

## Experimental Methods for Measuring Fabric Mechanical Properties: A Review and Analysis

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### ABSTRACT

This is a review article of the various experimental approaches used for measuring fabric mechanical properties important in apparel handling, including the biaxial tension and in-plane shear parameters. First, the paper discusses the important issues encountered during such a fabric test. Then most existing biaxial tension and shear fabric testers are introduced and critically analyzed. Based on this information, a new tester concept is proposed in which tensile and shear forces can be applied simultaneously.

Although the applications of woven fabrics have expanded into industrial and composite areas because of the unique performance of the material, our understanding of the mechanical behavior of woven fabrics is still limited.

Fabrics are typical porous media and can be treated as mixtures of fiber and air, having no clearly defined boundary and different from a classical continuum. They are not homogeneous, nor are they isotropic, *i.e.*, their properties are determined by the loading direction. Therefore, theoretical analysis of fabric behavior often becomes very complex, and experimental verification of theoretical predictions is more critical than for other materials.

Note that all testers that are theoretically capable of making the measurements are unsuitable for use with apparel fabrics or have serious limitations. In most tests of apparel fabrics, the tensile and shear properties have been measured during separate tests, but in order to measure the interaction between these, a more integrated approach is necessary where tensile and shear forces can be applied simultaneously. This review is intended to lead to such a design.

We examine conventional fabric testers of both biaxial tension and shear in some detail, pointing out some of their problems, with the aim of determining what is necessary to apply biaxial tensile stresses and shear stresses simultaneously and independently to the specimen. We show that the conventional shear tester is probably inaccurate when extensible fabrics such as knits are tested, and we suggest that some results of tests on

woven fabrics remain unexplained because the distribution of tensile stress during the test is inhomogeneous and unknown.

### Major Issues in Fabric Measurement

In tests for uniaxial and biaxial tensile properties as well as fabric shear, there are several important issues to be addressed for a successful experiment.

### NUMBER OF INDEPENDENT PROPERTIES

In general, there are three independent properties provided by the experimental apparatus to be chosen, *i.e.*, the tensile moduli in both warp and filling directions and the in-plane shear modulus (hereafter referred to sometimes as the fabric planar properties). An ideal experimental technique would involve many series of tests, each having one independent variable, but changing one or both of the other two independent variables between test runs, thus generating families of curves from which points can be taken for further analysis. Because the results are assumed to be time-independent, it is acceptable to have up to the three strain (or stress) components vary simultaneously during the test runs. This requires that different test runs trace different paths such that a wide distribution of strain component combinations is generated by the test series.

Note that because of the nature of fabric structure, the three parameters are actually interconnected, *i.e.*, a parameter will possess different values when the other two are set at different levels. Obviously a tensioned

fabric will have a different shear modulus from that of the same fabric when tension is released. So it is often necessary or advantageous to design a tester where the levels of different strains can be adjusted separately and simultaneously.

#### BUCKLING EFFECTS

During an in-plane test, because of the interactions between bending and the deformations within the fabric plane, such as tension and in-plane shear, an out-of-plane bending deformation, buckling, will occur. Bending tests and analyses have been the subject of quite a few studies [1, 8, 14, 30, 35, 38, 40, 55, 67, 82], but these interactions have never been measured.

An example [5] suggests that in many garment-like situations, fabric bending properties do not have a large effect, and it is to be hoped that the interactions between bending and fabric properties are of a similarly small magnitude, since they would be extremely difficult to measure experimentally. We neglect these interaction effects in this discussion, which is concerned with measuring only fabric planar properties.

#### TIME AND FRICTIONAL EFFECTS

The fabric stress at a particular time depends on the history up to that time of many physical and chemical conditions, including the strain history. The study of time-dependent properties such as viscoelastic effects and friction has received considerable attention [2, 4, 11, 15, 61, 62, 77], but only for cases involving uniaxial tension or pure shearing.

Sufficient information for including frictional and viscoelastic effects in analyses involving multiple independent and dependent variables is presently unavailable, and so in this work, we will assume that fabrics are approximately "ideally elastic" [27]. In an ideally elastic material, all of the strain energy imparted to the material by imposing any deformation is recoverable as mechanical energy when the deformation is removed, and the constitutive laws of the material are independent of time. This assumption does not restrict the stress-strain relationship to linear.

One hopes that the relationships obtained will be accurate enough for the purpose of modeling fabrics in garment-like situations. This requirement is unlikely to be met, since in experiments involving such situations as fitting fabrics to spherical surfaces, there are likely to be significant errors because it is difficult to control or specify time-dependent effects. The most convenient compromise will be to ensure that loads are applied and measurements are taken over similar scales of time in

both the fabric planar properties and three-dimensional forming tests.

#### STRESS AND STRAIN DISTRIBUTIONS IN TEST SPECIMENS

It is desirable that the distribution of stress and strain in the specimen be homogeneous. Yet, in most practical cases, the actual stress-strain distribution is not known accurately, and calculating material properties is difficult or impossible.

In most practical testers, perfect homogeneity of strain is never realized, but the strain can be assumed to be homogeneous over part or all of the specimen. In such cases, the tester should be designed so as to minimize any variation in strain that occurs. A more detailed analysis of stress distribution in fabric during testing is provided in reference 6.

#### TESTING STRAINS AND RATIOS VERSUS END USE

The design of any instrument will be influenced by the ranges of stress and strain with which it will be expected to cope. For example, many tests of fabric tensile properties are designed to record breaking strength. The levels of stress during normal garment use, on the other hand, are much lower.

#### *Maximum Values of Stress*

Little information is available on the values of stresses in fabrics during use. Some work on stretch fabrics by Kirk and Ibrahim [50] defined "available fabric stretch" as the extension at a stress of 2 lbf/in. (350N/m) in a uniaxial test, and they published results which showed that extensions during body movement reached only 40% of that extension value. If fabric behavior is assumed to be linear, then the stress would be approximately 140N/m. As a rough comparison, consider the force exerted by a tailor gripping a fabric between thumb and forefinger over a width of perhaps 20 mm. At a stress of 350N/m, this would be 7N (approximately 700 gf), which is a generous estimate of the maximum to be expected in a garment during normal use. The results in reference 5 show that important shear deformations occur under quite low tensile stresses, and instruments should be designed to have sufficient sensitivity to also accurately measure stresses more than an order of magnitude smaller than those in this example.

Due to the onset of buckling, certain combinations of tensile and shear stress are not possible except in small areas, e.g., near the clamps, where the fabric is constrained to remain flat.

### *Minimum Values of Stress*

Shear stress can take on values as large in magnitude in the negative as in the positive direction, negative shear stress simply being applied in the opposite direction to positive shear stress. Negative, *i.e.*, compressive, tensile stresses of significant magnitude are found in some areas of garments [5, 53].

Buckling tests on specimens with very short gauge lengths are sometimes used [24, 53] to test fabric properties under compressive uniaxial stress, but there is no known principle for measuring the effects of simultaneously applied biaxial tensile and shear stresses when one or more of the tensile stresses is negative. In the work described here, we will neglect negative tensile stresses.

### *Maximum Values of Strain*

The magnitudes of shear strains can be expected to be comparatively large. For example, shear strains of 0.5 rad (30°) can be observed in loosely woven shirting fabric, but 0.2 rad would be a more normal maximum for woven worsted outerwear fabrics. Tensile strains in most woven garments are quite small, but stretch or knitted garments might exhibit strains of the order of 25%.

### *Minimum Values of Strain*

Shear strain is similar to shear stress in that negative shear strains simply involve straining in the opposite direction. Due to shrinkage caused by the Poisson effect, negative tensile strains of the same order as the positive tensile strains can be expected.

## Previous Experimental Work on Fabric Planar Properties

Previous experimental work on determining fabric planar properties has usually only considered the variation of one stress or strain component at a time. Tensile properties are usually measured separately from shear properties, and most of these tensile tests use only uniaxial tensile stress [45].

A slightly more complex test was that by Lloyd and Hearle [56], who used short, wide specimens in addition to the normal long, thin ones in an Instron extensometer. Under the assumption that fabric properties are linear and that these tests represented respectively, tests at constant (zero) transverse strain and constant (zero) transverse stress, it should have been possible to calculate the fabric plane stiffness constants. However, they concluded that a still more complex test was necessary.

Such complex testing includes many biaxial tensile testers that have been constructed. Haas and Dietzius

[34] seem to have been the first in this field, and they tried testers of both of the two main kinds used subsequently, that is, those with flat and those with cylindrical specimens. Using a cylindrical specimen, it is possible to vary the three components of stress and strain independently, but only if the fabric is impermeable to fluid. Because they are permeable, fabrics have more commonly been tested with instruments that use flat specimens.

Treloar [76] was perhaps the first to employ pin grips in order to apply forces to a square sheet specimen, as illustrated in Figure 1a. This method was later adopted and modified by other researchers [5, 59, 66] and has recently been used to study the stability of fabrics under biaxial stretching [54]. Since then, there have been several similar biaxial fabric testers with slight variations, such as the grab specimen [13, 65] and the cruciform specimen [17, 29, 51, 69] using solid clamps, and also the technique using segmented clamps [42, 46, 47, 68] (see Figures 1b, c and d, respectively).

The most common method of testing shear properties involves gripping an initially rectangular specimen with clamps on opposite edges, and measuring the resistance to lateral movement of the clamps. Alternatively, there have been several attempts to measure shear properties by uniaxially extending the specimen along a bias direction. In the discussion that follows, testers are divided into two main classes: separate testers, which cannot vary the three components of stress or strain independently, and combined testers, which can in principle satisfy this requirement. We discuss the conventional fabric shear tester separately, since there are some important conclusions that can be drawn from closer analysis of this test method.

### SEPARATE TESTERS

First we discuss test methods for tensile or shear where the other is fixed.

#### *Biaxial Tensile Testers*

The use of a flat specimen is a logical extension of the common uniaxial test, but several complexities are introduced, especially in the fabric gripping arrangement. The chief difficulty is the need to allow the fabric to undergo tensile strain in the direction along each clamp. All the testers have used initially square specimens, but there have been two main approaches to accommodating the straining along the clamps.

The first method involves using a specimen in the form of a cruciform, so that only the central part of the specimen is in biaxial tension, while the arms of the cruciform are in uniaxial tension. There is thus no need to allow for strain

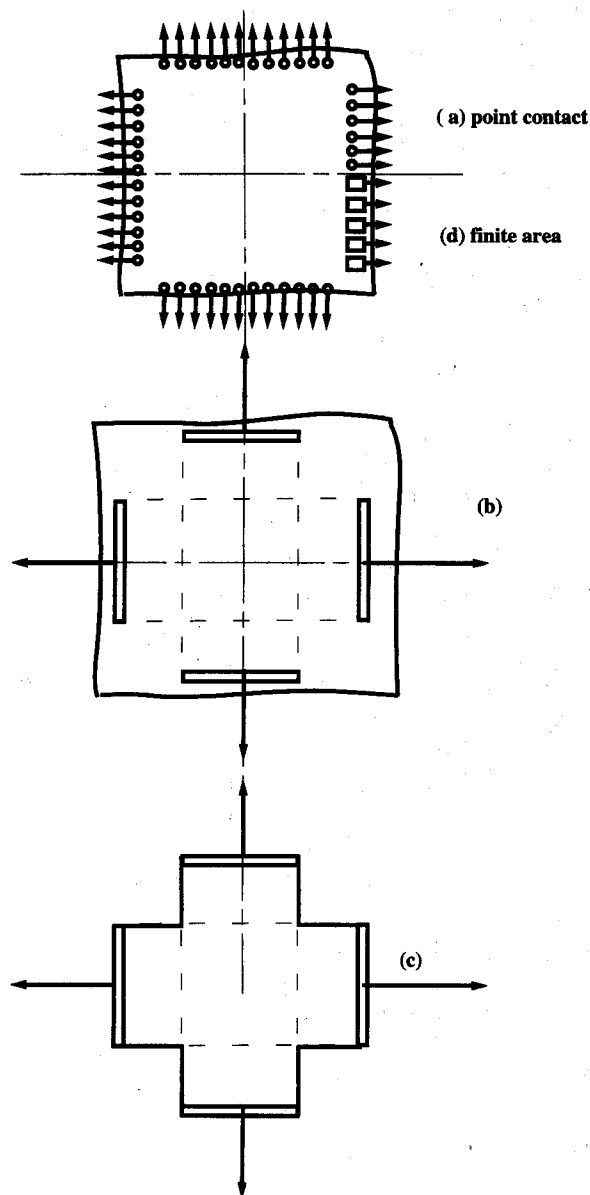


FIGURE 1. Different kinds of fabric gripping in biaxial fabric testers: (a) point gripping, (b) grab test, (c) cruciform test, and (d) segmented clamps.

parallel to the clamps in these areas (Figure 1c). Where the cruciform shape is not actually cut out and the specimen remains square, a grab test analogous to a uniaxial grab test is performed (Figure 1b). Strain is usually measured directly in a small area near the center of the specimen, while stress is calculated from the force/unit length of the clamps, and is subject to error because of the inhomogeneity of stress throughout the specimen. These errors would be accentuated by large tensile strains, such as would be found in tests of knitted fabrics.

One possible means of avoiding this problem, not described in the literature, would be to remove all of the transverse threads from the fabric in the arms of the cruciform, thus forcing the tensile loads to be carried by the central section. There are two disadvantages: first, this is impossible in knitted fabrics, and second, there may be inhomogeneity introduced due to variations in the stiffness and initial crimp of the yarns in what now are the fringes forming the arms of the cruciform. Normally the crossing threads cause load sharing if there are such variations.

The other approach is to use some form of segmented clamps to grip the edges of the biaxially strained area, with the segments of each clamp allowed to move freely in the direction parallel to the edge it grips. The clamps may have a finite area (Figure 1d), or be in the form of pins or wires (Figure 1a) pushed through the fabric. There are several sources of error in such testers. For example, stresses in the regions near and between the clamp segment are lower than elsewhere, and the regions between the clamp rows and the specimen edges may be only stressed uniaxially.

Table I lists some of the authors who have used various flat-specimen biaxial tensile testers. With the exception of Yendell's apparatus [81], none of these can apply (and vary independently) shear stress or strain. We discuss Yendell's apparatus and its limitations in more detail later.

#### Shear Testers

The testers most commonly used to test shear properties clamp two opposite sides of an initially rectangular

TABLE I. Clamping arrangements used by previous flatbed fabric biaxial tensile testers.

Authors	Reference	Year
1. Grab test, solid clamps		
Reichardt <i>et al.</i>	65	1953
Checkland <i>et al.</i>	13	1958
2. Cruciform specimen, solid clamps		
Haas and Dietzius	34	1912
Klein	51	1959
Clulow and Taylor	17	1963
Kim	49	1966
Freeston <i>et al.</i>	29	1967
Yendell	81	1971
3. Segmented clamps, segments with finite area		
Sakaguchi <i>et al.</i>	68 <sup>a</sup>	1968
Kawabata <i>et al.</i>	42	1973
4. Square specimen, pin grips		
Treloar	76	1948
Rivlin and Saunders	66	1953
Datta <i>et al.</i>	22	1958
MacRory <i>et al.</i>	59	1958
Liu and James	54	1995
Ghosh <i>et al.</i>	31	1997

<sup>a</sup> Used serrated edges on specimen to improve homogeneity of stress distribution.

specimen and measure the resistance of the clamps to relative lateral motion, from which fabric shear resistance is calculated. In order to delay the onset of specimen buckling as shear strain is increased, a uniaxial tension is applied in the direction perpendicular to the clamps. The actual form of the testers has varied from devices mounted on an Instron extensometer [7, 21, 41, 52, 57] to simple stand-alone devices [7, 25, 28, 75, 78]. The biaxial tensile tester of Kawabata *et al.* [44] can be reconfigured to operate as a shear tester, with only uniaxial tension applied in this case. An improved stand-alone tester developed by Hamilton [37, 38] can measure the shear hysteresis of wool plain knitted fabrics. Earlier work concentrated mainly on testing woven fabrics, and only in more recent times has much been published on the shear properties of knitted fabrics [9, 10, 32, 36, 74].

The first major problem of the test method to be given much attention was the onset of buckling of the specimen. Treloar [75] and Spivak [73] found through their experimental results that the onset of buckling didn't appear to agree with the criterion derived by Behre [7] and Cusick [21] based on the cantilever beam theory. Treloar proposed an alternative theory, which predicted that buckling would always occur if a shear stress was applied while the tensile stress in one thread direction was zero, irrespective of the magnitude of the stress in the other thread direction. However, this experimentally observed behavior remains unexplained.

Treloar [75] also investigated other test parameters. He measured the deviation of the clamps from parallel, and the contraction of the fabric in the thread direction initially perpendicular to the clamps. He also evaluated the effects on the initial shear modulus of different fabric tensions for different width (along clamps) to length (between clamps) ratios of the specimen. He found that specimens of higher width to length ratio (*e.g.*, 10:1) gave higher values of shear modulus with less dependence on fabric tension. The results of Treloar's experiments have not been completely explained. In spite of Treloar's recommendation of short, wide specimens, some testers constructed subsequently [28, 36, 38, 78] have retained square specimens.

Testing knitted fabrics brings a new problem in the form of an increased relative rotation of the clamps. It is experimentally convenient to constrain the clamps to remain parallel to prevent this rotation [10, 36, 38]. No theoretical explanation of the benefits of this action appears to have been offered.

#### Bias Extension Testers

Several authors [12, 34, 48, 63, 71, 80] have pointed out that when a woven fabric is extended uniaxially at a bias angle, a large part of the deformation is due to

shearing of the fabric in a trellis-like fashion. Some authors made such tests with normal solid clamps and a 45° bias angle [18, 71, 72], but the large transverse contractions of the specimen are a problem in such tests, since the solid clamps do not allow this contraction near the specimen ends. Spivak and Treloar [72] compared such bias extension tests to conventional shear tests, and found that the bias extension tests gave shear stresses 20–300% higher at a given shear strain. There was a similar effect in buckling tests on specimens mounted at bias angles, where the ratio of threadwise modulus to 45° bias modulus of woven fabric was only 3–4 (*e.g.*, Dhingra and Postle [24]). This is a much smaller ratio than one would expect, since the ratio of initial Young's modulus to initial shear modulus for woven fabrics is typically 120–500 (Table II).

TABLE II. Ratios of estimated initial modulus  $E$  to shear rigidity  $G$  for fabrics tested by Hart [39] and Gibson [33].

Fabric construction	Range of $E/G$
Woven	120–500
Double knitted	5–14
Warp knitted	11–50

Weissenberg *et al.* [12, 80] performed uniaxial tensile tests on specimens mounted at bias angles, using roller clamps and specimens sewn into cylinders, in order to allow lateral contraction to occur freely. But they did not present results in terms of stiffnesses or other parameters that could be converted to a shear modulus.

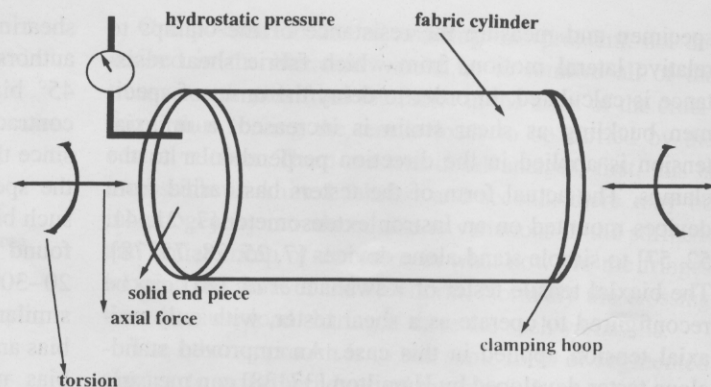
A basic limitation of the method, however, is the fact that usually only one independent variable, tensile strain or stress at the bias angle, is available. If roller clamps are not used, fabric orientation cannot be varied to angles other than 45°, since the ends of the specimen skew.

#### COMBINED TESTERS

##### Cylinders

The use of a cylindrical specimen was a natural step for Haas and Dietzius [34], who were working with fabrics for dirigibles. The principle of this test method is illustrated in Figure 2. If the fabric is impermeable to a fluid, *e.g.*, water, the stress in the circumferential direction can be provided by hydrostatic pressure inside the cylinder. Tensile stress in the axial direction can be varied independently by applying force to the ends of the cylinder. Further, fabric shear stress can be imposed by the application of torque to the cylinder ends, and the shear stress analysis is similar to that used by engineers for analyzing the torsion of hollow shafts.

FIGURE 2. Cylinder tester schematic.



An extra independent variable, which could theoretically be used to replace hydrostatic pressure when testing permeable fabrics, is the specimen orientation, since we know that fabric will behave differently if oriented in a different direction. End effects preclude the use of this variable, however, since the clamping system is analogous to that in a uniaxial tensile test where woven fabrics mounted at bias angles form triangulated systems near the clamps, hindering the large lateral contraction necessary to maintain homogeneous strain. Use of a roller clamp system to overcome this difficulty is not possible with a cylindrical test. (Actually, the roller clamp system can be considered to be a cylinder tester in which hydrostatic pressure is replaced by a pair of rollers inside the cylinder, parallel to the cylinder axis. However, neither an axial tension nor a torsion can be applied to the cylinder.) If fabric orientation were varied, another difficulty that would be encountered is that a seam must be made with extensibility properties negligibly different from the rest of the specimen, which would be difficult at bias angles.

Another option for testing cylindrical specimens of permeable fabric is to use some sort of bladder inside the specimen [20]. Since the obvious bladder material, *e.g.*, rubber, would be isotropic, its shear stiffness is likely to be high compared to that of the fabric, and the corrections necessary to compensate for the effect of the bladder would therefore be inaccurate. Even if such difficulties could be overcome, the test method would be unsuitable if the circumferential strains were large, due to the effect of the rigid end clamps.

A final possibility is the technique of Eeg-Olofsson [26], which made use of the fact that when a cylinder of fabric, held to constant diameter at its ends, is extended in the axial direction ( $x$ ), it contracts in the radial direction ( $r$ ), generating a circumferential stress dependent upon  $dr/dx$ . This enables biaxial stressing of permeable fabrics without the use of hydrostatic pressure. However, only a restricted range of biaxial stresses can be applied,

and the accurate measurement of the strains is difficult. MacRory and McNamara [58] also used this technique, but they concluded that it was unsatisfactory and subsequently constructed a flatbed tester [59].

For the reasons outlined above, tests on cylindrical specimens have mostly been confined to industrial fabrics, mainly for use in pneumatic structures. A list of authors who have contributed work in this field appears in Table III.

TABLE III. Biaxial tensile tests in which cylindrical specimens were used.<sup>a</sup>

Authors	HP	BA	AF	TQ
Haas and Dietzius [34], 1912	Y	Y	Y	Y
Anderson [3], 1946	Y			
Chadwick <i>et al.</i> [12, 80], 1947		Y		(Roller clamps)
Eeg-Olofsson [26], 1955		Y	Y	
Mellen <i>et al.</i> [60], 1960	Y			
Clark [16], 1963	Y	Y	Y	Y
MacRory and McNamara [58], 1967		Y	Y	
Skelton and Freeston [70], 1971	Y		Y	Y

<sup>a</sup> HP = used hydrostatic pressure, BA = mounted fabric at bias angle, AF = applied force parallel to cylinder axis, TQ = applied torque to cylinder ends.

### Two-Stage Flat Tests (Culpin)

This apparatus was proposed by Culpin [19] as a method for measuring the shear properties of sheet materials. It consisted of two parts, a pre-stretching jig in which the desired tensile strains were applied and held while the specimen was clamped in, and the test frame in the form of four clamps hinged together at their ends to form a square. After the pre-stretched fabric was clamped, the frame was transferred to an Instron extensometer and distorted by extending one diagonal, performing a shear test under the predetermined tensile strains.

Some principles of the apparatus were quite sound. The four sides of the specimen were gripped and held straight and parallel during shear. Provided the effects of the clamps and pivots were small, homogeneous strain was approximated. However, the authors paid insufficient attention to the mechanical details of the pivots. To achieve homogeneous strain, the pivots should have been at the clamped edges of the specimen (Figure 3). The position of Culpin's pivots resulted in inhomogeneity of strain at the corners of the specimen, causing buckling that could only be suppressed by very large pre-strains. Clamps with pivots in the indicated positions could be constructed, *e.g.*, using two bearings in a yoke arrangement at each corner. The tester also required that the clamped edges be sharply defined, so there would be no fabric slippage near the edges of the clamped regions. Additionally, the clamps needed to incorporate force transducers to enable calculation of the tensile stresses.

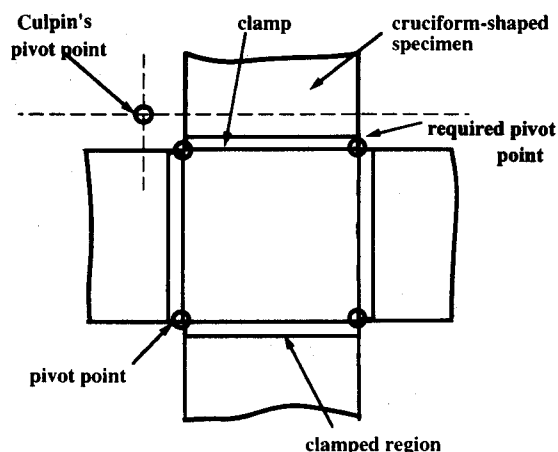


FIGURE 3. Possible biaxial tensile and shear tester: principles similar to those used by Culpin [19] (shear would be applied by diagonal extension).

Even with these improvements, however, several problems remain. Because the strains in woven fabrics are quite small, they may be difficult to control using the separate pre-stretching process, and the test would be sensitive to misalignment during mounting. The order of strain application would be fixed, and would include a pause in the test procedure during clamping of the fabric and transfer of the frame to the Instron. Stress relaxation during this pause might be undesirable. Additionally, the modifications to the clamp geometry proposed above may still not produce perfectly homogeneous strain.

### Single Flat (Yendell)

Among testers that have used flat, cruciform samples, this apparatus by Yendell [81] stands alone, because it can apply simultaneous shear and biaxial tensile stresses to the specimen. However, the apparatus has several undesirable features.

In common with all of the cruciform testers, the strain is not homogeneous. This may not have been a problem at the low strain levels found in its intended specimens, which were sailcloth, but it would cause errors in tests on garment fabrics. The other major problem concerns the arrangement of the pivots, which enable rotation of the clamps during shear tests, causing the fabric to buckle, *i.e.*, the system is unstable. Instability is more likely with large values of the ratio  $a:h$ , and with fabrics that shear easily but are stiff in tension. Yendell tested fabrics that were stiff in shear, and he used a small  $a:h$  ratio. However, large values of  $a:h$  are desirable since they promote homogeneity of strain.

### Conclusions

Only a few of the testers used previously to measure the planar properties of fabrics are able to apply the three desired components of stress and strain simultaneously and independently. Of these cylinder testers, most are unsuitable for testing apparel fabrics, or else they have other weaknesses that make them unsuitable for many applications.

The shear properties of apparel fabrics are usually measured under inhomogeneous uniaxial tensile stress. Such tests cannot always provide accurate measurements of the relationship between shear stress and shear strain and its dependence on the tensile stress and strain states.

A new tester of fabric biaxial tensile and shear properties needs to be constructed. If the tester uses an initially rectangular specimen, all four sides should be gripped by a clamping system that imposes a homogeneous edge-force distribution along each side of the sample, with no couples about the centers of the sides. Additionally, opposite sides should be loaded symmetrically. Such a system should have the three degrees of freedom required to vary the three components of stress and strain independently. Furthermore, the upper limit on the magnitude of shear stress and strain imposed by the onset of buckling in the conventional shear tester should be relaxed, subject to a constraint close to that derived in reference 5. In addition to providing the constitutive properties of a fabric as a starting point for modeling garments, etc., data from such an instrument might be used to help explain the behavior of fabrics in the conventional shear tester.



Note, however, that such an instrument will not provide data for situations in which one or both of the tensile stress components are negative (compressive), which would seem to be important in both the tailoring process [53, 79] and the subsequent use of garments [5]. The best means of estimating fabric behavior in such stress domains is probably to extrapolate from results of short-specimen uniaxial compression tests, assisted by the predictions made by a theoretical model based, for example, on models used by de Jong and Postle [23, 64] or Kawabata *et al.* [43].

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