout the impact event. Damage in composites can be evaluated using non-destructive techniques including ultrasonic measurements. Additionally, the effect of induced damage during impact tests are often evaluated using post mortem quasi-static compression after impact (CAI) tests [31, 32]. Drop tower tests use a combination of velocity and mass to impart desired impact energy. Another popular method to conduct dynamic impact tests on composites uses gas guns for the determination of impact damage resistance [33, 34]. Similar to drop tower tests, ballistic impact relies on projectile mass and velocity to impart a certain level of impact energy. In both of these tests it is difficult to control or predict displacement during impact. A third method used to perform dynamic tests on composites is the split Hopkinson pressure bar (SHPB) which is commonly used to evaluate high strain rate response of many different engineering materials [35, 36]. Traditional SHPB test utilizes elastic longitudinal stress
waves traveling in long high strength steel bars to perform high strain rate tests. The sample shapes may be varied to perform a variety of different tests. The SHPB has been used to determine the dynamic compressive strength [37, 38], tensile strength [39], and shear strength [40, 41] of composites.

In this study a number of 2D and 3D woven composites were tested using the SBS test method. This test method was modified in a number of ways to evaluate the effect of weaving architectures on both damage resistance and damage tolerance. A new method for performing dynamic SBS tests was developed using a modified SHPB. Results from static and dynamic SBS tests were compared to determine how loading rate affects the response of each architecture. This method for dynamic SBS was then modified to perform blunt impact experiments which were used to determine the damage tolerance of each composite when subjected to dynamic loading. Developing these experimental methods provides a tool which may be used to understand the relationship between damage resistance and damage tolerance in woven composites. This knowledge may then enable engineers to optimize composite architectures to resist and withstand damage caused by repeated impact loading.
Figure 1-1. Examples composites used in aerospace and marine industries. a) de Havilland Mosquito bomber constructed using balsa and plywood sandwich structures and composite skin and b) Finnish Hamina class missile boat with carbon fiber superstructure.

Figure 1-2. Schematics of double cantilever beam (DCB) test and end notch flexure (ENF) test used to determine fracture strengths of composite materials.
Figure 1-3. Schematic of short beam shear test.
CHAPTER 2
DAMAGE EVOLUTION IN 3D WOVEN COMPOSITES

An initial study was performed on a preliminary 3D woven composite to evaluate the damage induced when subjected to high rates of loading. A qualitative analysis of experimental results from small caliber ballistic impact and dynamic indentation on a 3D glass fiber reinforced composite is presented. Microscopic analysis of the damaged specimens revealed that the preliminary 3D weaving scheme inherently contains two weak planes which act as potential sites for delamination. It is concluded that while the z-yarns may be effective in limiting the delamination damage at low loads and at low rates of impact, at high loads and high loading rates delamination continues to be the dominant failure mode in 3D woven composites. It is shown that dynamic indentation can be used to capture the progression of damage during impact of 3D woven composites.

The major benefit of through-thickness reinforcement in a composite is its increase in impact damage resistance. Transverse impact tests performed [42] on a 3D woven composite, revealed that the damage mechanisms were dependent on the loading rate. Under low loading rates failure of the composite occurred due to excessive tensile and compressive stresses created by the bending moment. At higher loads the damage manifested in terms of matrix failure, fiber failure, and fiber pullout. It was noted that the z-reinforcement prevented delamination. Mouritz [15] studied a 3D woven composite subjected to high velocity ballistic impact and shock loading. While the z-yarn weaving did not prevent delamination during high velocity ballistic loading, it did reduce the damage during shock loading. It was inferred that ballistic loading at rates much higher
than the ballistic limit was the cause of severe delamination regardless of the level of z-reinforcement.

Low velocity drop tests on 2D plain woven, 3D stitched, and 3D pinned composites revealed that at low energy impacts, both pinned and stitched composites enhanced the inter-laminar shear strength [28]. However at higher loads the 3D pinned composite did not show any improvement over the 2D woven specimen, while the 3D stitched composite revealed much better strength. On the other hand, experimental studies by Grogan et al. [29] have also clearly shown that 3D woven composites provide better resistance to delamination under ballistic conditions then 2D woven composites.

**Materials and Microstructure**

A 3D glass fiber reinforced epoxy composite of thickness 16.5 mm was used in this study. The composite specimen was supplied by the US Army Research Laboratory, Aberdeen Proving Grounds, MD. The composite was made of 27 layers of tows stacked in a cross-ply sequence, with 13 layers in the 0° direction (x-tows) and 14 layers in the 90° direction (y-tows). Z-yarns are then used to weave the y-tow layers together, i.e. the z-yarn runs parallel to the x-tows. To analyze the microstructure, each specimen surface was polished using traditional metallographic techniques and then a final polish using a 0.05 μm colloidal silicon/alumina mixture. A 3D view of the composite microstructure and a schematic of the composite architecture are shown in Figure 2-1. It is shown that the z-yarns do not fully stitch all 27 layers of tows. Instead, two z-yarns are used: one weaves 9 of the y-tow layers and 8 intermediate x-tow layers, while the other weaves the remaining 5 y-tow layers and 4 x-tow layers. This weaving scheme leaves one layer of x-tows unstitched between the two stacks of woven tows as seen in Figure 2-1B. Since this layer is not woven, it is susceptible to delamination. To
minimize this weakness, the above weaving scheme is alternated in each adjacent row (i.e. on a given row one z-yarn weaves the top 17 layers together while the other weaves the bottom 9 layers. In the adjacent row one z-yarn weaves the top 9 layers and the other z-yarn weaves the bottom 17 layers). While this scheme marginally strengthens the weak x-tow layer, it does create two layers which have half the number of z-yarns running through them. The schematic in Figure 2-1 illustrates these concepts.

Using an optical microscope equipped with a digital camera and image analysis software, we have measured various dimensions of the tows and yarns of the 3D composite. As can be seen in Figure 2-2, the x-and y-tows are approximately rectangular in shape. They measure approximately 2.5 mm in width and 0.6-0.7 mm in height. The y-tows near the turn of the z-yarns are crimped into a semicircular shape. The z-yarns are more elliptical with major and minor dimensions around 1.3 mm and 0.5 mm, respectively. At high magnification (Figure 2-2C) the dimensions of the individual fibers within a tow can be measured. The average diameter was found to be around 10 μm. By counting the number of fibers within a given area of the tow, and using the average fiber diameter (10 microns), the fiber volume fraction was determined to be approximately 65% within the tows. The overall fiber volume would be much less than this value, due to the presence of large pockets of epoxy caused by the weaving of z-yarns.

**Ballistic Impact**

Small caliber ballistic impact tests were performed on specimens of size 40 mm x 40 mm cut from the 3D woven composite tiles. The specimens were held against a 9.5 mm thick sheet of oriented strand board (OSB). The OSB board served both as a
support structure as well as a witness plate to record penetration of the target. A model AR-15 rifle was used to fire a standard projectile at the specimen located approximately 18 m away. Two projectiles were used: A 5.56x45 NATO 55 grain (M193) projectile with a lead core and full metal (copper) jacket, and 5.56x45 NATO 62 grain (M855) projectile with a steel tip ahead of the lead core in a full metal (copper) jacket. Typical bullet velocities were around 940 m/s.

**Indentation Experiments**

Using a modified SHPB [35], dynamic indentation tests were performed on specimens cut from the 3D woven composite sample. In this method, momentum trapping technique [43] on the incident bar of a SHPB is used (Figure 2-3). A striker bar (50.8 mm diameter and 600 mm long) launched from a gas gun impacts the incident bar (50.8 mm diameter and 2.5 m long) creating one-dimensional stress waves within the incident bar. At the opposite end, a hardened steel conical indenter (with a cone angle of 45° and tip radius of 1 mm) is attached to the incident bar. The composite specimen is held against a rigid steel anvil. The stress waves travel towards the indenter and cause an indentation into the specimen. The momentum-trap ensures that only a single indentation is imparted onto the specimen. The duration of the impact was approximately 240 μs. Using the impact velocity and damage zone size it is possible to estimate an average strain rate during the indentation [21]. More details of the dynamic indentation process are provided in [35, 43, 44].

**Discussion and Results**

**Ballistic Impact**

In these experiments, the projectiles penetrated both the specimen and the OSB. The specimens sustained significant damage as seen in Figure 2-4. In both cases, fiber
breakage and bulging were present on both the front (impact) surface as well as the back (exit) surface (Figure 2-4A). The M193 projectile resulted in a large hole (approximately 25mm) in the OSB indicating a significant amount of expansion of the projectile upon impact, whereas the M855 projectile resulted in a much smaller hole (approximately 13 mm). The specimens impacted by the M193 projectile generated considerable delamination (Figure 2-4C). Extensive delamination damage was clearly visible towards the back surface of the specimens impacted with the M855 projectile (Figure 2-4B). These specimens were sectioned to assess the level of damage on the interior of the material. Bulk failure of the material in terms of fiber brakeage (tensile or shear failure), delamination, and matrix failure was clearly visible in the path of the projectile (Figure 2-4A). Surrounding this damaged region is a zone of extended delamination. Copper and lead fragments of the projectile were found in these regions. To enhance the contrast of the damaged regions, especially the small delamination regions away from the projectile path, a stain was introduced into the damaged composite. It was noticed that in some cases the delamination was prevented from propagating to the edge of the sample due to the z-yarn reinforcement. However, severe delamination extending far into the specimen in the lateral direction was clearly visible along one of the weak planes discussed before (Figure 2-4B). This mode of delamination suggests that the current 3D weave architecture creates inherently weak planes which are susceptible to severe delamination due to impact loading. It was noted by Mouritz [15] that although 3D reinforcement can prevent delamination during impact events, when a composite is subjected to impact at much higher velocities than
its ballistic limit, the delamination can still propagate through the specimen and the
effect of z-fiber reinforcement is negligible.

**Indentation Experiments**

In this study the striker bar was launched at three different velocities resulting in
different depths of indentation in three specimens. Consequently, the level of damage
was also different in each specimen. The average strain rate for each test was
estimated to be 1000/s. Immediately after each indentation, a strong smell of burnt
epoxy was noted in each of the tests. This smell was also noted during ballistic testing.
The goal of this experiment was simply to examine the level of damage and the damage
propagation characteristics within the composite as depth of penetration was increased
while the duration of the indentation was kept constant. The indenter penetrates the
specimen and creates a zone of damage consisting of matrix failure and fiber breakage.
The severity of damage increased with increase in indentation depth as shown in
Figures 2-5, 2-6, and 2-7. At low depths, the damage was mostly confined to a small
zone surrounding the indentation and mostly consisted of delamination and matrix/fiber
failure (Figure 2-5). Small cracks are also present in the pockets of epoxy created by
the z-yarn. At higher depths of indentation the size of the zone consisting of matrix and
fiber failure increased. Delamination cracks propagate away from the indentation region
but are often arrested at the z-yarn. However delamination is most severe along the
weak planes (Figure 2-1B) with less reinforcement and extends to the specimen edge
as seen in Figures 2-6 and 2-7. As the depth on indentation is further increased,
delamination occurs consistently between all layers. At the highest depth the presence
of “burnt” epoxy was detected indicating a significant rise in temperature during the
dynamic indentation process.
Clearly, the above dynamic indentation experiments capture the initial stages of damage during the ballistic impact. The dissipation of energy due to impact event on a 3D woven composite seems to occur through a sequence of damage mechanisms. At low-depths damage manifests into matrix cracking and fiber breakage whereas at high-penetration depths delamination dominates. The 3D stitching may be more effective in preventing delamination damage at low depths but at higher loads (depths) delamination continues to be a prominent damage mode in 3D composites.

Summary

Clearly in the tests described here, delamination along the weak layer seems to be the most severe weakness in the current 3D woven composite. It is also noticed that although z-yarns assist in reducing delamination during initial penetration, at high velocities as well as at large indentation depth, the 3D woven composites utilized in this study were susceptible to delamination damage. In ballistic tests it is noted that damage was highly dependent on the type of projectile used. Although both M855 and M193 projectiles have similar ballistic characteristics, the damage caused by their impact is very different most likely due to the deformation of the projectile. The above features are also consistent with the damage induced during dynamic indentation. While at low depth indentation the damage was limited to matrix cracking and fiber breakage, at high depth indentation delamination continues to be the dominant damage mode.
Figure 2-1. Schematic of 3D woven composite A) 3D representation of the woven composite. Each woven layer is color enhanced to add clarity. B) Schematic of the z-yarn reinforcement scheme in two adjacent planes revealing the position of the weak layer.

Figure 2-2. Microscopy images of a specimen sectioned along y-z plane A) x tows showing rectangular cross-section, B) cross-section of a z yarn and the weak layer, and C) high magnification image showing individual glass fibers.
Figure 2-3. Schematic of the dynamic indentation test set up. The inset shows a photograph of the steel indenter.

Impact face

Figure 2-4. Cross sectional images of the Induced-damage due to projectile impact on 3D woven composite. A) Cross section on y-z plane revealing fiber breakage and delamination due to M855 projectile, B) severe delamination along the weak plane, and C) x-z plane of specimen showing extensive delamination due to M193 projectile.
Figure 2-5. Cross-section along y-z plane showing low depth indentation damage consisting of matrix cracking and fiber breakage.

Figure 2-6. Cross-section along y-z plane showing damage due to intermediate indentation depth. A) Small delaminations arrested by z-yarn, and B) large delamination along weak layer.
Figure 2-7. Cross-section along y-z plane showing high amplitude indentation damage. A) Several delaminated layers and crack formation within y-tows. B) Delamination along weak layer of x-tows.
CHAPTER 3
STATIC SHORT BEAM SHEAR TESTS

Using the short beam shear test methods several tests (Figure 3-1) were conducted on woven composites including a single plain woven laminate and several 3D woven composites. These tests include monotonic, multi-step and cyclic short beam shear tests. The test results were used to determine the effect of z-yarns on the inter-laminar shear strength as well as the multi-loading behavior. The presence of z-yarns was found to affect not only the inter-laminar shear strength of the composite but also the behavior of the composite beyond the elastic limit. Microscopic examination of the damaged specimens revealed large delamination cracks in 2D woven composites while delamination cracks were hindered by z-yarns in 3D composites. This crack arrest phenomena resulted in a reduction in inter-laminar crack lengths and a higher distribution of the micro-cracks throughout the 3D composite. The multi-step and cyclic loading tests are found to be useful in the monitoring of specimen behavior during short beam shear testing. The induced damage was quantified in terms of the loss of strength and stiffness during each loading cycle. It was found that while the 2D composites have higher damage resistance, the 3D composites have a higher damage tolerance.

Materials

Several different woven composite plates measuring 150 mm x 150 mm and approximately 6.4 mm thick were supplied by the US Army Research Laboratory, Aberdeen Proving Grounds, MD. The woven pre-forms were manufactured by t.e.a.m. inc., Woonsocket, RI, using S-2 glass yarns of different linear densities. The pre-forms were consolidated using vacuum assisted resin transfer molding (VARTM) process with SC-15 epoxy. The orientation of the composite panels is defined such that the stuffer
yarns are along the $x$-axis while the fill yarns are along the $y$-axis. The $z$-axis defines the thickness direction. The microstructure of each architecture was examined using optical microscopy. Small specimens were carefully sectioned using a Buehler®, Lake Bluff, IL, low-speed diamond saw to minimize damage to the specimen. These specimens were then polished using a LECO®, St. Joseph, MI, auto-polisher following traditional metallographic techniques. Optical microscopic images were captured at low magnification detailing the weaving architecture along the $x$-$z$ plane. A schematic detailing the woven architecture and the optical images of the microstructure for all the composites are shown in Figure 3-2. The thickness, the estimated total fiber volume fraction for each architecture and the nominal percentage of z-yarns relative to the total fiber in the material are listed in Table 3-1. The following four composites were tested:

1) A baseline 2D woven laminated composite (referred to as BL in the subsequent discussions) consisting of nine layers of plain woven S-2 glass fibers with an SC-15 epoxy matrix. The layers were stacked in a $[(0^{pw} / 45^{pw})_2 / 0^{pw}]$, sequence, symmetric about the mid-plane, where the superscript $pw$ refers to plain weave. Due to its common use, well-known architecture, and for the sake of brevity, its microstructure is not shown here.

2) A 3% orthogonally woven 3D composite (Figure 3-2A), designated OG3, with a modified orthogonal weave and approximately 3% of the fiber volume consisting of z-yarns. This panel consists of 5 warp stuffer and 6 fill tows. A single warp weaver (or z-yarn) is woven around each column of fill tows. Two additional warp yarns weave the top and bottom fill tows. From the optical micrograph, shown in Figure 3-2A, it is noted that the z-yarns do not follow a vertical straight path through the thickness of the panel,
instead form an “S” shaped curve. The 3D weaving also creates large pockets of matrix material within the composite structure as indicated in the figure.

3) A 10% orthogonally woven 3D composite (Figure 3-2B) designated as OG10, consisting of 5 warp stuffer and 6 fill tows with two z-yarns weaving each column of fill tows. These z-yarns weave from the top and bottom of the composite and cross at the midsection of the panel. The z-yarns account for approximately 10% of the total fiber volume.

4) An angle interlock 3D woven composite (Figure 3-2C), designated as AI, containing columns of fill yarns in a 3-2 alternating pattern. Six warp weaver yarns are woven through the thickness of the plate at an 18° angle to the x-axis. There are no warp stuffer yarns present in this design. It was noted that large epoxy pockets were present in the structure similar to the orthogonal 3D woven composite. This weaving pattern contains the most undulation of all of the composite panels tested.

**Experimental Procedure**

To determine the effect of z-yarn architecture and z-yarn volume fraction on the behavior of the composites, short beam shear (SBS) tests were performed as per ASTM D2344 [18]. This method uses a three point bending fixture where the specimen is simply supported on two rollers with a fixed span of 35 mm and loaded with a central punch as shown in Figure 3-1. The specimens are loaded using a hydraulic MTS®, Eden Prairie, MN, testing machine using displacement control. The rate of loading, number of cycles, and total displacement are varied as described below. The anisotropic architecture of the 3D woven composites shown in Figure 3-2 results in an unequal strength along the warp and fill directions. Initially tests were conducted along these two directions on each composite. For the sake of brevity only the results from
specimens tested in the warp direction will be discussed as this direction represents the weakest and therefore the most likely direction of failure.

**Interlaminar Shear Testing**

Several test specimens measuring 50.8 mm x 25.4 mm were cut from each plate using a high-speed diamond saw. An average of five tests were performed on each composite. The applied load was measured using an inline static load cell. Both load and crosshead displacement were recorded during each test. The specimens were loaded at a rate of 1.0 mm/min and each specimen was loaded up to a central displacement of 2 mm to determine the load required to initiate failure in the specimen as well as the post failure behavior of the material. To compare the four composite structures the apparent ILSS is then calculated. Recall from above that this value does not necessarily represent the strength of the material but can be used to compare the relative performance of the different composites. The apparent ILSS is determined by the following formula [18]:

$$ ILSS = \frac{0.75 P_b}{b d} $$

where $P_b$ is the peak load, $b$ is the width, and $d$ is the thickness of the specimen. After the tests, specimens were sectioned and polished for optical microscopic observation. A dye was applied to the surface to enhance the visibility of damage in the interior of the composite.

**Multi-Step Loading**

Specimens were repeatedly loaded to incrementally larger displacements using the short beam shear test method. Initial loading sequences were 0.5 mm and 1.0 mm displacements followed by increments of 0.25 mm until a maximum displacement of 2
mm was reached. For each loading step the rate of loading was 1 mm/min. The total input energy ($U_t$) was determined by integrating the load displacement curve up to the final displacement. For each subsequent loading step the additional energy required for the additional displacement was added to the initial input energy. For the loading and subsequent reloading cycles the stiffness of the specimen was also calculated from the slope of the initial linear portion. For each cycle, a residual stiffness ratio was determined by dividing the stiffness from each reloading cycle by the initial stiffness. This residual stiffness ratio ($K_r$) for each reloading can then be plotted against the total energy from the previous cycles. Using this method it is possible to predict the behavior of each composite architecture, subjected to different input energies and determine the effect of z-yarns on the residual stiffness.

**Cyclic Loading**

Repeated loading can assist in determining the effect of z-yarns on the damage tolerance of the composite. For this purpose, short beam specimens were repeatedly loaded in displacement control for a selected number of cycles. Two sets of tests were performed: In the first test, each specimen was loaded in the initial linear regime (up to 0.8 mm deflection) for 250 cycles. The loading rate for this test was increased to 5 mm/min to reduce the time required to perform each test. In the second set of tests each specimen was loaded at a rate of 5 mm/min to a displacement just beyond the peak load determined from monotonic loading (1.5 mm deflection) for 20 cycles. The load at the final displacement during each cycle was recorded during the test. This load was normalized after each subsequent cycle by the load determined from the first cycle. The rate at which the stiffness decreases in each cycle during the test provides insight
into the effect of z-yarns on the propagation of damage in both the linear region and the region beyond the peak load.

Results

Interlaminar Shear Tests

For each composite architecture tested, a load-displacement curve was selected which best represents the average of five separate test specimens. The typical load-displacement curves for each of the four materials are shown in Figure 3-3A. The material response for each composite shows a nearly linear elastic trend during the early stage of loading. This continues until an apparent elastic limit is reached. At this point the behavior of the material follows one of three trends: the load decreases, remains constant, or increases.

Both the BL and OG3 composites showed a significant load decrease just beyond the peak load. The rate at which the load decreased then tapered off and the response began to plateau at a relatively constant load. The BL composite achieved the highest peak load among all the composites and maintained a higher load at 2 mm displacement compared to the OG3 composite.

The OG10 composite behaved much differently than the above two. The material reaches a peak load, slightly less than the OG3 composite, but then maintains that load over the remainder of the test. The load at the final displacement of 2 mm is slightly higher than the final load of the baseline material.

The AI composite reaches its elastic limit at the lowest load among the four composites. However, after this point the load continues to increase with intermittent small load drops which are accompanied by an audible crack. This architecture achieves the highest load at the final 2 mm displacement. For clarity, the load-
displacement behavior of all the composites beyond the elastic limit is shown in detail in Figure 3-3B.

From the load histories, the apparent ILSS is calculated using Equation 3-1. An average ILSS value is found from 5 tests for each composite and is reported in Table 3-1. It appears that as the percentage of z-yarn increased the apparent ILSS decreased. However the drop in strength after the initiation of failure at the maximum load decreases as the percentage of z-yarn increases as seen in Figure 3-3B. Thus a higher load is achieved at the final 2 mm displacement for the composites with a higher volume fraction of z-yarns. This result would indicate that while the damage initiation may occur at a lower load, the damage tolerance of the material increases with the addition of z-yarns. In a study by Rao et al [45] it has been shown that the in-plane properties decrease with the addition of 3D reinforcements when compared to equivalent unidirectional laminates. This decrease has been attributed to several factors including damage induced during the weaving process [10], large epoxy pockets, and the additional undulations (stress concentrations) created by the weaving architecture [6, 46]. It is likely that these defects cause premature failure in the composite.

Optical Micrographs

To assess the damage induced within the composites, optical micrographic investigations of sectioned specimens were undertaken. The induced damage for each composite is shown in Figure 3-4. Three main types of damage modes were identified in each of the four composite architectures; localized damage beneath the punch, tow cracks along the bottom of the specimen, and delamination between the various tows and yarns. The localized damage is caused by the large stress concentration just beneath the central punch [21] resulting in crushing of the matrix and fiber damage in
the tows. A tensile stress is generated at the bottom of the specimen due to the bending moment. This stress is significant enough to cause tensile cracks to form in both the tows parallel to the $y$-axis as well as in the matrix-rich pockets. However, the delamination damage presents itself differently in each composite. The extent, size and distribution of the delamination damage varied between each material architecture. Nevertheless, some general characteristics were noticed. Very little delamination was present at the center of the specimen (i.e., between the crushing zone at the top surface and tensile damage along the bottom), possibly due to the lack of a large shear stress in this region. None of the delamination cracks propagated through the entire sample to cause complete failure, i.e., each specimen remained intact and could continue to maintain a significant portion of its maximum load.

In the baseline (BL) composite, several large delamination cracks were observed to propagate on one side of the central contact region (Figure 3-4). The delamination damage is quite significant leading to the sudden drop in load. The delamination cracks follow the undulation in the fiber tows of the 2D woven layers thus absorbing more energy. This type of delamination is consistent with damage reported by Padmanabhan [47].

In the OG3 composite delamination cracks appear along one side of the contact region between the stuffer and fill tows. These cracks propagate between the rows of z-yarns over a large distance. However, along the rows of z-yarns the delamination damage is limited and the cracks are arrested at the z-yarn reinforcement as shown in Figure 3-4. On the other hand, in the OG10 composite the delamination damage appears as smaller cracks distributed along both sides of the central load. These
cracks are seen between the stuffer and fill tows. As in the OG3 specimen, along the rows of z-yarns the delamination cracks do not cut the z-yarns to form larger cracks (i.e. the z-yarns are still intact). This mode of cracking indicates that the z-yarns act to prevent propagation of delamination damage. The uniform dispersion of damage within the specimen allows the composite to support the load even after failure initiates and hence the load remains relatively constant during the inelastic regime as seen in Figure 3-3(b).

The architecture of the Al composite specimens consists of the highest volume of warp weavers of all the 3D woven composites tested as indicated in Table 3-1 (Figure 3-2C). Approximately half of the fiber volume consists of warp weavers which weave through the entire thickness of the plate. These undulations prevent delamination cracks from propagating parallel to the x-axis however they may also contribute to the lower strength of the material as discussed earlier. The damage observed in the optical micrograph in Figure 3-4 reflects this behavior. The micrographs revealed limited local damage at the top and bottom of the specimen. It appears that a majority of the damage is caused by the concentrated load beneath the indenter. The delamination damage takes the form of small micro-cracks between the various weaving tows as well as within the fill tows parallel to the y-axis. This behavior is clearly reflected in the load-displacement curves. The small intermittent load drops in Figure 3-3B are likely associated with this damage.

A common observation for the BL and the OG3 specimens was that the damage was concentrated on one side of the center punch. It is inferred that the damage initiates at a critical flaw which reduces the local strength and results in a loss in
stiffness. The drop in load observed in the BL and OG3 curves was presented in Figure 3-3. Due to the drop in load the shear stress is also decreased which may prevent new delamination cracks from forming and allow additional damage to accumulate by propagating existing cracks. However the loss in stiffness due to this delamination damage prevents the initiation of cracks on the other side of the indenter. This results in most of the observed damage to form on one side of the indenter. This behavior was not observed in the OG10 and AI specimens. The delamination cracks are prevented from propagating by the presence of z-yarns and hence the drop in load was prevented which allows the delamination damage to propagate on both sides of the indenter.

From all the above observations it is inferred that as the percentage of through-thickness reinforcements increased, the mode of damage in the composite changed. In the absence of z-yarns, delamination cracks dominate the behavior and with the introduction of z-yarns the delamination damage is reduced (Figure 3-4). The damage becomes less concentrated and the cracks become shorter. As the z-yarn volume fraction is further increased the damage becomes more dispersed. This behavior is reflected in the load-displacement curves as well. When the delamination cracking is dominant, as in the 2D woven composite, the elastic limit is high but upon delamination the load drops sharply. On the other hand, when delamination cracking is prevented by the introduction of z-yarns the load after the elastic limit remained either constant or increased with displacement due to distributed damage within the composite.

**Multi-Step Loading**

The multi-step loading curves for each specimen are shown in Figure 3-5. The residual stiffness (Kr) from the unloading curves is plotted against the total energy (UT) in Figure 3-6. Several observations can be made from these figures. It was noted that
the overall response of the step-loading curves (shown in Figure 3-5) follows similar trends noted in the monotonic curves (Figure 3-3). Although there appears to be a slight loss in load between successive cycles, each loading cycle approaches the final load from the previous cycle. This indicates that extra damage induced by the multistep loading sequence is minimal and the response of the multistep loading matches the response of the monotonic loading.

By examining the residual stiffness as a function of SBS energy, as shown in Figure 3-6, it is possible to assess the effect of input energy on the induced damage. For each composite architecture, there is a limit in energy after which a significant loss in stiffness is observed. The baseline composite appears to reach the highest input energy before this loss occurs while the AI specimen has the lowest energy. The curves shown in Figure 3-6 follow two distinct behaviors: after an initial loss in stiffness the rate of loss decreases as energy increases (BL and OG3) or the rate of loss continuously increases as the energy increases (OG10 and AI). This behavior coupled with the maximum energy before stiffness loss reveals two distinct modes of behavior: (i) the material is susceptible to damage initiation (i.e., low damage resistance) but resistant to damage propagation which indicates a high damage tolerance and (ii) the material has high damage resistance but has low damage tolerance. The OG10 and AI samples follow the first trend while the BL and OG3 samples follow the second. Although the baseline achieves a higher energy before stiffness begins to decrease, at higher energy levels the OG10 composite retains a greater portion of its stiffness. It appears that the presence of z-yarns reduces the damage resistance of the composite
by initiating cracks while increasing the damage tolerance by preventing the cracks from propagating.

**Cyclical Loading**

Load-Displacement curves for BL and OG10 specimens subjected to high-cycle and low-cycle loading are shown in Figure 3-7. It is seen that the peak load drops with each subsequent loading cycle indicating a loss in stiffness of the composite. The test results for both linear region as well as post failure cyclic loading SBS testing are shown in Figure 3-8. In each test the normalized stiffness of the specimen decreases gradually indicating progressive damage accumulation in each cycle within the specimen. In the linear regime (Figure 3-8A), the strength reduction and hence the damage accumulation, is small and does not become significant until after 50 cycles are reached. In this regime the addition of z-yarns appears to initiate more damage leading to a larger reduction in strength for the OG10 and AI samples. This reduction is greater as the volume fraction of z-yarns increases. When cycled beyond the initiation of failure (Figure 3-8B), the decrease in strength is more significant. After only 20 cycles the strength of the BL composite has decreased by at least 1/3 of the strength of the virgin specimen. The OG3 specimens also show a significant drop in stiffness although slightly less than the BL. However, the OG10 and AI specimens still retained a significant amount of their strength. These results demonstrate the increase in the damage tolerance beyond failure through the addition of z-yarns in 3D woven composites.

From the testing results discussed above it is apparent that the behavior of 3D woven composites subjected to SBS testing is quite complex. While the methods used in this research enhance our understanding of this complex behavior, additional
methods may be necessary to fully characterize the materials tested. As mentioned above, the structure of the 3D woven composites leads to a large discrepancy in the ILSS when samples are tested in different directions. It is conceivable that a ratio could be established comparing the ILSS in both direction to predict how damage would propagate during panel level testing. Comparisons could then be made between the predicted damage and the actual damage.

The test results suggest that 3D woven composites suffer a reduction in strength compared to 2D laminated composites. As mentioned above this reduction has been associated with defects resulting from the 3D structure and weaving processes. However from the micrographs it is difficult to determine if delamination is originating from the defects described above. To fully understand the source and magnitude of the reduction in strength, more in-depth analysis may be required. Experiments could be conducted while using high speed photography to identify the initial source of damage, how damage progresses, and then identify the damage’s effect on the load displacement curve. This may provide insight into how defects affect the strength of the composite.

**Summary**

Short beam shear testing of three 3D woven composites with different material architectures revealed a decrease in apparent inter-laminar shear strength when compared to a baseline plain-woven laminated composite. As the fiber volume of z-yarns increased the inter-laminar shear strength continued to decrease. Optical microscopic observations of cross-sections of the test specimens revealed delamination damage, however, in the 3% and 10% orthogonally woven specimens the propagation of delamination damage was arrested at the z-yarns. This allowed induced damage in
the 10% orthogonal specimen to be more evenly distributed. This distributed damage has led to different post-elastic behavior for each of the composite architectures. While the base line and 3% orthogonal specimens revealed a large drop in load after the elastic limit, the 10% orthogonal specimen maintained the failure load up to 2 mm deflection while the load continued to increase for $12^\circ$ angle interlock specimens. The distribution of damage and the ability to support a greater load in the post-elastic regime of the load-deflection curve demonstrated that the damage tolerance of 3D woven composites is higher than 2D plain woven composites. Multi step-loading allowed for the stiffness of the specimens to be observed at several points during the short beam shear testing. By comparing the residual stiffness to the input energy it was possible to infer the amount of damage which had accumulated as the input energy increased. While the baseline material demonstrated a higher resistance to initial damage the stiffness began to drop sharply as the energy increased. However, in the 10% orthogonally woven specimen, after an initial drop in stiffness the rate of stiffness loss decreased as energy increased. During the repeated loading of the specimens, the strength of the material continued to decrease. The presence of z-yarns allowed more damage to initiate under cyclic loading which reduced the strength of the material in the linear regime. In the post-failure regime, delamination cracks in the specimens continued to spread, however the presence of z-yarns hindered their propagation.
Figure 3-1. Schematic of SBS test configuration

Figure 3-2. Microstructure of 3D woven composites A) OG3, B) OG10, and C) Al. Matrix pockets are indicated.

Figure 3-3. Representative load-displacement curves for all the composites. A) Entire load displacement curves and B) magnified view of the post-elastic regime.
Figure 3-4. Optical micrographs detailing the observed damage in each of the four composite architectures. Samples were sectioned from the center region of the SBS test specimens.
Figure 3-5. Multi-step load-displacement curves for each composite architecture
Figure 3-6. Residual stiffness vs. energy from multi-step loading test results.

Figure 3-7. Comparison of load-displacement curves for monotonic and cyclic testing of A) baseline and B) OG10 showing both elastic loading and post elastic limit loading.
Figure 3-8. Normalized stiffness vs. number of cycles for A) elastic loading and B) post-elastic limit loading.

Table 3-1. Summary of the composite specifications as well as ILSS from SBS tests.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Thickness (mm)</th>
<th>Z-yarn fraction$^+$</th>
<th>Fiber volume fraction$^{++}$</th>
<th>ILSS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL</td>
<td>6.24</td>
<td>0%</td>
<td>45%</td>
<td>37.36 ± 0.99</td>
</tr>
<tr>
<td>OG3</td>
<td>6.00</td>
<td>3%</td>
<td>48%</td>
<td>32.66 ± 2.43</td>
</tr>
<tr>
<td>OG10</td>
<td>6.63</td>
<td>10%</td>
<td>48%</td>
<td>30.00 ± 0.94</td>
</tr>
<tr>
<td>AI</td>
<td>6.04</td>
<td>49%$^*$</td>
<td>41%</td>
<td>26.34 ± 1.84</td>
</tr>
</tbody>
</table>

$^+$ Z-yarn fraction represents nominal fraction relative to the total fiber volume

$^{++}$ Fiber volume represents the fraction of fibers relative to the composite

$^*$ AI specimen has a very high z-yarn fraction due to all warp tows being weavers
CHAPTER 4
DEVELOPMENT OF DYNAMIC SHORT BEAM SHEAR TEST

Although numerous methods exist for delamination testing of composites, few methods exist specifically for determination of delamination strength or inter-laminar shear strength under dynamic loads. Such methods are necessary to understand the dynamic response of composites under impact loads. A new test method for performing dynamic short-beam shear tests using a momentum trapped Hopkinson pressure bar is proposed. Angle-interlock 3D woven composite specimens were tested under quasi-static and dynamic loading conditions to determine the effect of loading rate on damage evolution. A high speed camera was used to capture delamination initiation and propagation during both quasi-static and dynamic experiments. Analysis of the load-deflection curves and the high speed images revealed a good correlation between the modes of damage initiation and propagation with the features in the loading response. The apparent inter-laminar shear strength and the bending stiffness increased with rate of loading. While the damage was observed to propagate at a relative steady rate during quasi-static loading, the high rate of energy input during dynamic loading resulted in a rapid propagation of damage and a subsequent loss of stiffness in the composite as noted in the load-deflection curve.

Experimental Procedure

To evaluate the effect of loading rate on the inter-laminar shear strength of a 3D woven composite, short-beam shear tests were performed at several rates of loading using both a universal testing machine and a modified Hopkinson pressure bar apparatus. The test specimens were cut from composite panels supplied by the US Army Research Laboratory, Aberdeen Proving Grounds, MD. A high speed camera was
used during both quasi-static and dynamic tests to capture the deformation and the modes of damage in the composite.

**Materials**

Angle-interlock 3D woven composite panels, manufactured by TEAM Inc., Woonsocket, RI, were used in this investigation. The preforms were woven from S-2 glass fiber and consolidated with SC-15 epoxy using vacuum assisted resin transfer molding. The weaving pattern consisted of 10 fill tows and 9 warp weavers. Each warp weaver is woven around two layers of fill tows and the weaving pattern is shifted by one column of fill for each row of weavers. The pattern repeats every four rows of weavers and results in 19 interwoven layers of S-2 glass/SC15 composite. Using rule of mixtures the total fiber volume was estimated to be 48% of the total composite volume. The architectural details as well as an optical micrograph are provided in Figure 4-1A. The original composite panels measured 660 mm x 700 mm and were nominally 12.7 mm thick. The as-received panels were sectioned into smaller 150 mm x 150 mm tiles. These tiles were then cut into the desired test coupons with approximate dimensions of 50 mm x 20 mm. The exact dimensions of each specimen varied slightly due to variability in the manufacturing process.

**Static Short Beam Shear**

The short beam shear [18] (SBS) test method was used to evaluate the apparent inter-laminar shear strength (ILSS) of the 3D woven composite at different rates of loading. This test method uses a three-point loading fixture to perform bending tests on a test specimen with a relatively small length to thickness ratio. This creates a large inter-laminar shear stress within the specimen on either side of the central load point.
and promotes delamination damage. The inter-laminar shear strength can be approximated using the following formula [18]:

\[
ILSS = \frac{0.75 P_b}{bd}
\]

(4-1)

where \(P_b\) is the peak bending load, \(b\) is the width, and \(d\) is the thickness of the specimen. Quasi-static SBS tests were first performed on several specimens at various rates of loading using a MTS® servo hydraulic universal testing machine. Figure 4-1B shows a schematic of the SBS test fixture with a fixed support span of 35 mm. Specimens were tested at three different rates of loading; 0.0001 m/s, 0.001 m/s, and 0.01 m/s. A 111 kN load cell was used to measure the force applied to each specimen while the deflection was measured using the LVDT of the MTS® test machine. A preload of 200 N was used to remove any slack between the fixtures and the specimen.

**Dynamic Short Beam Shear**

A modified Hopkinson pressure bar apparatus was used to perform dynamic short beam shear (dSBS) tests. This apparatus consists of three major components; a single stage gas gun, a 38.1 mm diameter incident bar with a momentum trap [35, 36, 43], and a rigid anvil which serves to support the specimen and the force sensors. The bar material used in this research is a precipitation hardening steel which has high yield strength, even in an annealed state. A schematic of the test system is shown in Figure 4-2A. The composite test specimens were supported on two 19 mm half-cylindrical support rods spanning approximately 38 mm and clamped to the rigid anvil. Two PCB® 210b dynamic force sensors are placed between the anvil and the supports (one for each support). These force sensors can measure a combined maximum load of 44.5 kN with a frequency response of 75 kHz. The sensors are conditioned using two Kistler
5010 charge amplifiers and are clamped in place with a preload of 2.2 kN. A 45° wedge shaped indenter with a tip radius of 2.4 mm is threaded into the end of the incident bar. The indenter was made from 7068 Aluminum to reduce the indenter mass, while maintaining sufficient stiffness and strength to resist forces during loading. A 350 Ω foil resistive strain gage was bonded near the midpoint of the incident bar and was used to monitor shape, amplitude and duration of the incident wave. The strain gage signal was conditioned and amplified using a Vishay 2310b dynamic strain conditioner. A pulse shaping technique [35, 36, 48] was used by placing a copper disk between the striker bar and the incident bar before each test. This technique results in a long rise time in the incident pulse which decreases acceleration of the bar and reduces signal noise from the strain gage and the force sensors. Although the acceleration during impact is reduced due to pulse shaping, the magnitude may still be in excess of 200,000 m/s². To measure this high acceleration, a PCB® 350B21 ICP shock accelerometer was attached to the end of the incident bar next to the indenter tip (Figure 4-2). The accelerometer has a maximum capacity of 980,000 m/s² and a resonance frequency of over 200 kHz. This sensor was conditioned using a PCB® 482A16 signal conditioner. Data was collected from the strain gage, force sensors, and accelerometer using a LDS-Nicolet Sigma 90-8 oscilloscope with a sample rate of 5 MS/s.

To conduct the dSBS test, a 600 mm striker bar was launched from the gas gun toward the incident bar. Upon impact, an elastic uniaxial compressive stress wave was generated in the incident bar with an amplitude and duration proportional to the velocity of impact and the length of the striker bar, respectively. This compression wave then travels down the length of the incident bar until it reaches the indenter/specimen.
interface. The compressive wave causes the flexure of the composite and, due to the low impedance of the specimen, reflects back as a tensile wave. In a traditional Hopkinson bar, once the loading is complete the reflected tensile stress pulse travels back toward the striker-incident bar interface and reflects back again into the incident bar as a compressive wave, which travels toward the indenter and causes a second impact on the specimen. This is often an undesirable consequence of the traditional Hopkinson bar testing.

If specimens were to be recovered after the test and analyzed either through microscopy or further experimental testing, it is important that the damage induced during testing is limited to a single impact. To prevent repeated loading, a momentum trapping technique has been developed known as recovery Hopkinson pressure bar technique [36, 43]. This technique has been used to induce controlled damage in brittle materials [49] and to determine dynamic hardness of several ceramics [50, 51]. A variation of this technique was used in this research. The recovery Hopkinson bar uses a ‘momentum-trap’ which consists of three components, a transfer flange, a sleeve, and a rigid mass. The transfer flange is either formed or machined onto the end of the incident bar. The flange and sleeve are impedance matched to the incident bar while the rigid mass is required to be large enough to act as a rigid surface. The technique used in this research uses a controlled gap placed between the flange and the sleeve. The details of this technique are described below and are shown as a schematic in Figure 4-2B.

1) As the striker bar impacts the incident bar creating the incident pulse, the gap is closed which then engages the momentum trap.
After performing the bend test the reflected tensile wave returns to the striker end of the incident bar. The stress wave is transferred by means of the flange into the sleeve as a compressive wave.

2) Upon reaching the rigid mass the stress wave reflects back into the sleeve as a compressive wave due to the large impedance mismatch between the sleeve and the rigid mass. This compressive wave then returns to the transfer flange.

3) Upon reaching the flange the compressive wave transfers into the incident bar as a tensile wave which then travels toward the indenter which then retracts from the composite specimen.

4) The wave then repeatedly reflects back and forth in the incident bar such that it is always tensile while traveling towards the specimen so that the incident bar is incrementally retracted causing the indenter to move away from the sample. The result is a single dynamic loading on the composite specimen followed by the retraction of the incident bar.

In this paper three possible methods to determine the displacement of the wedge indenter were examined: (i) a shock accelerometer mounted on the incident bar next to the indenter, (ii) a strain gage bonded on the incident bar and (iii) high speed imaging of the indenter motion during the test. The shock accelerometer measures the axial acceleration, from which velocity and displacement of the indenter were determined by successive integration of the acceleration signal. Integration naturally smoothes the noisy acceleration signal to produce smooth velocity and displacement profiles. The second method relies on the measurement of the stress wave using the strain gage on
the incident bar. The strain measured at a point on the bar is related to the particle velocity at that cross section through the following relation:

\[ U_p = C\varepsilon \]  \hspace{1cm} (4-2)

Were \( \varepsilon \) is the recorded strain profile of the incident pulse and \( C \) is the longitudinal wave speed in the bar (~5000 m/s) which may be determined by analyzing the time between two successive wave reflections and the distance the wave travels in the incident bar. From the above relation it can be shown that the velocity at the end of the incident bar (i.e., velocity of the indenter) may be determined using the incident (\( \varepsilon_i \)) and reflected (\( \varepsilon_r \)) strain signals as [52]:

\[ V = C(\varepsilon_i - \varepsilon_r) \]  \hspace{1cm} (4-3)

Once the velocity is determined the signal may be integrated to determine the displacement at the end of the incident bar. For dSBS tests, the impedance of the specimen is negligible compared to the impedance of the steel incident bar. This results in very little loss in energy during the loading of the specimen and therefore the reflected stress wave is equal in amplitude to the incident wave but opposite in sign (i.e., \( \varepsilon_r = -\varepsilon_i \)). Using this assumption we may simplify Equation 4-3 to estimate the velocity at the end of the bar as

\[ V = 2C\varepsilon_i \]  \hspace{1cm} (4-4)

This equation is useful to quickly determine the velocity of the impact loading and may also be integrated to find the estimated displacements at the end of the incident bar for comparison with other methods.

Finally, we have used a high speed digital camera (Phantom v710, Vision Research, Wayne, NJ) to image the specimen deformation during the impact. Using the
measured thickness of the specimen the images are calibrated to the proper scale. The displacement of the indenter tip during the dynamic bend test can then be determined using the images at different time intervals. However due to the limited number of data points, the low resolution of the images, and the small relative displacements between two consecutive frames it is difficult to accurately determine the velocity profile from the high speed images.

Recall that the load applied by the wedge indenter is measured by two force sensors beneath the two supports. The force measured by each sensor is half the applied load during dSBS tests. The signals from the two force sensors are summed to obtain the load-time curve. The displacement-time profile (from strain gages, accelerometer or high speed images) is then matched to the load-time profile to obtain the load-displacement curve for each dSBS test. From these curves the ILSS of the composite specimens subjected to a single dynamic loading is determined using Equation 4-1.

**High Speed Photography**

During the quasi-static SBS test conducted at 0.01 m/s and dynamic SBS tests, high speed imaging was used to record damage modes and damage evolution in the specimen. The camera was configured with a frame size of 1024 × 400 pixels and a frame rate of 18,000 fps during the static testing. The frame size was reduced for the dSBS tests to 256 × 376 pixels which allowed the frame rate to increase to 54,000 fps. During both cases a Carl Zeiss Makro planer 100 mm lens was used with the aperture set to f/8.
Results

Typical signals from the shock accelerometer, strain gage, and force sensors during a dSBS test are shown in Figure 4-3. The load-displacement response of the composite specimen during the dynamic impact test was obtained from these signals. It was observed that the acceleration data (shown in Figure 4-3A) contains a large amount of noise. The noise may be reduced using a digital filter to obtain a smooth acceleration curve as shown by a bold line in Figure 4-3A. However, the successive integration of the original acceleration signal reduces the noise resulting in smooth velocity and displacement profiles as shown in Figure 4-3D without the need for digital filters. Using the strain gage signal (Figure 4-3B) and Equation 4-4, the velocity profile of the indenter tip was calculated and compared to the velocity profile from the accelerometer signal in Figure 4-3D. This profile was then integrated to determine the displacement-time response. Lastly, the high speed images captured during the test were properly scaled and used to determine the displacement of the indenter during loading of the specimen. Comparisons of the velocity and displacement profiles determined from the accelerometer and strain gage as well as displacements determined from the high speed images are shown in Figure 4-3D. The three methods indeed show a good match in displacement measurements.

Using the load-time profile from Figure 4-3C and displacement-time profile derived from the strain signals (shown in Figure 4-3D) the load-displacement curves were determined for each dSBS test. Representative load displacement curves for several quasi-static loading rates (0.0001 to 0.01 m/s) and the dynamic (10 m/s) loading rate are shown in Figure 4-4. The features in these curves may be related to the locations of
damage initiation and damage modes observed in images captured using the high speed camera shown in Figure 4-5 and Figure 4-6.

For both quasi-static and dynamic tests the load-displacement response shows a fairly linear region, followed by a gradual decrease in slope of the loading curve until it reaches a maximum value. It was observed that the slope of the linear region is fairly consistent during quasi-static loading but increases significantly under dynamic loading. High speed images taken during this linear response for both loading rates show small tensile cracks initiated along the bottom of the specimen as seen in Figures. 4-5A and 4-6A. These cracks are due to the tensile stress induced by the bending but appeared not to affect the overall response of the load-deflection curve.

After the linear region the load plateaus for a short displacement which is more pronounced in the dynamic response. The incidence of this plateau response coincides with the initiation of delamination micro-cracks within the composite. The high speed images of the 0.01 m/s test, shown in Figure 4-5A, reveal additional tensile cracks and delamination cracks initiating midway between the indenter and the support. As the material is further deformed additional delamination cracks initiate between the warp weavers and fill tows along a band extending from the indenter to the support as shown in Figure 4-5B. The dSBS images show a column of delamination cracks which form near the center of the specimen, starting near the bottom with additional cracks forming above the initial delamination as shown in Figure 4-6A. While these cracks were concentrated on one side, delamination cracks did form on both sides of the indenter.

As the displacement increases, the stiffness continues to drop with further increase in delamination crack length. After a displacement of around 1.25 mm the
quasi-static load decreases gradually indicating a further loss in stiffness. During this loading period the delamination cracks which were formed previously, now propagate over a large distance (shown in Figure 4-5C) causing the loss in load bearing capacity as the stiffness of the specimen is significantly reduced. During dynamic tests the drop in load is much more significant, (Figure 4-4). Following the crack initiation, the propagation of delamination cracks occurs rapidly as shown in Figure 4-6B and results in the sudden drop in load. The rapid damage propagation and drop in load are associated with a large decrease in the stiffness of the specimen.

The above behavior continues to about 2 mm of central deflection at which point the load begins to increase gradually until the test was terminated (Figure 4-5). In the dynamic tests, additional drops in load were observed during this regime; after each drop, the load again began to increase. The increase in load could indicate that the rate of stiffness loss due to delamination has diminished, possibly due to some limitation in damage propagation. As the delamination cracks approach the supports or are hindered by the weaving structure of the composite the delamination growth will be reduced. Figures 4-5C and 4-6C show delamination damage saturation in the area between the indenter and the support region.

From these results it was observed that both stiffness and peak load increased as the rate of loading was increased from quasi-static to the dynamic loading regime. The severity of the load drop following the peak load was greater during dynamic testing. With the high speed images we can deduce the reason for this large drop. In static tests damage propagated at a relatively slow rate resulting in a gradual decline in the slope of the load curve. In the dynamic tests delamination damage propagation was much faster.
due to the higher amount of energy imparted to the specimen during elastic loading.
The energy is rapidly released during dynamic loading through severe delamination leading to a loss in stiffness of the specimen and sudden load drop as seen in Figure 4-4.

The maximum load during each test was used to determine the ILSS (Equation 4-1) and an average value was determined from five tests for each loading rate. The initial stiffness from the linear response was also determined from the load-displacement curves. Results from quasi-static and dynamic tests are summarized in Table 4-1. It can be seen that the ILSS increases as the loading rate was increased while the stiffness of the specimen only increased under dynamic loading.

The above results clearly point to the fact that delamination damage is more severe under dynamic loads than under static loads. Effective strategies are necessary to limit delamination damage in composites if they are to be successfully implemented in applications subjected to impact loads. It is also clear that to understand the effectiveness of new techniques in reducing delamination damage, controlled tests must be conducted at high rates of loading.

Summary

Results from dynamic short beam shear tests confirmed that displacement of the incident bar may be determined accurately from stress waves measured using the strain gage attached to the incident bar. All three methods utilized here (i.e., accelerometer, strain gage, and high speed imaging) for determining displacement during the dSBS test provided consistent results. The high speed images provide a good method to validate displacement results from either the strain gage or the accelerometer. However, the limited number of data points from the high speed camera and the
relatively small displacements of the indenter do not allow for an accurate determination of the velocity profile of the indenter. Strain gages provide the most affordable and the easiest method to implement while shock accelerometers of sufficient range are limited and prone to frequent damage during tests.

The interlaminar shear strength determined from quasi-static and dynamic short beam shear tests showed a steady increase as the rate of loading increased. The use of momentum trapping produced a single controlled indentation into the composite specimen. This technique allows for the recovery of specimens subjected to a consistent and measureable level of deformation. Additional tests can then be performed to determine the residual strength of the specimen after being subjected to a controlled dynamic loading. By modifying the test supports and the indenter tip, a number of different tests may be performed using the proposed test procedure.

This method for performing dynamic short beam shear uses small specimens to quickly compare several different designs of composites. The results from quasi-static and dynamic SBS tests of 3D woven composites indicate a change in both the load-displacement response and also in the initiation and propagation of damage. These results show the necessity to characterize the behavior of 3D woven composites under a range of loading rates.
Figure 4-1. Schematic and optical micrograph of 3D woven angle interlock composite specimen and schematic of static short beam shear test fixture. The shear stress distribution along the center line is also shown.

Figure 4-2. Dynamic short beam shear test fixture using a modified Hopkinson bar apparatus. Detail of supports, load cell placement and accelerometer are shown in the schematic and enlarged photo above. A schematic is shown detailing the process of the momentum trap technique.
Figure 4-3. Typical data acquired from dynamic short beam shear test. A) acceleration signal (bold line is filtered signal), B) strain profile at midpoint of the incident bar, C) typical load-time profile, and D) velocity and displacement profiles calculated from accelerometer (solid line), and strain gage signal (dashed line), and displacements from high speed images (circles).
Figure 4-4. Representative load-displacement response of angle interlock 3D woven composite for quasi-static and dynamic rates of loading.
Figure 4-5. High speed images of quasi-static SBS test at 0.01 m/s. Magnified images show detail of crack formation including: A) tensile cracks near bottom, B) a band of delamination cracks, and C) delamination propagation.
Figure 4-6. High speed images of dSBS test at 10 m/s. Magnified images show details of A) damage formation, B) propagation, and C) saturation of damage between indenter and support.

Table 4-1. Apparent ILSS and initial stiffness determined from short beam shear tests

<table>
<thead>
<tr>
<th>Loading rate (m/s)</th>
<th>Apparent ILSS (MPa)</th>
<th>Stiffness (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>45.40 ± 0.75</td>
<td>14.95 ± 0.92</td>
</tr>
<tr>
<td>0.001</td>
<td>48.11 ± 0.55</td>
<td>14.40 ± 0.40</td>
</tr>
<tr>
<td>0.01</td>
<td>50.62 ± 0.23</td>
<td>15.00 ± 0.54</td>
</tr>
<tr>
<td>10</td>
<td>59.78 ± 1.39</td>
<td>34.50 ± 1.17</td>
</tr>
</tbody>
</table>
CHAPTER 5
DYNAMIC TESTING OF 3D WOVEN COMPOSITES

Dynamic impact tests were performed on several 3D woven composites as well as one baseline 2D plain woven laminate to determine the effect of transverse reinforcements on damage resistance and damage tolerance. These results were compared to the quasi-static response to determine the effect of loading rate on the apparent interlaminar shear strength of each composite. The residual stiffness of specimens subjected to dynamic loading was then determined using quasi-static three-point bend tests. These tests are intended to elucidate the influence of impact induced damage on the quasi-static response of the structure which is a measure of the damage tolerance of the composite. During both quasi-static and dynamic tests the 2D woven laminate revealed the highest strength followed by a sharp loss in stiffness, whereas the 3D woven composites retained a greater percentage of their stiffness after impact when compared to the 2D woven laminate. These results reveal that 3D woven composites have lower damage resistance but higher damage tolerance when compared to a 2D plain woven laminate.

Materials

Several different 2D and 3D woven-glass fiber reinforced polymer composite panels were supplied by the US Army Research Laboratory, Aberdeen Proving Grounds, MD in the form of 150 mm x 150 mm tiles. The panels included one 2D plain woven (2DPW) laminated composite (which serves as a baseline), three orthogonally woven (OW) composites and two angle interlock (AI) composites. Each composite preform was created using S-2 glass fiber reinforcement and consolidated using SC-15 epoxy. The target thickness for each panel was 6.4 mm, however the final thickness
varied for each composite structure. Table 5-1 provides details of panels, their thickness (h) fiber volume fraction ($V_{\text{fiber}}$) and fraction of z-yarns ($V_{\text{z-yarns}}$).

**Baseline 2D Woven Composite**

The baseline 2D woven laminated composite (2DPW) consisted of nine layers of plain woven glass fibers. The outer layers were oriented with the fibers parallel to the x- and y-axes of the plate. Subsequent layers were rotated 45° creating a $[(0^{\text{pw}} / 45^{\text{pw}}) / 0^{\text{pw}}]$ sequence where the superscript $\text{pw}$ refers to plain weave. The architecture of the 3D woven composites are described below. The schematics for each composite architecture is also given in appropriate figures discussed later.

**Orthogonal Woven Composites**

Three orthogonally woven 3D composites were used in this research; one contained approximately 3% z-yarns by fiber volume (referred to as OW-3) and the second contained 10% z-yarns (OW-10). These two composites consisted of 11 layers of S-2 glass tows including 5 warp stuffer tows and 6 fill tows. The OW-3 contained a single warp weaver z-yarn which was woven around each column of fill tows and repeats for every two rows of warp stuffers. Between the z-yarns additional warp weavers were woven around the top and bottom fill tows locking the layers of tows into a single woven composite. The OW-10 composite contains two z-yarns weaving each column of fill tows. These z-yarns weave from the top and bottom of the composite and cross at the midsection of the panel and therefore additional warp weavers were not necessary to lock the layers together. The pattern is repeated after every row of warp stuffers resulting in a total of 10% z-yarn.
The third orthogonal woven composite is a layer to layer structure (OW-L2L) consisting of 9 layers with 4 warp stuffers and 5 fill tows. Two warp weavers were used between each row of warp stuffers. The weavers wrapped around each column of fill tows. The first weaver interlaces the top 3 fill tows while the second weaves the bottom 3 fill tows. The middle layer of fill tows is therefore woven by both top and bottom weavers. The pattern is shifted by one column for each row of warp stuffers interlocking all the fiber tows. The 3D weaving in each of the orthogonal structure creates large spaces which are filled with matrix material during consolidation. The influence of these matrix rich pockets on the behavior of the composite material will be discussed later.

Angle Interlock Composites

Two angle interlock weaves were used in this investigation: (i) a layer to layer interlock (AI-L2L) and (ii) a through-thickness angle interlock (AI-TT). The weaving pattern of the layer to layer consisted of 5 fill tows and 4 warp weavers. Each warp weaver is woven around two layers of fill tows and the weaving pattern is shifted by one column of fill for each row of weavers. The pattern repeats every four rows of weavers and results in 9 interwoven layers of S-2 glass/SC-15 composite. The through thickness angle interlock composite, designated as AI-TT, containing columns of fill yarns in a 3-2 alternating pattern. Six warp weaver yarns are woven through the thickness of the plate at an 18° angle to the x-axis. It should be noted that there are no warp stuffer yarns present in either AI designs resulting in a large volume fraction of warp weavers in either composite. Large epoxy pockets were also present in the AI structures similar to those found in the orthogonal 3D woven composite. For clarity on illustration and conciseness of the document the architectures of all the composite are given in the results section.
Two sizes of specimens were cut from each composite tile using a high speed diamond saw. The first set of specimens measured approximately 20 mm × 45 mm and was used in quasi-static and dynamic short beam shear tests. The second set measured 35 mm × 45 mm and were used for dynamic blunt impact experiments. Prior to being tested each specimen was polished along the cut surface to remove damage caused during the cutting process.

**Experimental Procedure**

**Static Short Beam Shear Tests**

Using an MTS® universal testing machine quasi-static SBS tests were conducted on specimens at three different loading rates: 0.0001 m/s, 0.001 m/s and 0.01 m/s. A schematic of the specimen loading configuration is shown in Figure 5-1. This configuration consists of two cylindrical supports with a fixed span of 35 mm and a central punch. Load and displacement data were collected from a 111 kN static load cell and crosshead LVDT, respectively. A minimum of 5 specimens were tested for each composite architecture at each loading rate. The apparent ILSS for each composite was determined from the peak load \( P_b \) during the linear response of the load-displacement curve using the following formula [18]

\[
ILSS = \frac{0.75P_b}{bd}
\]  

(5-1)

Where \( b \) is the width and \( d \) is the thickness of the specimen. The stiffness of the specimens was determined at 0.5 mm of deflection and the energy required to cause 2 mm of central deflection in the specimen was calculated using numerical integration of the load-deflection curve.
Dynamic Short Beam Shear Tests

Using a momentum trapped split Hopkinson pressure bar [43, 53] dynamic short beam shear (dSBS) [54] tests were conducted on each composite specimen at a velocity of approximately 10 m/s. This modified Hopkinson pressure bar apparatus consisted of the following: a single stage gas gun designed to launch a 38.1 mm in diameter and 610 mm long striker bar; a 38.1 mm diameter and 2,450 mm long incident bar modified to accept indenter tips attached to its end; a momentum-trap system [36, 43] used to limit the displacement of the incident bar; and a rigid anvil to attach support fixtures and dynamic force sensors. The striker and incident bars were made of high strength stainless steel. The load was measured using two PCB® 210B force sensors coupled with Kistler® 5010 charge amplifiers. A 19 mm diameter semi-cylindrical support is clamped in place on top of each force sensor with a span of approximately 35 mm (Figure 5-2). A strain gage is bonded at the center of the incident bar to measure displacement of the indenter during the test. The indenter tip is a wedge shaped indenter with a wedge angle of 45° and a tip radius of ~2.4 mm. The shape was chosen to match the radius of the punch used in static tests. Aluminum alloy 7068 was used as the indenter material to reduce the mass at the end of the bar and thus reduce the internal forces generated during the deceleration of the indenter. This alloy is of sufficiently high strength to resist the stresses caused by impact on the specimens. In addition to recording the impact forces and strain signals from the incident bar, a high speed camera (Phantom v710, Vision Research®) was used to record the deflection of the specimen and image the development of damage during the impact event. The camera frame was set to 512 pixels × 200 pixels with a frame rate of 63,000 fps. A Carl
Zeiss® 100 mm Makro-planar lens was used with an f-stop of f/8. Two 250w PAR lights were used to provide sufficient illumination during the test.

To conduct dSBS tests the striker bar was launched at a velocity of approximately 10 m/s using compressed nitrogen gas. The striker bar impacts the momentum-trapped end of the incident bar creating the incident stress pulse. A 19 mm diameter 0.8 mm thick 101 copper pulse shaper [48] was placed between the striker and the incident bar to prolong the rise time of the stress pulse. The long rise time of the incident wave reduces the acceleration of the bar and produces much cleaner signals from both the strain gage as well as the force sensors. This also reduces the inertial force produced by the acceleration of the specimen. An example of the typical force signal and strain gage data are shown in Figure 5-3. From the strain gage data it is possible to determine the velocity (v) at the end of the bar (during the flexural loading) using the following equation [52]

\[ v = 2C\varepsilon_i \]  

(5-2)

Where \( C \) is the wave speed in the incident bar material and \( \varepsilon_i \) is the incident strain signal. The wave speed of the bar was determined to be 4,931 m/s by measuring the time interval between two successive wave reflections using the strain gage bonded to the incident bar. It has been shown that this method can accurately determine the displacement of the indenter using numerical integration of the velocity-time profile, provided the specimen is sufficiently compliant compared to the incident bar material [54]. From the force sensor and strain gage data it is therefore possible to determine the load-displacement curves for each dynamic short beam shear test.
Blunt Impact Testing

Blunt impact tests were performed using a 25.4 mm diameter spherical punch to simulate the damage induced during low velocity impact. The large diameter of the punch is used to reduce localized damage caused by the contact stress between the indenter and the specimen. As with the dynamic short beam shear tests, the striker bar was launched at a velocity of approximately 10 m/s and a copper pulse shaper was used. The displacements were measured using the strain gage and the load was recorded for each test using the force sensors. The specimens were cut to a width of 35 mm to match the span of the semi-cylindrical supports. This results in a square plate with simply supported boundary conditions along two edges and free edges along the other two. The impact results in a controlled level of damage in each composite. A typical load profile from blunt impact of a composite specimen is shown in Figure 5-3. Five tests were performed for each composite specimen.

Residual Stiffness Measurements

While static and dynamic short beam shear tests give insight into the damage resistance of the composites, these tests may not reveal damage tolerance of the composite due to delamination caused by the test. To quantify the damage tolerance in each composite the effect of delamination damage on the quasi-static stiffness was examined. Specimens which were previously subjected to dynamic short beam shear tests and blunt impact tests were subsequently reloaded under quasi-static flexure to determine the residual stiffness of each specimen. To create bend specimens from the blunt impact specimens, a 0.8 mm wide section containing the induced damage was cut from the middle of the plate. Each specimen was loaded at a rate of 0.0001 m/s until a maximum displacement of 2.0 mm was reached. From the load-displacement data the
stiffness at 0.5 mm displacement was determined. This stiffness represents the residual stiffness of the dynamically damaged composite. An average residual stiffness was determined from at least five tests for each architecture and this value was then compared to the quasi-static stiffness of the virgin composite.

Results

Short Beam Shear Tests

Typical load-displacement curves generated from quasi-static and dynamic short beam shear tests are shown in Figure 5-4. Additional load-displacement curves may be found in the appendix. Also included in this Figure are insets of the composite architecture. These curves reveal distinct differences between the behavior of each composite architecture. Each composite tested exhibited a fairly linear region followed by a non-linear inelastic response. The non-linear response of the 2DPW and OW-3 specimens revealed a large drop in load after reaching a peak load, whereas the OW-10 and OW-L2L composites maintained a fairly constant load during this inelastic regime especially under quasi-static loading. However, under dynamic testing conditions, the load-displacement curve of the OW-L2L specimens revealed a considerable load drop followed by a plateau. While this drop in load is not as severe as in the 2DPW or OW-3 specimens, the drop is indicative of the formation of large delamination cracks in the specimen. On the other hand, the angle interlock specimens (AI-TT and AI-L2L) revealed initiation of damage and non-linear response at lower load, however the load continues to slowly increase with displacement.

From these results the average apparent ILSS was determined from a minimum of five specimens using Equation 5-1. These values are listed in Table 5-2. The slope of the linear region of the load-deflection curve at 0.5 mm of deflection was used to
estimate the stiffness of each specimen. Lastly, the load-deflection curve was numerically integrated to determine the energy required to cause 2 mm of deflection. Average stiffness and energy values were evaluated for each composite architecture and are listed in Table 5-2. It is noted from Figure 5-4 that the maximum load increased with increase in loading velocity indicating that the load bearing capacity of the composite is dependent on the rate of loading.

The average quasi-static and the dynamic apparent ILSS for each composite tested is plotted with respect to the loading rate in Figure 5-5A. It is clear that the ILSS increases as the rate of loading increases under both quasi-static and dynamic loading conditions. Trend lines are shown for each architecture illustrating this behavior. It was noted that the baseline 2DPW composite achieved the highest load during both quasi-static and dynamic loading rates. This indicates that the baseline material has a higher damage resistance then any of the 3D woven composites tested. Also, the OW composites consistently demonstrated a higher strength then the AI specimens at all rates of loading. Figure 5-5B shows the stiffness measured at 0.5 mm of deflection for each material at various loading rates. Unlike the ILSS results, the stiffness does not demonstrate a continuous increase during the quasi-static loading regime, however during dynamic loading there is a significant increase in stiffness. Lastly, the average energy required to cause 2 mm of deflection in each material is shown in Figure 5-5C. As with the ILSS these results indicate a steady increase in energy as the loading rate is increased. The two trend lines shown in Figure 5-5B and 5-5C indicate the high and low values and are intended to illustrate the relative behavior. However, for the sake of clarity the other trend lines are neglected.
Damage Evolution

By examining the high speed images taken during dSBS tests it is possible to track the progression of damage in each architecture at various stages of loading. Images were selected at approximately the same displacement near the end of a test for each architecture and are shown in Figure 5-6. Observations of these images show a large difference in the mode of damage induced in each composite architecture. 2DPW and OW-3 specimens revealed delamination cracks propagating over large distances whereas the OW-10 and Al composite specimens show smaller, distributed delamination cracks. In 2DPW specimens the cracks do not form along a single plane but instead follow the undulations of the woven layers. OW-3 specimens, in contrast, have long linear cracks aligned between layers of fill and stuffer tows. The damage in the OW-10 specimen manifests in the form of short cracks whose growth appears to be hindered by the presence of z-yarns. Due to this z-yarn resistance to delamination growth additional cracks form resulting in a more even distribution of cracks on both sides of the indenter. Both angle interlock specimens show cracks forming between the weaver and stuffer tows and this damage appears affected by the local weaver undulation angle. Similar to the 2DPW specimens, these cracks do not form on a plane but instead follow the undulations of the weavers. However due to the large amount of undulations in the architecture the delamination damage is minimized as it requires more energy for cracks to follow these tortuous paths. The large delaminations in the 2DPW and OW-3 result in a dramatic loss in stiffness as noted in the load-deflection curves shown in Figure 5-4.

The evolution of delamination damage in the orthogonally woven (OW-10) composites is shown in Figure 5-7 at three different time intervals. This sample was
chosen as it best represents the effect of z-yarns on the damage propagation in the 3D woven composites. The local regions of interest are enlarged as shown in the middle images of Figure 5-7. Image ‘A’ shows the formation of intralaminar crack in a fill tow located near the central region of the specimen. The cause of this type of delamination is likely due to the principal tensile stress oriented perpendicular to the fiber axis formed by the combination of shear stress and tensile bending stress. It is well known that a composites strength perpendicular to the fiber direction is much lower than its strength along its fiber axis. The tensile principal stress generated by the applied force is sufficient to cause failure perpendicular to the fiber due to this lower strength. As the crack develops, its propagation is impeded by a layer of warp stuffers as seen in image ‘B’. The cracks then cause an interlaminar delamination to propagate along the interface of warp stuffer and fill tows as shown in image ‘C’. Due to a high percentage of z-yarns in the OW-10 composite the delamination cracks are impeded. On the other hand, in the OW-3 composite the large spacing between the z-yarns allows the cracks to propagate over a large distance as seen in Figure 5-6 and results in a severe reduction in the stiffness of the composite. Thus, the effect of z-yarns is to impede the growth of delamination crack.

**Residual Stiffness**

As previously discussed, the specimens subjected to dynamic loading were subsequently retested under quasi-static loading conditions to determine the residual stiffness of the damaged composite. Three representative load-displacement curves were selected for each architecture and plotted in Figure 5-8. These curves include the quasi-static SBS response of a virgin composite, the reloading response of a previously damaged composite due to blunt impact testing, and the reloading response of a
specimen subjected to dynamic SBS testing. The loss in stiffness and drop in peak load can be easily observed in Figure 5-8. For each architecture the load-deflection curve of the blunt impact specimen had a lower stiffness then that of virgin specimen. The curves show a response that is initially linear but later becomes nonlinear as the sample is further deflected. The maximum load in both regions is lower when compared to the virgin SBS response. For the specimens previously subjected to dynamic SBS, the reloading curves appear linear throughout the test. The stiffness from these tests is lower than both the virgin response and reloading of blunt impact specimens. The loss in stiffness in the 2DPW and OG3 specimens is much more pronounced then the loss in the additional 3D woven composites. To compare the loss in stiffness from dynamic loading the stiffness at approximately 0.5 mm of deflection was calculated from each test and an average value was determined from these results. These average stiffness values were then normalized by the stiffness of the virgin 2DPW composite since it achieved the highest stiffness. The normalized results are shown in Figure 5-9. The average percent residual stiffness was also calculated for the blunt impact and dynamic SBS tests and is also shown in Figure 5-9. From this graph it is clearly noted that while the 2DPW achieves the highest initial stiffness, it suffers from a large loss in stiffness due to damage caused by either dSBS or blunt impact loading. The OW-10 and AI-TT specimens both had lower relative stiffness values than the 2DPW but had a higher residual stiffness and retained a higher percentage of their stiffness during subsequent loading. In addition to the stiffness values the energy necessary to cause the 2 mm deflection was also determined. The percent reduction in energy was found by subtracting these results from the energy determined from the static SBS tests
discussed above. The 2DPW and OW-3 specimens show a significantly larger reduction in energy. This is an indication of a lower tolerance for damage induced during the each test. These results indicate that while the 2DPW and OW-3 specimens achieved the highest damage resistance, they suffered the highest amount of damage when subjected to dynamic loading, i.e. their damage tolerance was lower.

Discussion

Short beam shear tests on composites can be used to examine their resistance to delamination by creating a state of stress conducive to delamination damage. The quasi-static and dynamic short beam shear tests conducted on six different woven composite architectures resulted in a range of material responses depending on the weaving architecture and volume of z-yarns used in 3D weaving. The response of 2DPW composites subjected to SBS tests showed the highest strength as well as large delamination damage resulting in a significant loss of stiffness. This indicates that while 2D laminates have a high resistance to damage, once the layers delaminate the structure suffers from a severe loss in stiffness indicating a poor tolerance to the damage. This tradeoff between damage resistance and damage tolerance is also observed in OW-3 specimens. From the high speed images it was noted that damage first initiates as intralaminar failure. The presence of z-yarns acts to contain this damage and prevents its propagation. However, between the rows of z-yarns the damage is allowed to propagate by forming interlaminar delaminations. For this reason as the volume fraction of z-yarns is increased and the spacing between rows of z-yarns is decreased, the damage tolerance is enhanced. The increase in z-yarns also lowers the stiffness and provides additional stress concentrations which may reduce the delamination strength. This tradeoff is also apparent in the angle interlock (AI)
specimens. The large percentage of warp weavers (approximately 50%, Table 5-1) creates undulations in the material reducing the stiffness and results in damage initiation at a lower load. However, the intralaminar delaminations in the fill tows are confined by the warp weavers and the lack of stuffer tows prohibits the formation of long linear delaminations. The interlaminar delaminations are limited to short cracks forming between warp weavers and fill tows. This increase in damage tolerance is also noted in the load-deflection curves. Despite the initiation of failure at a lower load, the load continues to increase as the specimen is further deflected. The results from the angle interlock specimens are in contrast to the behavior of the 2DPW and OW-3 specimens. The responses of these materials clearly illustrate the tradeoff between damage resistance and damage tolerance.

Note that while the virgin material response under SBS tests show various features depending on the type of composite as shown in Figure 5-4 the load displacement response for each of the damaged composites show very similar features. For instance, the blunt impact damaged specimens all show a parabolic response until a displacement of 2 mm is reached while the dSBS damaged specimens show linear trends. For each architecture the load level for the blunt impact damaged specimens is lower than the undamaged response. Similarly, the dSBS damaged specimens show a lower load then the blunt impact specimens throughout most of each test. This change in load is a reflection of the level of damage induced during each test. By examining the curves in Figure 5-8 it can be seen that the damage generated in the 2DPW and OW-3 specimens is much more severe than the damage produced in the OG-10 and OG-L2L
specimens. The AI specimens show the least amount of change in the response of all architectures tested.

**Summary**

Among all the composites tested, the 2D plan woven composite has the highest damage resistance and the lowest damage tolerance. The addition of a small percentage (OG3) of reinforcement shows a slight reduction in damage resistance and does not show significant improvements in the damage tolerance. Both 10% orthogonally woven and angle interlock composite have significantly improved damage tolerance. However, each of these materials also show a lower damage resistance than that of the 2D plain woven composite. As mentioned above, additional results for static and dynamic short beam shear tests may be found in the appendix.
Figure 5-1. Schematic of quasi-static short beam shear test.

Figure 5-2. Image of dynamic short beam shear test using modified Hopkinson bar apparatus. A Detailed view of instrumentation and supports is shown above next to an image of the wedge and spherical indenter used for dSBS and blunt impact tests respectively.
Figure 5-3. Load and strain signals from dynamic short beam shear test.
Figure 5-4. Load-deflection response of composites subjected to quasi-static and dynamic short beam shear tests.
Figure 5-5. Summary of SBS test results for various composites as a function of loading rate. A) Apparent interlaminar shear strength, B) stiffness, and C) energy.
Figure 5-6. Images of damage development in each composite architecture tested at 10 m/s.
Figure 5-7. Damage initiation and propagation in a OW-10 specimen. Image A shows intralaminar cracks initiating in fill tows. Image B reveals intralaminar cracks propagating into interlaminar cracks at the interface of fill and warp stuffer tows. Lastly, image C shows the propagation of interlaminar cracks.
Figure 5-8. Selected load displacement curves for quasi-static SBS tests and residual stiffness tests of blunt impact and dSBS test specimens. Each curve represents the typical response of the material.
Figure 5-9. Plot of normalized initial SBS stiffness residual, blunt impact stiffness, and residual dSBS stiffness for each specimen. Percentage value represents the loss in stiffness for the dSBS tests.

Table 5-1. Summary of the composite panels tested including average thickness (d) Z-yarn fiber volume fraction ($V_{Z\text{-yarn}}$) and total fiber volume fraction ($V_{\text{Fiber}}$)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Description</th>
<th>d (mm)</th>
<th>$V_{Z\text{-yarn}}$</th>
<th>$V_{\text{Fiber}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2DPW</td>
<td>2D plain woven laminate</td>
<td>6.24</td>
<td>0%</td>
<td>45%</td>
</tr>
<tr>
<td>OW-3</td>
<td>Orthogonally woven</td>
<td>6.00</td>
<td>3%</td>
<td>48%</td>
</tr>
<tr>
<td>OW-10</td>
<td>Orthogonally woven</td>
<td>6.63</td>
<td>10%</td>
<td>48%</td>
</tr>
<tr>
<td>OW-L2L</td>
<td>Orthogonally woven layer to layer</td>
<td>5.88</td>
<td>8%</td>
<td>50%</td>
</tr>
<tr>
<td>AI-TT</td>
<td>Angle interlock</td>
<td>6.00</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>AI-L2L</td>
<td>Layer 2 Layer angle interlock</td>
<td>6.04</td>
<td>49%</td>
<td>41%</td>
</tr>
<tr>
<td>Specimen</td>
<td>ILSS (m/s)</td>
<td>Stiffness (kN/m)</td>
<td>Energy (N-m)</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>------------</td>
<td>------------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0001</td>
<td>0.001</td>
<td>0.01</td>
<td>10</td>
</tr>
<tr>
<td>2DPW</td>
<td>37.36</td>
<td>41.97</td>
<td>44.75</td>
<td>53.15</td>
</tr>
<tr>
<td>OW-3</td>
<td>33.48</td>
<td>37.80</td>
<td>41.65</td>
<td>48.00</td>
</tr>
<tr>
<td>OW-10</td>
<td>30.00</td>
<td>34.60</td>
<td>36.34</td>
<td>43.79</td>
</tr>
<tr>
<td>OW-L2L</td>
<td>28.33</td>
<td>33.02</td>
<td>34.28</td>
<td>42.94</td>
</tr>
<tr>
<td>AI-TT</td>
<td>26.77</td>
<td>29.08</td>
<td>32.57</td>
<td>34.33</td>
</tr>
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</table>
CHAPTER 6
CONCLUSIONS

Throughout this study tests were performed on several different woven composites including a 2D plain woven sample and many 3D woven composites. Preliminary tests conducted on a layer 2 layer orthogonally woven specimen reviled that under impact loading z-yarn reinforcement did not fully prevent delamination from occurring especially along weak layer with minimal z-yarns. These results indicated that additional studies were necessary to evaluate the performance of 3D woven composite in terms of delamination resistance and tolerance. To begin this evaluation static short beam shear tests were conducted on several composite architectures supplied by ARL. Both monotonic and cyclical tests were conducted using this method. The apparent strength of these samples indicated that the addition of z-yarns reduced the delamination resistance when compared to a 2D plain woven composite. However analysis of cyclical loading revealed that once delamination occurred the presence of z-yarns helped prohibit the propagation of damage and increased the damage tolerance of the material. To determine the effect of loading rate a new experimental method was developed. Using a modified Hopkinson pressure bar dynamic short beam shear tests were conducted on a thick angel interlock composite specimen. Several methods were used to determine the displacement of a wedge shaped indenter tip into the specimen. It was shown that the velocity of the indenter tip could be accurately determined using a strain gage bonded to the incident bar. Results show an increase in the apparent interlaminar shear strength as well as the stiffness of the material. Using a high speed camera the damage initiation and propagation was determined for both static and dynamic testing and it was concluded these mechanisms were affected by loading rate. Using this
method dynamic short beam shear tests were performed on six composite specimens and compared with static results. In each material the apparent interlaminar shear strength, stiffness, and energy were shown to increase with increase in loading rate. High speed images revealed the development of intralaminar cracks within individual tows before the damage propagated into interlaminar delaminations. By modifying the indenter tip and specimen geometry blunt impact tests were also conducted on these composites. These specimens were then sectioned into bend specimens to be further tested. To quantify the damage induced in specimens subjected to dynamic loading the dynamic short beam shear test specimens and modified blunt impacted specimens were subsequently retested under quasi-static conditions. Results reveal a decrease in the stiffness of the specimens as well as a decrease in the energy required to cause 2 mm of deflection. These results were compared to determine how z-yarns influenced the damage tolerance of each composite. Results agreed with previous findings and revealed that damage tolerance was increased by the presence of z-yarns by minimizing stiffness and energy loss. Overall these tests have shown that in the specimens tests damage resistance was reduced with the presence of z-yarns yet reveal an increase in damage tolerance. The tradeoff between damage resistance and tolerance must be taken into consideration when designing with 3D woven composites.
As with many studies not all aspects and interests could be explored in the time available. There are several areas of interest that have been sacrificed to focus on the results discussed above. The following are just a few of these areas that should be evaluated in the future.

As discussed above, the drawback of using short beam shear tests is that the interlaminar shear strength cannot be determined from these results easily. Preliminary tests were conducted on how the span used during the tests affected the results. These tests revealed that with larger spans failure was not due to delamination damage but caused by tensile and compressive failure in the formation of a hinge at the central loading region. Shorter spans show only a slight increase in apparent interlaminar strength. Other test methods must be developed to fully characterize the true interlaminar shear strength of 3D woven composites.

The tests conducted using the Hopkinson pressure bar was limited to a velocity of approximately 10 m/s. This velocity was chosen to prevent the premature failure of the test equipment however further tests could be conducted using this method to further evaluate these materials at higher rates of loading.

This study has focused on the evaluation of these composites along a single material axis. However some tests not detailed above were conducted and revealed much different behavior. For example, the one layer to layer angle interlock specimen revealed one of the lowest apparent interlaminar shear strength of the composites tested. However, when the specimen was tested perpendicular to this axis it achieved
one of the highest strengths. This discrepancy should be further evaluated and explored by conducting further tests perpendicular to the direction used in this study.

Parallel to this study extensive work has been conducted using FEA to evaluation of local stress and strain caused by short beam shear tests and to determine the effect of z-yarns on the response of the composites. Several methods have been evaluated and each shows their own strengths and weaknesses. As this work continues parametric studies of the material parameters used in the FEA will be conducted and eventually optimization studies can be conducted on the effectiveness of each 3D weaving architecture.

Lastly, the latest composite panels being evaluated by ARL include the addition of carbon fiber layers on the top and bottom layers of the composite as well as the use of Kevlar z-yarns. UFL has received several of these panels and future studies are being planned to determine how the addition of these fibers affect the performance of the 3D woven composite.
APPENDIX A
ADDITIONAL QUASI-STATIC SHORT BEAM SHEAR RESULTS

Figure A-1. Quasi-static short beam shear tests of 2DPW at a rate of 0.1 mm/s.

Figure A-2. Quasi-static short beam shear tests of 2DPW at a rate of 1.0 mm/s.
Figure A-3. Quasi-static short beam shear tests of 2DPW at a rate of 10 mm/s.

Figure A-4. Quasi-static short beam shear tests of OW-3 at a rate of 0.1 mm/s.
Figure A-5. Quasi-static short beam shear tests of OW-3 at a rate of 1.0 mm/s.

Figure A-6. Quasi-static short beam shear tests of OW-3 at a rate of 10 mm/s.
Figure A-7. Quasi-static short beam shear tests of OW-6 at a rate of 0.1 mm/s.

Figure A-8. Quasi-static short beam shear tests of OW-6 at a rate of 1.0 mm/s.
Figure A-9. Quasi-static short beam shear tests of OW-6 at a rate of 10 mm/s.

Figure A-10. Quasi-static short beam shear tests of OW-10 at a rate of 0.1 mm/s.
Figure A-11. Quasi-static short beam shear tests of OW-10 at a rate of 1.0 mm/s.

Figure A-12. Quasi-static short beam shear tests of OW-10 at a rate of 10 mm/s.
Figure A-13. Quasi-static short beam shear tests of D1BL at a rate of 0.1 mm/s.

Figure A-14. Quasi-static short beam shear tests of D1BL at a rate of 1.0 mm/s.
Figure A-15. Quasi-static short beam shear tests of D1BL at a rate of 10 mm/s.

Figure A-16. Quasi-static short beam shear tests of OW-X at a rate of 0.1 mm/s.
Figure A-17. Quasi-static short beam shear tests of OW-X at a rate of 1.0 mm/s.

Figure A-18. Quasi-static short beam shear tests of OW-X at a rate of 10 mm/s.
Figure A-19. Quasi-static short beam shear tests of Al-TT at a rate of 0.1 mm/s.

Figure A-20. Quasi-static short beam shear tests of Al-TT at a rate of 1.0 mm/s.
Figure A-21. Quasi-static short beam shear tests of Al-TT at a rate of 10 mm/s.

Figure A-22. Quasi-static short beam shear tests of L2L at a rate of 0.1 mm/s.
Figure A-23. Quasi-static short beam shear tests of Al-L2L at a rate of 1.0 mm/s.

Figure A-24. Quasi-static short beam shear tests of Al-L2L at a rate of 10 mm/s.
Figure A-25. Quasi-static short beam shear tests of Al-20 at a rate of 0.1 mm/s.

Figure A-26. Quasi-static short beam shear tests of Al-20 at a rate of 1.0 mm/s.
Figure A-27. Quasi-static short beam shear tests of Al-20 at a rate of 10 mm/s.

Figure A-28. Quasi-static short beam shear tests of Al-60 at a rate of 0.1 mm/s.
Figure A-29. Quasi-static short beam shear tests of Al-60 at a rate of 1.0 mm/s.

Figure A-30. Quasi-static short beam shear tests of Al-60 at a rate of 10 mm/s.
APPENDIX B
ADDITIONAL DYNAMIC SHORT BEAM SHEAR TEST RESULTS

Figure B-1. Dynamic short beam shear tests of 2DPW at a rate of 10 m/s.

Figure B-2. Dynamic short beam shear tests of OW-3 at a rate of 10 m/s.
Figure B-3. Dynamic short beam shear tests of OW-6 at a rate of 10 m/s.

Figure B-4. Dynamic short beam shear tests of OW-10 at a rate of 10 m/s.
Figure B-5. Dynamic short beam shear tests of D1BL at a rate of 10 m/s.

Figure B-6. Dynamic short beam shear tests of OW-X at a rate of 10 m/s.
Figure B-7. Dynamic short beam shear tests of Al-L2L at a rate of 10 m/s.

Figure B-8. Dynamic short beam shear tests of Al-TT at a rate of 10 m/s.
Figure B-9. Dynamic short beam shear tests of Al-20 at a rate of 10 m/s.

Figure B-10. Dynamic short beam shear tests of Al-60 at a rate of 10 m/s.
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BIOGRAPHICAL SKETCH

Timothy Walter was born in Midland MI in 1979. He grew up with an appreciation for the outdoors, enjoying camping, backpacking, fishing, scuba diving, and canoeing. He was a member of the Boy Scouts of America for many years achieving the rank of Eagle Scout. He attended Midland public schools and graduated from H.H. Dow high school in 1998 where he developed an interest in engineering while taking courses in drafting and sketching. He enrolled at Michigan Technological University in Houghton, MI due to its well known engineering program and the remote location appealed to his love of nature. During his undergraduate studies Tim developed an appreciation to history and archaeology and even attended archaeology field school in United Kingdom were he participated in the excavation of iron smelting furnaces in the remote English country side. During his senior year, Tim participated in the ASME Human Powered Vehicle competition held at the University of California-Davis. In 2003 Tim earned a Bachelor of Science degree in mechanical engineering and quickly enrolled in MTU’s graduate school. He earned a Master of Science in mechanical engineering while studying the methods of testing and the analysis of plate bending of sandwich structures and their constituent materials. Tim enrolled at the University of Florida in August of 2007 and received his Ph.D. in mechanical engineering in the summer of 2011.