ABSTRACT

Wall, III, John William. An Investigation of the Ballistic Impact Resistance of Modified 2x1, Four-step, Three-Dimensionally Braided Composites with Axial Reinforcement. (Under the direction of Dr. Aly El-Shiekh, Dr. Abdelfattah Seyam, and Dr. Hechmi Hamouda)

The primary objective of this research was to determine the ballistic resistance of Modified 2x1, 4-step, 3-D braided Kevlar® and Spectra® fiber/epoxy composites with axial reinforcement. Four different preform constructions were evaluated, specifically: Kevlar® with Kevlar® axials, Spectra® with Spectra® axials, Kevlar® with Spectra® axials, and Spectra® with Kevlar® axials. The preforms were fabricated on the computer-controlled, fully automated, 3-D braiding machine developed at The College of Textiles, NC State University. The preforms were consolidated in epoxy matrix and then subjected to dynamic impact utilizing the 19-mm variable velocity impactor designed and built at the Mechanical Engineering Department, NC State University.

The composites in the study were fabricated to be similar in fiber volume, thickness, and areal density. This was accomplished using computer-aided design and standard fabrication methodology. The testing of the composite materials was conducted such that the impact energy of subsequent shots fired was similar so that direct comparison of material systems could be made. This research was conducted under a controlled dynamic testing environment.
AN INVESTIGATION OF THE BALLISTIC IMPACT RESISTANCE OF MODIFIED
2X1, FOUR-STEP, THREE-DIMENSIONALLY BRAIDED COMPOSITES WITH
AXIAL REINFORCEMENT

By

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Chairman of Advisory Committee
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Dr. George Hodge                  Dr. Hechmi Hamouda
Dedication

I dedicate this document jointly to my loving wife, Daniela, and to my parents, John and Nancy Wall, Jr. - for their support and encouragement that helped me to realize that I needed to finish up this chapter of my life.

I also dedicate this document to the loving memory of my grandfather John W. Wall, Sr. who taught me many things about life that have become an intimate part of my being.
Biography

The author was born in Greensboro, North Carolina on February 11, 1974. He is the oldest of three children born to John and Nancy Wall, Jr. The author graduated from Walter Hines Page Senior High School in June 1992. He then attended North Carolina State University. He was an officer and an active member of Sigma Alpha Epsilon Fraternity. In May 1996, he received his Bachelor of Science Degree in Textiles from North Carolina State University. He then enrolled in the graduate degree program at North Carolina State University to pursue a Master of Science degree at the College of Textiles.

As an undergraduate and during his time in the graduate program, Jay worked in the NASA Mars Mission Research Center at the college under the direction of Dr. Aly El-Shiekh. This experience working with three-dimensional braiding and high-performance fibers and composites was a strong influence on the author’s chosen career path. Before the defense of his graduate degree, he moved to Boston, MA and worked at Foster-Miller, Inc. in the Composites Technology Group as a staff engineer and project manager. With this experience base, Jay moved on to work with BF Goodrich Aerospace as an R&D Engineer with a focus on oxidized PAN textile processing. This R&D job opened a door of opportunity at a new Goodrich Corporation facility where he is now employed as a manufacturing engineer with oversight of the design, purchase, installation, and operations of a new textile department in Spokane, WA.
Acknowledgements

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Additionally, the author would like to thank his colleagues in the NASA Mars Mission lab: Keith Black, Howard Hardee, Rona Reed, and the host of undergraduate students. Finally, a sincere thanks to Mike Flanagan and Jared Baucom from the NC State Department of Mechanical Engineering for their assistance with the dynamic impact testing that was conducted in this study.
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Chapter 1
Introduction

A composite material can be defined as a material composed of two or more distinct materials with different properties, having a distinct interface between them. More specifically, they can be described as a fiber or particulate reinforcement, which is contained in a binder or matrix material [1].

Composite materials were first developed in response to the need for materials that exhibited mechanical, thermal, and/or chemical responses that were not available in any known homogenous material. The first fiber-reinforced composites were developed for the aerospace industry in response to the limitations of steel and aluminum alloys, which had been used in the past. Though these materials were being used in aircraft structural components, each had its limitations. Aluminum alloys provided good performance with their high strength and stiffness at a relatively low weight, but had problems with corrosion and fatigue. Steel on the other hand was limited by a low strength-to-weight ratio. [10]

Fiber-reinforced composites were developed to fit these structural needs and many other applications were found in the process. During World War II, fiberglass composites were developed for filament-wound rocket motors and other structural applications. Since 1950, fiber-reinforced composites have been used in a wide variety of industries - from aerospace to consumer goods. Today, in addition to expanded industrial use, many boats, tennis rackets, bicycle frames, and golf clubs are made with fiber-reinforced composites [10].
Textile-reinforced composites can provide many advantages over traditional homogeneous materials. These properties include, but are not limited to: high strength, low specific gravity, high tensile modulus, fatigue resistance, improved thermal properties, corrosion resistance, impact resistance, and ballistic response.

Composites can be divided into classes in various manners. One such classification scheme is based on the form of the reinforcement. This method outlines two classes of composites: particulate-reinforced and fiber-reinforced. Particulate reinforcements may be spheres, rods, or flakes. Fiber-reinforcements have lengths much greater than their cross-sectional dimensions. Generally, they have at least a 10:1 length to width ratio. Fiber-reinforced composite classification can be further divided into two groups, based on the types of fibers used as reinforcements: those containing continuous filament (CF) fibers and those containing relatively short discontinuous (staple) fibers.

Continuous filament usage in a composite material requires some type of fiber placement mechanism to align the fiber axes for desired response. Staple fibers are also used in composite materials – these structures typically use a partially oriented (carded) web or a random mat. The research detailed herein was conducted with continuous filament Kevlar® and Spectra® fibers, these fibers are discussed in detail in Sections 2.4.1 and 2.4.2 respectively.

The primary objective of this research was to determine the ballistic impact failure modes of modified 2x1, four-step, three-dimensionally (3-D) braided Kevlar® and Spectra® fiber/epoxy composites with axial reinforcement. The preforms were
fabricated on the computer-controlled, fully automated, 4-step, 3-D braiding machine developed at NC State University, College of Textiles. The preforms were consolidated in epoxy matrix and then subjected to dynamic impact loading utilizing the 19-mm variable velocity impactor designed and built at the NC State University, Department of Mechanical Engineering.

The composites in the study were fabricated to be similar in braid angle, fiber volume, thickness, and areal density. This was accomplished using computer-aided preform design and establishment of a standard fabrication methodology. Additionally, the dynamic testing of the composite materials was conducted such that the impact energy of subsequent shots fired was similar; therefore, a direct comparison of the material systems could be made. This research was conducted under controlled conditions in the dynamic testing environment.

In general, the research was conducted under the hypothesis that three-dimensionally braided Kevlar® and Spectra® fiber composites would resist ballistic failure in the velocity regimes tested due to the use of high performance fiber and the inherent reinforcement through the thickness of the preform. Specifically, the expectation was that the 3-D preform structure would force the dynamic stress of the impact to be transmitted along the integrated fiber axes rather than resulting in delamination and local tensile and shear failure that are the primary failure modes of other reinforcements. This research was a continuation of NCSU dynamic impact study of textile-reinforced composites that was published in the Journal of Composite Materials [8]. Where the 1996 study was an investigation of the dynamic
test methodology and involved many diverse textile reinforcements, the research covered in this thesis is a focused investigation of only three-dimensionally braided composites with axial reinforcement. Furthermore, a significant difference in the present study and the past research is that this initiative was designed around the utilization of stacks of composite panels to resist higher energy impacts and so that damage progression through adjacent stack members could be evaluated.

With the knowledge that structural composites formed from three-dimensionally braided preforms can be designed to yield excellent tensile, bending, and impact resistant properties [1], the specific objectives of this research are:

- Completion of the construction of the fully-automated 3-D braiding machine - including axial (0°) reinforcement capability,
- Fabrication of three-dimensionally braided composite test panels utilizing high performance Kevlar® and Spectra® fibers,
- Dynamic impact and Quasi-static post-impact coupon-level testing of the synthesized materials, and
- Identification of the failure modes of the systems when subjected to controlled simulated ballistic threats.
Continuous filament fibers or filaments are most commonly used in composites. This is attributable to the fact that these highly structured fibers exhibit the high strength and modulus characteristics that are desirable in composite materials for high-performance applications. When continuous filament fibers are used as reinforcements, the fibers provide virtually all of the load-bearing characteristics of the material. However, matrix materials are needed to fill the voids between the fibrous textile-network and improve material toughness.

2.1 Common Fibers Used in Composite Materials

Inorganic fibers used in composites include carbon, pitch, carbonized polyacrylonitrile (PAN), metal alloys, and glass. Glass fiber is widely used in boats, sporting goods, ballistics, and structural applications. Finally, ceramic particulate and fiber is often reinforced with ceramic matrices. These materials provide the high modulus and strength necessary in high temperature and pressure applications, such as aircraft engine components.

Many of the high performance continuous filament fibers used in composite materials are organic or polymeric in nature. Organic fibers used in composites include poly-aramids (PPD-T), polybenzimidazole (PBI), and polyethylene (para-aramid). Poly-aramids and para-aramids are known for their high modulus, and resultant strengths, and PBI is known for an extremely high temperature resistance. [21]
2.2 Common Matrices Used in Composite Materials

The most common matrix materials used in composites are organic resins. These resin materials are further divided into thermoplastic and thermoset resins. Thermoplastic resins are those that can be repeatedly softened by an increase of temperature and hardened at room temperature. This is a physical change rather than a chemical change, and the softened stage can be shaped by flow into a mold, or by extrusion. Thermoplastic resins include nylon resins, thermoplastic polyester resins, and polycarbonate resins. The most common thermoplastic matrix currently being used is polyether etherketone, or PEEK. PEEK is a linear aromatic crystalline thermoplastic. PEEK matrix composites may have a continuous use temperature of 250°C (480°F) [21]. Additionally, metals such as steel, copper, and aluminum are all used as matrix materials in composite formation.

Thermoset resins, on the other hand, are plastics that when cured by application of heat or by chemical means change into a substantially infusible and insoluble material. Thermoset plastic resins include epoxy and polyester resins. Thermoset epoxy resins were used in the current research and are discussed in detail in Section 2.4.3. High performance polymeric thermoplastic matrices also exist for specific applications.

Finally, carbon matrix material is commonly used in aerospace applications to form carbon-carbon composite structures. To form the carbon matrix, carbon particles are diffused through the fabric preform. This is achieved by bombarding the carbon preform with natural gas at elevated temperatures and pressures -
allowing the carbon molecules to pass through the preform, all under vacuum conditions. At higher temperatures, the particles move freely, and the diffusion is accelerated—though it is still fairly slow relative to other matrix infiltration processes.

### 2.3 Failure Modes of Composite Materials

Most high strength, high-stiffness traditional homogeneous materials fail due to the propagation of an inconsistency (weak-point) in the material. However, in the case of fiber-reinforced composites, a single fiber failure is localized, allowing the neighboring fibers to take on the load that the broken fiber formerly bore. This can possibly prevent the catastrophic breakdown of the material that would normally occur in a traditional material. Because highly oriented fibers are commonly used as the reinforcements, the molecular orientation of the fiber can be used to the material’s specific advantage by exact placement and orientation of the fiber in an engineered material. Further, the lengthwise modulus of the material can be increased well above isotropic values by using reinforcements such as aramid and carbon fiber. This improvement in the strength of the material is carried out by the introduction of these high performance fibers in the preferred orientation. Thus, the strength of the fiber-reinforced composite material can far exceed the strengths of any one of the components of the material. [4]

In continuous filament composite materials, there are many modes by which composites fail. On a macroscopic level these modes can be identified as crack formation and fiber failure. Crack formation and subsequent propagation occurs
when the material is subjected to stress, this is generally observed in the same
direction as the fiber orientation in that region. On the other hand, fiber failure is a
localized failure, which can be catastrophic. This mode occurs when the weakest
fiber fails, forcing neighboring fibers to carry the load, which has been transferred by
shear stress. [2]

Other failure modes occur due to the failure of the interface by which the fiber
and matrix materials interact. This interfacial bonding can be facilitated by
mechanical and chemical means. One bonding mechanism involves covalent
bonding of the matrix and fiber - this bond may provide a chemical bond that is
strong enough to unite the two dissimilar materials. Additionally, the interfacial bond
between fiber and matrix can be mechanical joining of the two elements.
Mechanical interlocking of the matrix into the microscopic “gaps” on the rough fiber
surface, and penetration of the matrix around the filaments of a fiber structure
occurs. However, these bonding mechanisms are by no way mutually exclusive, in
most cases, both mechanical and chemical interfacial bonding occurs. When either
or both mechanisms fail, they cause a failure of the interface between the fiber and
matrix materials, and can lead to catastrophic failure of the composite material. For
this reason, a coupling agent may be introduced into the composite material system
to aid in the fiber to matrix bonding.

Another problem, which may lead to composite failure, is the residual stress that
occurs as a result of the thermal residual stress of the two or more components.
This stress causes fiber crowding and fiber compression, and makes the shear
stress state more volatile. These events occur during the application of heat in the cure process due to the phase shift from a non-crystalline liquid (matrix) to a crystalline solid (fiber). In the case of interfacial failure and failure due to residual stress, the macroscopic failure is typically considered a matrix failure. [12]

2.4 Constituent Materials

2.4.1 Kevlar® Fiber

In 1927 while working for E.I. Du Pont de Nemours Company, Dr. Wallace H. Carothers headed a research team to conduct basic research on polymer formation. Polymers were not being studied very widely at this time due to (the then thought) insolubility, infusibility, and chemically unreactive nature of the substances. However, Dr. Carothers discovered a chemical reaction, which would drastically change the fiber industry in the future, the formation of polyamides. This is the reaction of a dibasic acid and a diamine - the basis for nylon and aramid fibers.

Aramid fibers are a class of these polyamides, which are, manufactured fiber in which the fiber forming substance is the long-chain synthetic polyamide, in which at least 85% of the amide linkages are attached directly to two aromatic rings. DuPont produces para aramid fiber under the trade name Kevlar®, introduced in 1973. However, other companies, namely Akzo-Nobel and Teijin have since introduced the fiber commercially, as Twaron® and HM-50™, respectively. These aramid fibers were first introduced as variants of nylon, but it was soon discovered that they had properties, which were very different from their nylon polymer predecessors.
Kevlar® 29 aramid fibers are typically used in composites because of their high degree of toughness, damage tolerance, and ballistic performance. However, it should be noted that there are other para-aramid fibers that have higher moduli used in structural applications. Additionally, Kevlar® KM2, a new, very high strength, high toughness aramid fiber designed for ballistic fragmentation resistance and energy absorption capacity is available. This 850-denier tow, containing 560 filaments, has 13 percent higher tenacity and more than 20 percent higher toughness than 1500-denier Kevlar® 29, which is currently used in military vests and helmets. [5] Table 2.1 is an illustration the physical properties of Kevlar® 29, which is sold as a 1500 denier tow with 240 filaments (0.24k tow).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filament diameter</td>
<td>.0047 (12)</td>
<td>in (μm)</td>
</tr>
<tr>
<td>Tenacity</td>
<td>23</td>
<td>g/den</td>
</tr>
<tr>
<td>Breaking Strength</td>
<td>338 (76)</td>
<td>N (lbf)</td>
</tr>
<tr>
<td>Breaking Elongation</td>
<td>3.6</td>
<td>%</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>575 (10.6)</td>
<td>g/den (psi)</td>
</tr>
<tr>
<td>Density</td>
<td>1.44</td>
<td>g/cc</td>
</tr>
</tbody>
</table>

The production of aramid fibers uses a solvent spinning process. The dissolved polymer may be spun into air or into a liquid bath. The polymer is dissolved into a
solvent, and the resulting solution is added to a strong mineral acid such as sulfuric acid. The sulfuric acid is metered through a spinnerette into air and then into water or a dilute sulfuric acid bath. The fibers are then heat-treated to increase the fiber modulus.

The chemical composition of Kevlar® fiber is poly para-phenylene terephthalamide. This fiber is also known as PPD-T because it is made from the condensation reaction of paraphphenylene diamine and terephthaloyl chloride. The aromatic ring structure contributes high thermal stability, while the para configuration leads to stiff, rigid molecules that contribute to high strength and modulus.

Para aramid fibers belong to a class of materials known as liquid crystalline polymers (LCPs). Because these polymers are very rigid and rod-like, in solution they can aggregate to form ordered domains in parallel arrays. This is a major contrast to conventional, flexible polymers, which in solution can bend and entangle, forming random coils. The chemical structure of the para-aramid is shown in Figure 2.1.
Para-aramid fiber is noted for its toughness and general damage tolerance characteristics. In part this is related directly to conventional tensile toughness, or the area under the stress-strain curve. Toughness is also related to impact resistance and ballistic stopping power. The para aramid fibrillar structure and compressive behavior contribute to composites that are less notch sensitive and that fail in a ductile, non-brittle or non-catastrophic manner, as opposed to glass and carbon.

2.4.2 Spectra® Fiber

Honeywell (formerly Allied-Signal) developed a high-strength, high-modulus polyethylene fiber for high-performance applications. The fiber is known for a high degree of stiffness, and high strength. Both of these factors are a function of its high
molecular weight and crystalline structure. The fiber is made up of slim, linear molecules, which are highly oriented, and highly organized. While this fiber exhibits superior mechanical properties at ambient temperatures, its properties decrease rapidly with increasing temperatures because of the relatively low melting point of the polymer. Also, due to the inert nature of the fiber, there can be a significant matrix-bonding problem in composite materials. Spectra® is classified as ultra-high molecular weight polyethylene or generically as a polyolefin fiber. The structure of the fiber is illustrated in Figure 2.2

![Figure 2.2 Chemical Structure of Polyolefin fiber (Spectra®)](image)

Spectra® has outperformed aramid fabrics in many ballistic resistance applications. This high strength fiber demonstrates good resilience and resistance to crushing and the higher axial modulus and lower density of Spectra® fiber accounts for its superiority to Kevlar® in these tests. [5, 15]
Spectra® fiber, like Kevlar®, is a liquid crystal polymer, or continuous crystal—a structure in which the molecules are virtually completely stretched out, making it a near-ideal structure. This conformation is excellent for a fiber used in composite reinforcement. A continuous crystal is typically relatively easy to achieve with a liquid crystalline polymer, because in the melt or solution, the molecules align in more or less parallel positions. However, to achieve the continuous crystal morphology with polyethylene (PE) requires elaborate processing to avoid chain entanglements and chain folding. Gel spinning of ultra-high molecular weight polyethylene (UHMW-PE) polymer is used. In gel spinning, a small amount of this polymer is dissolved in the solvent. The viscous solution is wet spun, whereupon the spinning solvent is exchanged with a volatile nonsolvent, causing gelation of the PE. [24] The gel is drawn at about 140° C under conditions that give the polymer high orientation. The resulting fiber has high orientation, modulus, and strength. [25] The physical properties of 1300-denier, 1000-filament (1K) Spectra® 1000 fiber are listed in Table 2.2.
Table 2.2  Physical Properties of Spectra® 1000 Fiber

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filament diameter</td>
<td>.00106</td>
<td>in (µm)</td>
</tr>
<tr>
<td>Tow Tenacity</td>
<td>35</td>
<td>g/den</td>
</tr>
<tr>
<td>Breaking Strength</td>
<td>446 (100.3)</td>
<td>N (lbf)</td>
</tr>
<tr>
<td>Breaking Elongation</td>
<td>3.4</td>
<td>%</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>1150 (10.6)</td>
<td>g/den (psi)</td>
</tr>
<tr>
<td>Density</td>
<td>0.97</td>
<td>g/cc</td>
</tr>
</tbody>
</table>

2.4.3 Epon® 862 BPF Epoxy Resin

Epoxy resins are used extensively in composite materials, due to their commercial availability and versatility. EPON® 862, formerly known as EPON® DPL-862 resin, is a low viscosity, liquid epoxy resin manufactured from epichlorohydrin and Bisphenol F. This resin contains no diluents or modifiers. The ideal structural formula is shown in Figure 2.3.
The resin system is suited for many end-uses including: (1) solventless or high solids/low volatile organic compound (VOC) maintenance and marine coatings, (2) chemically resistant tank linings, flooring, and grouts, (3) fiber reinforced pipes, tanks, and composites, (4) tooling, casting, and molding compounds, (5) construction, electrical, and aerospace adhesives, and (6) electrical encapsulations and laminates. Epon® resin systems have a low viscosity, crystallization resistance, chemical resistance, superior physical properties (as compared to other diluted resins), and it reacts with full range of standard epoxy curing agents.
2.5 Textile Structures Used as Preforms in Composites

2.5.1 Textile Laminates

Textile plied laminates may be composed of either unidirectional tows laid side by side in sheets, or woven laminates. In either case, the planar laminae are then stacked one on top of each other to form structures with the appropriate three-dimensional geometry. The orientation of each lamina allows designer to tailor the mechanical response of the resulting composite material. Textile laminates are generally materials that are purchased pre-impregnated with resin matrix material, commonly called “prepreg”, but they can be made from dry preform materials which are then impregnated with resin via heat press molding, resin transfer molding (RTM), or chemical vapor deposition (CVD).

Another way pre-impregnated laminates and other textile preforms can be formed, is by using a pre-impregnated tow, or “towpreg”. The towpreg is then used in a textile process to form the desired preform structure. This method is used less often than prepreg due to limiting resin/machine interactions, and handleability of the pre-impregnated fiber.

As stated earlier, though unidirectional fiber composites do exist, often the reinforcements used in composite fabrication are more commonly formed textile fabrics utilizing high-performance fibers. These fabrics, or preforms, are fabricated using many different textile processes. The processes incorporate interlacing, overlapping, or intertwining of the component fibers - yielding geometries and resultant mechanical properties unique to each formation technique.
Generally, textile structures can be classified according to method of formation, the geometric design of the structure, and the fiber type used. The preforms may also be loosely classified into two-dimensional (2-D) and three-dimensional (3-D) structures, depending on the degree of reinforcement that exists between layers. [21]

2.5.2 Two-dimensional Weaving

Two-dimensional, woven fabrics are formed by the ordered separation/closure and insertion of two sets of interlacing, mutually orthogonal tows. These tow sets are interlaced at right angles with the longitudinal (machine direction) tows being referred to as “warp” tows and the transverse (cross-direction) tows as “weft” or “fill”. A typical loom consists of several harnesses that control warp-tow separation, a shuttle that passes the weft-tow through the separated warp-tows, and a beat-up mechanism for fabric compaction. By controlling the separation sequence of the warp-tows, different fabrics may be fabricated. Two-dimensional woven fabrics offer a high degree of tow packing, enhanced impact resistance, and cost-effective fabrication. However, some in-plain elastic properties and strength are sacrificed due to the high degree of localized crimp inherent to the process. [1, 14]

2.5.3 Two-dimensional Knitting

Two-dimensionally knitted fabrics are essentially “chains” of interlaced loops. Knits are classified as either warp knits or weft knits - dependent upon the orientation of the tow that is being “looped”. Typically, many latch needles are used
in a cam-based lift/drop system to loop the tow in and out of itself. As this process cycles, the series of interlaced loops that are formed constitute the fabric. Knitted fabrics provide a high degree of formability and enhanced in-plane shear resistance. Finally, increased directional stability can be obtained by adding laid-in tows. These tows can be placed in orthogonal and/or polar arrangement to tailor a desired mechanical response. [14]

2.5.4 Two-dimensional Braiding

Braided fabrics may be either circular or flat - where the flat braid is a special case of the more common circular braid. Traditional circular braiding machines utilize a “horn-gear” arrangement. The gear train consists of two continuous tracks used to guide the tow carriers. The horn-gears “pass” the tow carriers to and from each other in an alternating “over/under” fashion. For the case of flat braiders, tracks do not form a continuous circle – but instead forms a selvage edge at the two exterior positions on the machine that correspond to the outside selvedge edge of the preform. The turn-around motion is achieved by modification of the end horn-gears. These terminal gears have an uneven number of slots, which allows the tow carriers to reverse their paths and form the flat braid.

Circular braids are usually formed over an axi-symmetric mandrel, which determines the final shape of preform. In addition, axial laid-in tows may be used to increase longitudinal stiffness. By specifying the location of tow carriers on the machine, different braiding patterns may be accomplished. Due to the symmetric machine arrangement, braider tows are oriented at equal and opposite angles about
the longitudinal axis. This angle may be directly determined by machine operating conditions. Finally, while two-dimensional braids offer cost-effective fabrication, the planar structure of the two-dimensional geometry has limited their use in engineered composite materials. [20, 14]

2.5.5 Three-dimensional Weaving

Three-dimensional weaving is achieved through a modification of the traditional 2-D weaving process. The two main types of 3-D woven fabrics are angle-interlock (Figure 2.4) and orthogonal structure (Figure 2.5). Angle-interlock weaving is carried out by utilizing multiple harnesses on a conventional loom. The shifting sequence of the harnesses determines the undulation of the warp tows. Many geometric variations are possible due to the unlimited combinations of loom configuration and harness sequencing. These multi-layer, interlocked structures are ideal for thick-section composites. The reinforcement in the thickness direction may be tailored to enhance composite impact resistance. [27, 29] Additionally, laid-in tows may be used to increase stiffness in a desired direction.
Figure 2.4 3-D Weave – Angle Interlock Architecture [29]

Figure 2.5 3-D Weave – Orthogonal Structure Architecture [27]
Orthogonally woven fabrics possess three sets of mutually perpendicular tows. Reinforcements formed in this manner have inherent “matrix rich” regions between the intersections of the three sets of tows. Fabrication of these preforms is accomplished by inserting alternating in-plane tows between the stationary thickness direction tows. In this fashion, both square cross-section and cylindrical geometries are possible. [14, 18]

2.5.6 Three-dimensional Braiding

Three-dimensional braiding is a method by which fiber preforms can be fabricated for use in composite materials. This fiber-placement method is described in more detail, as this method is the focus of this research. The three-dimensional braiding process was originally developed to overcome some of the limitations of laminated composites. The three-dimensional structure has fiber reinforcement in the thickness direction, which provides the structure with resistance to delamination. This is a clear advantage over a stacked two-dimensional sandwich structure formed by stacking of individual lamina.

The process can be traced back to Bluck, who in 1964 developed “Bias Weaving”. This patented process is regarded as the first continuous three-dimensional braiding technique. At the same time, Robert Florentine was working with General Electric’s Reentry Systems Division in the creation of the “Omniweave” process. This process was similar to Bluck’s, but was developed specifically for the production of heat shields, which required the use of brittle fibers. He revised the
design of the process – combining the tow supply and carrier into a single machine element. [9]

Florentine later developed two other methods of braiding; both loosely based on the “Omniweave” system. The first, called “Magnaweave”, had a Cartesian bed arrangement, which utilized the x and y movement of the tow ends about the machine bed. The other method, a circular bed machine, was called “Magnaswirl”. This technology was licensed to Atlantic Research Company and others to further the advancement of the commercial use of the process. Atlantic Research used the trademark Through-the-Thickness™ braiding to identify their proprietary products. The process was capable of producing complex shapes with rectangular cross-sections such as I-beams, T-sections, and hollow squares, and cylindrical cross-sections such as rocket nozzles and fuel veins. Both of these methods utilized a track and column machine bed configuration and involve four distinct steps in the formation of a single cycle in the braided structure. For this reason, the processes are commonly referred to as “Four-step” or “Track and Column” braiding.

Another major development in the 3-D braiding movement was the SCOUĐID process, [Figure 2.6] developed and patented in Germany in 1973. This was called the first automated three-dimensional braiding machine. This process is different than both Bluck’s and Florentine’s methods, due to the way which the fabric is formed on the machine. In this process, the ends do not travel around the machine bed to form the braided structure, but rather are vertically raised in inter-braided
elements. The structure produced by the process can also be fabricated on a four-step, Cartesian braiding machine. [1, 17]

Figure 2.6  3-D Braiding –‘SCOUIDID-Style’ Braiding Machine [28]

Popper and McConnell developed another type of three-dimensional braiding, the two-step process, in 1987. The two-step braiding process is so termed because it involves two distinct motions of each tow carrier. The braid consists of an array of longitudinal (axial) tows arranged in a prescribed configuration such as rectangular, circular, box, etc., and braider tows positioned at select locations on the perimeter of the axial array. The shape of the axial tow configuration will determine the final shape of the preform. The braider tows, which move along alternating diagonals of the axial array, interlink the axials and hold them in the desired shape. This process uses both axial tows, ends that are held straight along the longitudinal direction of the preform, and braiders, which move around the machine bed. The braiders
interconnect the axial ends by their interlacing motion and therefore stabilize the structure. This process required no beat-up motion and can be easily automated.

However, this process did have limitations in that it required twice as many axial tows as braiders to produce a structure of comparable size to one produced on a four-step machine. The two-step braided composite not only offers high stiffness and strength in the axial direction, but also yields enhanced in-plane reinforcement due to the presence of the braider tows. [20] Furthermore, the addition or subtraction of axial tows during fabrication allows for on-line change of preform cross-section. Du and El-Shiekh improved this process separately, by adding motorized carriers to move the tows, and a computer-controlled, belt-driven carrier movement method, respectively. [1, 11]

Finally, an automated circular four-step three-dimensional braiding machine was designed and built by Dr. Aly El-Shiekh, at NC State University College of Textiles. The four-step braiding process involves four distinct Cartesian (square machine bed) or radial/polar (circular machine bed) motions of groups of tows termed rows and columns. For a given step, alternate rows (or columns) are shifted a prescribed distance relative to each other. The next step involves the alternate shifting of the columns (or rows) a prescribed distance. The third and fourth steps are simply the reverse shifting sequence of the first and second steps, respectively. A complete set of four steps is called a machine cycle. It should be noted that after one machine cycle the rows and columns have returned to their original positions. Four-step braided composites offer excellent shear resistance and quasi-isotropic elastic
behavior due to their symmetric, intertwined structure [14]. Additionally, the inclusion of axial reinforcement results in higher stiffness and strength and lower Poisson-effect as compared to bias-only structures. [14] The three-dimensionally braided structure is shown in Figure 2.7.

Figure 2.7 Four-Step, 3-D Braid (with Axial Reinforcement) Architecture [3]

Over the past thirty years, the structure has been refined in an effort to increase the process productivity, and to identify and better characterize the most critical parameters of this process. There are a few advantages of this method of fabric formation as used in preform materials. First, less crimp is introduced in the braiding process than in the weaving process. This is due to the fact that the incident angle
of the tows as they interlace each other is much less than 90° as is the case in orthogonal woven fabrics. Finally, the three dimensional braiding process allows each end to be separately fed and controlled. For this reason, like the 3-D weave, the 3-D braid is a true three-dimensional structure, in that each end moves in x, y, and z directions. This structural integrity gives the 3-D braided preforms a resistance to delamination upon impact in composites. [7]

Like woven preforms, incorporation of braids into composites can be achieved in a number of ways. The first method involves braiding the material and then placing the material into a mold. This method is most typical for sandwich structures.

The second method requires the use of a mandrel around which “near net-shaped preforms” are formed. The mandrel moves through the fabric-forming zone as the braid is formed. Due to the automatic tendency of the braided structure to collapse, the fabric preform conforms to the shape of the mandrel on which it is being braided. Both sandwich structures and near-net shape preforms were fabricated in the current research. Helmets were fabricated around a shaped mandrel for consolidation and testing by Dr. Frank Ko’s group at Drexel University [13], while sandwich structures were fabricated for dynamic testing at NC State University and evaluation of the braided structure (the primary subject of this thesis).

2.6 Ballistic Response of Composite Materials

Laible and Barron considered the advent of modern body armor to have occurred during World War II, when many American bombers returned from battle having
survived many shell and fragment penetrations. Formerly, many crew deaths often resulted from such fragments before the use of heavier cladding on bomber planes. Though the bombers still received enemy-fire, these fragments were often traveling at considerably lower velocities after having penetrated the aircraft hull. This reduction in velocity was significant, as studies have shown that fragment velocities as low as 243 m/s can penetrate flesh and 337 m/s can penetrate bone. [7, 16]

Again, during the Vietnam War, many U.S. Army helicopter crews were exposed to machine-gun and rifle fire and the need arose for better protective coverage. In 1962, a jacket was designed to counter this threat. The jacket consisted of 149 titanium plates backed with ballistic nylon, a polymer fiber developed by DuPont in the 1930’s. An aluminum oxide (AlO3) coating was also used to dull the projectile upon entry into the jacket. However, the coating was later replaced with a lighter coating of boron-nitride. [7]

After this success, DuPont continued development of fibers tailored for ballistic impact protection. Out of these efforts came a new aramid fiber – originally, PRD-49 and later Kevlar® 29 (discussed earlier in this section). The fiber has been adopted by military and law enforcement agencies as the standard in ballistic protection. In 1978, the Kevlar®-based helmet replaced the steel-based M1 helmet, with a 20%-weight plastic matrix for rigidity (and wearer comfort due to weight-reduction) [7].

Ballistic testing of materials can be separated into three categories: (1) a single target impacted by multiple projectiles, 2) multiple targets impacted by multiple projectiles, and 3) a single target impacted by a single projectile. [7] Furthermore,
Projectile geometries include: spheres, steel-core and tungsten-carbide projectiles, flechette, long-rod penetrators, high-explosive (HE) shell fragments, and steel projectiles of various geometries. Finally, specific tests include the pistol ball test (no longer used), the arena test (“Yankee stadium” test), the side-spray fragmentation test, the forward-spray test, the cube or sphere test, the munition-fragment test, the fragment-simulating projectile test, and the yaw-dart projectile test.

[7]

Though the ballistic failure modes of composite materials have been investigated, a lot of variability has been experienced in this experimentation. This variability is due to the wide variety of physical characteristics of projectiles used and energy levels. However, most investigations of fiber-reinforced composites have found failure by delamination and fiber tensile failure. [7, 22]

The present research is a continuation of research that was conducted at NC State University by the author and Mike Flanagan in 1996 [8]. The results of this research led the team to conclude that the typical failure modes of textile-reinforced composite materials were a function of velocity. Specifically, the team identified the relationships shown in Table 2.3 (for the energies and areal densities studied). The results of this study led to the more focused evaluation of three dimensionally braided composites that is the focus of the subject research.
Table 2.3  Primary Failure Modes of Textile Reinforced Composite Materials [8]

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Velocity Ranges (m/sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Breakage &amp; Pull-out</td>
<td>Up to ~350</td>
</tr>
<tr>
<td>Laceration – Square Hole Formation</td>
<td>Up to ~350</td>
</tr>
<tr>
<td>Matrix Cracking</td>
<td>Up to ~105</td>
</tr>
<tr>
<td>Delamination</td>
<td>Up to ~350</td>
</tr>
<tr>
<td>Deformation</td>
<td>Up to ~105</td>
</tr>
<tr>
<td>Shear Plugging</td>
<td>Up to ~650</td>
</tr>
</tbody>
</table>

In this 1996 study, all three of these failure modes were observed in 3-D braided Kevlar® 29 composites. Example images of the impacts at the three velocity ranges are illustrated in Figure 2.8, Figure 2.9, and Figure 2.10.
Figure 2.8  Typical Low Velocity Damage (Matrix/Fiber failure) [8]
Figure 2.9  Typical Intermediate Velocity Damage (Delamination) [8]

Figure 2.10  Typical High Velocity Damage (Shear Plugging) [8]
These failure modes were determined by the team to be a transition from strain energy (deformation) to kinetic energy (shear plugging). [8] A graphical representation of this relationship can be seen below in Figure 2.11.

**Figure 2.11  Relationship of Failure Mode to Velocity [7]**
Figure 2.12 is a further illustration of the evolution of failure mode as a function of the impact velocity. They are labeled with the nominal velocity (V_{xxx}) at which each of the failure modes was seen in meters/second. Additionally, the primary failure mode is annotated at the bottom of each of the images. In the lower velocity range (the first image; \sim 105 m/sec.), the primary failure mode was conical deformation (normal to the impact location). The labeled regions in the Intermediate velocity range (V_{350} image) are: (A) Local fiber shear failure (B) Matrix cracking, (C) Fiber failure and pull-out, and (D) Delamination. The labeled regions in the V_{650} image are: (A) Delamination (separation of matrix and preform), (B) Matrix cracking, and (C) Local fiber shear failure.
Chapter 3
Experimental Procedures

3.1 Three-dimensional Braiding Machine Modifications

The fully automated, circular, four-step, 3-D braiding machine was developed at NC State University in response to the successful research conducted on the manual, circular, four-step 3-D braiders. The iterative approach to machine design by Dr. El-Shiekh and graduate students in the NASA Mars Mission Research Center led to a significant redesign. The machine was based on the proven four-step, circular, 3-D braiding machine design that allowed for uniform tubular and near net-shape structure fabrication - a technology that was used in older manual models. [1, 3, 11]

The machine has the ability to incorporate axial and bias braiders with a total capacity of 504 carrier-fed ends. The braider utilizes the "track and column" concept whereby both the moving and stationary rings of the machine bed are grooved so that carriers can pass in and out of their range of control. Each of the moving rings has the capability to be individually controlled for the formation of asymmetric forms, but typically the rings are shifted in two paired groups yielding a symmetric braided preforms.

The machine bed consists of two main components. These are the moving rings that displace the braiding carriers radially in the braiding zone, and the stationary rings that allow for "spill over" movement outside of the braiding zone (external elements of the braided structure). The size of the braider and maximum size of the
resultant preform is a function of the size of these components. For this reason, the machine bed components were designed to be as compact as possible.

The machine motions can be discretely described as: (1.) Shift of Ring set 1 (group of three moving rings); (2.) Shift of Ring set 2 (the other three moving rings); (3.) Shift of Carrier set A inward (every other row); (4.) Shift of Carrier set B outward (the opposing rows). (See Figure 3.2) These motions constitute one-half cycle on the machine. The rings and the carriers are moved back to their original positions to complete a full cycle.

The machine is actuated by pneumatic cylinders tied directly to the moving ring undercarriages. These cylinders are plumbed such that the alternating moving rings of the machine actuate at the same time.

The new machine design included: automated machine motions, “quick mountable” carriers, and horizontal fabric withdrawal (rather than vertical). Each of these changes is significant – automation of the process significantly sped up the production throughput, the carrier design allowed for simplified material change-out and improved tow tension control, and the horizontal fabric withdrawal facilitated automatic convergence of the braided structure. A final significant change to this machine was the inclusion of solid-state control of the pneumatic actuation and the development of a control program to time and sequence each of the machine motions. This actuation is triggered by energizing a solenoid valve (one for each of the moving ring groups) in the rear of the machine. The sequence and timing of the actuation is controlled by the Opto 22 I/O board/AC5 solid state module controller
(driven by the custom machine-driver program). Further, the incorporation of the worm-geared traverse of the adjacent Spiraltex 2-D braider into the control scheme provided for step-controlled uniform braid fabrication at higher speeds when compared with the manual predecessors. The braider is pictured in Figure 3.1.

Figure 3.2

Figure 3.1. Fully-automated, 4-Step, Circular, Three-Dimensional Braider
3.1.1 Axial Tow Tube Addition

The addition of axial tow tubes to the machine bed was completed to allow for the insertion of longitudinal (0°) reinforcement in preforms. Holes were drilled into the machine bed plates to allow for the fiber to pass through to the rear of the machine. These holes were also tapped and extension rods were fashioned so that the material fed in these positions would be at the same delivery height as the top of the braider carriers. However, due to machine bed geometric constraints, materials in this study were fabricated using the modified 2x1 setup (discussed further in Section 3.1.3).

3.1.2 Automation of the Four-step Machine Cycle

Automated sequencing of machine motions was accomplished using a custom developed software program and I/O board. The full control program listing is included in Appendix A. Timing of motion actuation was critical in the operation of the machine - each quarter- cycle motion was optimized using for-next loops based on the IBM PC-AT Intel 8086 processor clock-speed. The optimization of the machine motions was done in an empirical experimental manner; the end result was a smooth operating machine - where the manual machines were plagued with regular jamming occurrences.

3.1.3 Modified 2x1 Braiding – ‘Near 1:1’ Bias/Axial Ratio

Typically, 4-step, 3-D braiding (“Track and Column braiding”) is done on Cartesian (or circular braiding) in a 1x1 fashion – in that each of the fiber ends
moves in a one track (ring) by one column (polar track) manner around the machine bed. In the subject research, however, the circular braiding machine was modified to facilitate 2x1 braiding – whereby the rings shifted ± two absolute positions during each half-cycle resulting in a two polar column carrier displacement. The machine was modified to achieve this construction by doubling the stroke length of the pneumatic cylinders so that the rings would be “thrown” twice as far with each cylinder actuation.

With either 1x1 or 2x1 braiding, the inclusion of axial tows has to be done from the rear of the machine bed via holes and guide tubes in the machine bed. Due to the high machine size to resultant part ratio of 3-D braiding [14], this causes significant issues on the interior diameter of the circular machine. Specific to the fully-automated circular braiding machine used in this research, the inclusion of axial tow tubes in this manner was not a possibility on the two innermost (smallest diameter) moving rings.

Therefore, to achieve the desired 1:1 bias to axial ratio (for quasi-isotropic material response), the machine was again modified. The new method involved the disabling of every other polar pneumatic cylinder. The effect of this final modification is that the axial tows in the non-functioning columns are never displaced in the polar direction. Instead the ends in these polar columns simply shift back and forth under the control of the ring shifting in their track. With this method of axial inclusion, the 0° are truly integral to the structure throughout the thickness of the preform – the
bias tows braid around them from the outermost machine bed position to the innermost position. A graphic visualization of this machine set-up is shown in Figure 3.2.

Figure 3.2  Modified 2x1 Braider and Axial Element Movement
3.2 Panel Specimen Synthesis

3.2.1 Preform Design

In both the near-net shape helmet fabrication and fabrication of the sandwiched panel structures, a computer CAD model was used in the design of the preforms. By this method, a theoretical structure can be modeled before the fabric preform is fabricated. The input variables (for a circular three-dimensional braiding machine) include the following:

- Braider surface area
- Desired diameter of the fabric
- Axial (if used) tow size
- Carriers per ring
- Axial surface area
- Axial tow denier
- Axials per ring
- Desired design volume fraction
- Braider tow size
- Desired fabric thickness
- Braid surface angle
- Desired fabric length
- Braider tow denier

The model was adapted from the work of previous investigators in the NCSU NASA Mars Mission Lab at the College of Textiles. This model relates fiber volume fraction, braid angle, preform dimensions, and machine set-up to directional fiber volume fractions, and estimates machine limitations. [3] An example of the design
worksheet based on the model is included in Appendix C. This example is the Kevlar® design that was used for the ARO helmet material fabrications.

With the near net-shape fabrication (as was the case in the helmet design), cross-sectional units have to be determined based off of the unit cell height. With each longitudinal fabrication cycle, a new design may apply as the diameter and dimensional characteristics of the mandrel change. [14, 29]

3.2.2 Spool Winding

The automatic, 3-D braiding machine can hold much more fiber than the manual machines used earlier in the lab. While short lengths of fiber (approx. 1-meter) had to be cut and taped to elastics by hand on the manual machines, the automated machine uses a carrier and spool design which allows the machine to hold much more fiber. This carrier design is discussed in detail in section 3.2.3.

The supply spools, which are mounted onto the carriers on the machine bed, must first be filled with fiber. A Hacoba commercial winding machine was utilized for this winding step. This machine was modified to hold the unique spools, tow guides were added to route the fiber from the package to the spool, and capstan-tensioning devices were incorporated to ensure adequate packing of fiber onto the spool. The machine is an automatic winding machine, but the operator had to remove and replace the spools as they were filled. For this reason, this was one of the most labor-intensive steps in the fabrication of these preforms. Once the spools were wound, they were ready to be placed onto the carriers.
3.2.3 Carrier Loading

The fiber carrier used in braiding is an important factor in the braid fabrication. The NCSU designed and patented (US Patent #5,156,079) carrier (shown in Figure 3.3) used in this research was ideal in that it provided tow rewind, maintained tow tension, and was compact in size. This is important because as tow carrier moves across the machine bed, the distance between carrier top and braided fabric changes. This causes a slackening and tensioning of the tow being supplied and can lead to interference with adjacent over or under-tensioned tows and/or undesirable braid angles.

Rewind, tensioning, and tow feed in this design are all accomplished through interaction of carrier elements with the spool (A in the carrier figure). The design includes a slip-plate clutch mechanism (B). This mechanism uses plates that are independently tied to the spool inner diameter housing and the geared clutch shaft (D) in an alternating manner. The carrier drive consists of an adjustable length coil spring with one end rigidly attached to a geared shaft (C) coupled with this clutch. The other end of the spring is bent to produce a small flange. This end is free to scrape along the inside of the aluminum housing until it contacts one of two set screws which protrude into the cavity. When this happens, the spring acts as a rewind mechanism. After a predetermined number of revolutions, the spring slips to the next set screw allowing for tow feed. The length of this spring was optimized for optimum tensioning of the fibers being braided.
The entire spool mechanism is enclosed (F) and self-contained. In this way, the spool may be easily wound with tow then inserted into the holder. The holder also guides the tow from the spool to a top-central location (E).

A hardened plastic Delrin® “boot” was responsible for movement of the carrier in relation to the machine motions. As the machine would move, the cylinders would push the outermost and/or innermost carrier boots to move a radial column.

Figure 3.3 NCSU Patented Carrier Design
The length of the carrier boot determined the spacing between the carriers in the radial direction. The soft but tough material, tight tolerances, and chamfered edges of this boot design allowed the machine to function without binding. However, in the rare event that one of the carrier boots got lodged between two alternate rings, the machine would jam. This would necessitate the manual return of the machine to the “home” position.

“Home” position was the starting point for all braids; at this position none of the air feed-tubes on the machine were empty. Thus, this was a safe position at which to start braiding and, to work out problems that may have arisen. However, because the computer program was still holding the machine at the position (or in between a position) where the jam had occurred, the operator was required to set the manual switches and walk the machine back to home. Once the machine was back in “home” position, the toggle switch was returned to the automatic position before the computer program was reset. The procedure for the machine operations are described in detail in Appendix B.

A tongue on the boot upper provided a snug joining mechanism to the carriers. Carriers were pushed down onto this tongue, and adjustable ball-pins in the carrier body fastened the carrier to the boot. This boot design made it easy to change any of the carriers if a malfunction occurred, the fiber ran out, the fiber type needed to be changed, or the carriers were being removed to be set up for a new run. The material design and resultant machine bed set-up dictated the order which the carriers were mounted.
3.2.4 Mandrel Insertion and Convergence

A mandrel is typically used for the tubular preform fabrication. The use of a mandrel gives a termination point for the formed braid compaction. If a mandrel is not used, the braid will jam due to adjacent fiber crowding and over-tensioning at convergence. The diameter of this mandrel is one of the design inputs for a resultant braid surface angle.

Preforms in this study were fabricated around a collapsible mandrel, which consisted of a longitudinally slit 3” OD PVC pipe with ¼” x ½” flat steel rod inserts. The rods were taped into place along the long edge of the pipe. This design allows the operator to remove the bars at the end of a run and remove the preform material. The tubular mandrel was positioned in the center of the open hole inside the machine bed for axi-symmetric braid formation on the tube. The tube was supported in the rear by rollers and on the front (withdrawal side) by the worm-geared mandrel carrier of the adjacent 2-D circular braider mentioned earlier.

Converging mechanisms are used in braiding to pull the exterior tows up to the desired orientation and then allow inter-tow friction and interlacing to hold the tow in place on the mandrel. It was essential to have precise control of the amount of take-up as take-up distance directly determines the braid pitch length and resulting architecture. With the worm-geared traverse control method, discrete take-up distances in increments of 0.10" could be maintained. Again, the driven traverse mandrel advance was controlled on one of the channels of the I/O board and the
timing of actuated by the computer program. This braid withdrawal was done upon completion of each half-cycle.

Convergence is analogous with the fabric tightening step, or “beat-up”, in weaving, and is generally accomplished by sliding two stainless steel rods along the fiber axes. However, as stated earlier, convergence occurred inherently as the radial ends were held in a near equilibrium state under near-equal tension from all orientations, and the structure did not have to “fight” gravity due to the horizontal machine configuration. Automatic convergence causes little fiber damage (<1%) because the filaments are not mechanically contacted after the leave the supply spool.

The convergence point was monitored and held constant, and marked by a plumb line hanging from the ceiling. Occasionally, fine-tuning of the computer timing variables had to be done to maintain this constant convergence point. For the panel preform fabrication, the convergence point was held constant approximately 16" off of the machine bed.

3.2.5 Fiber draw-in

Prior to the initiation of any braiding, each of the ends were first pulled-in to a central location on the mandrel. Each end was taped in place until all of the ends had been pulled, and then a single wrap of tape was used to ensure an axi-symmetric braid “fell-point”. This fell-point was maintained at a predetermined distance in-plane with the machine bed as calculated in the braid design model. This point was held constant during the braid formation by the constant movement of
the mandrel as the braid was formed back toward the machine bed. The position of this convergence point and the withdrawal rate of the braid during fabric formation have a direct effect on the resultant braid angle. The braid angle can be described as the surface angle, $\Theta$, formed by the fiber axes relative to the 0° axis of the mandrel about which the braid is formed. A geometrical representation of this angle is pictured in Figure 3.4.

**Figure 3.4 Geometrical Representation of Braid Angle [3]**

The maximum "braidable" length of preform for this machine configuration is only limited by the length of travel of the take-up mechanism, with a caveat. Due to the long length of fiber and the horizontal position of the machine bed, it is possible to braid a length of braid only limited by the amount of tow that can fit on the spools of
each carrier. As a point of reference, this length was approximately 30-feet for a 1300 denier Spectra® tow.

3.2.6 Preform Fabrication

To characterize the textile composite failure modes as a function of material properties, composites were designed with different preform materials, and an epoxy resin as the matrix material. The preforms vary by fiber type – Kevlar® 29, Spectra® 1000, and hybrids of the two fibers. In the homogeneous fiber constructions, all 504 ends were loaded with the designated fiber choice and modified 2x1 braiding was initiated. The hybrid configurations included both fibers as bias and axial members with the other fiber type. Therefore, the four material systems can be defined as:

- Spectra® 1000 Bias with Kevlar® 29 Axial Reinforcement
- Kevlar® 29 Bias with Spectra® 1000 Axial Reinforcement
- Kevlar® 29 Bias with Kevlar® 29 Axial Reinforcement
- Spectra® 1000 Bias with Spectra® 1000 Axial Reinforcement

A graphical description of the modified 2x1 braiding machine set-up for each of the hybrid constructions can be seen in Figure 3.5 and 3.6. The modified 2x1 configuration will be referred to in this paper as the 3-D braided samples with axials. The preforms were fabricated in an effort to maximize the fiber volume fraction in the final composite, while still maintaining the required 45° braid angle.
Figure 3.5  Machine Bed Loading Configuration (S/K Axials)
Figure 3.6  Machine Bed Loading Configuration (K/S Axials)

- **K** = Kevlar® Column
- **S** = Spectra® Column
- **Ø** = Position Holder

1/4 Machine Bed Shown
3.2.7 Cutting of Fabrics from the Tubular Mandrel

Due to the additive movements of the stepped mandrel advance, continuous lengths of fiber longer than ~15 feet could not be run. Therefore, these discrete fabric lengths were cut and removed. The mandrel then had to be reinserted into the machine for continued braid fabrication. This requirement, along with the fact that the fibrous materials used in this experiment were chosen due to their high strengths posed issues with the cutting of the fabric from the mandrel. The problem was most severe with the Kevlar® fiber – however, specially suited, very finely serrated scissors were used to cut the fiber. [8, 19] With the Spectra® fabrics, the problem was eased by the use of a heated air-knife due to the low melting point of the fiber. However, due to the small filament diameter and the tendency of this fiber to take on a static charge, there were other problems that had to be overcome. Most of the fiber-handling problems were resolved simply by being attentive and using precise cutting methodology.

3.2.8 Composite Consolidation

All of the preforms were consolidated using Shell Chemical Epon® 862 Epoxy BPF resin system. The resin was cured using Epon® RSC-2181 curing agent at a 16.9 parts per hundred (pph) mix ratio. The consolidation technique involved hand lay-up of the preform materials into aluminum molds, vacuum evacuation of the preform in the mold, heated compression molding, and post curing in a laboratory oven.
The aluminum 10"x13" mold, assembly screws, and presser bars were first treated with Trewax® carnuba wax, a common mold release agent. The preform was then preheated to 60º C in the aluminum mold. Preheating of these items insured maintenance of the elevated resin temperature during evacuation. The resin was also preheated to reduce the viscosity for easier infiltration into the preform.

After the resin was preheated, it was mixed with the curing agent. A variable speed drill with a mixer attachment was used to insure thorough mixing of the components. This action, however, introduced a lot of additional air bubbles to the system. For this reason, once the resin was into the mold, the mold and its contents were placed in a vacuum chamber and evacuated to 1-torr to remove this residual air.

The mold was then removed from the vacuum desiccator and the preform was placed in the resin system. Steel bars were then used to restrict the tendency of the air accumulations under the preform to cause it to lift during further evacuation. A staged mold is shown in Figure 3.7. Again the mold and its contents were placed in the desiccator and evacuated down to 1-torr (~5 minutes). When the preform had been sufficiently infiltrated with the resin/curing agent mixture, and most of the air had been removed from the mold, the mold was taken out. The steel bars were then removed and replaced with the top panel of the mold. The mold was then wrapped in Mylar® film, and taped to prevent resin leakage.
The mold was then placed on a Wabash® hydraulic lab press (see Figure 3.8), which had preheated upper and lower platens to 80ºC (176ºF). The mold was left on the press for one hour under 1000-lbs. compressive force. The mold was then removed from the press and placed in an oven for post curing. This post cure was performed at 177ºC for one hour. After the post cure procedure, the mold was removed from the oven and allowed to cool before the composite panel was removed.
3.3 Helmet Fabrication

Investigations into textile manufacturing of helmet preforms were undertaken as a part of the Army Research Office (ARO) Multiple University Research Initiative (MURI). The following goals were accomplished during these investigations:

(1.) Fabrication of a 60" long, 60 layer, 3-D Braided Kevlar® preform for helmet fabrication and testing at Drexel University. This preform was constructed around a 6” OD mandrel with a target preform thickness of 0.500".
Fabrication of a 60" long, 60 layer, 3-D Braided Spectra® preform for helmet fabrication and testing at Drexel University. This preform was also constructed around a 6" OD mandrel with a target preform thickness of 0.500".

Fabrication of a 60" long, 60 layer, 3-D Braided Kevlar® and Spectra® fiber hybrid preform for helmet fabrication and testing at Drexel University. This preform was also constructed around an 8" OD mandrel with a target preform thickness of 0.500".

All of the preforms were fabricated using the standard 1x1, 4-step machine configuration with no axial reinforcement. The hybrid preform consisted of 20 layers of each of the fibers on the outermost and innermost layers with a 20 layer transition region of "hybrid" braided layers (both Kevlar® and Spectra® fiber co-bias braided).

Finally, a change in mandrel diameter was necessary to allow for easier consolidation for Dr. Ko and his colleagues at Drexel University. A preliminary helmet forming trial is shown in Figure 3.9.

Issues that were encountered (and overcome) during these fabrications included:

- Maintenance of the braid angle with a continuously variable diameter mandrel,
- Open-hole formation at the top of the helmet due to braid of “sock-structure” over a mandrel,
- Slippage of layers relative to one another with new layer addition, and
The cutting of preform from mandrel which plagued the panel structure preform fabrication efforts.

Preforms designed and fabricated at NC State were consolidated and tested at Drexel University. [13]

**Figure 3.9  Helmet Preform Formation**
The consolidation of the helmets was conducted at Drexel University utilizing the Gradient Design Concept (GDC). This design calls for the inclusion of tightly packed ceramic spheres on the strike-face of the composite to dull the projectile prior to arrest by the lower density fiber-reinforced composite second phase.

3.4 Dynamic Impact Testing

The team subjected the four stacked composite panels to controlled ballistic impact with 19-mm projectiles - monitored by firing pin dislocation lining the barrel of impactor as displayed on four Hewlett-Packard oscilloscopes. A visual representation of the reference positions of each of the panels in the stack is shown in Figure 3.10. Two repetitions of each of the four material systems were tested so that an averaged material response could be assigned to each group.

A detailed pre-fire checklist was followed prior to the impact, and followed up with a gun cleaning routine. Each shot and recovery required approximately three hours to complete. Each experiment began with the preparation of the velocity pins, rigging of the residual velocity device, packing of the soft recovery box, loading of the shell, and staging of the projectile.
3.4.1 19-mm Powder Gun

The NCSU 19-mm powder gun used in the study was rebuilt to investigate the penetration resistance, velocity dependent failure modes, and damage progression of the textile reinforced composites tested in this study. The gun was rebuilt by CPT Mike Flanagan to ensure that: (1) the target and the projectile were precisely aligned for coaxial impact, (2) the projectile was in free flight; (3) that there was a vacuum in front of the projectile to prevent air shocks from falsely triggering the instrumentation;
(4) the projectile was capable of accelerations that result in a velocity range of 150 m/s to 1500 m/s; (5) velocity measurement could be obtained along the barrel and at the muzzle of the gun; and finally, so that velocity measurements could be obtained at the back side of the specimen after impact. [7]

A 12-gauge shotgun shell was used to accelerate the projectile along the 2.9-m long gun barrel and into the target chamber. Holes were machined in the barrel for velocity pin placement and the vacuum pump receptacle. The firing pins were fabricated so that as the projectile past them in the barrel of the gun, the copper wire would be grounded to the sidewall of the hole.

Standard gun cleaning solvent and tailor-made cleaning rods were used to clean the barrel after each shot. The 19-mm gun assembly is pictured below in Figure 3.11; labeled items are (A) Shell-loading station, (B) Vacuum pump, (C) Target Holding Section, and (D) Protective Wall.
3.4.2 Catcher Assembly

A custom catcher assembly was designed to capture the projectile and target debris after impact and allow for soft recovery of both. The catcher assembly is 94-cm long and was fabricated from steel tubing. The assembly pivots into and out of alignment with the target chamber for easy post-impact debris removal. Clay, bricks, sand, rags, impacted panels, wood, and cardboard were all used in the catcher assembly to arrest the projectile when the material failed to stop its flight. [7]
3.4.3 Residual Velocity Device

The Residual Velocity Device was designed to measure the velocity of the projectile after target impact and penetration. The device was pre-strung with 30-gauge electrical wire across the centerline and attached to two posts to complete a circuit (See Figure 3.12). One of these posts was insulated, while the other post was not. This circuit was monitored on the one of the oscilloscope channels for residual projectile velocity measurement upon panel exit (in shots that resulted in full-penetration).

Figure 3.12 Dynamic Impact Testing - Residual Velocity Device [8]
3.4.4 Target Holder

A target holder was designed and built to hold the composite targets. This holder was designed to accommodate targets with dimensions of 13.3-cm x 13.3-cm and a maximum thickness of 5.08-cm. The target holder was clamped onto the targets with a 7.62-cm diameter aperture plate. The assembly was then aligned with the offset plate and exit assembly of the 19-mm gun barrel. Finally, the target holder assembly was fixed into place by screws and sealed with a rubber gasket. The main function of the target holder assembly was to provide rigid support for the target during projectile impact. The holder assembly is pictured in Figure 3.13. Labeled areas are: (A) Aperture plate and (B) Target stack loaded in test position.

Figure 3.13 Dynamic Impact Testing - Target Holder Assembly [8]
3.4.5 Test Instrumentation

Three HP oscilloscopes were used to monitor the voltage in each of the velocity circuits. The oscilloscopes were chosen over timers because of the availability of the oscilloscopes and the low reliability of available timers. Each oscilloscope triggered the voltage trace from the first of two channels monitored. The time base was set for the trace based on the anticipated time interval. The scope delta time-function was used by positioning starting and ending cross hairs over the pre-trigger and trigger points on the trace. The trigger channel was offset by 15 volts on the oscilloscope to provide a clear distinction between the each of the two signals and the trigger time for each signal. [7]

3.4.6 Projectile

A 19-mm diameter, 12.4-gram Lexan® projectile was used as a standard projectile for this research. This projectile was custom-designed for compatibility with the 19-mm gun-tube. This oversized projectile was used so that the damage area, failure mode, and damage progression could be studied on a larger scale. Figure 3.14 shows both a powder loaded (A) and projectile only (B) view of the projectile. The projectile includes two diametrically countersunk o-rings to insure a good vacuum seal of the test environment when the projectile was loaded into staging area prior to shot fire.
3.5 Compression After Impact (CAI) Testing

All of the panels that were dynamically impacted in this study were individually evaluated in quasi-static compression after the impact. This testing was employed for identification of the total strength loss of the stack and for the identification of the damage progression from strike-face through to the wear-face of the stack. To facilitate this assignment of strength loss as a percentage of the original material strength, an un-impacted control specimen was also tested for each of the material systems so that a baseline value could be associated with each material system.

Boeing Specification Support Standard (BSS) 7260 (Open-hole Compression Test Method) was used for this post impact compression loading, but was modified due to the target geometrical restrictions of the 19-mm gun. Specifically, the BSS
calls for the use of the Class 2 C-A-I specimen hold down jig which accepts 4”X6” test specimens, however, for this testing the jig support tabs were modified to accept the 5”x5” composite specimens. These minor modifications included extension of the loading plate to accommodate the 5” wide specimen and adjustment of the side-support rails via the included fine-tuning mechanical fasteners (slotted plates with socket-head cap screws). The coupon is rigidly supported on all four edges by this adjustable jig.

The testing was conducted at the NC State University College of Textiles on an Instron® machine with a 50,000 lb load cell. The test sequence was initiated by placing the specimen in the support stage of the jig. After the specimen was loaded into the lower support fixture, the top plate (loading plate) was placed on top of the exposed specimen fourth edge. Finally, the fully assembled fixture (with coupon in place) was then positioned in an unconstrained manner on the bottom platen of the Instron® machine. During the test, compressive loading was applied directly to the top plate of the fixture by the crosshead of the testing machine. All tests were conducted at a crosshead speed of 5-mm/minute and at a data acquisition rate of 20-hertz. Finally, load and displacement curves were constructed for each of the samples so that the yield point and maximum load at failure could be identified.
Figure 3.15  CAI Testing – BSS 7260 Open Hole Compression Test Jig [26]

Figure 3.16  CAI Testing – NC State, COT Instron® Facility
3.6 Microscopic Specimen Evaluation

3.6.1 Scanning Electron Microscopy (n-SEM)

An environmental scanning electron microscope (n-SEM) was used to identify the damage area and failure modes of the composite panels post-impact. A SEM forms an image in a cathode ray tube synchronized with an electron probe as it scans the surface of an object. The resulting signals are acquired from secondary electrons, back-scattered electrons, characteristic x-rays, and photons of various energies. To achieve good results using a SEM, the sample must be conductive, or must first be sputter coated with a metal. This allows the electron probe to collect the secondary electrons as they bounce off of the material surface. However, an n-
SEM is used for organic materials which are non-conductive and which would not be easily sputter-coated with metal. In this type of SEM, the image is made by collecting the back-scattered electrons as the bounce off of the surface of the organic panel.

In this research, panels were investigated post-impact using an n-SEM with integrated back scattered electron detector, image analysis software and photographic capabilities. First, the samples were mounted on posts with double-sided tape, and put into the chamber. The chamber was then evacuated and pressurized to 1-bar pressure. The image was then displayed on a CRT display. The integrated software allowed the user to adjust the scan rate to enhance the image clarity, to adjust the gray level threshold to provide better contrast between specific elements, and allowed the user to output the digital image to an analog hardcopy. Photomicrographs were made to document the three-dimensionally braided structure and precision fiber placement capabilities. A sample image is shown in Figure 3.18. Furthermore, a section of typical composite material failure due to dynamic impact loading was examined in the n-SEM to magnify the impact location for micromechanical evaluation of the resilience of the material. A sample image is included as Figure 3.19. It can be seen from this image that matrix cracking and local filament failure were present.
Figure 3.18  Photomicrograph of 3-D Braid Fiber Architecture (20X Mag.)

Figure 3.19  Photomicrograph of Impact Site (80X Mag.)
Chapter 4
Results and Discussion

4.1 ARO-MURI Helmet

The results of the collaborative NCSU and Drexel University research preliminarily indicate that a helmet structure can be fabricated utilizing three-dimensionally braided preform reinforcement. At the time of publication of this document, consolidation of the helmet forms had been completed, but dynamic impact testing of the composite helmets had not yet been conducted.

4.2 Dynamic Impact Testing

The results of the dynamic impact testing generally supported the findings of the preliminary tests completed in 1996 [8] in that the failure modes of the fiber-reinforced composites were typical for the velocity regime at which the shots were fired. For the shots that resulted in full projectile arrest, the energy reduction was calculated using the following equation [7]:

\[
\frac{1}{2} (M_{\text{initial}}) (V_{\text{impact}})^2 = \frac{1}{2} (M_{\text{final}}) (V_{\text{residual}})^2 + E_{\text{absorbed}}, \quad \text{where} \quad [1]
\]

M_{\text{initial}} = \text{Mass of the stack (in grams)},
V_{\text{impact}} = \text{Incident velocity of the projectile (in meters/second)},
M_{\text{final}} = \text{Mass of the stack after impact (in grams)},
V_{\text{residual}} = \text{Terminal velocity of the projectile (V_{\text{residual}} = 0), and}
E_{\text{absorbed}} = \text{Total Energy absorbed}
Again, due to the failure of the residual velocity mechanism in tests that resulted in full penetration, the energy absorption was only calculated for materials that fully arrested the projectile (where $V_{\text{residual}} = 0$). It should be noted that all of the energy absorbed ($E_{\text{absorbed}}$) cannot be attributed to the material, since some of the energy was lost due to projectile deformation. Furthermore, the energy reduction was normalized by the average areal density of the composite stack using the following equation [7]:

$$E_{\text{spec}} = \frac{E_{\text{absorbed}}}{\text{AD}_{\text{comp}}}, \text{ where } [2]$$

$E_{\text{spec}} = $ Specific Energy Absorbed (J/g/cm$^2$)

$E_{\text{absorbed}} = $ Total Energy absorbed (Joules, from Eq. 1), and

$\text{AD}_{\text{comp}} = $ Areal Density of the composite (g/cm$^2$)

This specific energy reduction equation allows the material system response to be directly evaluated in comparison to one another without the results being skewed by differences in the fiber density or composite consolidation efficiency.

4.2.1 Dynamic Impact Testing Results

Images of each of the dynamic tests are included in the following pages. Each set of images shows the strike-face and the wear-face of the composite stack both in the target holder and in free-form post-impact. A discussion of the material response and result of each of the shots is included below the images.
This 232 m/s impact resulted in full projectile arrest. This equates to an energy reduction of 334 Joules. The material damage was primarily only visible on the strike-face, where there was a distinct indentation (and transverse deflection) caused by the projectile impact. However, there was minimal fiber damage to the strike-face or any of the other member panels of the stack. The only indication that there was an impact on the other panels was minor fiber displacement and
deflection caused by the impact energy. The mean transverse deflection of the panels was 5.5-mm. The total mass loss of the stack was negligible at 0.5 g.

Figure 4.2  Shot#2 [Kevlar® / Spectra® Axials]

This 271 m/s shot resulted in full-penetration of the stacked material. The strike-face was plugged in a circular manner – with evidence of bias and axial fiber shear failure as a result of the impact. Both the 1° and 2° position panels showed signs of significant axial loading and subsequent shear failure. The wear-face was marked
by a vertical slit through which the projectile exited. There was significant transverse
deflection in all of the member panels of the stack, with a mean value of 11.8-mm.
Additionally, the target experienced 4.8 grams of mass loss during the impact.

**Figure 4.3  Shot #3 [Kevlar® / Kevlar® Axials]**

This 247 m/s impact resulted in full projectile penetration of the target. Projectile-shaped (in cross-section) plugging was observed on the face of each of the panels in the stack. Furthermore, the exit-side of each of the panels seemed to “open up” in
a petal-like fashion - probably due to tensile loading and failure along the primary fiber axes. Transverse deflection of the panels in the stack was the primary mode of failure in this test (10-mm on average). The mass loss of the target due to impact loading was counter-intuitively at zero – this may be attributable to mass measurement error or simply a result of the material system toughness although it failed catastrophically.

Figure 4.4 Shot#4 [Spectra® / Spectra® Axials]
This 235 m/s test resulted in full projectile arrest. The strike-face showed definitive signs of the projectile strike; however, no signs of the impact were observe in the rest of the stack members. The rear of the strike-face panel showed axial movement in response to the impact loading, however, there were no signs of fiber failure. This shot was the “best performer” in terms of the minimal visual signs of damage to the target. Mass loss and transverse deflection of the panels was minimal – the stack only lost a total of 0.3-grams of mass and the mean deflection was 3.0-mm. It should also be noted that the panels in this stack had the lowest areal density of any of the composites tested – which gives the author further confidence in the material system. The lower areal density of the panels is the result of the use of 100% Spectra® fiber, which has ~48% higher fiber density.
This 275 m/s shot was the highest velocity test conducted during this research. Though the same amount of powder was used in this test, the projectile velocity was ~25 m/s higher than any of the other tests. The higher velocity was most probably due to variability in the powder components. The stacked target was fully penetrated by the projectile. Major fiber failure was observed on all of the member panels. Petal-like fiber-failure was observed on the exit-side of the first three panels in the stack. The wear-face was marked by major shear failure of the bias and axial
tows, though the petal-like exit mode was not visible as it was in Shot#3. The debris seemed to be contained within the target stack, as there was only 0.2 grams total mass loss. However, there was significant transverse deflection of the panels – approximately 7.0-mm on average.

Figure 4.6   Shot#6 [Kevlar® / Spectra® Axials]

The quantity of powder was reduced 0.5-grains for this test in response to the high velocity that was experienced in shot#5. Unfortunately, the reduction in powder
for this shot limited the projectile velocity to 200 m/s – the lowest velocity generated in this research. Accordingly, the target resisted full-penetration of the projectile for a net energy reduction of 248 Joules. However, the stack showed signs of significant fiber failure – both in axial and bias tows. Additionally, there was a vertical opening perpendicular to the axial fiber reinforcement axes. This can most probably be attributed to the failure of axial fibers as the local stress of impact was transferred when the bias fibers failed. It should be noted, that though the stack resisted full penetration, due to the low velocity and the severity of the damage to the target, this was not viewed as a "good" shot and would have probably resulted in full-penetration at the 245 m/s average velocities at which the other material systems were tested. Further support of this belief can be found in the fact that the strike-face was fully penetrated and showed signs of the formation of the petal-like exit phenomenon observed in other target failures.
This 245 m/s shot resulted in full projectile arrest. This is an equivalent energy reduction of 372 Joules. The strike-face showed fiber failure and pull-out on the rear. However, the other panels in the stack exhibited little to no fiber failure except for the 2° panel which showed minor fiber pull-out from the matrix. This was probably a result poor localized fiber to matrix bonding during consolidation. The major failure mode during this test was transverse deformation. However, this shot was different than all other tests in that the deformation was convex with respect to
the line of projectile flight –negative deflection of ~2.6-mm on average. There was no mass loss of the stack due to impact.

Figure 4.8 Shot #8 [Spectra®/ Spectra® Axials]

This 258 m/s shot resulted in full projectile arrest – equivalent to a 413 Joule reduction in energy. The strike-face panel had some evidence of the impact – primarily fiber movement on the rear of the panel, but no major fiber failure. The other panels in the stack had virtually no damage other than matrix cracking. Again,
the member panels of this stacked target had low areal densities due to the use of Spectra® fiber.

4.2.2 Dynamic Impact Testing Discussion

The results of the dynamic impact testing are summarized in Table 4.2 – ordered by the highest average energy reduction. With the exception of the 100% Spectra construction, all of the material systems both resisted penetration and were fully penetrated. This indicates that the tests were conducted at or around the V50-limit of the material systems – a standard which was discussed earlier. At this limit, the 50% of the time the material fails and 50% of the time the materials resist penetration. Though the number of tests typically conducted is greater than the two tests per material system that were conducted in this research.
<table>
<thead>
<tr>
<th>Shot</th>
<th>Construction</th>
<th>Mass Loss (g)</th>
<th>Energy Reduction (Joules)</th>
<th>Specific Energy Reduction (J/g/cm²)</th>
<th>Impact Velocity (m/s)</th>
<th>Transverse Deflection (mm)</th>
<th>Primary Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$S_{Bias}/K_{Axial}$</td>
<td>0.5</td>
<td>334</td>
<td>2.35</td>
<td>232</td>
<td>5.5</td>
<td>Projectile Arrest</td>
</tr>
<tr>
<td>2</td>
<td>$K_{Bias}/S_{Axial}$</td>
<td>4.8</td>
<td>-</td>
<td>-</td>
<td>271</td>
<td>11.8</td>
<td>Fiber Failure</td>
</tr>
<tr>
<td>3</td>
<td>$K_{Bias}/K_{Axial}$</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>247</td>
<td>10.0</td>
<td>Conical Deformation</td>
</tr>
<tr>
<td>4</td>
<td>$S_{Bias}/S_{Axial}$</td>
<td>0.3</td>
<td>342</td>
<td>2.95</td>
<td>235</td>
<td>3.0</td>
<td>Projectile Arrest</td>
</tr>
<tr>
<td>5</td>
<td>$S_{Bias}/K_{Axial}$</td>
<td>-0.2</td>
<td>-</td>
<td>-</td>
<td>275</td>
<td>7.0</td>
<td>Fiber Failure</td>
</tr>
<tr>
<td>6</td>
<td>$K_{Bias}/S_{Axial}$</td>
<td>0.3</td>
<td>248</td>
<td>1.58</td>
<td>200</td>
<td>3.6</td>
<td>Projectile Arrest</td>
</tr>
<tr>
<td>7</td>
<td>$K_{Bias}/K_{Axial}$</td>
<td>0.0</td>
<td>372</td>
<td>2.68</td>
<td>245</td>
<td>-2.6</td>
<td>Projectile Arrest</td>
</tr>
<tr>
<td>8</td>
<td>$S_{Bias}/S_{Axial}$</td>
<td>0.0</td>
<td>413</td>
<td>3.58</td>
<td>258</td>
<td>1.9</td>
<td>Projectile Arrest</td>
</tr>
</tbody>
</table>
Table 4.2  Construction Specific Shot Summary

<table>
<thead>
<tr>
<th>Rank Order</th>
<th>Fiber Construction</th>
<th>Average Areal Density (g/cm²)</th>
<th>Average Incident Velocity (m/s)</th>
<th>Maximum Energy Reduction (Joules)</th>
<th>Maximum Specific Energy Reduction (J/g/cm²)</th>
<th>Penetration Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S_{Bias}/S_{Axial}</td>
<td>116</td>
<td>247</td>
<td>413</td>
<td>3.58</td>
<td>0:2</td>
</tr>
<tr>
<td>2</td>
<td>K_{Bias}/K_{Axial}</td>
<td>138</td>
<td>246</td>
<td>372</td>
<td>2.68</td>
<td>1:2</td>
</tr>
<tr>
<td>3</td>
<td>S_{Bias}/K_{Axial}</td>
<td>126</td>
<td>254</td>
<td>334</td>
<td>2.35</td>
<td>1:2</td>
</tr>
<tr>
<td>4</td>
<td>K_{Bias}/S_{Axial}</td>
<td>136</td>
<td>236</td>
<td>248</td>
<td>1.58</td>
<td>1:2</td>
</tr>
</tbody>
</table>

*Penetration Ratio = Ratio of shots that resulted in full-penetration to those that were arrested.

It can also be seen from the table that the $S_{Bias}/S_{Axial}$ material was the most successful at stopping the projectile in the ~245 m/s velocity test range. It is theorized that this improved resistance to dynamic impact loading is a function of the higher breaking strength and tensile modulus of the fiber as compared with the Kevlar® composites. With an average areal density ~15 g/cm² lower (per panel) than the other material systems, it should also be noted that the specific energy reduction of the material system leaves further promise that by raising in the areal density of the composite acceptable performance at higher energy levels could be achieved.

However, the 100% Kevlar construction was the second-best performer (though at a slightly higher average areal density) in this study —therefore, the presence of Spectra® fiber cannot be established as the sole criteria for successful projectile
arrest. In both of the top-performers, the fiber-type used was the same for both axial and bias tows. For this reason, it is theorized that another key factor in the performance of the material system may be the interfacial-bonding characteristics of the two fibers. This bonding mismatch may cause disproportionate stress concentration in hybrid materials and more uniform stress dispersion in materials with homogeneous fiber-type reinforcements.

4.3 Compression After Impact (CAI) Testing

As mentioned previously, the preforms were designed to be similar in terms of the absolute tow count (504 ends), composite fiber volume fraction (~45%), and composite areal density (~130 g/cm²). However, in practice, it was extremely hard to control these parameters, therefore, for direct comparison of the material systems, all of the values were normalized to a 48% fiber volume with respect to the fiber volume of each of the specimens. The following equation was used to normalize the results:

\[ X_n = (0.48/V_f) X \]  

where

- \( X_n \) = Normalized value,
- \( V_f \) = Actual fiber volume fraction of the specimen, and
- \( X \) = Measured value.
There was quite a bit of variation in the results of the CAI tests both between the impacted panels and the control, and between adjacent panels in the stack. Though a great deal of attention was paid to the design and consolidation of the materials, the exact alignment of panels in the test jig was difficult due to the crude fixture method. It is theorized that this misalignment proved to be a key contributor to the damage progression – the impact energy was absorbed differently based on whether there was fiber in projectile’s the line of flight where it was needed or whether a local area of high matrix content was encountered. This misalignment and local failure of the material resulted in higher local damage which affected the strength of the composite panel in compressive loading.

4.3.1 Damage Progression through Composite Stack

Each of the panels was evaluated under compressive loading conditions and compared to a control coupon test for determination of the strength loss of each of the panels in the stack. The intent of this testing was the determination of the damage progression through the stack. However, it can be seen from the data presented herein, the results of the compression after impact testing are somewhat inconclusive as to the damage progression through the target stack. A summary of results and a graphical representation of the damage progression through the stack as a function of strength loss of each of the member panels for each material system are presented in the figures over the next few pages.
These two shots were very similar in that the 1° position and wear-face panels both took most of the impact energy and had resultant higher strength losses. Additionally, the 2° panel in both shots seemed to be the least effected by the impact. However, the strike-face on shot#5 was not damaged nearly as significantly as the corresponding strike-face in shot#1. The strength loss of the stack in both shots was similar; Shot # 1 had an average strength loss of 56.4, while Shot#5 panels lost 37.9% of their strength on average. It should be noted that the panel in the 2° position in both of the shots seemed to be very lightly damaged – only 5.8% strength loss was exhibited in this panel for Shot#5.
These shots had similar profiles, though the levels of damage to the stack were significantly different. The target stack in shot#2 was significantly weakened upon impact, with an average panel strength loss of 74.8%, while Shot#6 only had strength loss of 25.3% on average. In both shots all of the panels in the stack seemed to share the dynamic impact load nearly equally. It should be noted that the level of damage is counterintuitive as Shot#6 was conducted at a higher energy level than Shot#2 (discussed earlier).
The panels in these two shots seemed to “take” similar amounts of damage due to the impact: Shot#3 panels had 33.6% strength loss, while Shot#7 panels had 35.3% strength loss. In both shots, the 1° position panel had a relatively low level of damage (∼18%), while the wear-face panel seemed to take a large amount of the impact energy independently. The major difference in the two shots was the damage to the strike-face and 2° position panels, in the two shots – more damage was seen in the 2° panel and a relatively low strength loss in the strike-face in Shot#3, while the opposite occurred in Shot#7.
These two shots seemed to have similar damage progression profiles with the exception of the 2° panel, which was more severely damaged in shot#4. Shot#2 adjacent panels in the stack seemed to take more of the energy – especially the strike-face and wear-face panels. The average strength loss to the Shot#4 and Shot#8 was 44.2% and 39.5, respectively.
4.4 Discussion

4.4.1 Test Method Discussion

There were a few problems that were encountered using the dynamic impact gun, most significantly the reliability of the residual velocity measurement system left room for improvement. Often during impacts, the projectile would “tumble” upon entry and exit of the composite panel. For this reason, the live “trip wire” residual velocity trigger could be “by-passed” by the projectile. This phenomena occurred in a few of the shots which are reported herein, it should be noted that this tumbling is most likely a result of the fiber constituent (Kevlar® or Spectra®) orientation and signifies an absorption of energy by the material system. Additionally, due to the analog nature of the oscilloscopes that were used to capture the projectile flight, the research team had to ensure that all of the scopes were pre-set to the correct window and “live” – more than once the velocity delta could not be attained due to a misjudgment of the projectile velocity. Flanagan notes in his thesis that a much better collection method for these activities would have been a computer data acquisition card that could collect multiple points all on the same machine. [7] This problem was compounded by the rough powder-packing method. Though the team was attempting to hold impact energy constant for the shots fired in this study, often the velocity would significantly up or down due to unavoidable powder volumes and standard powder consistency variations.
4.4.2 Material System Discussion

It is theorized that the unit-cell size could be tailored for a positive response to a specific threat. Further, utilizing a stacked architecture, the panels could be tailored to be resistant to multiple threat types (projectile geometries/energies).

As stated earlier, the unit cell size as a function of angular orientation changes can be made to the braided structure easily in one of two ways. First, the effect can be achieved by varying the withdrawal rate of the braided structure. This rate variation causes a shift in the visible surface fiber angle and all of the internal angles of the braid. This rate change will also cause a shift of the convergence point of the braid relative to the machine bed. Second, the use of a larger or smaller mandrel on which the braid is formed will change the angular architecture of the braid. [3, 14]

Additionally, a tailored response of the material to a specific threat could be achieved by the use of varying fiber linear density and filament count. By variation of the size of the fibers used will yield a different response. This could be experimented with in an empirical fashion to further optimize the textile reinforcement for a specific threat. With this modification, the change of the filament packing and spreading phenomena will also need to be taken into account in the preform design.

However, a factor that needs to be kept in mind with the use of higher linear density tows. The use of larger toes causes the crossover angles of the structure to increase, with this, the internal shear stress on the fibers upon impact will increase. Further, due to the larger interstices in the fabric, resin-rich areas will occur in the
composite which are prone to delamination and a negative additive to the mechanical strength of a material.
Chapter 5

Summary and Conclusions

Construction of the fully-automated, three dimensionally braiding machine was completed during the course of this research. With this new braiding machine development, more consistently braided fibrous performs could be constructed due to the horizontally machine-orientation, precisely timed motions, and automatic braid fell-point withdrawal. Additionally, new functionality was added as part of this thesis research to facilitate the inclusion of axial reinforcement via tubes, modified carrier movement via columnar isolation was investigated, and a computer control program was developed to allow for automated braid fabrication.

Furthermore, the fiber-reinforced composite coupons tested in the study were fabricated utilizing epoxy resins and traditional compression molding techniques. However, due to the high-strength fibers that were used in the research, novel preform cutting and extraction techniques had to be devised. One such development was the use of a lengthwise-split mandrel around which the fabric was formed. Finally, aluminum mold preparation and preform evacuation techniques were optimized during this research in an empirical fashion.

The experimental investigation of the ballistic impact tolerance and failure modes of 3-D braided Kevlar® and Spectra® fiber composites agrees with the work that was previously completed by the author and Mike Flanagan in 1996. However, it should be noted that further investigations of the material systems discussed for a complete characterization of the material response to impact loading conditions is needed.
Based on this research, the following formal conclusions can be made:

- The circular 3-D braiding process can be fully automated via computer control,
- The 4-step, 3-D braiding process can be modified for the inclusion of axial reinforcement by disabling every other shifting column and utilization of a 2x1 machine set-up,
- 3-D Braided Kevlar® and Spectra® composites can be successfully used to resist ballistic threats within the energy levels tested in this research,
- And the primary failure mode of 3-D Braided Kevlar® and Spectra® composites is conical deformation at the energy levels tested in this research.

Furthermore, the presence of axial reinforcement in 3-D braided composites seemed to have a positive effect on the energy dispersion of the material system at the energy levels tested in this research. The use of two different fiber types in hybrid reinforcement structures also shed some light on the factors that may have an effect the ballistic impact performance of a material. Specifically, it was observed that the material systems composed of one fiber type performed better than the hybrid reinforcements. It is theorized that this reduction in performance was a result of the interfacial bonding differences between the two fiber types.

Finally, the study was designed to study the damage progression through the material stack; however, the author acknowledges that this approach neglects the possible influence of the interfacial space between plates in the stack.
Chapter 6
Recommendations for Future Research

The anisotropic nature of fiber-reinforced composites is a key factor when attempting to characterize materials. Due to the enormous number of fiber orientations, the varying properties of the fibers, and the use of multiple fiber types, the task becomes much harder. However, because the strength of a composite material can be determined by the placement of fibrous reinforcements in the composite, engineered materials can be developed to resist specific threats. With this goal in mind, here is a list of possible improvements specific to the present research, textile-reinforced composites for impact resistance in body armor:

(1.) Development of an in-situ cutting and tensioned take-up mechanism on the automated 3-D braiding machine to facilitate removal of the preform material in panel form instead of as a tube which has to be slit after removed from the machine. This may help with the maintenance of the braid angle in an otherwise somewhat dimensionally unstable process.

(2.) Continued quasi-static testing of the 3-D braided Kevlar® and Spectra® fiber composite materials to establish mechanical properties and engineering constants to be used in modeling new composite materials.

(3.) Use of Resin Transfer Molding (RTM) or Seemann Composite Infusion Molding Process (SCRIMP®) technologies in the composite consolidation. These methods allow greater fluid control and may exhibit a higher attainable fiber volume fraction in practice.
(4.) The use of a more dependable velocity measurement system in the dynamic impact testing facility. This could be easily facilitated by the use of laser or IR beams, which are broken as the projectile passes between an emitter and a sensor. These systems could be used in the gun barrel in place of the firing pins, and in place of the “trip- wires” in the residual velocity device.

(5.) Incorporation of pressure gauges in the composite materials to capture the magnitude of impact stress and how it propagates through the composite. These gauges accurately measure the surface pressures on the composite for analysis.

(6.) The use of high-speed photography to characterize the failure of the materials when subjected to impact. This could also be used to determine the velocity of the projectile by capturing timed exposures of the projectile with distance markers in the background.

Finally, although this research was conducted in a full-factorial design with a replication; however, additional tests of each of the material systems should be conducted to build statistical confidence in the ballistic limits of these composite materials.
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   http://www.muratec.net/jp/braider/weaving.html

Appendix A

Automated Four Step 3-D Braiding Machine Driver Program

5 CLS
10 PRINT "**************************************************************************
15 PRINT "**
20 PRINT "** Automatic Circular Braiding Machine Driver ***
30 PRINT "** Version 1.1 for use with OPTO 22/AC5 ***
40 PRINT "** Created at NCSU by Jay Wall - Aug. 1995 ***
50 PRINT "**
60 PRINT "**************************************************************************
70 PRINT "
80 BASE% = &H220
90 OUT BASE% +1, 0
100 OUT BASE% +0, &HEF
110 OUT BASE% +1, &H34
120 CHN0% = &H1 : CHN1% = &H2
130 CHN2% = &H4 : CHN3% = &H8
140 CHN4% = &H10 : CHN5% = &H20
150 CHN6% = &H40 : CHN7% = &H80
160 CHN% = &H0
170 VAR% = &HFF
180 GOSUB 1000

235 PRINT "                          *******************
240 PRINT "                       **** MAIN MENU ****
245 PRINT "                           *******************
250 PRINT "
260 PRINT " 1. Begin Braiding"
270 PRINT "
280 PRINT " 2. Stop Braiding"
290 PRINT "
300 PRINT " 3. Set New Timing Variables"
310 PRINT "
320 PRINT " 4. Control Motions Individually"
350 PRINT "
360 PRINT "
370 INPUT " ENTER SELECTION \_\_\_\_:Q1:CLS
380 ON Q1 GOTO 2000, 3000, 3995, 6000
995 REM turn off 0-7
1000 VAR% = VAR% OR CHN%
1010 OUT BASE% +0, VAR%
1020 RETURN
1025 REM turn on 0-7
1030 V% = VAR% AND CHN%
1040 IF V% = &H0 THEN GOTO 1070
1050 VAR% = VAR% - CHN%
1060 OUT BASE% +0, VAR%
1070 RETURN
2000 TIME = 300
2010 RS1ON = 2: RS2ON = 2: RS1OF = 2: RS2OF =2
2020 ADMON = 2: ADMOF = 2
2040 REM
2050 LOOP = TIME * RS1ON : GOSUB 5000 : GOSUB 7000
2060 CHN% = CHN0%: GOSUB 1030
2070 LOOP = TIME * RS2ON : GOSUB 5000 : GOSUB 7000
2080 CHN% = CHN1%: GOSUB 1030
2090 LOOP = TIME * FOON : GOSUB 5000 : GOSUB 7000
2100 CHN% = CHN2% : GOSUB 1030
2110 RS1ON = 2: RS2ON = 2: RS1OF = 2: RS2OF =2
2120 ADMON = 2: ADMOF = 2
2130 REM
2140 LOOP = TIME * RS1ON : GOSUB 5000 : GOSUB 7000
2150 LOOP = TIME * RS2ON : GOSUB 5000 : GOSUB 7000
2160 LOOP = TIME * FOON : GOSUB 5000 : GOSUB 7000
2170 LOOP = TIME * FEON : GOSUB 5000 : GOSUB 7000
2180 LOOP = TIME * FEON : GOSUB 5000 : GOSUB 7000
2190 LOOP = TIME * FEOF : GOSUB 5000 : GOSUB 7000
2200 LOOP = TIME * FEOF : GOSUB 5000 : GOSUB 7000
2210 LOOP = TIME * FEOF : GOSUB 5000 : GOSUB 7000
2220 LOOP = TIME * FEOF : GOSUB 5000 : GOSUB 7000
2230 LOOP = TIME * ADMON : GOSUB 5000 : GOSUB 7000
2240 LOOP = TIME * CHN5% : GOSUB 1030
2250 END
2260 REM
3000 PRINT " **MACHINE HAS BEEN STOPPED**"
3005 PRINT " (ALL VALVES ARE NOW OFF) "
3010 OUT BASE% + 0, &HFF
3020 END
3030 REM
3995 PRINT "*********************************************************
4000 PRINT "*** EDIT THE VARIABLES, AND THEN CHOOSE START BRAIDING ***"
4010 PRINT "*** FROM THE MAIN MENU ***"
4015 PRINT "*********************************************************
4020 PRINT ""
4030 INPUT "RING SET #1 ON DELAY_"; RS1O
4040 INPUT "RING SET #1 OFF DELAY_"; RS1F
4050 PRINT "---------------------"
4060 INPUT "RING SET #2 ON DELAY_"; RS2O
4070 INPUT "RING SET #2 OFF DELAY_"; RS2F
4080 PRINT "---------------------"
4090 INPUT "EVEN ON DELAY_"; EO
4100 INPUT "EVEN OFF DELAY_"; EF
4110 PRINT "---------------------"
4120 INPUT "ODD ON DELAY_"; OO
104

4130 INPUT "ODD OFF DELAY "; OF
4140 PRINT "---------------------"
4150 INPUT "MANDREL ADVANCE DELAY ON "; MAO
4160 INPUT "MANDREL ADVANCE DELAY OFF "; MAF
4170 CLS : GOTO 240
5000 N=0
5010 N=N+1
5020 IF N<LOOP THEN GOTO 5010
5030 RETURN

5000 N=0
5010 N=N+1
5020 IF N<LOOP THEN GOTO 5010
5030 RETURN

5000 N=0
5010 N=N+1
5020 IF N<LOOP THEN GOTO 5010
5030 RETURN

5000 N=0
5010 N=N+1
5020 IF N<LOOP THEN GOTO 5010
5030 RETURN

5000 N=0
5010 N=N+1
5020 IF N<LOOP THEN GOTO 5010
5030 RETURN

5000 N=0
5010 N=N+1
5020 IF N<LOOP THEN GOTO 5010
5030 RETURN

6000 PRINT " "
6010 PRINT "                   CHANNEL         TURN ON         TURN OFF"
6020 PRINT "RING SET #1        0               1               2"
6030 PRINT "RING SET #2        1               3               4"
6040 PRINT "EVEN               2               5               6"
6050 PRINT "O FF               2               5               6"
6060 PRINT "ADVANCE MANDREL  5               9               10"
6070 PRINT ""
6080 PRINT " TO RETURN TO MAIN MENU ENTER 11"
6090 PRINT ""
6100 INPUT " ENTER SELECTION "; Q4
6110 CLS
6120 ON Q4 GOTO 6130, 6140 , 6150, 6160, 6170, 6180, 6190, 6200, 6210, 6220, 6230
6130 CHN% = CHN0% : GOSUB 1030 : GOTO 6000
6140 CHN% = CHN0% : GOSUB 1000 : GOTO 6000
6150 CHN% = CHN1% : GOSUB 1030 : GOTO 6000
6160 CHN% = CHN1% : GOSUB 1000 : GOTO 6000
6170 CHN% = CHN2% : GOSUB 1030 : GOTO 6000
6180 CHN% = CHN2% : GOSUB 1000 : GOTO 6000
6190 CHN% = CHN3% : GOSUB 1030 : GOTO 6000
6200 CHN% = CHN3% : GOSUB 1000 : GOTO 6000
6210 CHN% = CHN5% : GOSUB 1030 : GOTO 6000
6220 CHN% = CHN5% : GOSUB 1000 : GOTO 6000
6230 GOTO 235
7000 REM CHECK SWITCH SUB
7010 RETURN
Appendix B

Machine operating instructions

FOR AUTOMATIC OPERATION:
1. TURN ON SWITCH ON SIDE OF MACHINE (BOX) AND MAKE SURE THE ROCKER SWITCH IS IN THE ‘A’ (AUTOMATIC) POSITION.
2. MAKE SURE RINGS ARE IN HOME POSITION (ALL OF THE BLUE STARS ON MACHINE BED LINE UP).
3. TURN ON BOTH AIR SUPPLY VALVES.
4. PRESS ‘F3’, THEN TYPE ‘36CAR’ (36CARRIER) OR ‘72CAR’ (72CARRIER).
5. PRESS F2.
6. AT THE INTRO SCREEN, PRESS ‘1’ AND RETURN.
7. AT THE # PROMPT TYPE IN THE NUMBER OF CYCLES YOU WISH TO COMPLETE.

TO STOP MACHINE IN MID CYCLE:
1. PRESS PAUSE (DO NOT PRESS PAUSE WHILE MANDREL IS ADVANCING).
2. MAKE NECESSARY ADJUSTMENTS.
3. PRESS ‘F2’.
4. MACHINE WILL NOW RUN.

FOR MANUAL OPERATION:
1. MAKE SURE ALL SWITCHES ARE DOWN (‘HOME POSITION’).
2. FLIP ROCKER SWITCH TO ‘M’.
3. TOP SWITCHES ARE RINGS, BOTTOM SWITCHES ARE CYLINDERS.
4. RETURN ALL ROCKER-SWITCHES TO ‘HOME POSITION’ (ALL SWITCHES DOWN).
5. PRESS ‘F2’ ON COMPUTER.
6. FLIP ROCKER-SWITCH BACK TO ‘A’ (AUTOMATIC).
## Appendix C

Four-step, 3-D Braid Design Worksheet – ARO Helmet

<table>
<thead>
<tr>
<th>DESIGN CALCULATION</th>
<th>ARO Helmet w/o axials</th>
<th>1500 den</th>
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### INPUT VALUES

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axials Tow Size (na)</td>
<td>1 K</td>
</tr>
<tr>
<td>Braiders T. Size (nb)</td>
<td>1 K</td>
</tr>
<tr>
<td>Axial Area (Aa)</td>
<td>1.79E-04  in²</td>
</tr>
<tr>
<td>Braider Area (Ab)</td>
<td>1.79E-04  in²</td>
</tr>
<tr>
<td>Inner Diameter (Di)</td>
<td>3 in</td>
</tr>
<tr>
<td>Outer Diameter (Do)</td>
<td>3.065 in</td>
</tr>
<tr>
<td>Carriers/Ring (S)</td>
<td>72</td>
</tr>
<tr>
<td>Axials/Ring (Sa)</td>
<td>72</td>
</tr>
<tr>
<td>Design Vf</td>
<td>70%</td>
</tr>
<tr>
<td>Theta (θ)</td>
<td>45°</td>
</tr>
<tr>
<td>Axial Tow Denier (da)</td>
<td>0 per K</td>
</tr>
<tr>
<td>Braider Tow Denier (db)</td>
<td>1500 per K</td>
</tr>
<tr>
<td>Length of Part Lp</td>
<td>5 in</td>
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### ACTUAL Vf

<table>
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### UNIT CELL INFORMATION

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<tr>
<td>Number of Mov. Rings (Nr)</td>
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<tr>
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<td>5</td>
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<tr>
<td>Weight, in</td>
<td>3.48 GR</td>
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<tr>
<td>Max. Band Width</td>
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</tr>
<tr>
<td>Average Band Width (bw)</td>
<td>0.13</td>
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<tr>
<td>Min. Band Width</td>
<td>0.13</td>
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<tr>
<td>Max. Repeats/Inch</td>
<td>12.37</td>
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<tr>
<td>Average Repeats/In</td>
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<tr>
<td>Min. Repeats/Inch</td>
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</tr>
<tr>
<td>Number of Braiders</td>
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</tr>
<tr>
<td>Number of Axials</td>
<td>360</td>
</tr>
<tr>
<td>Total Number of Tows</td>
<td>792</td>
</tr>
<tr>
<td>% Number of Braiders</td>
<td>54.55%</td>
</tr>
<tr>
<td>% Number of Axials</td>
<td>45.45%</td>
</tr>
<tr>
<td>Braider Volume</td>
<td>0.15 in³</td>
</tr>
<tr>
<td>Axial Volume</td>
<td>0.06 in³</td>
</tr>
<tr>
<td>Total Volume</td>
<td>0.21 in³</td>
</tr>
<tr>
<td>% Braider Volume</td>
<td>69.55%</td>
</tr>
<tr>
<td>% Axial Volume</td>
<td>30.45%</td>
</tr>
<tr>
<td>Braider Length Requirement</td>
<td>28.12 in</td>
</tr>
<tr>
<td>Axial Length Requirement</td>
<td>15.00 in</td>
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<tr>
<td>Preform Volume, in</td>
<td>58.40</td>
</tr>
<tr>
<td>% AXIAL VOLUME FRAC.</td>
<td>0.24</td>
</tr>
<tr>
<td>% HOOP VOLUME FRAC.</td>
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### Actual Designed Vf

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Appendix D

Raw Data
### 19-mm Impactor Data

<p>| Shot ID | Pmass AD Gpow Pen? Vf E Red Spec E | #cai Fcai %SSL Norm%Vf |
|---------|--------|----------------|------------------|
| 1       | 12.4   | 142.08 16.0 0 232 0 334 2.35 | 125 273 - - 45.9% |
| Lamina Notes | FACE-Fiber shifting; Impactor indentation; Minimal fiber breakage REAR-0 |
|           | FACE-Transverse crack;Wavy axis; REAR-Bias shear visible |
|           | FACE-Sm. transverse crack; REAR-Speca (axial) fiber failure on back-side |
|           | FACE-Bias fiber movement; REAR-Wavy axis |
|           | V3.4 Only; pix 1-4 |
| 2       | 12.4   | 142.88 16.0 1 271 - - - 117 272 - - 47.7% |
| Lamina Notes | FACE-circular plug (B&amp;A shear); REAR-25X33 plus-shaped proj exit |
|           | FACE-Plus REAR-0; axial shear; SHAPED proj exit (B&amp;A shear) |
|           | FACE-Sig; Axial pull; REAR-42X55 PSP exit (B&amp;A shear) |
|           | FACE-Primary vert. opening (B&amp;A shear); REAR-Round bulge [35 diam.] |
|           | V3.4 Only; pix 5-8 |
| 3       | 12.4   | 135.95 15.5 1 247 - - - 48 152 - - 46.3% |
| Lamina Notes | FACE-0 fiber shift; REAR-PSP Exit (B&amp;A shear); Petal-like plugging; little axial movement |
|           | FACE-some axial shift; REAR-PSP (B&amp;A shear) |
|           | FACE-lateral crack (B&amp;A shear); 0 fiber movement; REAR-PSP |
|           | FACE-75 (lat.)x38 crater; REAR-PSP |
|           | V3.4 Only; pix 9-12 |
| 4       | 12.4   | 116.23 15.5 0 235 0 342 2.95 | 41 114 - - 50.0% |
| Lamina Notes | FACE-Impact marking; 0 fiber movement; REAR-wavy axis |
|           | FACE-0; REAR-0 |
|           | FACE-0; REAR-0 |
|           | FACE-0; REAR-0 |
|           | V3.4 Only; pix 13-16 |
| 5       | 12.4   | 110.35 15.5 1 275 - - - 43 152 - - 43.7% |
| Lamina Notes | FACE-Petal breakage at impact site; REAR-B&amp;A shear |
|           | FACE-Petal breakage at impact site; REAR-B&amp;A shear; Spectra fiber fusion |
|           | FACE-0; Minor matrix cracking |
|           | FACE-0; Major B&amp;A shear |
|           | V3.4 Only; pix 13-16 |
| 6       | 12.4   | 156.77 15 0 200 0 248 1.58 | 61 155 - - 48.7% |
| Lamina Notes | FACE-0; Vertical crack; PSP attempt &amp; matrix cracking; REAR-Ribbon; petal break-out (not successful) |
|           | FACE-0; Vertical crack; axis shear; REAR-Minor B&amp;A shear |
|           | FACE-0; PSP attempted; B&amp;A shear; REAR-Some fibrillation |
|           | FACE-0; Bias fiber shear between axis (single line); REAR-Bias fiber shearing along axis |
|           | V3.4 Only; pix 17-20 |
| 7       | 12.4   | 139.16 16.9 0 245 0 372 2.88 | 30 98 - - 53.1% |
| Lamina Notes | FACE-Convex (fiber stretch &amp; recovery); REAR-Fiber pull evident |
|           | FACE-Convex; REAR-0 |
|           | FACE-Convex; REAR-Minor matrix cracking |
|           | FACE-Convex; REAR-0 |
|           | V3.4 Only; pix 17-20 |
| 8       | 12.4   | 115.20 16.5 0 258 0 413 3.58 | 61 138 - - 49.0% |
| Lamina Notes | FACE-Impact marking; 0 fiber movement; REAR-wavy axis |
|           | FACE-0; Minor matrix cracking |
|           | FACE-0; Minor matrix cracking |
|           | FACE-0; REAR-0 |
|           | V3.4 Only; pix 17-20 |</p>
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<thead>
<tr>
<th>Shot ID</th>
<th>L</th>
<th>W</th>
<th>Thk</th>
<th>m1</th>
<th>m2</th>
<th>m1-m2</th>
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### Lamina Notes

- **Strike-face**: 8°, 3°
- **Wear-face**: 3°

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