K. L. Peil, E. J. Barbero and E. M. Sosa, Experimental Evaluation of Shear Strength of Woven Webbings, SAMPE 2012 Conference and Exhibition, Baltimore, May 21-24, 2012

EXPERIMENTAL EVALUATION OF SHEAR STRENGTH OF WOVEN WEBBINGS

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The development of Finite Element Models (FEM) of inflatable structures made from woven webbings used to seal conduits and large pipes with irregular shapes requires not only the typical material properties such as modulus of elasticity, axial strength, density, and Poisson's ratio, but also an estimation of the shear behavior to account for the drape-ability of the inflatable necessary to conform to the irregularities of the section to be sealed. Because the fibers in woven webbings are not continuous along the two principle directions, a priori it is not possible to calculate analytically the shear properties based on the fiber elastic modulus and Poisson’s ratio. Due to this limitation, mechanical testing is necessary to determine the shear behavior. An experimental methodology for determining the shear characteristics of woven webbings is proposed. Experimental methods are developed for testing the materials using the denominated "picture frame" designed to produce a shearing effect from an axial force. These frames allow the materials to be stressed biaxially prior to the shear testing to observe the shear performance under similar axial stress states, which will be seen in the material for specific applications. Testing yields load and displacement data, which can be used to determine the shear modulus as a function of the materials angular displacement.

The Department of Homeland Security, Science and Technology Directorate, Infrastructure Protection and Disaster Management Division provided funding support for this research.

1. INTRODUCTION

The shear characteristics of fabrics have been analyzed in a number of ways ranging from mathematical models, which predict the material behavior based on fiber geometry and friction coefficients, to mechanical testing, which directly measures a materials bulk resistance to shear deformation [1][2]. The shear mechanisms influence the draping and pliability of a fabric and determine the ability of the material to conform to a three dimensional surface [1]. The ability of a fabric to conform to a double-curvature surface depends mainly on the in-plane shear behavior [3]. Because the fibers within a webbing are not continuous and are not connected along any two principle directions, the materials cannot be considered isotropic or homogeneous. These types of micro-materials can also display non-linear and unpredictable behavior under multiple stress states. Because of this, a theoretical analysis can become very complex or impossible and experimental determination of the material behavior becomes necessary. The shear properties of webbings will be dependent on the biaxial state of stress, which the material will be under. The material must be tested in a manner where the tensile and shear forces can be applied simultaneously [4].

Material Selection

Two materials, nylon and Vectran®, HT, were used to categorize the shear behavior of the woven outer layer of the inflatable structure being analyzed in the FEM. The use of two materials was necessary due to the limited supply of Vectran available for testing. The nylon webbings that were used had the same width and thickness as Vectran and similar coefficients of friction. The principle difference between the two materials is the ultimate tensile strength. A table summarizing the key properties of the two materials is shown in Table 1. Because the mechanisms of shear are a function of weave pattern, friction coefficient, and pre-tensioning, and are roughly independent of the tensile strength of the individual fibers [1], conclusions on the shear characteristics of the outer layer of the inflatable structure could be drawn from tests run using both materials.

Table 1**:** Material properties of Nylon and Vectran HT webbings

	Width	Thickness	Coefficient of friction	Ultimate Tensile Strength	Weave pattern
Nylon	2 inches	0.1 inch	~0.5	7,000 lb	herringbone
Vectran	2 inches	0.1 inch	~0.5	24,000 lb	herringbone

Material Preparation

Twelve strips were initially cut from a bulk roll of material to be woven together to form a representative volume element (RVE) of a section of the inflatable structure being analyzed. The weave pattern used was a square weave. Strips were cut 27 inches in length to allow for attachment to the picture frame shear test stand and pre-tensioning pulley system. A smaller RVE could have been used to measure the shear behavior of the material under small angular displacements (0-20 degrees), however jamming of the fibers and wrinkling of the material, which occurred at large angular displacements (20-36 degrees), would not have been observable. Samples were prepared under dry conditions at ambient air temperatures.

Picture Frame Shear Test Stand Preparation

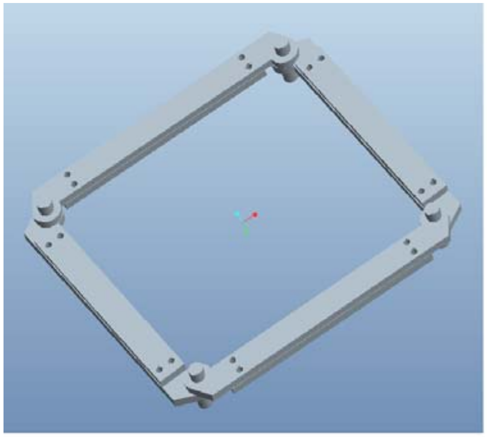

Figure 2**:** CAD image of picture frame shear test stand

A picture frame shear test stand was used to apply the shearing loads to the sample during testing. A computer-aided design (CAD) image of the frame that was built is shown in figure 2. The arms of the frame measured nineteen inches in length, two inches wide and one inch thick. The design of the frame allowed the material to be pre-tensioned along each principle direction prior to attachment, permitting the measurement of shear under a biaxial state of stress. While in the frame, the strips of material were held in place using a 'dead man' system, which uses the materials self friction to hold the bottom of each strip in the frame and a steel plate secured with bolts to hold the top of each strip. Because of the design of the frame, while the material was being sheared, the distance between any two co-linear connection points would remain equidistant. This allowed the biaxial stress state in the material to remain constant during testing. The frame was constructed using half-inch thick 304 stainless steel plate. The pivot bearings were made from smoothed, one-inch diameter, solid stainless-steel shafts cut four inches long. Between the steel arm plates were thin Vectran shims used to ensure uniform contact along the length of the frame.

2. EXPERIMENTATION

Material Pre-Tensioning

Pre-tensioning of the webbing strips began with attachment of the bottom of each strip to the shear test frame using a ‘dead man’ gripping method. Six strips of webbing material were laid side by side on top of the disassembled shear test frame, perpendicular to the length of the bottom arm with two inches of overhang. The overhang of each strip was then folded over top of a half-inch, plain carbon steel rod and held in place using four staples. Once all six webbings were folded over the rod, Vectran shims were laid across the length of the arm to assure even contact with the steel holding plate. The top of the shear test frame arm was then attached over the folded webbings.

The top of each webbing strip was then attached to a specially designed pre-tensioning pulley system. The pulley system was comprised of three two-inch diameter wheels spaced four inches apart from one another. The wheels were mounted on a set of steel plates, which allowed independent movement of each wheel relative to one another. Steel cables with attached mounting plates were then wrapped over the pulleys for attachment to the top end of each webbing strip. Due to the design of the pulley system and the method of attachment, when a tensile load was applied to the top arm of the system the load would be equally distributed to each webbing, resulting in a uniform stress across the width of the sample.

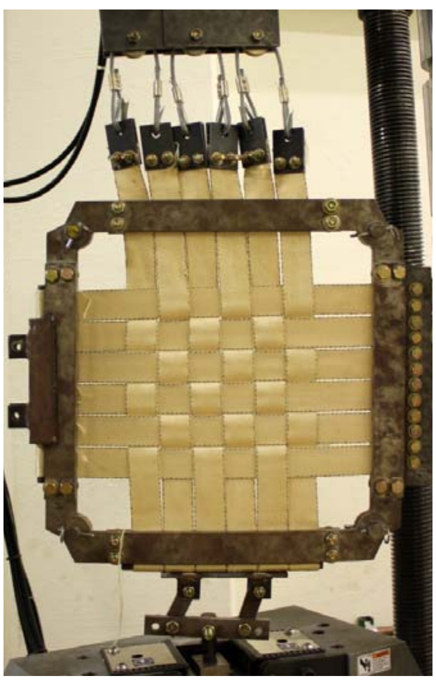

Figure 3: Vectran sample attached to pulley system and frame for pre-tensioning

To apply the required pre-tensioning load, the pulley system and shear test frame were connected to an Instron HDX1000 tensile test machine. Connections were made to the machine via two one-inch diameter steel shafts, which were attached to solid steel blocks held in place using the machines hydraulic wedge grips. The pulley system was initially lifted into place and secured to the top bolt. The bottom crosshead on the tensile test machine was then raised into position to attach to the bottom of the shear test frame. An image of the pulley system and shear test frame attached to the tensile test machine with Vectran webbings at the pre-tensioning stage can be seen in figure 3.After attachment to the tensile test machine, the system was tensioned to approximately 600 pounds per webbing and held at this load for 10 minutes to allow for stress relaxation within the system. A top holding plate was secured to the ends of the webbings using 12 bolts. Attachment of the holding plate required all components to be held tightly in place using four C-clamps and wedges.

Had the material not been held tightly in place, as the fibers were broken by the drill to produce bolt holes, they would have been pulled down within the frame resulting in a local loss of tension in the vicinity of each bolt. This would have resulted in premature wrinkling of the sample as well as an overall inaccuracy in the representation of the material layer that was to be modeled.

Once attachment had been completed, the shear test frame and pulley system were removed from the tensile test machine and the excess material connecting the shear test frame to the pulley system was cut. The procedure was repeated for the set of perpendicular webbings resulting in a representative volume element of the woven outer layer of the inflatable structure being held in place within the shear test frame under a uniform biaxial state of stress.

Shear Testing of the Prepared Sample

After sample preparation and detachment from the pulley system, the shear test frame was reattached to the tensile test machine from two pivot points on opposite corners of the frame. Using Instron's Partner® software, a program was written that would move the top bearing of the shear frame upward at a rate of 0.02 inches per second. The program recorded crosshead displacement, load on the frame, and time. The displacement of the top of the frame resulted in the material being deformed into a diamond shape, shearing the material as the frame was displaced. From the data collected, the nominal shear stress in the material and the angular displacement of the fibers could be calculated. Each sample was sheared five times to an angular displacement of approximately 36 degrees. Tests were stopped when large amounts of wrinkling were observed. An image of a sheared sample of nylon is shown in figure 4.

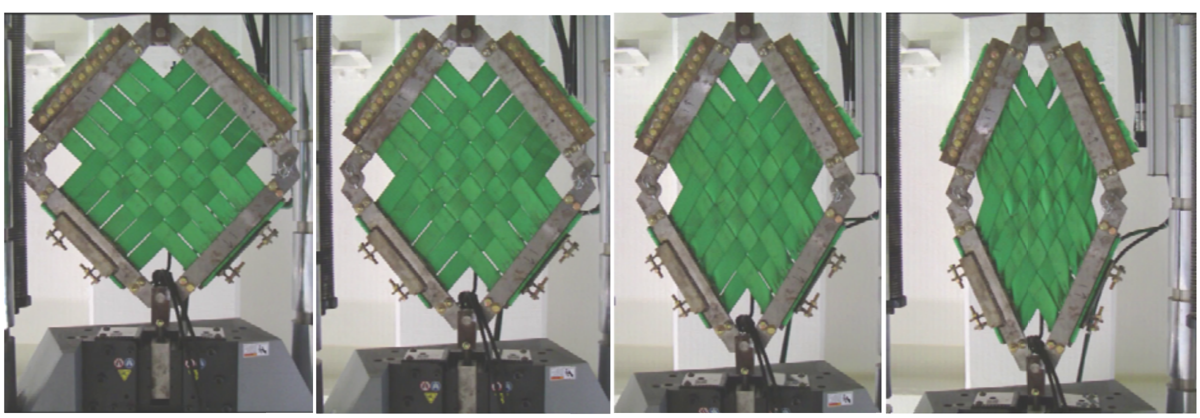

Figure 4: Images of Nylon sample under varying angles of shear deformation

3. RESULTS

Analysis of shear was done in a manner that would yield results usable within the FEM of the inflatable structure being investigated. The model was developed using Abaqus software, which requires an input plot of nominal shear stress versus fiber change in angle [5]. As such, this information was calculated and plotted based on the deformation of the frame and the required load to cause the deformation. After plotting the results from each test, the values were averaged to form a single representative plot of nominal shear stress versus fiber change in angle.

Each test had a slight difference in the amount of measured pre-load after sample attachment. This was due to fiber slippage caused by the holes that were drilled for attachment and tightening of the interface between the top steel holding plates and the top arm of the shear test frame. The recorded initial pre-loads and loads after attachment for each of the principle directions are supplied in table 2.

The experimental setup of the tests was seen to be a major factor in the accuracy of each trial. Sample placement within the frame must be exact to assure the material is sheared properly. All connections along the frame for securing the webbing materials must be made while minimizing any fiber slippage to maintain a uniform preload along the length of the sample. Material was monitored during testing to assure damage was not induced as a result of over deformation.

Table 2: Material Pre-load in the two principle directions

Sample	Initial Pre-load (direction 1)	Load after attachment (direction 1)	Load per webbing	Initial Pre-load (direction 2)	Load after attachment (direction 2)	Load per webbing
Sample 1 (Nylon)	4000 lb	2860 lb	477 lb	4000 lb	2780 lb	463 lb
Sample 2 (Nylon)	4000 lb	3180 lb	530 lb	4000 lb	3264 lb	544 lb
Sample 3 (Nylon)	4000 lb	3280 lb	547 lb	4000 lb	3411 lb	569 lb
Sample 4 (Nylon)	4000 lb	3500 lb	583 lb	4000 lb	3500 lb	583 lb
Sample 5 (Vectran)	4900 lb	4174 lb	696 lb	4900 lb	4500 lb	750 lb

The frame geometry, deflection, and data from each test were used to calculate webbing change in angle. Knowing that the initial distance between two opposite pivot points on the frame was 26.87 inches in the un-deformed (i.e., square) configuration and that the side length of each arm between each pivot point was 19 inches, equation 1 could be used to determine the change in angle of the webbings as a function of the crosshead displacement at any given time. Figure 5 shows a schematic of the information needed from the tests frame to perform the calculations.

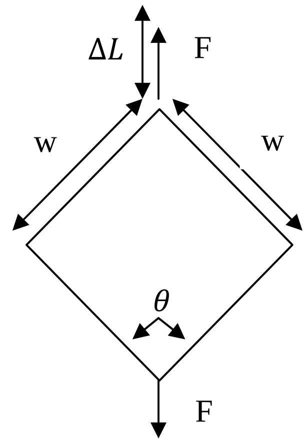

Figure 5: Schematic of picture frame shear test pertinent information

The nominal shear stress (T_{12}) in the material is calculated as a function of material thickness, width of the sample, applied load, and angular displacement. Nominal shear stress was calculated using equation 2.

Equation 1: $\theta = 90 - \left(2 * \cos^{-1}\left(\frac{26.87+\Delta L}{2*19}\right)\right)$

Equation 2: $T_{12} = \frac{F}{\left(2*t*w*\sin\left(\frac{\pi}{4}+\frac{\theta}{2}\right)\right)}$

Where ΔL is the displacement of the tensile test machine crosshead, *F* is the applied load to the frame as measured by the tensile test machine, *t* is the material thickness of .2 inch, *w* is the edge width of the sample (12 inches) and θ is the angular displacement of the webbings. Data produced by the tensile test machine were reduced using MATLAB, producing figure 6 showing the results from each trial.

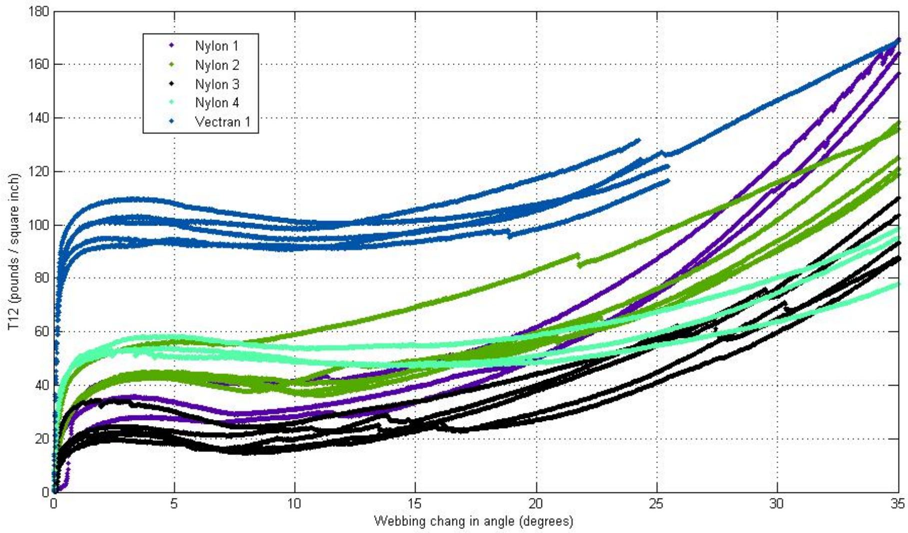

Figure 6: Complete results of each trial.

A more compact and easily understood plot was produced by taking the average of all trials for each test. Best fit curves were mathematically forced through the origin in accordance with experimental observations. A plot of the averages from each test can be seen in Figure 7.

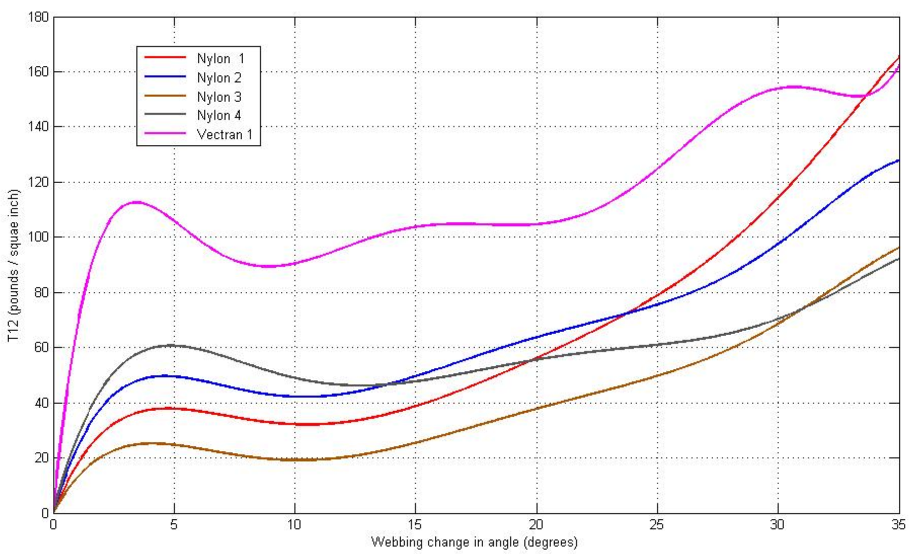

Figure 7: Averaged results for each test

From the above results, points can be chosen to represent key elements of the curve that define the shear behavior. For the FEA model, 12 points were used, each separated by three degrees. There are four shearing mechanisms that can be observed from the results. Under angular displacements between zero and 2.5 degrees, the deformation of the material is too small to overcome the friction between the strips of webbing. As such, the material acts as a rigid body and the slope representing the shear modulus is large. Between 2.5 and 20 degrees of angular displacement, there is yarn slippage at the intersection and elastic bending resulting in the flattening of the curve. At angles above 20 degrees, there is jamming and wrinkling within the material requiring larger shear stresses to produce the displacements. The final plot used to define the material shear behavior can be seen in figure 8.

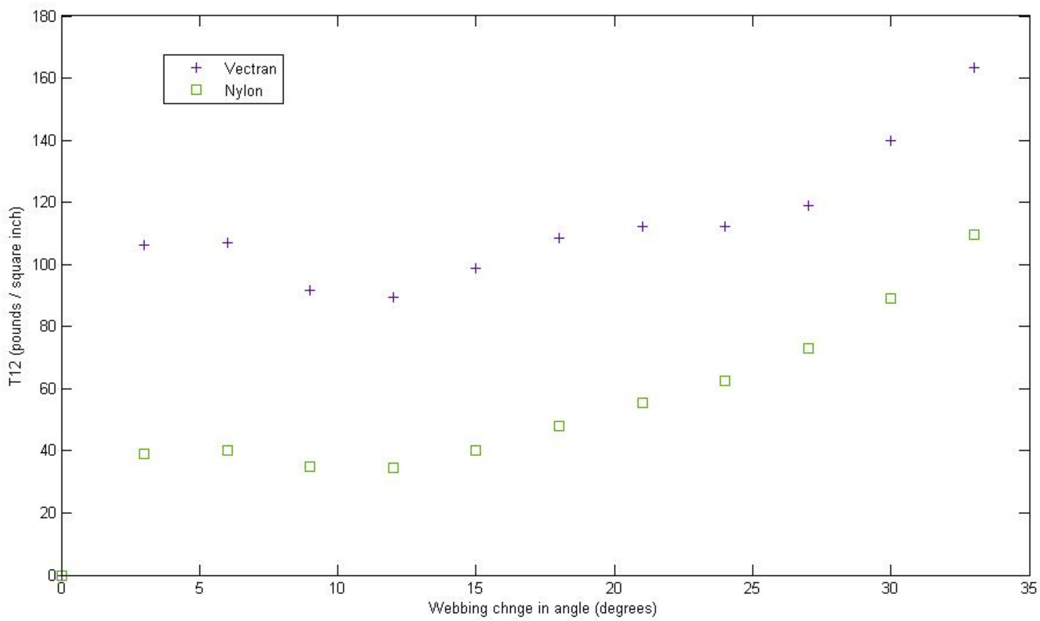

Figure 8: Data points defining the material shear behavior for Vectran® and Nylon

The tests showed a large amount of variability between samples, speculatively due to the differences in pre-load between tests. Fiber micro-mechanic behavior was an additional source of variability, due to the differences in tension across the width of the sample caused by fiber slippage during sample attachment.

Future work will be done to visually map the individual changes in webbing angle using digital image correlation, which will then be compared with equation 1 to determine the accuracy of the assumption that the webbing change in angle is equal to that of the frame. As shear deformation angle increases and jamming of the material occurs, angular displacements of the webbings in the vicinity of the intersection points were seen to be larger than that of the bulk of the surface. These intersections will require further study and evaluation to determine the stress state at these points.

4. CONCLUSIONS

The use of a picture frame shear test stand was seen as a viable method for evaluating the shear characteristics of a woven material. The ability to pre-tension a fabric sample prior to shear testing is required due to the nature of the fiber interactions as the sample is displaced. Experimental measurement of the shear performance of fabrics is required as no method for accurately calculating the behavior is available. Tests must be performed under the same state of biaxial stress, which will be seen by the material when in use. Friction between fibers was seen to be the primary mechanism for shear resistance. Evaluation of the results indicates that the outer layer of the inflatable structure will show little resistance to shear deformation as is required for the structure to conform to irregularities within the conduits it will be housed within.

5. REFERENCES

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