Reprinted from TEXTILE RESEARCH JOURNAL, Vol. 51, No. 2, February 1981
Printed in U. S. A.

Triaxial Woven Fabrics

Part I: Behavior Under Tensile, Shear, and Burst Deformation

FRANK L. SCARDINO AND FRANK K. KO

Philadelphia College of Textiles and Science, Philadelphia, Pennsylvania 19144, U.S.A.

ABSTRACT

This paper describes some of the unique properties and performance characteristics of triaxial woven fabrics. With three systems of yarn interlacing at sixty-degree angles with one another, triaxial woven fabrics provide less of an anistotropic behavior and offer an alternative to the inherent structural weaknesses of biaxial woven fabrics. It is shown that triaxial woven fabrics exhibit a relatively higher and more uniform resistance to extension, shear deformation, and burst deformation than comparable biaxial woven fabrics.

Introduction

The fundamental principles of triaxial woven fabric technology were first reported in 1970 by Norris F. Dow, inventor of triaxial fabric structures and of the triaxial weaving machine [2]. A review of the general properties and structural characteristics of triaxial woven fabrics was presented by John Skelton the following year [3]. More recently, a paper dealing specifically with the advantages of using triaxial fabrics in inflatable structures and related applications was presented by Gene Alexandroff [1]. Although triaxial weaving technology has been around for several years, the unique properties and performance characteristics of triaxial fabric structures are not widely understood.

Most woven fabrics are biaxial structures wherein two systems of yarn intersect and interlace at right angles with one another. It is well known that biaxial fabrics exhibit a relatively low modulus or low resistance to extension when deformed on the bias (45° to warp and filling) as compared with deformation in the warp or filling directions. Also, it is established that biaxial fabrics exhibit very little resistance to shear in the warp and filling directions as compared with shear deformation on the bias.

Triaxial woven fabrics are composed of three systems of yarn, which intersect and interlace at sixty-degree angles with one another. With three systems of yarn, triaxial structures provide for a more uniform distribution of load during fabric deformation. Consequently, triaxial fabrics do not contain

0040-5175/81/0200-0080$01.00/0

extremely weak directions in tensile and shear deformations similar to those found in biaxial woven fabrics. Also, during ball-burst deformation, triaxial woven fabrics exhibit a much more uniform isometric strain. With only two systems of yarn, biaxial fabrics are considerably more anisotropic in all mechanical properties than triaxial fabric structures.

The performance and durability of most textile products are a function of minimum, not maximum, resistances to deformation. By eliminating weak directions and extremely low resistances to deformation in fabrics, the performance and lifetime of many industrial products would be substantially improved. The purpose of this paper is to demonstrate that when tested under realistic conditions, triaxial woven fabrics exhibit a relatively higher and more uniform resistance to extension, shear, and burst deformation than comparable biaxial woven fabrics.

Tensile Deformation

To characterize and compare the tensile behavior of biaxial and triaxial woven structures, several fabric strips were cut at successive angular increments to the filling direction. Plain-weave fabric composed of 22-mg/m (200-denier) polyester filament yarn was selected for comparison with triaxial biplain woven fabric composed of 22-mg/m (210-denier) twisted polyester filament yarn. A description of the fabric samples is given in Table I. Both fabrics were heat-set under commercial operating conditions.

TABLE I. Description of plain-weave and triaxial biplain polyester fabric samples.

Properties	Plain weave	Triaxial biplain
Areal density, g/m²	107.83	150.22
(oz/sq. yd)	(3.18)	(4.43)
Texture		
ends per meter	1988	1732R, 1732L
(ends per inch)	(50.5)	(44R, 44L)
picks per meter	2008	1881
(picks per inch)	(51)	(46)
Thread density		
yarns/m²	1.57×10^5	2.08×10^5
(yarns/in²)	(101.5)	(134)
Fabric thickness,[a] m	19	25
(mil)	(0.8)	(1.0)
Air permeability,[b] m³/s/m²	.38	.54
(ft³/min/ft²)	(74)	(107)

[a]Tested on a Randall and Stickney device according to ASTM D1777; 1 1/8 in. presser foot diameter, 0.1 psi or 7 g/m².
[b]Cubic meter per second per square meter of fabric for a pressure drop of 12.7 mm.

Traditionally, the tensile properties of woven fabrics have been characterized by the deformation of narrow fabric strips cut in the warp and filling directions. Tensile deformations on fabric strips cut in directions other than the warp and filling lead to anomolous results, because very few, if any, yarns, are gripped by both jaws during testing. Consequently, massive yarn slippage, closing of the trellis configuration at yarn intersections, Poisson contractional edge effects, and rip-slippage deformation all combine to yield results that are entirely unlike those exhibited in real-use situations. To avoid some of these problems while deforming strips cut at angles to the warp and filling, a special specimen-folding technique was developed. The original geometry and the folded configuration of the specimen is illustrated in Figure 1. The main objective of the folding technique is to effectively tense a large proportion of the free-yarn segments not held by both grips in order to prevent slippage and to insure a more uniform loading during initial extension. It is thought that this technique is a compromise between strip tests, which provide a well-defined area of stress concentration, and grab tests, which avoid the edge effects.

Fabric specimens were selected with the long dimension parallel to the following orientation in the samples: 0°, 15°, 30°, 45°, 60°, 75°, and 90° with respect to the filling direction. The specimens were folded to a 5-cm width and mounted in 5×5-cm vise grips at a gage of 16 cm for testing on a constant-rate-of-extension (CRE) machine. A cross-head speed of 4 cm/min was selected to insure a well-defined curve during initial extension of the specimens. To characterize the resistance of the fabric specimens during early stages of deformation, the load was read from the force-extension curves at the 3%, 6% and 9% levels of elongation.

Results of this characterization technique are given in Table II. The same results were also interpolated with cubic spline functions, as shown in Figures 2 and 3. It is pointed out that, in general, the triaxial fabric sample exhibits a substantially greater initial resistance to extension.

To show the angular dependence of the ability of the fabrics to resist tensile deformation more clearly, the specific moduli of the fabrics were plotted in Figures 4, 5, and 6 as functions of the test direction of the fabric with respect to the filling yarn. It is obvious that the plain-weave fabric has the lowest resistance to deformation in the bias direction (45° to filling) at all three levels of extension. In the triaxial fabric, the machine direction (90° to filling) shows the lowest resistance to deformation at all three levels of exten-

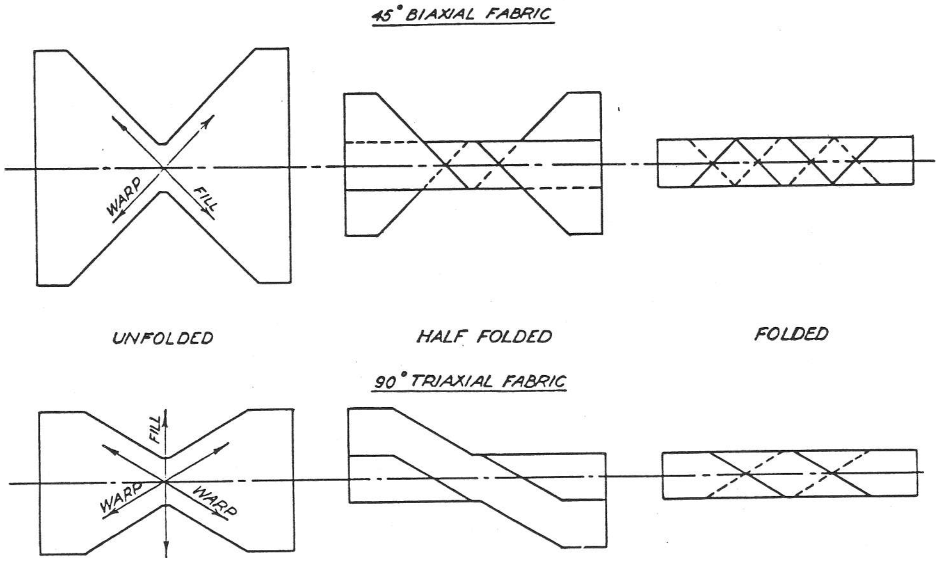

FIG. 1. Original geometry and folded configuration of fabric specimens for tensile deformation.

TABLE II. Load at various elongations of the plain-weave and triaxial biplain fabric strip samples.

Direction of extension with respect to filling	Plain-weave load (kg) at			Triaxial biplain load (kg) at		
	3%	6%	9%	3%	6%	9%
0°	14	30	41	29	49	68
15°	13	27	33	15	31	43
30°	2	4	8	5	12	33
45°	0.8	1.2	1.8	30	41	50
60°	5	9	15	50	82	101
75°	28	42	50	32	51	63
90°	30	45	60	2	3	5

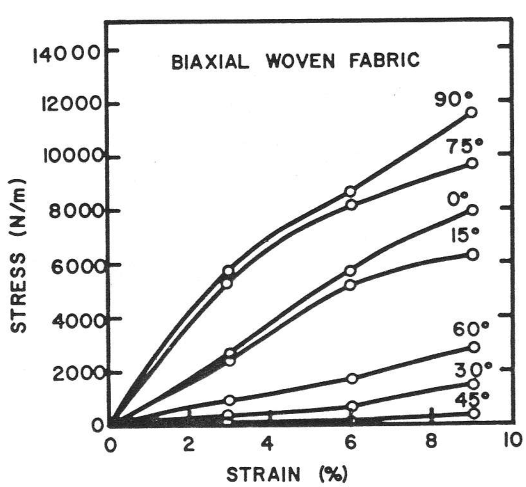

FIG. 2. Stress-strain curves of biaxial woven fabrics tested at various orientations with respect to the filling.

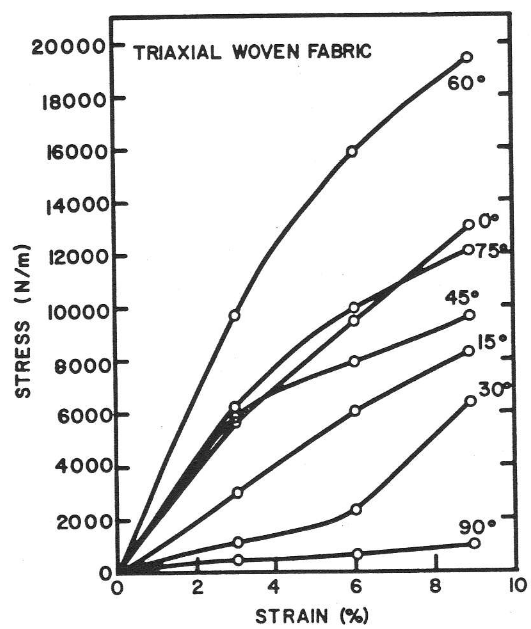

FIG. 3. Stress-strain curves of triaxial woven fabrics tested at various orientations with respect to the filling.

sion. Even though both biaxial and triaxial fabrics have a weak direction under tensile loading, one should note that the magnitude of the modulus at the weak direction for the triaxial fabric is approximately two to three times greater than that of the biaxial fabrics.

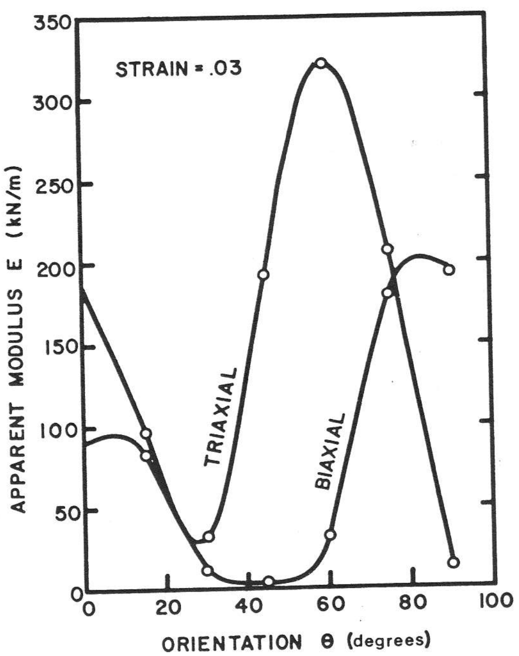

FIG. 4. Effect of test direction on the tensile modulus of triaxial and biaxial fabrics; $\epsilon = .03$.

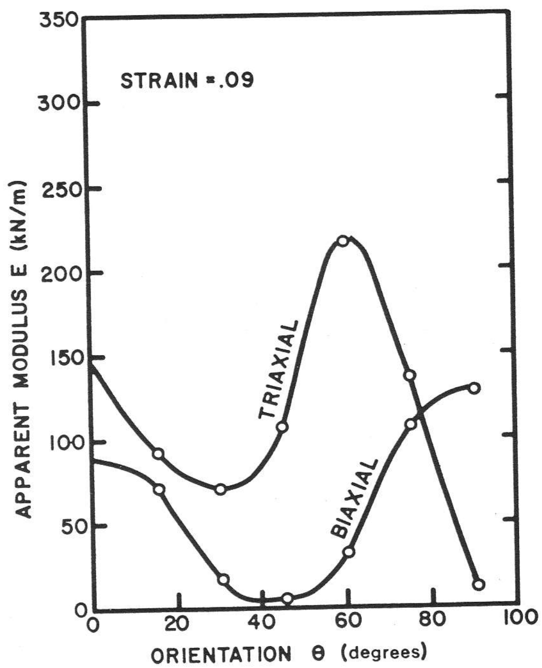

FIG. 6. Effect of test direction on the tensile modulus of triaxial and biaxial fabrics; $\epsilon = .09$.

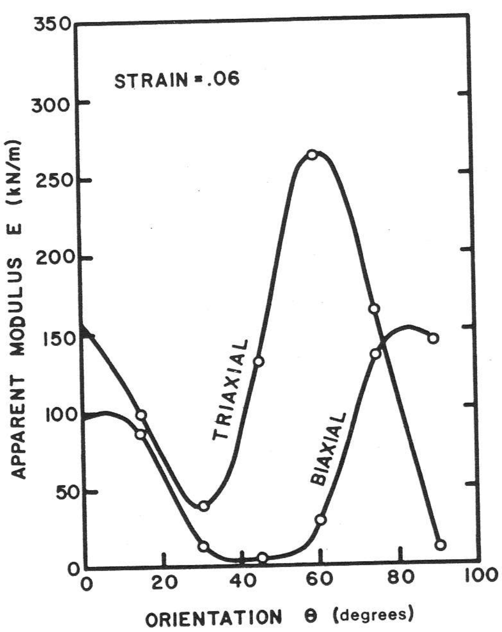

FIG. 5. Effect of test direction on the tensile modulus of triaxial and biaxial fabrics; $\epsilon = .06$.

The ratio of minimum tensile resistance of triaxial fabric to minimum tensile resistance of plain-weave fabric at three selected elongations is shown in Table III. The minimum tensile resistance values are expressed in kN·m/kg of fabric in order to normalize differences in areal density between samples. It can be seen that the ratio of triaxial minimum tensile resistance to biaxial minimum tensile resistance is 2:1, approximately.

TABLE III. Ratio of minimum tensile resistance of triaxial to minimum tensile resistance of plain-weave in polyester fabric samples.[a]

Elongation, %	Minimum tensile resistance[b], kN · m/kg × 10^{-3}		Ratio triaxial
	Triaxial	Plain-weave	Plain-weave
3	150.0	83.4	1.8
6	225.5	125.5	1.8
9	375.6	188.3	2.0

[a]Based on data from Table II normalized for differences in areal density.
[b]kN · m/kg = mN/areal density (g/m^2) × specimen width (mm).

Shear Deformation Under Normal Loads

Narrow fabric strips cut at successive angular increments to the filling direction can also be used to characterize shear behavior under various conditions of normal loading. Such shear tests were made on biaxial plain-weave and triaxial basic-weave fabrics composed of 133-mg/m Beta Fiberglas[1] twisted-filament yarns. A description of the fabric samples is given in Table IV. It can be seen from the values that the samples are quite similar in several fabric geometric parameters.

TABLE IV. Description of plain weave and triaxial basic-weave fabric samples composed of 1200 denier beta fiberglas twisted-filament yarn.

Properties	Plain weave	Triaxial basic
Areal density, g/m^2	281.5	284.8
(oz/yd^2)	(8.3)	(8.4)
Texture		
ends per meter	945	630R, 630L
(ends per inch)	(24)	(16R, 16L)
picks per meter	945	630
(picks per inch)	(24)	(16)
Thread density		
yarns/m^2	7.44×10^5	7.44×10^5
(yarns/in^2)	(48)	(48)
Fabric thickness,[a] μm	521	645
(mil)	(17.6)	(20.6)
Air permeability,[b] m^3/s/m^2	2.39	2.42
(ft^3/min/ft^2)	(470)	(477)

[a]Tested on a Randall and Stickney device according to ASTM D1777; 1 1/8 in. presser foot diameter, 0.1 psi or 7 g/m^2.
[b]Cubic meter per second per square meter of fabric for a pressure drop of 12.7 mm.

The device used for shear tests is a duplicate of the one developed by Spivak and Treloar at The University of Manchester Institute of Science and Technology. The duplicate was made at The Textile Research Institute and is adaptable to any CRE tester with cyclic-extension capability. A description of the shear device and a method of interpretation of related shear test data have been published by Spivak [4].

It had been shown by Spivak and Treloar that a long, narrow specimen is much less sensitive to normal stress than a square specimen of fabric during shear tests and, consequently, contained less "experimental error." Accordingly, all specimens were cut to allow for a 10:1 ratio of length to width during testing, the longer dimension being parallel to the clamps. The effective area of the fabric specimen between clamps was 40 square centimeters (20 cm × 2 cm). A specimen was selected with the longer dimension parallel to each of the following directions: 0°, 15°, 30°, 45°, 60°, 75° and 90° with respect to the filling.

[1]Trademark of Owens-Corning Fiberglas Co.

The specimens were mounted and tested under the following conditions: 70°F, 65% RH: cross head speed of 1 cm/min; and, a constant cyclic extension to 0.3 cm and return to origin for three complete cycles. The 0.3-cm extension represents a maximum shear angle θ of 8°30′. Each specimen was subjected to increased normal loads W in successive tests, as follows: 100g, 200g, 400g, 800g, 1600g. The greater normal loads tend to reduce fabric buckling experienced with most specimens sheared.

The shear curves obtained during testing are of total force F *vs.* tan θ. To obtain the force due to shear resistance F_s, one must subtract $W \tan\theta$ (the force on the fabric due to normal load) from F. According to Skelton [2], the shear resistance (or specific shear stress) R of a fabric can be expressed in terms of a shear couple per unit area

$$R = (F - W \tan\theta)/L,$$

where L is the length of the fabric specimen. The fabric shear stiffness S, the shear couple per unit area required to produce unit angular deformation, is

$$S = (F - W \tan\theta)/L\theta \quad .$$

Results of the shear tests are listed in Table V. Shear resistance in N/m is listed for each specimen at $\tan\theta = 0.05$, 0.1, and 0.15 (corresponding to 0.1-cm extension divided by specimen width of 2 cm, 0.2 cm ÷ 2 cm, and 0.3 cm ÷ 2 cm, respectively).

The resistance of the fabrics to shear deformation was expressed in terms of the shear stiffness S, thus $S = \tau/\gamma$ ($\gamma \simeq \tan\theta$). In Figures 7 to 12, the shear stiffness was plotted as functions of the test direction with respect to the filling yarn for various strain levels under different normal stresses. As expected, the plain-weave specimens yield very little resistance when sheared in the filling (0° to filling) or warp (90° to filling) directions.

In general, the shear stiffness for both biaxial and triaxial fabrics depends on test direction, strain level, and normal stress. Shear stiffness tends to increase as normal stress increases for both triaxial and biaxial fabrics. The most significant distinction between biaxial and triaxial fabrics is their dependence on the test direction. The plain-weave fabrics have little resistance to shear deformation when sheared in the filling (0° to filling) or warp (90° to filling) directions. At test directions between 40 to 60° with respect to the filling, the shear stiffness of the biaxial fabrics reaches a maximum. The resistance of shear deformation or shear stiffness of the triaxial fabrics is relatively insensitive to the direction of shear.

The minimum shear resistances of the triaxial and

TABLE V. Shear resistance (N/m) of plain-weave and triaxial beta fiberglas samples at various orientations, normal stresses, and deformations.

Orientation of clamps	Normal stress, (N/m)	Plain-weave Deformation at tan θ = 0.05	0.10	0.15	Triaxial Deformation at tan θ = 0.05	0.10	0.15
0° to Filling	5	1.2	1.8	2.5	14.2	16.0	17.8
	10	1.2	1.8	2.5	16.0	21.0	24.0
	20	1.2	1.8	2.0	19.5	27.2	30.5
	40	0.8	1.0	1.5	23.5	36.2	41.2
	80	0.5	0.5	0.2	33.0	53.5	60.5
15° to Filling	5	6.8	7.0	7.0	14.0	18.0	20.2
	10	8.0	9.0	9.5	16.0	23.0	27.5
	20	9.5	10.7	11.8	19.0	30.5	36.5
	40	12.2	14.0	15.0	20.0	42.0	55.5
	80	16.5	20.2	21.5	23.5	52.0	87.0
30° to Filling	5	22.8	23.8	24.2	14.8	19.5	22.2
	10	24.5	26.5	28.0	14.5	23.0	29.8
	20	30.2	33.2	35.5	15.8	28.0	40.2
	40	41.5	47.2	49.8	16.2	32.0	58.5
	80	51.5	68.5	72.0	24.5	53.2	118.0
45° to Filling	5	29.8	29.5	29.8	19.2	21.5	23.2
	10	31.5	35.5	38.5	19.0	27.8	32.0
	20	32.0	46.0	50.2	24.0	38.0	44.5
	40	35.0	64.5	70.0	27.0	52.0	65.5
	80	26.0	89.5	110.5	32.5	68.2	108.0
60° to Filling	5	35.0	39.5	41.2	15.8	17.5	19.0
	10	31.5	47.0	55.8	16.5	21.0	24.0
	20	37.5	66.0	80.5	21.0	26.5	30.0
	40	29.2	76.0	113.0	26.0	35.2	39.2
	80	19.8	87.0	169.2	36.0	52.0	58.5
75° to Filling	5	21.8	35.2	45.2	15.8	19.0	22.2
	10	12.5	33.0	54.0	16.5	22.2	27.5
	20	14.0	36.0	71.0	18.0	24.0	30.5
	40	18.0	40.0	74.0	23.0	30.5	37.2
	80	11.0	37.0	86.8	26.5	36.0	43.8
90° to Filling	5	1.2	1.5	2.2	16.2	21.5	26.5
	10	1.0	1.5	2.0	13.5	21.0	31.0
	20	1.0	1.5	2.0	13.5	22.5	37.0
	40	1.0	1.0	1.5	14.0	23.5	43.5
	80	0.5	0.5	0.2	15.0	26.5	52.5

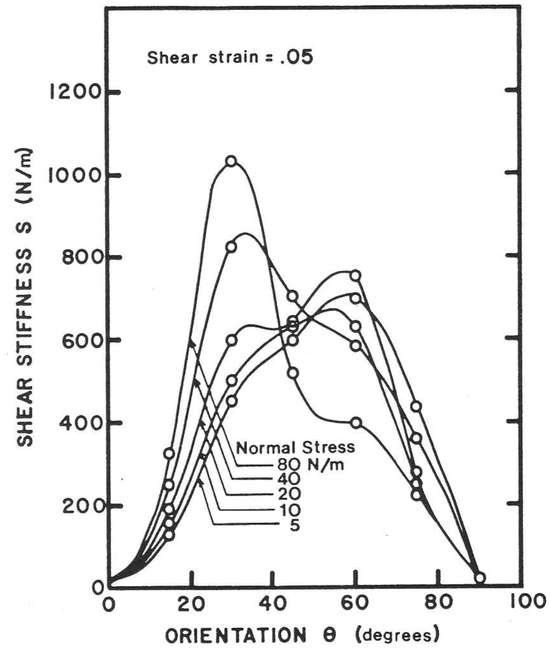

FIG. 7. Effect of test direction on shear stiffness of biaxial fabrics at various normal stresses; γ = .05.

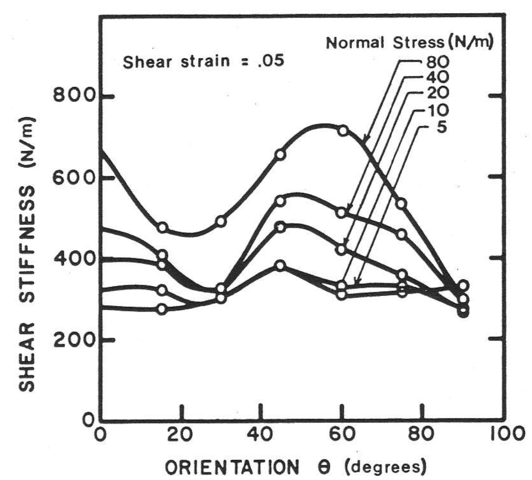

FIG. 8. Effect of test direction on shear stiffness of triaxial fabrics at various normal stresses; γ = .05.

of the plain-weave samples for each level of normal stress and for each level of shear deformation reported in Table V have been relisted in Table VI in order to show the ratio of minimum shear resistance of triaxial to plain-weave. It can be seen in Table VI that the minimum shear resistances (N/m) in triaxial fabric are at least an order of magnitude greater than those in the comparable biaxial fabric. Also, as illustrated in Figure 13, it can be seen that the ratio of minimum shear resistance of triaxial to plain-weave increases with increasing normal stress. These trends indicate quite clearly that triaxial fabric structures do not have the extremely weak directions or low resistance during shear deformation exhibited in biaxial woven fabrics, and that the shear resistance in triaxial fabrics increases as the tension in the plane of the fabric increases.

Shear Deformation Under Biaxial Loads

The relevance of test results obtained under conditions of uniaxial deformation has been questioned for many years. It is widely accepted that tests under conditions of biaxial deformation are much more

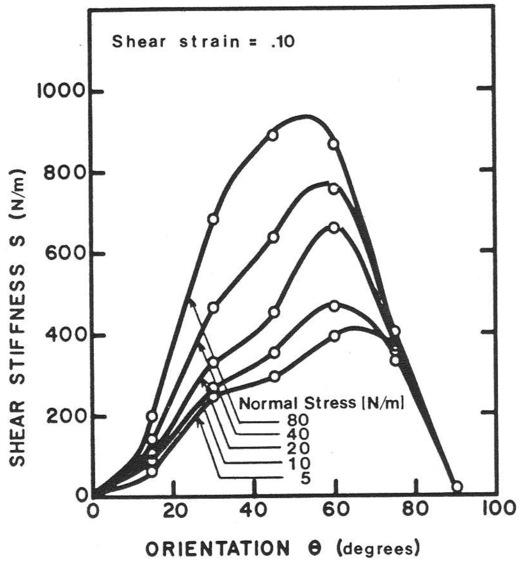

FIG. 9. Effect of test direction on the shear stiffness of biaxial fabrics at various normal stresses; $\gamma = .10$.

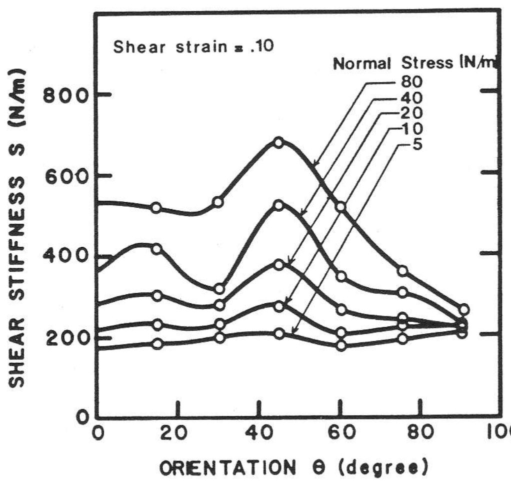

FIG. 10. Effect of test direction on the shear stiffness of triaxial fabrics at various normal stresses; $\gamma = .10$.

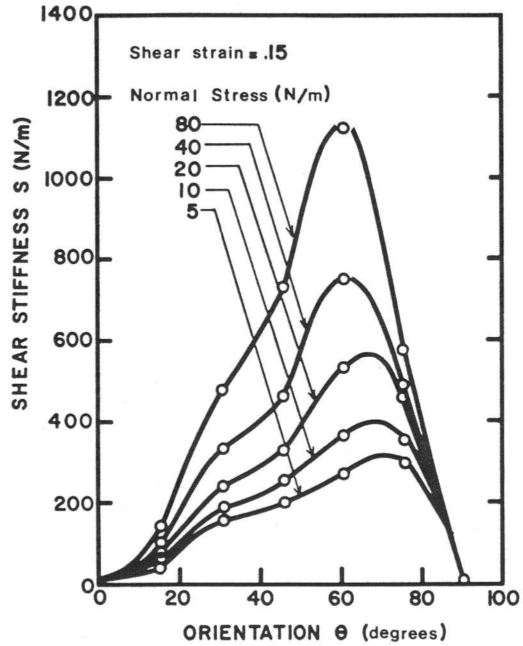

FIG. 11. Effect of test direction on the shear stiffness of biaxial fabrics at various normal stresses; $\gamma = .15$.

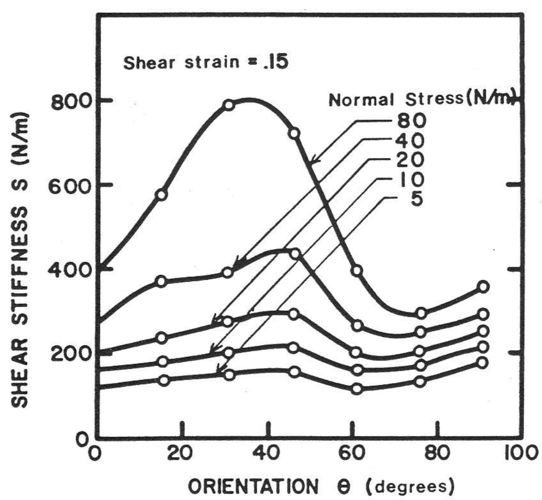

FIG. 12. Effect of test direction on the stiffness of triaxial fabrics at various normal stresses; $\gamma = .15$.

representative of the conditions to which fabrics are normally subjected in actual use. However, because of the lack of practical equipment and of standard procedures for biaxial testing, most fabric specifications and evaluations have been based upon uniaxial deformation techniques.

Fortunately, a device is available for conducting fabric shear tests under conditions of biaxial loading. The device, known as the Automate/Yendell, was developed a few years ago as part of a sail research program at the University of Southampton [5]. A cruciform specimen is mounted biaxially in four sets of grips which bound a 10 × 10-cm fabric panel, as illustrated in Figure 14. Biaxial loading is applied through a simple system of levers and hand-operated screw jacks. The magnitude of the load is measured by spring balances through which the screw jacks act. The corresponding fabric extensions are indicated by micrometer dial gauges. With the text panel biaxially loaded, a shear load can be applied by means of a

TABLE VI. Ratio of minimum shear resistance of triaxial to minimum shear resistance of plain-weave in beta fiberglas samples.[a]

Normal stress, N/m	Shear deformation, tan θ	Minimum shear resistance, N/m		Ratio Triaxial / Plain-weave
		Triaxial	Plain-weave	
5	0.05	14.2	1.2	12
5	0.10	16	1.5	10
5	0.15	17.8	2.2	8
10	0.05	13.5	1	13.5
10	0.10	21	1.5	14
10	0.15	24	2	12
20	0.05	13.5	1	13.5
20	0.10	22.5	1.5	15
20	0.15	30	2	15
40	0.05	14	0.8	17.5
40	0.10	23.5	1	23.5
40	0.15	37.2	1.5	24.8
80	0.05	15	0.5	30
80	0.10	26.5	0.5	53
80	0.15	43.8	0.2	219

[a]Based on data from Table V.

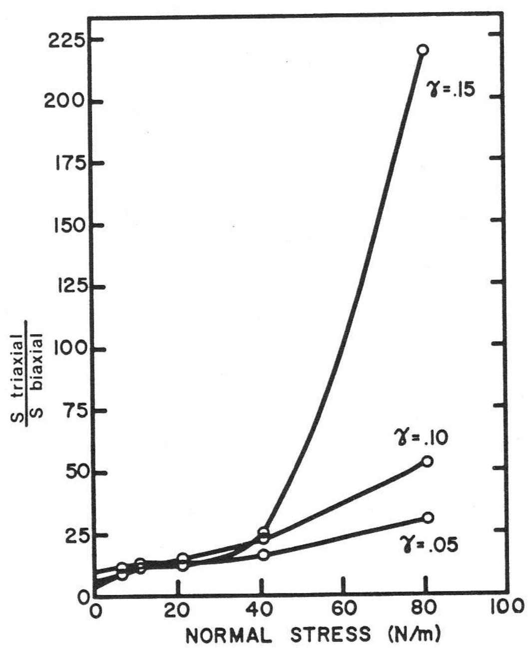

FIG. 13. Effect of normal stress on the ratio of minimum resistance in triaxial fabrics to minimum resistance in plain-weave fabrics for various shear strain levels.

weigh-beam arrangement in which a weight is moved along a pivoted lever. The resulting distortion is measured by a simple pointer and scale.

Shear tests were performed on an Automate/Yendell device for a 5-harness satin and a triaxial double basic woven from a 93-mg/m (840 denier) nylon twisted-filament yarn. A description of the fabric samples is given in Table VII. As indicated by the geometric parameters listed, the samples are comparable in structure.

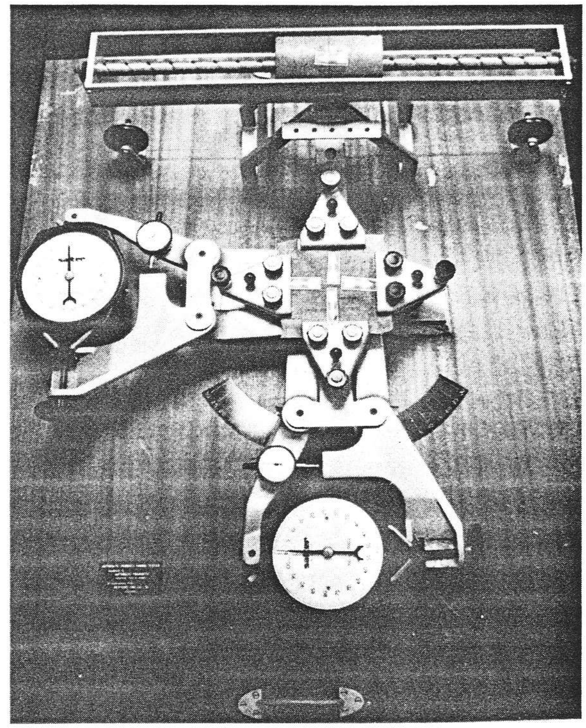

FIG. 14. Photograph of Automate/Yendell fabric testing machine.

TABLE VII. Description of biaxial and triaxial fabric samples woven from 840-denier nylon yarn.

Properties	5-Harness satin	Triaxial double basic
Areal density, g/m^2	406.9	406.9
(oz/yd^2)	(12)	(12)
Texture		
ends per meter	1890	1260R, 1260L
(ends per inch)	(48)	(32R, 32L)
picks per meter	1811	1260
(picks per inch)	(46)	(32)
Thread density		
yarns per sq. meter	1.46×10^5	1.49×10^5
(yarns per sq. inch)	94	96
Fabric thickness,[a] μm	1050	1550
(mil)	(36.2)	(54.2)
Air permeability,[b] m^3/s/m^2	.49	.29
(ft^3/min/ft^2)	(97)	(57)

[a]Tested on a Randall and Stickney device according to ASTM D1777; 1 1/8 in. presser foot diameter, 0.1 psi or 7 g/m^2.
[b]Cubic meter per second per square meter of fabric for a pressure drop of 12.7 mm.

Fabric specimens were mounted so that two opposite sets of grips were parallel to the warp direction and the other sets of grips were parallel to the filling direction. The specimens were biaxially loaded simultaneously, and the shearing load was applied parallel to the filling direction (normal to the warp yarns). This was the direction of minimum shear resistance in the samples tested. Shear deformation was measured in degrees for various combinations of shear loads and biaxial loads. Results of the tests are shown in Figure 15. It can be seen that the triaxial fabric exhibits a shear stiffness which is an order of magnitude greater than that found in the biaxial fabric. Also, it is quite clear that, with increasing biaxial load, shear deformation increases in the biaxial fabric but decreases in the triaxial fabric. Both of these factors indicate the superior behavior of triaxial fabric structures when combinations of high shear and tensile resistance are desired in applications such as sails and lighter-than-air structures.

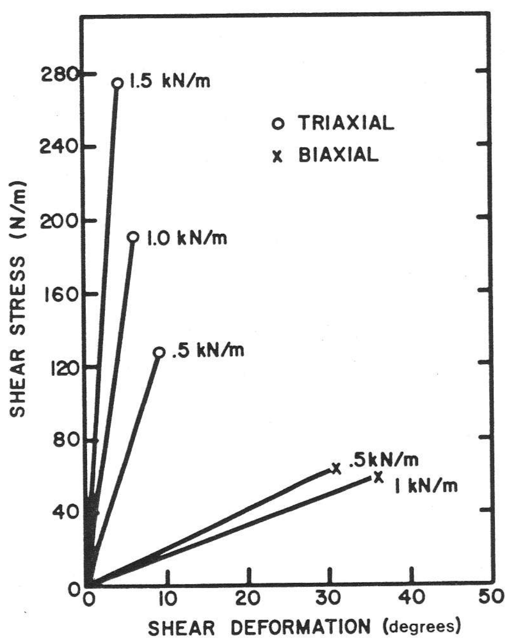

FIG. 15. Shear stress-strain curves for triaxial and biaxial nylon fabrics under various conditions of biaxial stress.

Burst Deformation

A series of ball-burst tests were made on the plain-weave and triaxial fabric samples described in Table IV according to the ASTM Standard D231-62, Standard Method of Testing and Tolerances for Knit Goods. Specifically, D231-62 requires that all specimens be cut no less than a half inch (13 mm) greater than the outside diameter of the ring-clamp mechanism of the testing apparatus. Also, a constant rate of extension tester is specified.

All burst deformations were made on a Thwing-Albert Electronic Tensile Tester at a cross head speed of 5 cpm with the regular Thwing-Albert ball-burst mechanism and ring clamps. As expected, no appreciable differences in bursting-force values were recorded, because the plain-weave and triaxial woven samples were similar in construction (same fabric weight, yarn content, number of yarns per square inch, etc.). However, an outstanding difference was noticed in the visual inspection of the burst-deformed specimens, as indicated in Figure 16.

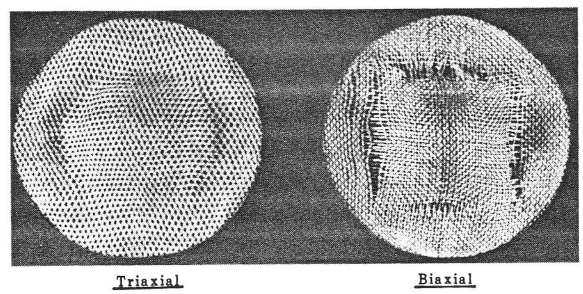

FIG. 16. Triaxial and plain-weave fabric specimens partially deformed (50% of maximum force) in ball-burst test at same displacement of ball into fabric plane.

In general, the plain-weave fabrics show considerable distortion as a result of severe localized slippage of yarns in the warp and filling directions. While the triaxial fabrics also show permanent 3-dimensional deformation, the strain is apparently distributed more uniformly throughout the fabric plane. These results suggest that triaxial woven fabrics would also be more adaptable to 3-dimensional draw molding than biaxial fabrics made from the same yarn.

Discussion of Results

It has been demonstrated that, with three systems of yarn interlacing at 60° angles with one another, triaxial fabrics provide a greater degree of isotropy in mechanical properties than comparable biaxial fabrics. In tensile deformation and in shear deformation under normal and biaxial loading, triaxial fabrics do not exhibit as low a directional minimum resistance as that commonly found in biaxial fabrics. In general, under burst-deformation, triaxial fabrics are strained more uniformly than biaxial structures because loads are distributed more evenly throughout the plane of the fabric.

It was shown in biaxial fabric deformation that minimum resistance to shear decreases with an increase in biaxial stress or tension. Conversely, it was shown in triaxial fabric deformation that the minimum resistance to shear increases with an increase in biaxial stress. The implication is that triaxial fabrics become more resistant to shear deformation as fabric tension increases. Accordingly, triaxial structures should provide superior performance in applications wherein fabrics are loaded in all or several directions, rather than uniaxially, during product use.

It cannot be concluded, however, that triaxial woven fabrics are isotropic in behavior. Although triaxial fabrics are less anisotropic than biaxial wovens or than any other commercial fabric made from yarn (weft knits, warp knits, weft-inserted warp knits, etc.), much anisotropy is evident in the triaxial samples examined. The degree of anisotropy in triaxial woven fabrics is a function of the geometry of yarn interlacing, the interactions between the weaving process and the yarn systems, and the finishing of the fabric after weaving.

The primary forces on the warp yarns during weaving of triaxial fabrics include cyclic tension, compression, bending, shear, and torsion. Hard-twisted warp yarns can cause considerable buckling and distortion in the greige fabric, as indicated by the height of yarn crowns at points of interlacing, looping out of a yarn system when bending or folding in certain directions, etc. Slightly twisted or untwisted filament warp yarns are more compatible and cause much less distortion at points of interlacing. Textured filament yarns are the most conforming and cause the least amount of buckling or distortion in the bending and folding of triaxial woven fabric.

The yarn crimp geometry is usually much less in the filling direction than in either of the warp directions. Also, the yarn crimp geometry tends to be different in the left-hand and right-hand warps, depending on the pattern of interlacing, yarn twist and direction, and other constructional factors. The direction of rotation of the warp systems relative to the direction of twist in the warp yarns appears to be a contributing factor to variable crimp geometry and fabric anisotropy.

Finishing of triaxial woven fabrics can have a substantial effect on minimizing or increasing the differences in yarn crimp geometry in the warp and filling systems. If a more isotropic behavior is desired, prescribed tensions or stretch in the fabric length direction and prescribed contraction in the fabric width direction must be performed during fabric setting to equalize the yarn crimp geometry throughout the fabric. To more nearly approach isotropy, the initial modulus must be similar in all directions within the fabric plane. Consequently, consideration must be given to the combined effects of yarn crimp, the deformation of the trellis or triaxial structural unit cell, jamming of the constituent yarns, and the inherent yarn modulus, in all directions of the fabric.

Part II of this series will present an analysis of triaxial woven fabric geometry and the effect of geometry on the stress-strain behavior of triaxial woven fabrics.

ACKNOWLEDGEMENTS

The work described in this paper was made possible through the support and encouragement of Norris F. Dow, originator of triaxial fabric technology. Also, the design of the folded-strip method for tensile testing of fabric samples is credited to Norris Dow. The authors are grateful to Textile Research Institute for use of the shear mechanism for conducting tests on fabric strips under normal-load conditions. Comparable biaxial fabric samples were woven for this study by Professors Paul Siminuk and Lee Clawson of the Philadelphia College of Textiles and Science staff.

Literature Cited

1. Alexandroff, E. E., "Design Development and Testing of New Aerostat Material," Proceedings, Eighth AFCRL, Scientific Ballon Symposium, Sept 30–Oct 3, 1974, AFCRL-TR-74-0393, Special Reports, No. 182.
2. Dow, N. F. and Tranfield, G., Preliminary Investigations of Feasibility of Weaving Triaxial Fabrics, *Textile Res. J.* **40,** 986–998 (1970).
3. Skelton, John, Triaxially Woven Fabrics: Their Structure and Properties, *Textile Res. J.* **41,** 637–647 (1971).
4. Spivak, S. M., The Behavior of Fabrics in Shear Part I:Instrumental Method and the Effect of Test Conditions, *Textile Res. J.* **36,** 1056–1063 (1966).
5. University of Southampton, "Automate/Yendell Fabric Testing Machine," Automate Products, Pitts Lane, Binstead, Ryde, I.W. England.

Manuscript received September 29, 1980.