INVESTIGATION INTO THE BALLISTIC PROPERTIES OF THREE DIMENSIONAL BRAIDED FABRICS

An Undergraduate Research Scholars Thesis

by

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Submitted to the Undergraduate Research Scholars program
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by Research Advisor: Dr. Terry Creasy

May 2017

Major: Mechanical Engineering

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ABSTRACT

Investigation into the Ballistic Properties of Three Dimensional Braided Fabrics

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High performance fabrics are an integral part of modern soft ballistic body armor. Currently, the most common practice has been to use woven fabrics in these applications. This work is intended as an early study exploring the feasibility of replacing these conventional fabrics with three-dimensional (3D) rotary braided fabric. Low velocity tests were conducted on plain woven and 3D braided fabrics to quantify out of plane deformation properties of the different fabric structures. A tensile tester was used to determine the force-displacement properties of one sample of each different fabric type. The single layer and four layer 3D braided fabrics were found to have similar specific energy absorption capabilities to the woven fabric. The two layer 3D braided fabric was found to have over 300% of the specific energy absorption of other fabric types, indicating that this class of fabrics may be made to have desirable qualities for soft body armor. Possible explanations for this occurrence include successive failure of the fabric structure layers and inconsistencies in fabric production, however, more experimentation is necessary to arrive at a satisfactory explanation for this phenomenon.

ACKNOWLEDGMENTS

It has been a great privilege to participate in this program and conduct research on a topic that I believe has potential to have a positive impact on the world. I would like to express my gratitude to my advisor, Dr. Terry Creasy, for his advice and support throughout this process, as well as for making this research project a possibility by sponsoring it.

DEDICATION

I would like to dedicate this work to my parents, Mitch and Michelle New, without whose love and patience this project would never have been completed.

CHAPTER I

INTRODUCTION

Fabrics play an integral role in modern soft body armor by providing vital protection from bullet and stab wounds while allowing the wearer to retain flexibility. Currently, soft body armor uses woven fabrics to provide this protection to soldiers and law enforcement[1]. While these fabrics have been effective for decades in this application, alternative fabric structures may provide better qualities. One candidate for such a fabric structure is a three-dimensional braided fabric.

Three-dimensional braided fabrics

This thesis focuses on the properties of a fabric known as three-dimensional rotary braided fabric (herein referred to as a 3D braided fabric). These fabrics are produced with the use of a braiding machine, which intertwines parallel yarns by rotating bobbins around one another in a plane. As the bobbins are continually rotated around one another, the interlocking of neighboring yarns forms the fabric. This method of production gives rise to two defining features of 3D braided fabrics: the ability to produce any number of fabric layers in a single textile and interlocking between those layers. This is in contrast to traditional methods of fabric production. In conventional woven or knitted fabrics, only a single layer of fabric is produced at a time. Thus, for many high performance applications, such as soft body armor, sheets of fabric must be layered together to achieve the desired strength[1].

The production of this type of fabric is illustrated in Figure 1. Bobbins carrying yarn are wound around one another. The bobbins are motorized using horn gears, and the pattern that each bobbin follows is determined by a track plate. The track plate forces bobbins to wind around one another in a specific order, producing different braids. As the bobbins wind around one another, they create intersections between the yarns. These intersections are pushed up from the bobbins to the braid face, forming new fabric. The braid face is simply the point at which the free yarns meet the braided fabric, and is the location that new fabric is formed[2].

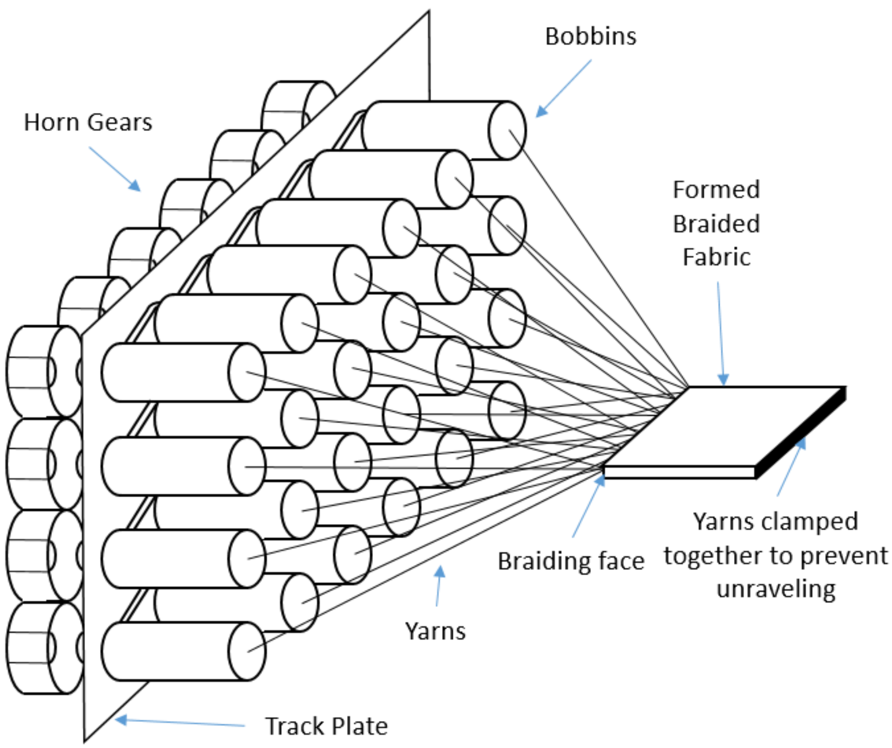

Figure 1: Braiding machine in operation

The majority of previous work on 3D braided fabrics has sought to explore their properties as composite preforms. While this is an important application, little research exists on the behavior of the fabrics outside of their use in composites despite the fabrics themselves exhibiting several features which make them potentially attractive alternatives to conventional fabrics in some applications[3].

Problems with conventional ballistic fabrics

Conventional fabrics suffer from several problems when placed under ballistic conditions. The use of conventional fabrics for ballistic vests also poses a problem of yarn orientation. In order to efficiently cover a large area, yarns are placed orthogonally or near orthogonally to the path of an incoming ballistic object. This arrangement leads to stress concentrations at the point of impact. Furthermore, stresses are shared along the warp and weft directions. The sharing of stresses in fabrics often gives rise to unexpectedly high strengths, a phenomenon termed *fabric assistance*. As a result of fabric assistance, plain and twill woven fabrics display higher strengths than would be expected based on their constituent yarns[4]. However, this effect may be improved upon by increasing the number of directions that the yarns share load in. 3D braided fabrics offer exactly this capability. The particular fabric type used in this paper shares load in a total of 4 axes.

Conventional fabrics also suffer from decreased performance in multiple impact tests. Three dimensional fabrics have been shown to not experience the same degree of performance degradation after impact, making them much more viable in a realistic firefight scenario[5].

A final weakness of conventional fabrics is that they do not have naturally high resistance to penetration from a stabbing motion. In fact, the properties desirable for a stab-resistant vest are directly contrary to those desirable for a bullet-resistant vest. In particular, a tight weave is desirable to prevent penetration in a stab scenario and a loose weave is desirable to absorb energy in a shooting scenario. This weakness necessitates the use of multiple different fabric types when producing armor resistant to both stabbing and ballistic impact, leading to thicker and less efficient armor. A similar issue does not appear to the same degree for 3D braided fabrics, as the fabrics have naturally high penetration resistance[4]. This potentially means that using a 3D braided fabric designed for a ballistic impact could produce similar stab resistance to conventional fabrics.

Properties of 3D braided fabrics

Three dimensional fabrics exhibit a number of differences from conventional fabric structures, many of which are likely to make them suitable for protection against high velocity impacts.
A lack of distinct, orthogonal biases serves to mitigate directional weakness, a major problem in conventional fabrics with clear bias directions[6]. While biases do exist in 3D braided fabrics, biases that run parallel to the fabric face do not occur in the structure under investigation. In theory this would minimize flexion and stress concentration during an impact. Furthermore, said construction has more bias directions and no orthogonal biases, which is likely to give the fabric excellent dimensional stability while allowing it to retain flexibility as happens in triaxial, two-dimensional (2D) weaves[6].

CHAPTER II

METHODS

Fabric construction

It was necessary during the course of this investigation to devise a consistent method to produce 3D braided textiles for testing. This proved to be a substantial challenge because all textiles were constructed by hand due to the scarcity of rotary fabric braiding machines. This necessitated the development and refinement of a hand operable braiding apparatus and a systematic method of production to ensure consistent results between textiles.

Fabric structure

The 3D braided fabric structure used in this investigation was selected for its simplicity. The bobbin pattern to produce the structure in question can be found in Figure 2. This fabric structure produces yarn intersections where the directions of the yarn form a tetrahedral structure.

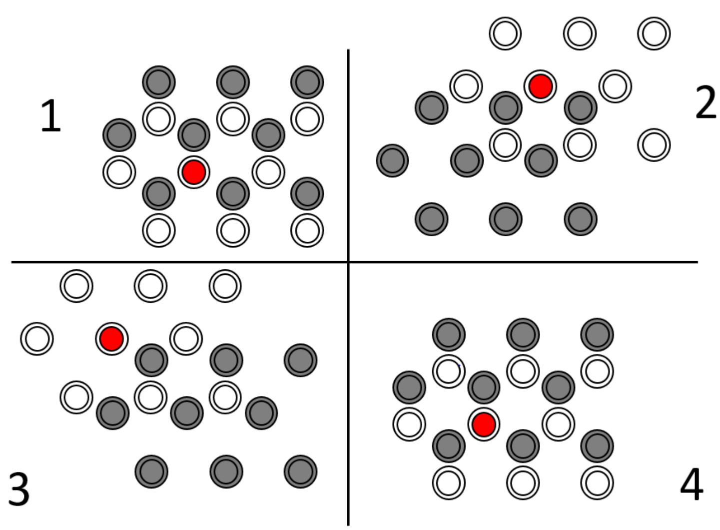

Figure 2: Bobbin pattern to create the structure used for experimentation

Braiding apparatus development

Several prototype braiding apparatuses were developed over the course of the investigation in order to produce textiles suitable for testing. Design elements of the final braiding apparatus were selected in order to maximize consistency in the braiding process. In order to accomplish this, several departures were made from conventional braiding methodology.

The most significant departure from conventional methods was the decision not to use bobbins to perform the braiding of the yarns. Instead of bobbins, lengths of yarn were attached at the moving end to a pin. The pins were then moved individually by hand on a board in the same pattern that the bobbins would have followed. The bobbins were deemed unnecessary because their primary function is to produce a continual feed for yarn allowing for increased production on a single reload and the procedures followed only called for a small amount of. This became an important feature in producing fabrics that had a consistent structure both at the edges and the center. With the comparatively thin pins, a shallower angle between edge yarns during braiding was achieved. This is significant because, during the braiding process, the angle between yarns will affect the final structure by affecting the braid angle. Thus, the comparatively bulky bobbins force the braiding end of the machine to space the yarns out more, leading to increased yarn angles at the edges of the fabric, ultimately creating discrepancies between the edge and center of the fabric. Figure 3 illustrates this concept and the difference between the configurations of conventional braiding machines and the apparatus used in this investigation.

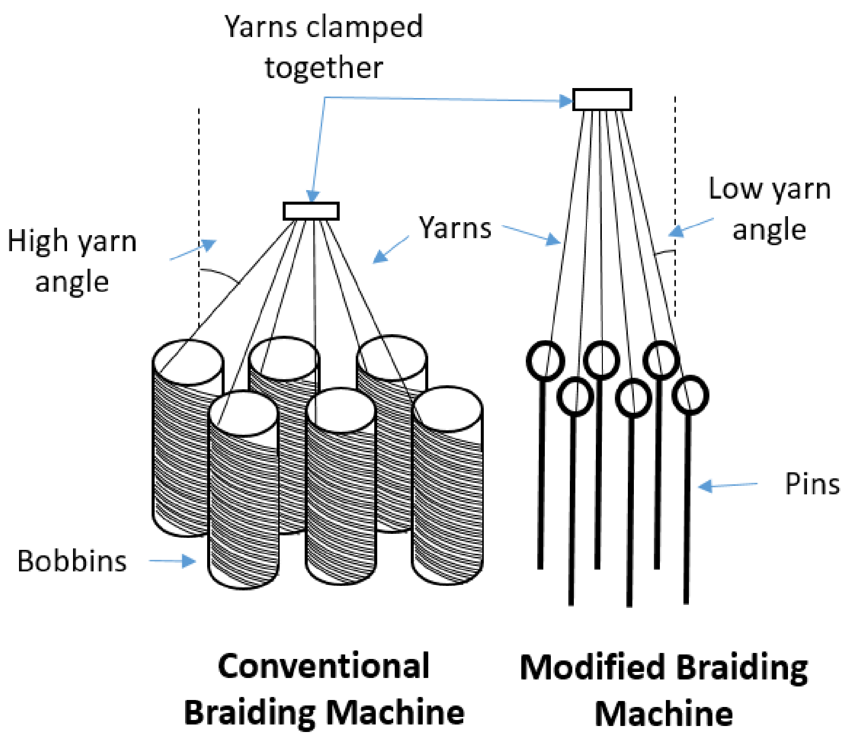

Figure 3: Conventional horn gear braiding machine yarn feed compared to apparatus developed for this project

Additionally, because the fabrics were produced by hand, a system of braiding was implemented to ensure consistency in the braid design. The two significant considerations in this process were ensuring similar tension on yarns during the formation of the fabric and minimizing yarn wear from constant rubbing with intersecting yarns.

Braiding process development

In order to ensure a consistent tension on the yarns, each yarn was pulled taught after each step of braiding. After the yarn was pulled taught, it was allowed to relax and settle to its natural position under friction. This action served a dual purpose of ensuring a high degree of regularity in the fabric structure by preventing any knots or loops forming in the structure of the fabric itself, a major issue that was encountered early on in the braiding design process. This method ultimately consistently produced textiles that appeared similar to one another and showed few errors in each textile.

The minimization of yarn wear necessitated the use of another technique. After each layer of intersections was made on the braiding end of the braiding apparatus, the interlacing of the fabric were moved to the braiding face. This was found to cause wear on the yarns as they would rub against one another. This effect was minimized by moving one intersection up to the braiding face at a time. Doing this allowed the braider to prevent high force contact between the yarns as they slid past one another.

Experimental methods

The properties that were measured in this work were aimed at characterizing the out of plane loading and deformation behavior of the 3D braided fabrics relative to a conventional plain 1-1 woven fabric. All tests were conducted at low velocities in order to better control extraneous variables and ensure high quality of data. The number of fabric layers of the 3D braided fabrics was varied, and its effect on the energy absorption, ultimate strength, extension at yield, and extension at failure are characterized. These properties were derived from a force-displacement curve obtained using a tensile tester. In order to minimize the effect of as many variables as possible, the material that was chosen as yarn to construct the fabric was a natural fiber 8 pt twine that was found to be approximately linear in its stress-deflection curve until failure.

Due to time limitations, only one trial of each fabric type was conducted. However, as this thesis is intended as an exploratory study into the feasibility of the fabrics in ballistic scenarios, this was deemed acceptable.

Design of the apparatus

A method was devised to test the out of plane force-displacement behavior of fabrics. The measurement apparatus consisted of a tensile tester and a device to hold the fabrics taught and attach them to the tensile tester. The design of the device is shown in Figure 4. In order to hold the fabric taught, two metal rings were clamped around the fabric. The metal rings used were 1.5" threaded metal flanges. The fabric was clamped between the flanges and the base of one flange was inserted into the jaws of the tensile tester, so that the fabric face was perpendicular to the tensile tester action. Next, a 3/16" bolt was inserted through the face of the fabric and attached on either side using a 5/16" washer and nut. The nut and washer were tightened on either side of the fabric. The end of the bolt was then fastened to the load arm of the tensile tester and the fabric was pulled until failure.

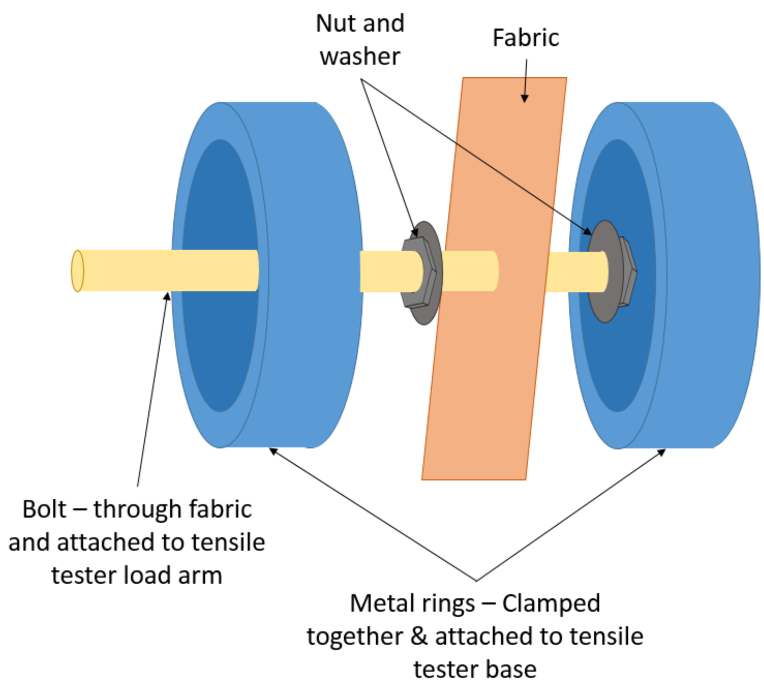

Figure 4: Fabric testing apparatus

CHAPTER III

RESULTS

The specific load and energy absorption capabilities of the different fabrics relative to their weight per unit area are detailed in Figure 5. The weight per unit area normalization of the data was necessitated by the lack of a direct comparison of layer counts of 3D braided and woven fabrics, as well as slight discrepancies between different layer counts of 3D braided fabrics. The results obtained indicate that 3D braided fabrics overall have slightly lower specific out of plane strength than conventional fabrics. However, the results for energy absorption are closely comparable between 1 layer, 4 layer, and conventional fabrics. Because this is the most significant feature in a ballistic impact, this suggests that 3D braided fabrics perform with approximately the same efficiency as conventional fabrics. Furthermore, the results for the 2 layer count 3D braided fabric show a much higher energy absorption than any other case.

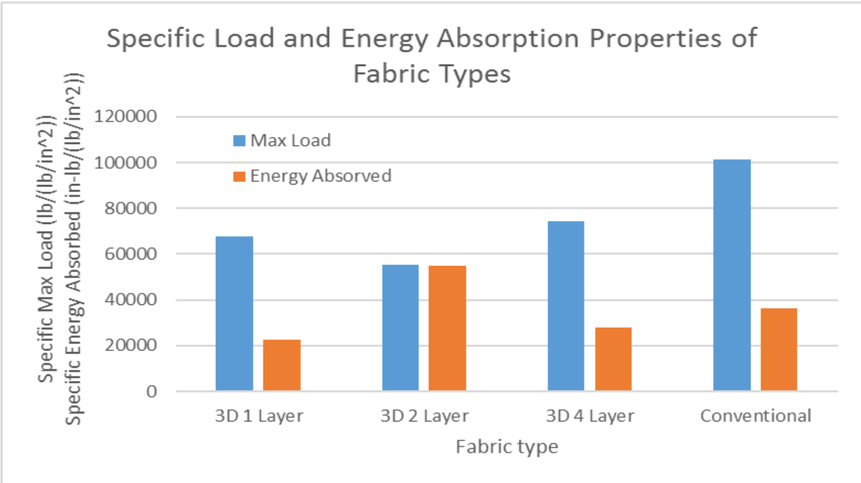

Figure 5: Specific load and energy absorption of fabric types

The fabrics' ability to deform, shown inFigure 6, provides some insight as to why the 2 layer 3D fabric was able to absorb such a significant amount of energy. All fabrics extended a similar degree at yield. However, most of the fabrics failed very quickly thereafter. The 2 layer 3D fabric continued to extend and absorb energy after this point.

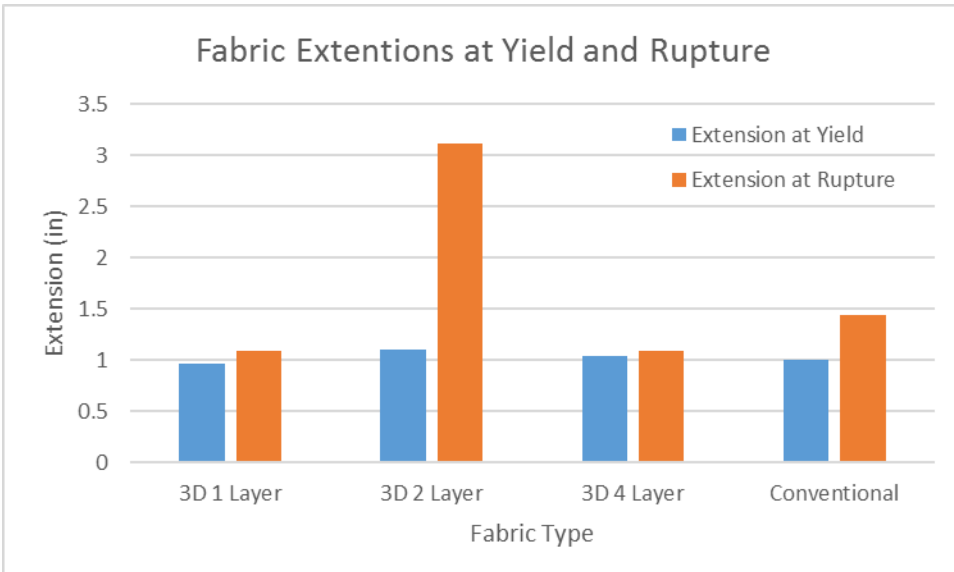

Figure 6: Fabric extensions for yield and rupture

It is not possible to say with certainty that this phenomenon is inherent in the 2 layer structure itself because the fact that only one sample of this fabric type was tested, meaning that it cannot be verified that no extraneous variables affected the results. The most likely confounding variable is inconsistency in the fabric construction method. This is because the results shown are consistent with the results of tight vs loose weaves in conventional fabrics. That is, tight weaves tend to exhibit lower energy absorption because they tend to fail abruptly, while loose weaves tend to deform much more before failure. Yarn inconsistency is also possible but unlikely. Environmental factors such as heat and moisture that the fabric was exposed to during the braiding process may have altered the properties of the yarn. This is supported by the fact that a natural twine was used as yarn, however, it is unlikely that such a dramatic difference would be observed in this case.

Alternatively, it is possible that this effect is the result of the fabric structure itself. This is unlikely given the extreme discrepancy between this data point and the others, however, the 2 layer structure is unique in that it is the thinnest 3D braided structure that includes both boundary yarn layers and internal yarn layers. The boundary yarn layers only interconnect with two neighboring yarns so they lay in a plane, while the internal layers interconnect with three neighboring yarns, making their path three dimensional. This combination of thread orientations may mean that individual layers fail independently, each time allowing the next layer to continue resisting the deformation, ultimately leading to a much greater deformation and therefore energy absorption than the other fabrics.

Evidence supporting this theory can be found in the load profiles of the different fabric structures, shown in Figure 7. Examining the load profile of the 2 layer fabric, it is clear that the fabric began to fail sooner than would be expected if the fabric strength were to increase linearly with layer count. This is further supported in Figure 5, which shows that the 2 layer fabric has the lowest specific ultimate strength of all the fabric types. Looking again to the load profile of the two layer fabric, the load begins climbing again even after yield, suggesting that an unyielded part of the fabric resists the load. Then the load peaks, declines and then starts to climb again, suggesting another layer yielded, leaving the following layer to resist the load.

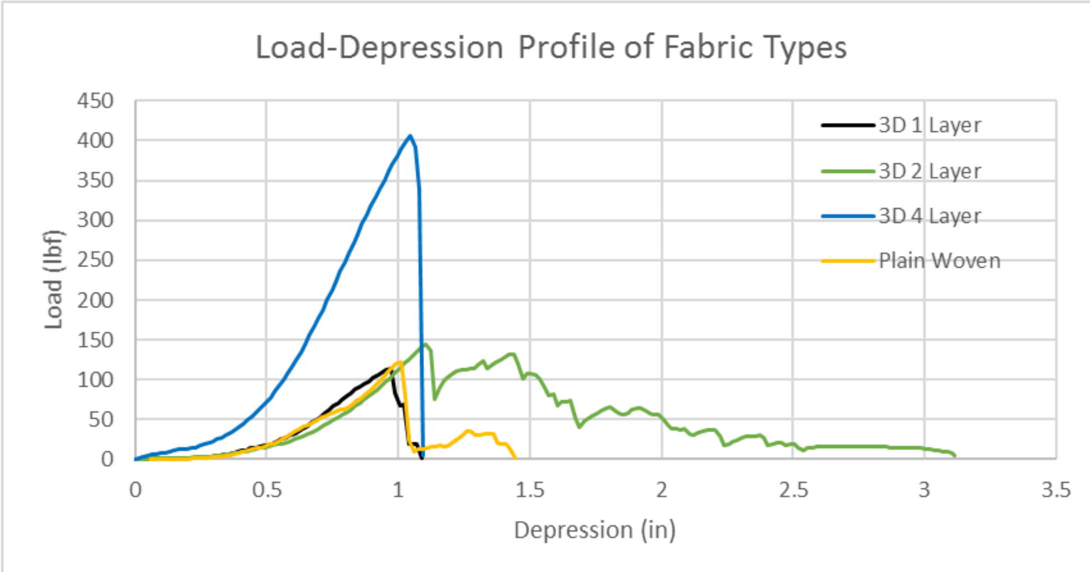

Figure 7: Load-depression curves for fabric structures

While the reason for the discrepancy between the two layer and other fabric types is not entirely clear, some insight can be gained from the fact that it exists at all. Assuming that yarn inconsistencies are not a significant factor, which is considered a reasonable assumption given the high degree of discrepancy observed, this data shows that it is possible to achieve relatively high energy absorption with 3D braided fabrics. While further exploration will be needed to understand the reason that the two layer sample absorbed substantially more energy than its counterparts, it is clear that this class of fabrics has the capability to produce qualities that are desirable for soft body armor.

CHAPTER IV

CONCLUSION

Compared to conventional fabrics, 3D braided fabrics exhibit several unique characteristics. This class of fabrics exhibits a high degree of load sharing among layers and high natural penetration resistance, but has been underexplored in most applications not involving composites. This work aims to test the properties of this fabric for use in soft body armor. The viability of 3D braided fabrics for use in ballistic vests was analyzed with the use of a tensile tester. The fabrics are shown to have comparable specific energy absorption and deflection at yield to conventional plain woven fabrics despite a slightly lower specific ultimate strength. Unexpected and potentially very attractive properties were found for the 2 layer 3D case, which had 300% of the specific energy absorption of any other fabric. There are several possible explanations for this. Inconsistencies in the fabric construction process that resulted in the fabric being looser than other samples are possible. It is also possible that the fabric structure itself causes this discrepancy by allowing each layer to fail individually, increasing the distance over which the fabric fails. Irrespective of the reason that the fabric failed in this way, it is clear that high energy absorption is possible with 3D braided fabrics.

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