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Roberto Felicissimo

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Exploration of the Mechanical Properties of Both Ridged and Inflated Drop Stitch Fabric Material

THESIS

Submitted in partial fulfillment of the requirements for the degree Master of Engineering (Mechanical) at The City College of New York of the City University of New York

By

Robert Felicissimo
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Approved:

Professor Ali Sadegh, Thesis Advisor
Department of Mechanical Engineering

Professor Feridun Delale, Chairman
Department of Mechanical Engineering
ABSTRACT

The mechanical properties of drop stitch fabric materials in tension and shear has been investigated for use in designing structural applications such as ship construction, modular buildings, inflatable structures, aquatic vehicles, sporting goods and temporary field equipment installations. The goal of testing is to improve the understanding of the mechanical properties, which can aid in application development for structural deployments using these unique materials. The benefits of using rigid drop stitch fabric panels in ship and building construction are their light weight and rigidity. The epoxy resin infused fabric is corrosion and degradation resistant while providing a more robust resistance to loads and damage in hazardous environments. Inflatable drop stitch fabric materials can form rigid shapes that resist bending and bowing better than those utilizing standard fabric materials. The inflated drop stitch panels can be highly pressurized to allow for greater load capacities and higher resistance to flexing. The greatest benefit of using inflatable structures over rigid ones is their inherent portability which can greatly reduce setup times and transportation needs in rugged environments and over difficult terrain. These materials can be used to replace rigid structural elements in applications that were previously thought impossible for an inflatable design. The many benefits of using drop stitch fabric materials has spurred a great interest in better understanding how to best utilize their unique properties.
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1 Introduction

Inflatable structures are utilized in a variety of industries such as aerospace, military, automotive, marine and recreation. Some applications include airships, airbags, rigid inflatable boats, life jackets and spacecraft landing cushions [1]. Inflatable structures are preferred over traditional structures for applications that require lightweight design, efficient packaging, rapid deployment, and low transportation costs. Research for inflated structures using fabrics, outside of simple beams, is not very extensive despite the wide array of applications to industry.

There is extensive research previously performed on the mechanical properties of inflatable fabric beams [5,6,7,8,9,10]. In order to consider using inflated fabric beams in aerospace applications, an accurate and efficient method of structural analysis needed to be developed. Fabric Beams were structurally analyzed for potential application in the aerospace industry using inflated circular-cylindrical beams [3]. Structural analyses of inflated circular-cylindrical beams have been performed using a number of different strategies mostly concerning the determination of the state of stress in the fabric of the inflated beam. The resulting model shows that the bending behavior of an inflatable beam is identical to that of a conventional solid elastic beam so long as the fabric remains unwrinkled. In predicting when and where eventual collapse of a fabric structure will take place, a reliable indicator is local wrinkling of the fabric face [1].

Drop Stitch fabric is an interesting advanced material that is used for inflatable structures. It was reported to be used in the 1950’s by Goodyear and the U.S government, who subsequently patented the drop stitch technology, to experiment on inflatable airplanes [2]. In the 1960’s the U.S. Navy built a hull form using drop-stitch technology and performed impact testing to determine the impact tolerance [2]. These structures are made from advanced fabrics that are designed to withstand high pressure when inflated and their mechanical behavior depends greatly on the fabric’s design and directional orientation. The inflated structures are subject to tensile pre-stress, caused by inflation. This pre-stress adds rigidity to the structure, but the exact nature of the rigidity is dependent on the mechanical properties of the fabric under conditions such as axial loading, lateral bending and torsional or translational shear along with the internal structure of the drop stitch yarns stitched between the outer walls of the fabric.

Some common geometric shapes of inflatable structures made from drop stitch fabrics such as rectangular and cylindrical beams, tubes and panels, have been previously investigated for their
mechanical properties [11,12,13]. Some of the loading conditions studied are bending, buckling, axial loading and torsional shear. The mechanical properties measured under these loading conditions were determined using either numerical analysis methods (Finite Element Analysis) or pure theoretical means. The focus of this study is to explore methods to determine the elastic modulus, also called young's modulus, and the translational shear modulus of the drop stitch fabric materials. The study also attempts to explores the directional dependence of these aforementioned material properties through experimental testing. From these two quantities, a third key material property can be calculated called Poisson's ratio through the use of the generalized Hook's law. Two experimental apparatus were designed and manufactured along with test methods developed in order to measure these mechanical properties.

1.1 Overview of Drop Stitch Fabric Materials

Fabric weaving is a fascinating process with infinite variations of patterns and materials. Many standard weave patterns for fabric use a specific patterned arrangement of ninety degree (weft) and zero degree (warp) fiber bundles called yarns. To clarify, thread is a type of yarn that is spun by twisting the bundled fibers tightly. This action creates a yarn which is easier to use in hand or machine sewing. Since all the drop stitch fabric specimens used yarns that showed no sign of spinning, no machine thread was used in the process.

As previously stated the yarns are woven in a consistent wave like pattern where every warp yarn passes under or over every subsequent weft yarn. The warp yarns alternate in direction of pass so that no adjacent two warp yarns pass the same way over an adjacent weft yarn. This even symmetrical pattern is called a plain weave. The style of the patterned arrangement of the yarns can range from common patterns such as the twill weave where multiple warp yarns weave alternately over and under multiple weft yarns to the satin weave which is very similar to the twill weave but is designed to produce a fewer number of intersections of warp and weft yarns [14]. In the figures presented below, illustrations of these weave patterns are shown:
Compared to others, the plain weave produces a very tight and strong fabric. Used extensively in fabric goods and composites industry, the plain weave is not only simple to produce but the pattern also imparts more desirable structural properties due to its tight weave construction. This quality makes it an optimum choice for a drop stitch material since it is best for keeping drop stitch yarns in place. For this investigative study, its noted that all the specimens tested used a fabric with a tight plain weave construction.

As previously stated drop stitch fabric materials are created by weaving yarns between two or more fabric sheet layers that are spaced a specific distance apart. The yarns can be at normal angles to the fabric sheet planes or angled slightly in various directions to achieve a V or W like shape to the pattern of interlacing yarns. An illustrative example of this type of pattern is presented in the figure below:
The weaving process of fabrics and how the machines operate lend a considerable amount to the orientation of the drop stitch yarns. The machines that weave the material, known as looms, produce a continuous length of fabric at a finite width which is wrapped onto tubes in rolls of finite linear length. The continuous weave process and the finite width cause the weave pattern of the drop stitch yarns to take on a very specific form. During the weaving process the drop stitch yarns are not cut to form individual lengths attached to the fabric sheet without direct connection to neighboring yarns. Instead the yarns are woven in a straight line along the continuous direction axis and are in line with the warp yarns. The drop stitch yarn is pull through one fabric layer and then the other where it then wraps over and under multiple weft yarns following next to the adjacent warp yarn in the pattern. The yarn then either passes back through the fabric layers continuing the pattern or, as in multilayer fabrics, continues in the original direction through the next layer until the opposite side of the fabric is reached and the pattern continues. The drop stitch yarns are patterned to form evenly spaced rows which are either identically symmetric or patterned to have every two rows at a close distance and/or offset. However, even in a staggered pattern the fabric is still symmetric with respect to every two rows in a repeating pattern. The figure below shows the outer surface of the fabric sheet with drop stitch yarns weaved in, notice the pattern as yarns pass in and back out of the sheet:

![Figure 3: View of measurements of face stitch pattern](image-url)
Some of the commonalities regarding the construction of drop stitch fabrics, centers on the patterns and design. The core structure of these fabrics is composed of two pieces of woven polyester or nylon support fabric that are connected by a series of rows of stitches. The two pieces of material are separated by a distance equivalent to the length of the stitch. The fabric is woven, and not stitched as the name implies, from Dacron, Vectran or Nylon yarn. The “stitching” process is crucial to the strength of the material. Each yarn is woven in the warp direction, up and down, and at times in the weft direction, left to right continuously. This technique ensures that the fabric does not unravel. There are approximately at least 50 threads per square inch and the thickness is at minimum 2 inches up to a reported maximum of 30 inches, depending on the physical constraints of the loom. Once the material is woven together an airtight coating or laminate is bonded to the faces of the fabric. The purpose of the coating is to hold pressure since the drop stitch fabric is not inherently airtight. The coating also works to keep fluids like water out which severely degrade the strength of the fabric materials most notably Nylon. Coating materials are typically non impermeable elastomers such as neoprene, polyester, urethane, vinyl, etc. Once the coating is applied as solid sheets that are bonded or fluid films that are cured to the faces of the fabric the edges of the laminates are sealed [2].

Figure 4: Cutaway of rubber backed 2.5" thick drop stitch fabric
1.2 Theoretical Framework

Materials testing is the best way to predict the properties of solid materials. Various tests can be conducted to find out different types of information about how the material responds in order to better predict its behavior when used in applications. The drop stitch materials under consideration vary significantly from other common materials tested for material properties. The key difference is that at its core it is not a homogeneous material with uniform properties throughout, nor is it a standard composite material with varying lamina orientations that produce symmetric property distributions. Instead it is a 3-dimensional composite material with a varying cross sectional yarn pattern. Even the variation in weave patterns and yarn angles of the woven fabrics lend to the characteristics of its mechanical properties. To properly evaluate the materials being tested, each specimen needs to be tested as a whole and not as individual parts. Another difference is connected to the application of the materials. For the inflated fabric there is an internal pressure and a finite volume which is altered during deformation. Thus, deformation changes the internal pressure and the loading on the drop stitch yarns that alters the shearing and bending properties of the material. In the following sections the theoretical background for the testing performed will be described.

1.2.1 Tensile Testing

Tensile testing involves subjecting a specimen to an axial load (P) and observing the change in length (δ) with the change in load (dP) or time (dt). The specimen is subjected to uniaxial loading as the load is applied in a singular direction with respect to specimen orientation. The load and the subsequent reaction load are oriented in opposing directions which causes a stretching of the specimen. Axially a region where deformation is likely to take place, is measured in length (L), called the gauge length. The cross-sectional area (Ao) of this region is measured prior to testing. The elongation of this region during testing is measured and called gauge length elongation (e). An example of a common type of test specimen geometry is presented in the figure below:
The load applied to the specimen actually represents the resultant of the elementary forces that are distributed across the entire cross sectional area. For the circular bar in the above illustration, the resulting stress in the bar ($\sigma$) actually represents the average intensity of the distributed forces over the cross section and is equal to the load applied divided by the original cross-sectional area of the gage region. This stress resulting from the given case of uniaxial loading is called tensile stress. The typical imperial units used to describe stress are measured in pounds force per square inch or psi. The strain ($\varepsilon$) is defined as the deformation the specimen experiences in the gage region divided by the original length of the region. This is called normal strain and is typically measured in imperial units as the change in length per unit length which is fundamentally a dimensionless value.

However the simple relations given which describe the stress and strain depend greatly on the fact that the cross-sectional area of the gage region is uniform. If the gage region cross-section varies then the stress distribution axially in the specimen is not uniform and varies with the cross-section. Because of the difficulty of making certain measurements of the cross-section of specific sample types, assumptions were required that introduced error into the results and will be explained where relevant.
Typically the data from the tests are used to calculate the stress and strain measurements which are then graphed versus each other in what is called a stress-strain diagram. An example of a stress-strain diagram for a tensile specimen is presented in the figure below:

![Stress-strain diagram](image)

**Figure 6: Typical tensile stress versus strain curve [15]**

These diagrams are used to determine the specific properties of a material specimen. They can also provide insight into the general patterns of behavior common to many material types and sub-types. In order to explain how data was interpreted from the tests performed the method of defining material properties by analysis of these diagrams will be discussed.

The area of greatest interest is usually the initial section, also called the elastic region, where the data line begins to curve. This section can be expanded for evaluation as shown in the figure presented below:
For the previous cylindrical bar specimen discussed, the gage cross-sections are constant and $A_0$ and $L$ are thus considered constant. For a given specimen which is loaded to a finite value of force which starting from zero at the graphs origin, if the load is removed and the strain produced under load also follows and goes to zero as well, then the specimen is defined as exhibiting purely elastic deformation which is within its elastic limit. This is because as the material deformed no permanent deformation, also called plastic deformation, was caused. This behavior is usually visible in the initial portion of the previous stress-strain curve as a straight line. The slope of this linear section is measured as a value of stress over strain called the elastic modulus ($E$). During calculation, two data points are selected from this section and the difference of stress and strain is found. These values are then used to determine the elastic modulus for the test specimen. The linear nature of elastic material behavior is usually seen in homogeneous materials and follows the general definition of Hook's law where stress is equal to the elastic modulus multiplied by the strain.

Figure 7: Close up of elastic region of stress-strain curve [15]
modulus multiplied by the strain. However, many common materials usually experience some small amount of deformation when initially strained past a specific point. This can be seen when the specimen does not return to its original length when unloaded and is called permanent strain. For the above figure, when the curve begins to significantly change direction (point A), then the specimen is starting to experience plastic deformation. This is the point when the elastic limit of the material is reached and is typically referred to as the proportional limit.

A common method to determine when a material has deformed enough plastically to cause significant weakening is to draw a line parallel to the elastic section (line ML in the above figure) that intersects the strain axis at the point of strain equal to 0.2. The point at which this line intersects the stress-strain curve is called the yield point and the associated value of stress is called the yield stress \( (\sigma_{ys}) \) or tensile stress. This 0.2% offset method is commonly used to predict the amount of load that induces inelastic behavior or yield in a structural member.

As the specimen is loaded past the yield point plastic deformation becomes dominant over the elastic deformation. As the material specimen plastically deforms the cross-sectional area of the gage region begins to change and reduce as it is continually loaded. It is at this point that the material weakens significantly and causes a loss of resistance to deformation or loss of strength. However, as the material deforms a phenomena known as strain hardening can occur. Normally seen in ductile materials, such as metals, the stress and strain experienced continue past the yield point and the stress increases until a maximum value is reached. This is another important point on the curve called the ultimate stress \( (\sigma_u) \) or ultimate tensile stress and is defined as the maximum value of stress the specimen experienced.

If between the yield point and the ultimate point the stress experienced increases, then the strain-hardening effect is greater than the strength loss effect, which can be seen in the previous figure. After the ultimate point the stress reduces and the strength loss effect becomes dominant leading to the final point on the curve, the failure point. The point when the specimen fails can be abrupt, as seen in a brittle material, or never truly occur, as is the case with soft plastics which just keep deforming beyond the limits of measure of the testing apparatus. [15]
1.2.2 Shear Testing

Unlike tensile testing, which is usually done the same way for most materials, shear testing of materials is an area that displays much more variability as to the types of tests performed. Shear can occur in various forms and orientations in a structural member. It is defined as:

"A force applied so as to cause or tend to cause two adjacent parts of the same body to slide relative to each other, in a direction parallel to their plane of contact." The stress due to shear (τ) is defined as: "The instantaneous applied shear load divided by the original cross-sectional area across which it is applied." [17] To illustrate the origin of these terms, an examination of a cubic material element with side length equal to one will be discussed. An illustration of the material element to be discussed is presented in the figure below:

![Figure 8: Stress tensor vector components acting on cubic element][16]

On the visible sides, which are planes with positive normal vectors, the normal and shear stress vectors are displayed. If, for example, a shear stress was applied in the x-axis direction on the surface whose normal vector is parallel to the y-axis, the shear stress would be labeled τ_{yx}. If the side opposite this one was held fixed then a resultant equal shear stress in the opposite direction would result. Since the surface is held fixed, rotation cannot occur. This causes the cubic shape to deform into an oblique parallelepiped. This distorted shape causes a reduction of element volume which is counteracted by the compressive strength of the material. These shear stress vectors are shown in the figure presented below:
This combination of stress vectors places the element under a state of shear. As the element deforms, the change in angle at the corners of the sides parallel to the shear stress vectors represents the shear strain. For the shear stress the units are the same as normal stress but the cross-sectional area used for calculation is not normal to the stress vector. The shear strain on the element can be measured as this angle change in radians or as the horizontal deflection over the element's original height. [16] The shear strains for the deformed element are displayed in the figures below:
In general shear testing is usually performed by three common methods. One is a compressive method where two equal opposing forces directed towards each other in a compressive fashion about a specimen act parallel but offset by a parallel plane through a material. Another is a similar style but performed using tension such as when testing the shear strength of bolts. Illustrations of these two methods are shown in the figures presented below:

A third common test method uses torsion or tension applied axially to a specimen. For this type the maximum shear stress occurs along a plane angled at 45 degrees to the axial direction in a specific orientation. The element can be visualized as having a smaller element section rotated at 45 degrees at its center under a state of pure shear. An illustration of this is presented in the figure below:
From these three common examples the most likely method that can be used for drop stitch material is the tension method; however, the method requires significant modification because of the nature of drop stitch materials. The actual test method is similar to the material element case of shear previously discussed. Two opposite sides of a cubic specimen are restrained, then one is fixed with the other having a load applied in a direction parallel to the surface. As with elastic modulus, the stress versus strain relationship for elastic deformation is called the shear modulus (G).

1.2.3 Material Properties and Directionality

Similar to composite materials, drop stitch fabrics exhibit differences in material property behavior with respect to directionality. For reference purposes, the theory for defining material property directionality is now discussed.

Some materials have properties consistent in all directions, which is called isotropy. This is in contrast to other materials which can have material property variations at all points and in all directions. This complete lack of consistency is called anisotropy, which is simply a material that is not isotropic. In order to describe the relation of stress and strain in a material with directionality, Hook’s law can be generalized. In this generalized form both normal and shear types of stress and strain in all three major directions are related by a proportionality constant called the stiffness matrix. Written in matrix form the full stiffness matrix for an anisotropic material has 36 independent constants. Below; the generalized hook’s law in matrix form is presented:
Through various assumptions, the constants of the stiffness matrix can be simplified. First if the material displays elastic behavior indicating a strain energy density function can exist, then the stiffness matrix becomes symmetric. This reduces the number of independent constants from 36 to 21. If at least one plane of symmetry exists then the material is considered monoclinic and the independent constants reduce to 13. If two orthogonal planes exist then the independent constants reduces to 9 and the material is called orthotropic. If at every point in the material a plane exists where material properties are the same in all directions then the material is called transversely isotropic and the number of independent constants reduces to 5. Lastly if there are infinite planes of symmetry then the independent constants reduce to only 2 and the material is isotropic. When relating strain to stress, the proportionality constant is called the compliance matrix. For an orthotropic material, the stain-stress relations in matrix form are shown:

\[
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\gamma_{23} \\
\gamma_{31} \\
\gamma_{12}
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} & S_{13} & 0 & 0 & C_{16} \\
S_{12} & S_{22} & S_{23} & 0 & 0 & C_{26} \\
S_{13} & S_{23} & S_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & S_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & S_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & S_{66}
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\tau_{23} \\
\tau_{31} \\
\tau_{12}
\end{bmatrix}
\]

Where: \( i, j = 1,2, \ldots, 6 \)

Figure 14: Stiffness matrix (stress-strain) for anisotropic material [18]

Using engineering constants such as the elastic modulus, shear modulus and Poisson's ratio, the compliance matrix constants can be calculated [18]. Below the compliance matrix is presented in matrix form using the engineering constants:
The drop stitch material can be considered either orthotropic or transversely isotropic as determined by measured material properties. This depends on if the material properties in the fabric sheet plane are equal or not in both directions. Material testing can determine how the material properties vary with directionality.

### 1.2.4 Materials to be Tested

For this investigative study, the materials being evaluated are of two distinct types. One is a rigid composite specimen, Parabeam, and the other is an inflatable fabric specimen. For the Parabeam specimen, the material is fabricated as multiple layers of evenly spaced fabric with drop stitch yarns passing through and weaving into individual layers. The multilayer weave
passes the drop stitch through the top layer and then through the first inner layer. The yarn is then passed back over and under multiple weft yarns before continuing through the next layer. The fabric material is then infused with epoxy resin so as to form a relatively hollow internal structure. This causes the material to retain mostly the fiber properties but the matrix lends to the rigid nature of the material as a whole when under shearing and bending stresses.

For the inflatable fabric specimen, the material is a simple one layer fabric with a single layer of drop stitch yarns between two sheets of plain weave fabric. The fabric is made from nylon 6,6 and several specimens with various thicknesses were provided by the manufacturer. Below is a list of the various materials tested during the study:

Specific materials tested:
- 2.5” rubber backed Nylon 6,6 -420d 100mm 7/48-17 ppcm (picks per cm)
- 4.5” Nylon 6,6 -420d 100mm 7/48-17 ppcm (picks per cm)
- 6.5” Nylon 6,6 420d 165mm 7/48W-18 ppcm
- 60mm thick, 4-layer paraglass beam, fiberglass drop stitch fabric and epoxy resin

1.3 Overview of Objectives

The focus of this study is to explore methods to determine the elastic modulus, also called young's modulus, and the translational shear modulus of the drop stitch fabric materials. The study also attempts to explores the directional dependence of these aforementioned material properties through experimental testing. From these two quantities, a third key material property can be calculated called Poisson's ratio through the use of the generalized Hook's law. This property describes the negative ratio of transverse axial strain which is a measure of how the volume of a loaded material will deform. Through research it was found that no apparatus has been created to properly test the shear modulus of inflated fabric panels. Thus an apparatus using novel methods of confinement, sealing and pressurization needed to be developed to correctly measure this property of the material. Two experimental apparatus were designed and manufactured along with test methods developed in order to measure these mechanical properties.
2 Construction of Experimental Apparatus

The manufacturer, provided multiple specimens of drop stitch fabric material to test. To test the materials, two apparatus were constructed. One for tensile testing, the other for shear testing. Also in order to properly test the inflatable specimen in shear, a system was constructed to contain and pressurize the specimen. Due to the complexity and effort spent, this system is included in this section as its own apparatus. Also because of cost and time constraints, only a small number of fabrics provided by the manufacturer will be tested in various tests.

2.1 Construction of Tensile Testing Apparatus

To measure the elastic modulus, tensile testing will be performed on the specimens. For tensile testing, the key challenge involves developing a method to hold a specimen in place which best represents the conditions the materials experience under normal use. The Goal is to measure the tensile properties in the axial direction of the drop stitch yarns.

2.1.1 Testing Schema overview

For this test a load is applied in the direction normal to the outer surface on one side of the specimen with the other side held fixed. The other two directions of the fabric were not tested as the bulk of their measured properties would be due to the fabric sheets and not to the drop stitch and thus outside the scope of this study. This style of testing measures macro level material properties which are more similar to properties the fabrics would display in application. The load will start at zero and increase gradually at a very slow pace. This slow pace allows the test to more static than dynamic in that the material is allowed to stay close to equilibrium with the applied load. The load applied and the deflection of the sample from the original starting value are recorded over time. The specimen is stretched either to a certain load or until it either rips out of the clamp or all the threads break. The former is a simple elastic test while the latter is an ultimate test. The former allows for determination of elastic/plastic behavior as when the material relaxes any permanent strain can be measured. This type of test can also be performed repeatedly until failure occurs due to fatigue in a rapid cyclic fashion.
2.1.2 Design Overview

The goal of the design is to securely hold the fabric sheets on the outer faces of the specimen to prevent buckling in the holder. During tension tests the inflatable fabric specimens are left open to atmospheric pressure. This allows for the test to represent only the breaking strength of the drop stitch yarns and their pull out strength from the fabric. The plates are securely held in a holding clamp sturdy enough to prevent the fabric from buckling and pulling out of the test section area. The machine would also need to be able to apply a significant amount of load to the specimen and measure the applied load and displacement accurately in real time.

2.1.3 Apparatus Structure

In order to transfer the load properly to the specimen, a strong and rigid structure is required. The strength and rigidity are key since any deflection of the framing will cause distortion to the results of testing. In essence we want the elastic modulus of the specimen being test not that of the apparatus. Thus a rigid metal frame structure was chosen utilizing t-slot framing and aluminum plates. The t-slot framing consists of 1 inch by 1 inch frame rails produced by 80/20 Inc. The framing is made from 6105-T5 aluminum with minimum yield strength of 35 ksi. The ends of the frame rails are secured to ½” thick 6061 aluminum plates using aluminum L-brackets and steal fasteners. The aluminum plates serve as mounting points for not only the framing rails but also the loading system and sensors. A separate top “deck” attached to the top plate was created for attachment of the load sensor since recessing the sensor in the top plate saves vertical height space for testing long materials. The top plate has a slot cut in it to allow the sensor to protrude slightly. The figures below show the testing section frame and the top deck.
Figure 18, 19: 3D model of testing section frame and US patent drawing, respectively

Figure 20: Top plate of tensile apparatus showing top deck location and sensor cutout

The testing section frame then has a second smaller section attached to the bottom metal plate which houses the load generation and transmission system. This section also uses the t-slot rails but uses an acrylic plate instead of aluminum since the forces exerted here are much less than the testing section.
2.1.4 Sample Loading System

When performing previous testing, it was noted that a sample of 10 drop stitch yarns required over 250 Newton of force to break. After evaluating the material specimens, for a two inch by two inch test area, the number of possible drop stitch yarns present could range between 150 to 200. As a result the apparatus would need a minimum of 4000 Newton of force or approximately 1000 lbs. After several design considerations, it was decided that the load applied to the sample would be generated by a mechanical system driven by an electric motor. The system consists of two parts, the loading deck and the fixed deck. The specimen is secured to the two deck plates with the load applied to one and a reaction load generated at the other. Two ACME power screw rods are used to support and move the loading deck. The loading deck consists of a ½” 6061 aluminum plate with notches at apposing ends for attachment of the screw bearing assemblies which ride on the power screws. The screw bearing assemblies each consist of a thread shaped bearing that rides on the power screw which is bolted to a support mount made from ½” thick 6061 aluminum plate. The bearing assemblies are attached to the loading deck by a high strength alloy steel bolt. The bolt also acts as a pivot joint which prevents the loading deck assembly from suffering binding issues due to slight misalignment. Also the single bolt allows for the deck assembly to be easily removed and replaced facilitating rapid test turnaround. The figure presented below shows the loading deck and the bearing assemblies:

Figure 21: Specimen attached to loading and restraint decks with bearing assemblies visible
The torque to the ACME rods is supplied via an electric gear motor through a worm gear drive system. The figure presented below shows the system:

![Figure 22: Apparatus load generation and transmission system](image)

The electric gear motor consists of a AM 9015 electric motor coupled to a PG27 two stage planetary gear system with a 26.9:1 gear ratio. The motor assembly can output a maximum of 39.2 ft-lbs of torque. Note that the motor assembly can output more torque than this but at the stated value the output shaft will shear. The worm gear drive train attached to the gear motor greatly increases the torque output and because of the locking nature of the gear train it allows for the motor power to be turned off while the specimen remains loaded. The output of the gear train is transmitted to the power screws via a toothed drive belt. The toothed belt also allows for synchronization between the two power screws which prevents one side from slipping which would cause the loading deck to become misaligned. To keep the belt tight to further prevent slipping, a spring loaded idle pulley is situated on the belts outer surface in the area between the power screws. The figure presented below shows the rotation of the pulleys relative to the belt direction:
2.1.5 Sample Holder

One of the key components of the apparatus is the specimen holding system. The Specimen must be gripped in a manner that holds it securely but prevents the fabric from buckling through the test section. A specimen is prepared by cutting a sample larger than the size of the tested area. The excess drop stitch yarns are cut away leaving a central section the size of the desired test area. This creates an outer flange of fabric material which is used to secure the sample in the holder. The holder consists of a clamping plate made from 1/2" thick 6061 aluminum plate with a 2" x 2" square hole at the center. Through this center hole, the specimen is pushed through so that the drop stitch yarns are situated unrestrained say for the fabric it is sewn to. The clamping plate is then secured to the deck plate of either the loading deck or the restraint deck which is attached to the load cell. The surface of the plates are rouged using abrasives to leave a textured finish. This is so that when the fabric flange is secured between the two plates, there is a greater amount of friction keeping it in place. The figure presented below shows a specimen secured in the sample holder attached to the loading deck, the loose yarns in the image are the result of prior testing activity:
2.1.7 Data Acquisition

Experimental data is measured using two types of sensors. The applied load is measured using an S-beam style load cell that is secured at one end to the restraint deck. The load cell consists of a precision machined beam shape fashioned from hardened steel. The type of steel it is made from is chosen for its consistency of material properties. The sensor contains a hollow area with internally mounted strain gauges to measure deformation. As the beam deforms the resistance of the strain gauges changes and the output is measured using a Wheatstone bridge based system.
The displacement of the specimen is measured using a custom made displacement transducer. It consists of a spring loaded potentiometer housed in a 3D printed case. The sensor is mounted to the top plate of the testing frame and measures the change in distance to the loading deck. Inside the rotary potentiometer has an attached drum wound with fine cable. As the cable is pulled, the potentiometer rotates thus changing its resistance and subsequently, the output voltage of the sensor read by the data acquisition module.

![Image]

Figure 26: Displacement transducer and cutaway diagram, respectively

Data is gathered from the sensors by a MCC-DAQ USB 201 Data Acquisition (DAQ) system connected to a desktop computer. The DAQ system connects to a computer via USB and has a voltage resolution of approximately 0.0048 volts. Data from the module is collected, displayed and stored in real time through a program written in the Matlab programming environment. A 3D CAD model of the final apparatus is shown in the figure presented below:
2.2 Construction of Planer Shear Testing Apparatus

The apparatus developed for shear testing will assess how the drop-stitch fabric behaves when under shear loading only. The key emphasis in the shear test is to ensure that the panel is not under any bending or tension loads. Thus a purely planar shear load is desired while still allowing the sample to deform freely. Due to the high loads capable of the apparatus, Finite Element Analysis was also implemented on various critical parts to ensure structural integrity.

2.2.1 Testing Schema overview

For shear testing an apparatus was developed that could apply a load parallel to the surface plane in a specific direction on one outer fabric surface while the other is held fixed in place. During shear testing the rigid specimens are tested as is and open to atmospheric pressure while the inflatable fabrics will be tested in a sealed pressurized containment system. The sealed testing
simulates the real world usage in inflatable structures as the material reacts when shearing stresses are applied due to the change in volume which augments the measured mechanical properties. The drop stitch specimen is first secured in a holder and then is installed between the top and bottom plates via the gripping mechanism. Testing will be conducted in an automated fashion with a computerized control system. The automated testing allows for fast turnaround time for tests while reducing operator induced error.

2.2.2 Design Overview

The key design goal is to ensure that the specimen experiences a pure shear load only. Other types of load such as residual bending load should be limited to near zero. Additionally for a realistic material properties analysis the sample should be allowed to deform freely. This means the machine’s equipment that makes contact with the sample cannot interfere or prevent the sample from deforming as it naturally would. The apparatus is separated into three main frame structures, the testing section, the support section and the control section. In the latest iteration, the forces experienced on the testing section frame and joints could be in excess of 2000 lbs. Thus the structure of the apparatus needed to be made as rigid and study as possible. Unlike the tensile testing apparatus, the shear testing would cause significant torques in the machine. During previous iterations the frame exhibited significant twisting at primary joints. Deflections in the frame members needed to be minimized through substantial bracing and reinforcement. Since the weight of the device has become very high, it was built to be left in place on a bench top surface.

2.2.3 Apparatus Structure

The bulk of the machine's frame is made up of the testing section. The testing section's structural frame consists of a rectangular box frame made from 1.5” square cross-section solid t-slot framing material fashioned from 6061-T5 aluminum. At the corners of the frame in the plane of loading, custom 6 inch long 45 degree angle braces were fashioned from the same t-slot material. The angle braces are further supported by custom triangular support plates made from 1/4" thick 1020 mild steel. These plates secure to the angle brace as well as the vertical and horizontal
frame members that intersect at a corner of a frame by two high strength alloy fasteners each. The figure presented below shows two of the corner joints with angle brace and support plate installed:

![Figure 28: Corner structure of testing section frame](image)

The loading system is secured to the vertical frame members via high strength alloy steel fasteners mounted in the t-slot channels located on the inside area of the frame. This mounting style allows for the loading system height from the base to be easily adjustable since it can be moved along the t-slot channels. To transfer the applied load on the specimen into the frame structure, a sturdy base was created. The base consists of a large 1/2” thick 1020 mild steel plate which spans the full length and width of the frame's bottom side. The rectangular plate has corner cut-outs for the vertical frame members and angle braces. This prevents issues when installing and allows it to sit on the inside area at the bottom of the frame. The plate edges are secured by 5 high strength 5/16-18 alloy steel fasteners each to all four connecting frame rails. This allows for the load applied to the specimen to be distributed across the frame evenly. In order to mount the specimen, holes were drilled and threaded in a 3 wide pattern spaced 1 inch apart lengthwise along the length of the plate. This setup allows for versatility in adjusting of the position of the holding jaws. Also slots were cut in the center of the sample area to
accommodate the pressure supply tubing for inflatible specimens. The figure presented below shows the steel base plate with one jaw mounted, installed in the testing frame:

![Figure 29: Base plate as installed in testing section frame](image)

At the top of the testing section frame a small sub-frame is attached made of 1" square cross section 6061-T5 aluminum t-slot framing and corner brackets. The frame is used to support the constant force springs which carry the weight of the loading jaw assembly to prevent it from causing compressive loading of the specimen. This makes the top jaw plate seem effortless to move so the specimen is unaffected by its presence. The frame has a 1/2" diameter ceramic coated aluminum rod attached to its center span to carry them. The long rod's surface is low friction and allows the spring to translate easily in the loading direction as the load transfer system moves. The figure presented below shows the sub-frame attached to the top of the testing section frame:
Figure 30: Spring support sub-frame

figure 31: Completed testing section frame
The right side of testing section is attached to the support frame. The support frame is a simple structure with the purpose of supporting the back end of the loading system and act as a connecting frame between the control system frame and the testing section frame. The support frame consists of a simple rectangular box frame section fashioned from 1.5” square cross-section solid t-slot framing. The t-slot frame is attached to the test section by four horizontal rails made of U-shaped steel strut channel. The horizontal rails are connected via angle brackets and steel fasteners. The t-slot frame is used because the loading system requires six t-slot mounting points, four in the testing section and two in the support frame. The figure provided below shows the support frame mounted to the test section with the loading system installed but the control system frame has been removed:

![Figure 32: Rear view of support frame](image)

Lastly the control system frame is a simple box frame used to house the control system electronics. The frame consists of 1" x 2" hollow aluminum box beams which are connected together via aluminum angle brackets and fasteners. On the front side of the box, several 1/4" thick plastic sheets are installed using threaded fasteners to create a control panel. This gives simple mounting locations for screens, gauges and controls. Inside the box on the bottom a 1/2"
thick acrylic sheet is installed for mounting additional electronics. The control system frame is attached to the support frame at four points using threaded bolts. The upper and lower rear beams of the frame connect via two bolts to the upper and lower strut channels on the support frame. The figures presented below shows the control system frame from the rear and side.

Figure 33: View of completed control system frame with front instrument panel

With all the frames secured together the apparatus is roughly 60 inches long, 24 inches tall and 18 inches deep with the control panel protruding 10 inch on the right side from the support frame. The figures presented below show the completed apparatus:
Figure 34: Completed apparatus front view ready for testing
2.2.4 Sample Loading System

It was also realized, while researching the drop stitch technology that machines that can produce accurate results to determine the shear properties of the materials would have to be adaptive machines. This means the mechanism used to apply the shearing force on the drop stitch panel would have to keep the direction of force horizontal to prevent error due to specimen rotation. A shearing force as shown in the figure, is applied on the top outer surface of the drop stitch panel.
Since the apparatus must apply over 2000 pounds of load, a sub-frame for the loading system was incorporated for support. The loading system frame consists of three aluminum I-beams which were machined into C-shaped beams. The beams were then CNC milled to accommodate mounting of the load generation system and the load transfer system components. The three beams are connected together by four steel strut channel rails and 1/2"-20 steel bolts. The rails sit near the outer edges on both the top and bottom surfaces of the beams to form a ridged box frame. The ends of the beams have holes drilled for mounting onto the t-slot rails. The figure presented below shows the loading system frame with all components installed:

Figure 36: Diagram of specimen under simple shear [16]

Figure 37: 3D CAD model of final loading frame
2.2.4.1 Load Generation Component

One of the major modifications that are clearly visible in this design is the use of pneumatic pistons, instead of an electric power screw system, as a loading source. This decision was based on the fact that pneumatic pistons are force controlled as opposed to the displacement controlled electric motor systems. The force applied by the pneumatic piston on the sample can be precisely controlled using a pressure regulator and is not dependent upon displacement. This allows for a force to be applied and the specimen to then respond with displacement in an unrestricted manner. The loading force of the system is provided by two custom pneumatic pistons from Bimba Manufacturing Company. The pistons, Model number 7024-dxp, have an internal diameter (bore size) of 3 inches and a stroke length of 24 inches of travel. The force of the pistons is transferred into the frame via large 1 1/2" - 12 thread nuts. The nuts screw onto threads machined in the nose and tail of the piston locking it in place when tightened. The figure presented below shows both pistons secured in the loading sub-frame:

![Figure 38: View of pneumatic pistons in loading frame](image)

Each piston is capable of up to 250 psi air pressure and can produce a maximum of approximately 1060 pounds force each or 2120 pounds force total at 150 psi which is the maximum pressure of the attached pressure regulator. The air pressure driving the pistons needs to be controlled precisely to allow for accurate loading since a single rise of 1 psi in pressure equates to a force increase of approximately 7.068 pounds force. To facilitate an automated testing protocol, the regulator needs to be computer controllable since the ramping up of applied
load at a slow pace could take over an hour for a single test. After testing various pressure regulators, it was decided to manufacture a setup which can meet the control goal of 0.1 psi minimum resolution. The final device is a custom made electromechanical pressure regulator. The pressure control aspect is accomplished by a manually operated high precision, high flow dual diaphragm pressure regulator. The pressure regulator is operated by rotating a knob which is attached to a fine threaded screw. The screw enters the regulator housing and applies a load to the main diaphragm spring. To control the regulator a stepper motor with an attached planetary gear box is used to rotate the screw. Since as the screw is rotated it travels into the housing, the stepper motor needs to move with the screw.

To accomplish this it is mounted to a sliding chassis. The sliding chassis rides on plastic linear bearings along two ceramic coated aluminum rods. The whole assembly is attached to an aluminum plate which is mounted vertically to the control system frame. When designing the valve it was important to consider the torque required to turn the control screw since it influences motor selection. The more the screw is rotated into the housing, the greater the pressure output of the regulator. However as the regulator pressure output increases, the torque required to turn the screw increases. Tests were performed using a torque wrench and a standard hex bolt threaded into the housing in order to determine how much torque would be required from the driving motor. During the test, the applied torque reach over 20 ft-lbs. However the torque wrench used was not easy to get a specific value to torque since its manual gauge resolution was 5 ft-lbs. Thus a stepper motor was chosen that was far greater in strength then required in order to prevent any future problems. The figure presented below shows the completed pressure control assembly:
The stepper motor chosen is a high torque NEMA 23 stepper motor with an attached 3-stage planetary gearbox with a 47:1 gear ratio. The stepper motor assembly is capable of 60 Newton meters of torque and has a rotation control resolution 0.039 degrees of rotation per step. This fine degree of rotation allows for precise control of the pressure regulator. The regulator selected is has an output pressure range of 0 - 150psi and an accuracy of ±0.05% over this range which gives a maximum resolution of 0.075psi.

2.2.4.2 Load Transmission Component

When designing the apparatus for shear testing the two major design goals were: (1) to allow for the application of a pure-horizontal planar load to the top of the test specimen and (2) while simultaneously allowing for unrestricted deformation of the sample in the vertical direction. This is accomplished through the use of the 2 DOF carriage sub-system for load transfer. The
system implements four heavy duty linear bearings for horizontal displacement and four more for vertical displacement. The bearings are heavy duty linear bearing which use steel balls in oval raceways. The bearing are capable of supporting 1900 lbs of radial load each. These bearing are held securely in a two part carriage assembly made from high strength 7065-T65 Aluminum which is bolted together using #10-32 high strength alloy steel fasteners. The linear bearings travel along 1 inch diameter guide rods made from 4140 chrome-moly steel. The rods have a minimum yield strength of 60,000 psi, a minimum surface hardness of Rockwell C25 and are precision ground to a diameter tolerance of ±0.0005\". Chrome-moly steel was selected for the rods mainly for its high strength and ability to resistance fracture from repeated stress application. In the load transfer system, the vertical guide rods transmit the load applied to the carriage assembly to the specimen holder and the horizontal guide rods support the torque loads on the carriage created by the shearing motion.

The load from the pistons is collected and applied to the carriage through a member called the loading block. The loading block is made from a single piece of high strength 7065-T65 aluminum alloy. The block has threaded holes at its ends for the piston rods and two linear bearings which ride on the horizontal rods. Between the loading block and the carriage assembly is where the load cell sits mounted to a loose threaded rod. The system is designed this way so that the carriage and the loading block are independent from one another and allow for the load to transfer between the two through the load cell. The figure presented below shows the load transfer system assembled:

![Figure 40: Load transfer system mounted in sub-frame](image-url)
The design allows for pure horizontal loading, such that all the load applied to the specimen is restricted to the shearing direction. At the same time the system allows for unrestricted vertical deformation of the specimen without applying. In other words, the sample would be allowed to deform as it pleases while experiencing any applied loading normal to the top surface (tensile or compressive) which demonstrates a loading case of simple shear.

2.2.5 Sample Holding System

To transfer the shear load effectively to the specimen, a system for holding it in place was devised with the goal of reducing turnaround time for repeated testing. The holding system consists of two key surfaces. One is the base plate which restrains the motion of the bottom of the sample. The other is called the top jaw plate which transfers the shearing load from the vertical rods of the load transfer carriage assembly to the specimens top surface. The top jaw plate is made from the same material as the base plate, 1/2” thick 1020 mild steel and has a bolt hole pattern similar to the base plate for mounting the jaws. The plate secures to the vertical rods through a connecting block made from high strength 7065-T65 aluminum alloy. The connecting block has two recessed holes on one side which fit snugly over the outside of the vertical rods, matching recessed holes in the bottom hide high strength alloy steel fasteners which bolt the rods in place. This socket like connection to the rods is designed to reduce bending moment applied to the ends of the rods since the block helps to restrict the motion. The connecting block is then bolted to the top jaw plate with high strength alloy steel fasteners.

The weight load from the assembly on top of the sample is eliminated using constant-force springs that are connected to the vertical rods as previously mentioned. The jaws on the two key surfaces which hold the specimen consist of 2” x 5/8” 6061 aluminum bar with a 45 degree angle cut into one side. The 45 degree cut in the jaws is accompanied by an opposite 45 degree cut in the surface plates of the specimen. This creates a dove tail shaped joint between the specimen end plates and the jaws which locks it in place in the loading direction but still allow it to easily slide sideways in and out of the jaws for fast test turnaround. The figures presented below show the jaws on the base plate with half a rigid specimen installed:
Surface. On each surface when under shear loading one jaw resists the horizontal load while the other resists the normal load caused by the specimen trying to rotate against the shearing load. Thus the two are designed slightly different. The horizontally loaded jaw has three holes for three bolts to give it maximum strength. The other jaw has three 1" long slots in the loading direction for three bolts. These slots allow for some degree of adjustability in the distance between the jaws to get a proper alignment for the specimen plates to slide in. For rigid specimens the outer surfaces are attached to 1/2" thick acrylic plates using an 1/8" thick flange made of aluminum. The plate has a large groove machined in its surface which works to lock the specimen in place. This can be seen in the previous figure of half a rigid specimen. The inflated specimens are held in a containment system which will be discussed later.

2.2.6 Automated Electronic Control System

In order to facilitate an automated testing protocol, the apparatus is designed to be computer controlled. The automated electronic control system is housed in the control system frame. In the figure present below the rear of the control system frame is shown with all electronic components installed:
The Control system is divided into 6 areas: 1) the electronic control unit, 2) the piston control unit, 3) the sample pressure control unit, 4) the relay unit, 5) the stepper valve control unit and 6) the operator interface unit. The electronic control unit or ECU is the brain of the control system. The unit consists of a custom fabricated control board powered by an Atmel 16-bit microprocessor. The system is programmed using the Arduino coding environment using the C programming language. The unit uses analog and digital interfaces to acquire and transfer sensor data and operator input, control actuators and output operator instruction through the connected 32 character LCD screen.

The piston control unit consists of a valve train connected to the main air supply line. The valve train starts with the electromechanical pressure regulator which then feeds the output pressure to a 1/4" pipe size, 4-way, 5-port spool valve that controls the directional actuation of the pneumatic pistons. The pressure output of the pressure regulator is monitored by the operator using a high accuracy pressure gauge mounted to the front of the control panel. Between the two is a 2-way solenoid actuated poppet valve with spring return that acts as the supply control valve and can open or close the air pressure supply to the pistons. Between the supply valve and the
spool valve is a second poppet valve that vents to the ambient environment and is used to bleed pressure in the system off when the supply valve is closed.

The other air pressure system is the sample pressure control unit. The unit is used to initially pressurize an inflatable test specimen to a set pressure prior to conducting a test. Connected to the main supply line, the unit consists of two sections. One is a manually regulated side and the other is an electronically regulated side. This two way pressure regulation allows for the test specimen to be pressurized either using a pressure set manually by the operator or through an electronic regulator controlled by the ECU. The two pressure regulator each have a poppet valve connected to their output in order to close off the airflow to the specimen once pressurized prior to beginning the test. The outlets of the regulators is combined at a small manifold with a connected poppet valve used to vent off system pressure. Pressure output of the regulators is monitored by the operator through separate pressure gauges mounted to the front of the control panel.

All the electronic valves in the pressure control systems are actuated using the relay unit. The relay unit consists of a control board with 8 individual coil operated single pole dual throw relays. The relays each have a transistor connected to the actuation coil. This allows for the connected microcontroller to switch the relays without supplying more than a few milliamps of current. When the microcontroller sends a 5 volt signal to the relay, it triggers the transistor which sends 5 volts from the on board supply connection to excite the coil. The relay then closes and sends the connected supply voltage to the solenoid actuating it. Cutting the 5 volt signal from the microcontroller returns the relay back to its open state.

Another area is the stepper motor control unit or MCU. The MCU allows the ECU to control the movement and direction of rotation of the stepper motor in the electromechanical pressure regulator. The ECU interfaces using 3 simple digital signal connections: enable, direction and step. Sending a 5 volt signal to enable activates the MCU which even when not in motion, can provide power to generate torque to resist rotation or holding torque. If the signal is removed, the stepper can move freely. However the high gear ratio of the attached gearbox provides significant resistance to any applied torque. Sending a signal to the direction pin will cause the stepper to rotate clockwise while no signal results in anti-clockwise rotation. Lastly the step pin controls the stepping motion of the motor. sending a short 5 volt pulse as a 1 millisecond long
square wave causes the stepper to move one step. As previously stated a single step results in a shaft rotation of only 0.039 degrees. Every pulse sent results in a step in the selected direction. Lastly the operator interface consists of a cluster of buttons, LEDs, a keypad and LCD screen mounted to the front of the control panel. The figure presented below shows the operator interface on the front of the control panel:

![Front view of instrumentation panel](image)

**Figure 43: Front view of instrumentation panel**

The operator interface uses several items for operator input consisting of 3 push buttons, a knob using a rotary potentiometer, and a keypad unit. The buttons are labeled Test, Mode and Select. The keypad has numbers 0-9, a decimal point and enter. The knob allows for 'volume control' style rotary input. These control can be used to manipulate setting without the need for reprogramming the ECU. The LCD screen is used to display information such as data values, control settings and instructions to the operator. Lastly LED lights are used to provide visual
indicators such as GREEN for safe or RED for danger test in progress keep hands clear as well as power on or configuration mode engaged. All these parts come together to produce an automated control system capable of simple operation and rapid automatic testing.

2.2.7 Data Acquisition

The sensors for data collection are a load cell, a digital pressure sensor and one to two displacement transducers. The load cell is a doughnut shaped unit usually used to measure axial loading in bolts. The load cell is connected to a 1/8 DIN panel meter with a four digit readout and analog voltage output. The meter provides accurate excitation voltage to the sensor and includes various calibration settings. The meter also outputs an analog voltage which is proportional to the load measured by the load cell. This allows for the load data to be gathered by the data acquisition system. The load cell selected is model ____ from Omega Engineering and measures compressive loading up to a maximum value of 2000 lbs force. The figure presented below shows the load cell described:

![Figure 44: LC8150 Load cell and panel meter](image)

The vertical and horizontal displacement of the top jaw plate which moves with the top surface of the sample relative to the base plate, is measured using displacement transducers. As the specimen deforms these measurements will represent the change in length relative to the start of the test. The displacement transducers consist of a high accuracy multi-turn potentiometer coupled to a small drum. The drum is wrapped with a fine multi-strand wire cable that is designed for minimal elongation under light tension. The end of the cable is attached to the surface to be measured using a loop formed at its end with a fastener through the eye. As the cable is pulled the potentiometer rotates and thus change the ratio of the internal voltage divider.
A power spring coil is also coupled to the shaft of the potentiometer. This spring allows for the cable to remain under constant light tension and acts to rewind the cable when the load is removed. Thus by applying a steady voltage to the potentiometer, its output can be read and interpreted as a displacement measurement. The figure presented below shows the displacement sensors used:

![Figure 45: LX-PA-25 displacement transducer](image)

The main displacement sensor is connected to the load transfer carriage to measure the horizontal displacement. A second displacement sensor is connected to the top end of the vertical rods to measure the vertical displacement of the specimen. The transducers are supplied a steady voltage of 5 volts by a voltage regulator in the control system and the output voltage is measured by a 10 bit analog to digital converter. The last sensor is a digital gauge pressure sensor. The pressure sensor is used to measure the internal pressure of inflated fabric specimens. The sensor is connected to the control system through a 2-wire I2C interface. The interface allows for parallel communications over one wire between a master, the control unit, and a slave device, the sensor. The sensor reads the pressure using an 12-bit analog to digital converter and has a measurement range of 0-150 psi gauge with an accuracy of ±1% over its full measurement range. Calibration of the sensors output for accurate measurement and the measurable resolution will be discussed later.
2.2.8 Data Processing and Real Time Display

Data from the sensors is output as raw analog electric signals which require post processing to be turned into meaningful data. During testing, the raw sensor data is read by the DAC system in real time and processed using calibration settings into real values in engineering units. This data is then output to the connected Windows desktop host computer running Matlab. The data is transmitted from the control system through a two way serial data connection encoded in the American Standard Code for Information Interchange format or ASCII as 7-bit binary integers. The data is read into the computer through a virtual serial port through a USB connection via an FTDI connection chip.

Matlab software is used to read the encoded data and interpret it back to its original English characters. The data is sent as a sequence of comma delimited values terminated with a line return. The sequence starts with the character sequence header "DATA!" since it is a sequence of characters that will never be repeated otherwise so that the software can easily tell where a sequence of data begins. The data strings are then separated from the continuous stream and the values separated or parsed as it's called and saved into cells of an ever increasing data collection array. As new data comes in it is processed by performing calculations to find the stress and strain as well as other important values. Once a few points of data are saved, a plot can be created to graph important data such as stress versus strain. This plot is then refreshed in repeatedly as new data comes in to produce a real time plot of measured values. Upon completion of a test, a character sequence is sent to the host computer to signal completion. Upon receipt of the message the computer closes out data collection monitoring and saves all plots as picture files and unsaved data as text files before closing the program. The host computer graphic interface or desktop is displayed through an LCD screen mounted to the control system panel. This screen will display the real time plots as the data is collected. The host computer can be in laptop or desktop form and simply sits next to the apparatus.

2.3 Construction of Inflated Sample Containment System

In order to properly test the inflatable specimens in shear, a system was constructed to contain and pressurize the specimen. This pressurized interior represents the real world scenario of a pressurized structure environment. The finite volume environment inside an inflated structure
under an initial inflation pressure would have a specific internal volume. When pressurized the internal pressure pushing outwards on the insides of the fabric would cause the drop stitch yarns to be loaded in tension as they resist the loading. As the structure is deformed under applied loading, the internal volume would decrease which in turn would raise the internal pressure. This rise in internal pressure would cause the tension on the yarns to also increase thereby stiffening the fabric. It is this equilibrium balance between the drop stitch yarns and internal pressure that plays a crucial role in the shear modulus of the material.

2.3.1 Design Overview

To be able to pressurize the specimen interior but not skew the shear testing results, a novel design was created to seal and contain the specimen. Considerations were that the specimen needs to be air tight to properly represent the sealed environment of an inflatable structure. Also the seal of the specimen about its perimeter must contribute as little as possible to the shearing characteristics. The seal must also not be allowed to deform beyond the bounds of an oblique parallelepiped since the specimen itself will take on this shape. Lastly a pressure inlet must exist in order to pressurize the specimen and provide a port for actively measuring internal pressure changes during testing. The holding system design has three main parts which will be discussed.

2.3.2 Sealing System

The seal system for a pressurized specimen begins by creating an air tight environment. After various design iterations, it was decided that an outer envelope will encase the specimen on the four exposed sides with flanges of material that extended inward on the top and bottom sides to form flanges. Since the material of the seal needed to be flexible but also air tight it was decided that a rubber material would be best since it can be molded in liquid form to shape and cured to a flexible solid. The seal is attached and sealed to the specimen using acrylic plates. Acrylic was chosen over aluminum because of its lower cost, easier machinability but higher stiffness and strength compared to other common plastics. The use of plastics allow for the plates to be disposable since they are bonded to the specimen's surface and cannot be reused without considerable effort. To create the rubber seal, a novel molding technique was developed. The
mold was CNC machined from multiple 1" thick acrylic plates. These plates are then assembled together with interconnecting pins to provide strong connecting joints. The plates form a box representing the outer dimensions of the rubber seal. At the center of the mold, a large acrylic block composed of multiple sheet layer bonded together is machined to form the inside area representing the dimensions of the specimen. Cutouts in the top and bottom of the block for the flanges in the seal. All the surfaces of the mold which will come into contact with the rubber material are then buffed and polished using several coats of mold release wax. The mold is then assembled together using high strength hot melt adhesive to form a strong airtight seal. At opposing corners on the top and bottom surfaces, barbed hose connections are threaded into holes to form paths for material entry and air evacuation. The figure presented below shows a completed mold fully assembled and ready for molding:
The mold is then connected via vacuum hose to a rotary vane vacuum pump with attached material trap for infiltrate prevention. Next a two component liquid rubber is mixed with a thinning agent and degassed in a vacuum chamber to remove air bubbles. The container with the mixture is then placed on a surface lower than the mold and the lower hose end is submerged in it. Vacuum pressure is then drawn to coax the material through the hose and slowly up into the mold. As it rises it slowly fills the mold evenly. To help assist the infusion process and coax remaining air bubbles to the surface, a vibrating sander is placed on top the mold. Once the mold fills, excess rubber is allowed to enter the resin trap taking with it any remaining air bubbles. Finally the vacuum is shut off but the mold itself has contracted slightly due to the vacuum pressure. If left as is, material left in the outlet hose would be drawn in and cause air to enter with it. To solve this, the trap is inverted prior to pump shut off. This provides a large volume of excess material which can be drawn back into the mold. To speed up the process, low pressure air is forced into the trap forcing the material into the mold. Finally the inlet hose is clamped shut and the outlet hose is removed. Any remain pressure differential in the mold causes a small amount of excess material to ooze out the outlet connection. After curing 24 to 48 hours the rubber is then removed from the mold and allowed to fully cure over the course of a few days to a week.

2.3.3 Wall System

Since the rubber seal about the specimen must also not be allowed to deform beyond the specimen's edges during testing, a wall system was developed to restrain the seals deformation. Since the specimen is deflected in a single direction, two of the containment walls located on the sides of the specimen can be stationary while the other two on the front and rear need to deform with the specimen. The two stationary walls each consist of an aluminum plate 1/4" thick and measuring 8" high and 10" wide. The plate is rigidly reinforced by four 6 inch long ribs measuring 3/8" thick x 1.5" wide. The ribs are secured to the wall plate via two 1/4"-20 steel fasteners each. Due to height changed made later on, the wall plate surface was extended in height and length by two pieces of 1/2" thick aluminum by 2 inches and 3 inches respectively. The walls are then secured to a base plate made from 1/2" thick aluminum measuring 10 inches square. The base plate has slots cut into it to allow the walls to be secured at the ribs and
adjusted snug to the specimen surface. The base plate also has a hole pattern of 20 countersunk holes for fastening the specimen to its surface. Lastly a 2 inch diameter hole is milled in the center to accommodate the pipe for pressurizing the specimen. The figure presented below shows the stationary walls and base plate fully assembled:

Figure 47: Assembled stationary walls and base plate

For the walls on the front and back of the specimen, a novel design was developed to allow them to move with the specimen. The walls are designed as two sets of 1/8" wide fingers. These fingers interlock creating a nearly solid surface to restrain the pressurized seal. One set of fingers has holes drilled laterally while the other set has slots. The holes and slots are sized to
allow a 1/4" diameter hardened steel rod to thread through the fingers. These rods are simply held in place by the fiction of the holes they passes through. This allows for the walls to extend and contract as the specimen stretches vertically under load so as to not restrain its movement. The arrangement of the rods facilitate easy assembly and disassembly when loading specimens since fasteners are not required. These wall connected to the upper and lower plates via support blocks. A curved tang on the wall fits in a notch on the support blocks and contains sleeve bearings for low friction rotation. A 1/4" diameter steel shaft threads through the assembly like a pin in a door hinge. The completed walls measure 6 inches in width and vary in height depending on the height of the specimen being tested. Due to the size of the wall and restrictions on cutter lengths available, the part had to be broken down into three 2 inch wide sections and then assembled together in order to facilitate machining. The figure presented below shows a single completed wall assembly in full extension:

Figure 48: Assembled moving walls and top plate

(Note one wall is separated to allow view of the rods which secure the fingers)
The moving walls are the bolted to the top and bottom plates by steel fasteners at a location adjacent to the specimen walls. The upper moving wall sections attached to a 6 inch wide, 1/2" thick aluminum plate. The plate and walls along with the top jaw plate are sized to fit snugly between the stationary walls. When assembled it was noticed that the friction between the rubber and the walls was quite high. To resolve this, Teflon grease was applied to the stationary walls to provide a low friction surface. The figure presented below shows the containment system fully assembled with a specimen secured inside:

![Figure 49: Assembled containment system](image-url)
3 Experimental Procedure

In the following section the experimental procedures for specimen preparation, testing and calibration will be discussed for both test types performed.

3.1 Tensile Testing

The following section outlines the experimental procedure for tensile testing the drop stitch specimens.

3.1.1 Machine Calibration

Before testing can begin, the machines sensors needed to be calibrated. First the alignment between the top and bottom decks that the specimen's attach to are checked using a digital caliper. If required, adjustments are made to the loading deck by loosening the tension pulley and manually rotating the power screws. Next the load cell must be calibrated. This is done by removing the stationary deck so that no load is applied to the sensor. Measurements of the output signal are then recorded for a period of time. Next a known load is applied to the sensor and the output signal is again measured for a period of time. If desired, multiple increasing loads can be applied to produce a calibration curve in Microsoft Excel. From the curve a trend line can be created and the correlation equation used to process the output signal. However since the output from the sensor was shown to be nearly linear with respect to loading, a simple linear relations was used. Lately the displacement sensor is calibrated. Using a ruler, measurements of the output signal are taken at various known displacements and a correlation equation is created as stated previously.
Figure 50: Calibration of load cell and displacement transducer

Figure 51: Calibration data for load cell
3.1.2 Machine Operation

To perform a test, the machine must be powered up and the control software readied. A prepared specimen can then loaded into the mounting plates and clamped securely at each end. Prior to testing the height of each specimen is recorded for later calculation. For inflatable fabric specimen, the number of drop stitch yarns in the test section area is also recorded. One secured the software is initiated and the load is slowly applied. The load and displacement are recorded by the software as the test takes place. To pause or end the test, the user simply clicks a button on the program screen. The test data is recorded and saved in a text file on the computer desktop for post processing later.

3.1.4 Inflatable Sample Preparation

Similar to the rigid specimen, the inflatable specimen needs a flange of material created. The drop stitch yarns are carefully trimmed away to leave a clean flange of material. The outer surfaces of the flange are either coated in an epoxy resin outside the test area to produce a hardened zone or adhered to acrylic sheets using an industrial grade spray adhesive. The figure presented below shows a prepped specimen ready for testing:

Figure 52: Calibration data for displacement transducer
3.2 Shear Testing

The following section outlines the experimental procedure for shear testing the drop stitch specimens. Before using the shear testing apparatus, care should be taken to check the apparatus components over. The sliding rods should be lubricated prior to each use with a light machine.
oil. The operator should exercise caution while the machine is active as the release force of the piston is very high. The operator should also be cautious of the residual material off the rigid specimens after testing especially when the machine has completely sheared it.

### 3.2.1 Machine Calibration

Before testing can begin, the machine's sensors needed to be calibrated. First, the height between the top and bottom jaw plates is adjusted by moving the loading system frame along the slots. This is done so that the distance the vertical rods extend downward at the start of the test is minimized. This reduces the resulting torque on the load transfer carriage as the specimen deforms. Next, the load cell must be calibrated. This is done by inserting a piece of aluminum I-beam what has angled notches machined in its top and bottom surfaces. This allows for the beam to be inserted into the jaws locking the top and bottom plates in place. Next, the load cell is adjusted to ensure a state of zero load. On the output meter, the configurations allow for this state to be recorded. Next, since the inside area of the piston is known, pressure can be applied and accurately measured to predict the force output. The force output is set to 2000 lbs as accurately as possible. At this point, again the meter is used to record the output signal. The meter then adjusts the sensor settings to ensure an accurate measurement across the range of force applied. The meter setting are also adjusted for a ratiometric analog voltage output over the range of 0 to 5 volts relative to the load measured in the applied range. Next, to calibrate the displacement sensor, a finely graduated ruler is used. Measurements of the output signal are taken at various known displacements and a correlation equation is created as stated previously.
Figure 55: Horizontal displacement transducer calibration curve

Figure 56: Vertical displacement transducer calibration curve
3.2.2 Machine Operation

To perform a shear test, the operator must first power up the machine using the switch on the front panel. Next the computer system is powered up and the used data cable is connected. Once the computer is powered up, the Matlab software for data post processing is opened and made ready to run. The next step is to install a prepared specimen into the machine. This is accomplished by first loosening the adjustable jaws on the top and bottom loading plates. The specimen can then be inserted perpendicular to the loading direction from the front of the testing area. Once in place, the adjustable jaws can be pushed inward tightly against the specimen holder to remove any slack and be locked into place by tightening the jaw fasteners. Once the test specimen is securely installed, the operator can adjust the testing parameters through the operator interface.

To do this the operator must first enter the setup environment by holding the MODE button on the front panel for 3 seconds. The LCD screen will indicate that the system is in setup mode. Various test parameters can be selected by cycling through the list using the TEST and MODE buttons. The adjustable parameters include: 1) maximum force applied, 2) force application rate and 3) deflection limits for ending a test (if desired). If performing tests on inflated specimens additional parameters include: initial internal pressure (if using electronic pressure regulator) and pressure limits for ending a test (if desired). Once all the test parameters are set to their desired values, the operator will need to start the Matlab code for data acquisition on the computer console. The operator then initiates a test by holding down the test button for 5 seconds. The red TEST light on the front panel will illuminate to indicate that a test is in progress and that the test area is unsafe to enter. At this point the apparatus performs the automated test to the set parameters and outputs the data to the computer system. The recorded data is displayed in real time on the LCD monitor and the current applied load and displacements are displayed on the LCD displays. When the test is completed the load transfer carriage is automatically returned to the starting position and the test light extinguishes while the STATUS light returns to green to indicate the test area is safe to enter.

If for emergency reasons the test must be interrupted, the operator can depress the TEST button to disengage a test immediately. If the TEST button is depressed while a test is in progress, all pressure to the pistons is immediately shut off and vented so that all force is removed. To return
the carriage to the starting position and reset the apparatus after an emergency stop, the TEST and MODE buttons must be held together for 3 seconds.

### 3.2.3 Rigid Sample Preparation

To prepare a rigid specimen for tensile testing, a flange of sheet material must be machined around its perimeter. First the panel of material is marked so indicated the size of the specimen and then cut from the panel using a vertical band saw. The cut block is then placed in a vice on a vertical milling machine. Using a carbide cutter, a section of yarns is machined from each side of the specimen to form a uniform flange of material on the top and bottom surfaces. The figure presented below shows a fully prepped specimen ready for testing:

![Prepared Parabeam Specimen](image)

**Figure 57: Prepared Parabeam Specimen**

For shear testing, rigid specimens are prepared in an identical manor to those prepped for tensile testing. Once machined to shape for testing, a sample holding plate is attached to each outer
surface of the specimen using flanges secured by screws and then is ready for testing. If desired the specimen can be bonded using high strength adhesive to the holding plates to decrease any undesired deflection during testing.

### 3.2.4 Inflated Sample Preparation

The full seal system assembly begins with a specimen prepped with an outer flange of fabric on both sides that is devoid of drop stitch yarns. Next a 0.65" thick acrylic plate measuring 5.75" square is bonded to the outer surface of both sides of the specimen. The plate has been CNC milled with holes on both sides for fasteners that do not penetrate through the full thickness of the material. At the center of one of the plates, a hole is milled through the thickness of the plates and taped with threads to accept an 1/8" size pipe. The fabric flanges are then further secured to the plates via two C shaped clamp plates per side cut from 1/8" thick aluminum. These clamp plates ring of holding pressure around the perimeter of the specimen. The figure presented below shows a specimen completed to this stage of assembly:

![Prepared inflatable specimen](image)
Next the rubber seal is slipped over the specimen and adjusted into place. Next the outer acrylic plates made of 1/2" this acrylic and measuring 6 inches square are fastened to the inner plates through holes in the rubber seal. To create a good seal, a torque of at least 10 foot lbs beets to be applied to the fasteners. The figure below shows a specimen completed to this stage of assembly:

![Prepared inflatable specimen with seal installed](image)

Figure 59: Prepared inflatable specimen with seal installed

Next an 1/8" size metal pipe is secured to the pressure port using pipe thread sealant. Once the pipe is attached, the specimen is secured using fasteners to the top and bottom plates of the containment system. With the plates installed, the moving walls can then be fastened connecting the top and bottom plates. Please note that care must be taken as to the orientation of the walls. The walls are designed to deflect 90 degrees in one direction but only 30 degrees in the other. Be sure to mount the walls so that they rotate the same amount in the same direction. Also the heights of the support blocks are different. This allows for proper deflection since the top of the
wall on the front and the bottom of the wall on the rear must rotate around the corner created by the acrylic plates. The front should have the longer support blocks attached to the top plate and the opposite for the rear wall. Lastly the stationary walls can be installed and adjusted against the specimen surface.

4 Results for Tensile Testing of Rigid and Inflated Drop Stitch Fabric

4.2 Tensile Strength of Inflated Drop Stitch Fabric

For the inflatable drop stitch fabric specimens, several tests were performed on materials with various heights. Initially several tests were conducted on the 6.5 inch thick nylon specimen to determine the best method for holding it securely. The table presented below lists the tests performed, the types of specimens and modifications made:

<table>
<thead>
<tr>
<th>Teeth</th>
<th>Epoxy</th>
<th>Maximum Force (lbs)</th>
<th>Displacement at Maximum Force (in)</th>
<th>Elongation % at Maximum Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>Yes</td>
<td>160</td>
<td>1.80</td>
<td>27.7%</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>193</td>
<td>2.82</td>
<td>43.4%</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>216</td>
<td>2.07</td>
<td>31.8%</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>235</td>
<td>1.6</td>
<td>24.6%</td>
</tr>
</tbody>
</table>

Table 1: Tests and data to develop specimen holder

From the testing is was concluded that using epoxy to strengthen the flange area of fabric around the test section and augmentation of the clamping plates was the best method and so the rest of the following tests on other samples used the same preparations.
The load versus displacement curves for the 6.5 inch height Nylon material is presented in the figure below:

![6.5 inch Nylon Specimen: Force vs. Displacement](image)

Figure 60: Load vs. displacement curves for 6.5" thick nylon tests

The load versus displacement curves for the 4.5 inch height Nylon material is presented in the figure below:

![4.5 inch Nylon Specimen: Force vs. Displacement](image)

Figure 61: Load vs. displacement curves for 4.5" thick nylon tests
From the tests several key data values gathered for the specimens is presented in the table below:

<table>
<thead>
<tr>
<th>Teeth</th>
<th>Epoxy</th>
<th>Maximum Force (lbs)</th>
<th>Displacement at Maximum Force (in)</th>
<th>Elongation % at Maximum Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>No</td>
<td>118</td>
<td>0.76</td>
<td>16.9</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>95</td>
<td>1.10</td>
<td>24.4</td>
</tr>
</tbody>
</table>

Table 2: Data for 4.5" nylon tests

The load versus displacement curves for the 2.5 inch height rubber backed Nylon material is presented in the figure below:

Figure 62: Load vs. displacement curve for 2.5" thick rubber backed nylon test

From the tests several key data values gathered for the specimens is presented in the table below:
Table 3: Data for 2.5" thick rubber backed nylon test

The data shows that the drop stitch yarns are extremely strong for their weight. A 5" x 5" specimen would require over 1500 lbs of load to fail. However there are several issues revealed by testing that should be discussed.

First It should be noted that the control code written for the machine output the data as load versus displacement, not stress and strain. Using the graphs, the elastic modulus was found for the 6.5" thick nylon material. This data is presented later with the shear data to show the calculation for Poisson's ratio. Also there are several serious inaccuracies with the apparatus. The main issue is that specimen holder is not truly effective at retaining the specimen. Even when clamped very strongly the specimen still stretches out and away from the test area. This throws the strain data off since this buckling reduces the strain extension strain on the drop stitches. Thus a more effective way of holding the specimen needs to be developed to reduce the buckling issue. Other inaccuracies stem from the construction of the apparatus. The drive system still demonstrates slip under high loads causing the loading deck too become misaligned. Lastly the control system was built using a minimum budget and thus requires its own development. Ultimately another iteration is required to produce a apparatus capable of measuring quality data.

5 Results for Shear Testing of Rigid and Inflated Drop Stitch Fabric

5.1 Shear Modulus of Rigid Drop Stitch Fabric

For the rigid drop stitch fabric specimen, only 2 tests were performed do to time constraints caused by issues with apparatus construction. The specimen was tested in two orientations (1
and 2) to determine the directional nature of mechanical properties. The data for the tests are presented in the figure below:

Figure 63: Stress vs. strain curve for Parabeam direction 1

Figure 64: Displacements vs. load for Parabeam direction 1
Figure 65: Stress vs. strain curve for Parabeam direction 2

Figure 66: Displacements vs. load for Parabeam direction 2
From the tests performed, the data was processed to yield the following mechanical property data presented in the tables below:

<table>
<thead>
<tr>
<th>Parabeam Shear Results Direction 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Modulus (Psi)</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>309.0510879</td>
</tr>
</tbody>
</table>

Table 4: Mechanical properties for Parabeam direction 1

<table>
<thead>
<tr>
<th>Parabeam Shear Results Direction 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Modulus (Psi)</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>321.4991915</td>
</tr>
</tbody>
</table>

Table 5: Mechanical properties for Parabeam direction 2

During testing, the newly created specimen holders performed much better. They experienced far less deformation and movement. However, the specimens did show signs of slight buckling at high loads. A possible solution may be to bond the specimen to the holder surface with a high strength adhesive. Also, the machine performed excellently experiencing zero visible flex or groaning/creaking when fully loaded.

From the testing, it was noted that the failure mode of the material is not sudden. The material layers are prone to collapse before failure. It was even seen that the layer that collapsed was never the one to fail. This is likely because as the layer collapses, loading on the yarns between layers becomes uneven. This causes more of a tearing motion at failure rather than a true shearing motion. Also, as the material reaches the failure point, yarns continuously crack and fail ending in a sound similar to pulling apart hook and loop fastener strips.
From the data it can be concluded that the material is truly orthotropic. Failure in one direction occurred at nearly twice the load of the other. The two directions seemed to begin experiencing deformation at about the same time but one failed soon after while the other held up to nearly double in load. This variation in material properties shows that when designing structures using this material, care should be taken to orient the stronger axes in the direction of the greatest stress.

5.2 Shear Modulus of Inflated Drop Stitch Fabric

For the inflated drop stitch fabric specimen, only 3 tests were performed due to time constraints caused by issues with apparatus construction. The intricate nature of manufacturing the specimen containment system moving walls proved extremely time consuming. This coupled with the fact that different heights of material required separate walls to be fabricated lead to testing of only one height of specimen. Further testing of other heights of material will be relegated to other research efforts performed later on. The data was processed to yield the figures presented below:

![Stress Vs Strain Curve: 6.5" Thick Inflated Nylon Direction 1](image)

Figure 67: Stress vs. strain curve for 6.5" thick inflated nylon direction 1
Figure 68: Stress vs. strain curve for 6.5" thick inflated nylon direction 2

Figure 69: Displacements vs. load for 6.5" thick inflated nylon direction 1
Figure 70: Displacements vs. load for 6.5" thick inflated nylon direction 2

Figure 71: Internal pressure & load vs. time for 6.5" thick inflated nylon direction 1
using the data from both the tensile tests and the shear tests, the mechanical properties can be determined for the 6.5" thick inflated nylon material. The results of these calculations are presented in the table below:

<table>
<thead>
<tr>
<th>Direction</th>
<th>Shear Modulus (Psi)</th>
<th>Elastic Modulus (Psi)</th>
<th>Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction 1</td>
<td>12.65109901</td>
<td>367.25</td>
<td>13.514549</td>
</tr>
<tr>
<td>Direction 2</td>
<td>11.00162396</td>
<td>367.25</td>
<td>15.690718</td>
</tr>
</tbody>
</table>

Table 6: Mechanical properties for 6.5" thick inflated nylon material

Also, consideration needs to be taken as to the accuracy of the data. The specimen holder incorporates a rubber seal to make an air tight environment to hold in internal pressure. The rubber the seal is made from has properties of its own as it deforms. the idea was that this data could be removed from the measurements of previous tests to increase accuracy of the results.
Therefore a test was carried out to measure the shear modulus of the rubber seal in the specimen holder. An unpressurized test with no specimen inside was performed.

The figures presented below show the data from the test:

![Stress Vs Strain Curve: Rubber Seal Only](image1)

Figure 73: Stress vs. strain curve for rubber seal only

![Displacements Vs Applied Load: Rubber Seal Only](image2)

Figure 74: Displacements vs. applied load for rubber seal only
From the data, the shear modulus was determined using two approaches. The first used the cross-sectional area of the rubber seal itself while the second used the area as measured from the outside of the rubber (rubber plus internal volume). These results are displayed in the table below:

<table>
<thead>
<tr>
<th>Shear Modulus (Psi)</th>
<th>Rubber Only (its area)</th>
<th>Rubber Only (Full sample Area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120.91617</td>
<td>11.099727</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Rubber seal shear modulus

Due to the difficult nature of fabricating the seals, and a lack of funding and time for materials, tests were performed at low pressure to simply measure the elastic region. From the data, a slight but distinct variation in shear modulus can be seen between the directions tested. This again supports the conclusion that these materials are orthotropic in nature. In shear even at a low initial internal pressure, the specimens shows a strong resistance to deformation. A drop in pressure in the second test indicated that a leak had sprung in the process of adjusting the specimen in the holder. However the rapid nature of the test still caused a sufficient rise in pressure once enough deformation had occurred. As jumpy as the data was at times, the specimens demonstrated a very linear elastic nature with a fairly strait curve.

Also when testing the rubber seal only, most of the force seemed to occur at the beginning. It is at this point the rubber is working to overcome the static friction with the wall. Once moving, the deformation occurs quickly. This could be the reason for such a high shear modulus for the rubber. Once strained past a point the load experienced is constant.

From the testing it can be noted that the seal work very well to seal the specimen. However the friction of the rubber needs to be reduced either by greasing the walls or other methods. Also the rubber chosen was too soft and tore very easily when making adjustments and installing
specimens. A stronger rubber may be required but care should be taken to keep the resistance to deformation low.

6 Conclusion

In closing it can be noted that drop stitch fabric materials do exhibit variation in mechanical properties along both orthogonal planes. This leads to classifying them as orthotropic composite materials. However it should be noted that variation in measurements up to collapse for the rigid specimens and all other test data for inflated specimens was less than 2%. Therefore, it seems appropriate that for most calculations, the material could be treated as transversely isotropic and use an average value for material properties. However for the rigid materials, ultimate strength varied significantly with direction.

As far as testing, measuring tensile and shear modulus of flat inflatable drop stitch fabric material is a difficult task. The issue with holding tensile specimens can be overcome possibly with adhesive but a more temporary solution should be developed. To replicate the conditions of an inflated environment, great care needed to be taken in restricting the motion of the surrounding seal wall. The use of an interlocking finger style wall system greatly improved the freedom of movement vertically so that the drop stitch yards could deform under tension. This loading is very similar to how the material would perform in application. However the effort required to manufacture the system can be a considerable cost of time and effort for a single height of specimen. Efforts to improve the wall system in future studies should focus on modifying the design the reduce manufacturing complexity.
References


