Reprinted from TEXTILE RESEARCH JOURNAL, No. 67, No. 8, August 1997
Printed in U.S.A.

Shear Strength of Fibrous Sheets: An Experimental Investigation

NING PAN AND XIAOSHAN ZHANG

Division of Textiles and Clothing, Biological and Agricultural Engineering Department, University of California, Davis, California 95616, U.S.A.

ABSTRACT

This study of the shear strength of fibrous sheets first measures the in-plane shear strengths of various samples, including woven and nonwoven fabrics and paper, using a custom-made apparatus attached to an Instron tester. The structure of the apparatus and the measurement procedures are introduced in this article. The tested shear strength values are then compared with theoretical predictions from an earlier work. Discrepancies and possible causes are analyzed. Load-elongation curves for both tensile and shear are compared for individual fabrics and between fabrics. The relationship between the anisotropy of fabric tensile strength and the ratio of tested and predicted shear strength is explored. Also, the effect of fiber movement during textile deformation is examined. Finally, the original Tsai-Wu theory used for shear strength prediction of anisotropic materials is modified for application to the fibrous sheets, and the new predictions are provided for comparison.

Fibrous materials have increasingly been used in areas other than clothing, especially for industrial applications. Fiber sheets such as woven and nonwoven fabrics have been used for constructing large civic structures including domes and roofs for stadiums. Also, because of good dimensional stability, high fiber packing density, and relatively low cost due to the textile industry's maturity, fabrics have become very popular as reinforcements for composite materials. All these new applications call for a better understanding of the mechanical properties of these materials.

Of all mechanical properties, those related to the shear behavior of fabrics are the least understood, mainly because they are difficult to investigate, both theoretically and experimentally.

The shear behavior of a fabric has long been considered an important aspect of its properties, and shear determines to varying degrees the fabric's drape, wrinkle, and buckle. Therefore, many works have been devoted to the study of fabric shear properties and the results have been reviewed in books by Hearle *et al.* [2] and Postle *et al.* [7]. Kawabata's [3] fabric shear tester is a well known example. More recently, Subramaniam *et al.* [10], Asvadi and Postle [1], and Sinoimeri and Drean [11] also reported on their studies of fabric shear behavior. However, all these investigations have focused exclusively on the elastic or low stress state, and the issue of fabric shear strength is rarely tackled.

In our previous studies, we first adopted the chain-of-subbundle model to predict the tensile strengths of woven fabric for uniaxial and biaxial loading cases in which the ultimate saturated length for the subbundle was calculated based on the interactions between yarns during fabric extension [5]. We then investigated other issues related to woven fabric strengths [6]. We examined the direction-dependence or the anisotropy of the tensile strength, as well as the breaking strain and initial modulus, of the fabrics using experimental data. Moreover, we used the Tsai-Wu failure criterion [13], and determined its unknown coefficients using the experimental results. We then predicted fabric shear strength based on the measured uniaxial tensile strengths of the fabric at the principal and off-axial directions. We also discussed the influences of various directions of the off-axial tensile test on the predictions of fabric shear strength [6].

In this experimental study, we have actually measured the in-plane shear strengths of various fibrous sheets, including woven and nonwoven fabrics and paper, using a custom-made apparatus installed on an Instron machine. The structure of the apparatus and the measurement procedures are introduced and illustrated in this paper. We then compare the tested shear strength values with our earlier theoretical predictions [6], and we analyze the discrepancies and their possible causes.

We compared the load-elongation curves of both tensile and shear for individual fabrics and between fabrics, and investigate the relationship between the anisotropy of fabric tensile strength and the ratio of tested and predicted shear strength. Then, based on our analysis, we modify the original Tsai-Wu theory used for

0040-5175/$2.00

shear strength prediction of anisotropic materials so as to apply it to fibrous sheets, and we provide the new predictions for comparison. It is our hope that this modified theory can be used to obtain shear strength with reasonable accuracy for fibrous sheet materials so as to replace the inconvenient experimental approach.

Theoretical Prediction of Shear Strength

As introduced in our previous paper [6], if treated as an ordinary anisotropic sheet, a fabric's shear strength τ_L at the longitudinal (or warp) direction can be calculated according to the Tsai-Wu failure criterion [13] as

$$\tau_L = \frac{1}{\sqrt{F_{66}}} \quad , \tag{1}$$

where F_{66} is a coefficient that can be solved from an equation given by Pouyet and colleagues [8] for paper materials:

$$\sigma_\phi[F_{11} \cos^4 \phi F_{22} \sin^4 \phi + (2F_{12} + F_{66}) \sin^2 \phi \cos^2 \phi] = 1 \quad , \tag{2}$$

where σ_ϕ is the tensile strength at a bias direction ϕ in relation to the longitudinal direction, and the other factors are defined using the tensile strengths at the longitudinal σ_L and the transverse σ_T directions as

$$F_{11} = \frac{1}{\sigma_L{}^2} \quad , \tag{3}$$

$$F_{22} = \frac{1}{\sigma_T{}^2} \quad , \tag{4}$$

and

$$F_{12} = -\frac{1}{2\sigma_L\sigma_T} \quad . \tag{5}$$

Therefore, once fabric tensile strength σ_ϕ at direction ϕ is known, the coefficient F_{66} can be solved from Equation 2. Fabric in-plane shear strength τ_L can then be obtained from Equation 1.

We would like to mention here that in the following text, because of the difficulty of determining the cross-sectional areas of fibrous sheets, rather than strength, we used the breaking load. For brevity, however, we will still call these breaking loads strengths, but provide a unit for them to avoid confusion.

Experimental Investigation

In this study, besides the five woven fabrics we used in the earlier work [6], we also added another five fibrous sheet materials. Table I gives a detailed description of all the materials and their tensile strengths σ_L and σ_T in both longitudinal and transverse directions, respectively, as well as their breaking strain ϵ_L and initial modulus E_L in the longitudinal direction only.

The shear strengths in the longitudinal direction predicted using this method and denoted as $\tau_{L\text{pre1}}$ for these materials are shown in Table II. The most logical approach to validate predictions of shear strength is through experimental verification. For this purpose, we use a custom-made apparatus designed especially to test shear on an Instron. The basic principle of our shear test is shown in Figure 1a, which is in essence identical to the conventional test scheme in Figure 1c. Treloar [12] has recommended that in order to achieve a uniform shear stress distribution due to the shear force F on the fabric, the ratio of width W to length L of the specimen should be at least greater than 10. For that reason, on our apparatus, the specimen length L between the two clamps is almost zero, so that an ideal shear stress distribution is generated in the specimen. Figure 1b illustrates the case when a specimen has completely failed due to shear.

Specimens in this test are strips cut to a size of 3″ × 1″ (76.2 × 25.4 mm), and the crosshead speed for

TABLE I. Data of fabric samples.

Sample	Fiber[a]	Type	Thickness, mm	σ_L, N	σ_T, N	ϵ_L, %	E_L, $\frac{kg}{mm^2}$
1 woven	PET-F	plain	0.27	430.71	355.74	49.11	187.08
2 woven	acetate-F	plain	0.35	190.61	197.37	25.04	133.67
3 woven	acetate-F	satin	0.43	261.66	270.77	18.76	194.63
4 woven	cotton-S	plain	0.40	201.78	159.25	6.39	118.78
5 woven	cotton-S	plain	0.40	207.47	196.69	7.74	159.35
6 nonwoven	PET-S	highloft	1.80	41.16	5.00	10.00	51.16
7 paper	wood cellulose	wiper	0.094	147.78	91.83	1.40	58.11
8 woven	cotton-S	plain	0.34	216.38	189.63	3.29	152.19
9 nonwoven	polyethylene-F	flashspun	0.19	35.48	20.97	9.10	83.40
10 nonwoven	polytetrafluoroethylene-S	hydroentangled	0.53	25.68	18.42	24.48	31.26

[a] F = filament yarn, and S = staple yarn.

TABLE II. Properties of fabric samples in the longitudinal direction.

Sample	σ_{max}, N[a]	σ_{min}, N	a	τ_{Ltest}, N	τ_{Lpre1}, N	b	τ_{Lpre2}, N	b_{new}
1	430.71 (0°)	142.20 (75°)	3.03	187.08	133.35	1.40	242.43	0.77
2	190.61 (0°)	180.09 (15°)	1.76	133.67	79.59	1.68	84.05	1.59
3	270.77 (90°)	128.58 (75°)	2.11	194.63	120.44	1.62	152.48	1.28
4	201.78 (0°)	83.99 (75°)	2.40	118.78	87.18	1.36	125.54	0.95
5	207.47 (0°)	78.99 (75°)	2.63	159.35	96.43	1.65	152.17	1.05
6	41.19 (0°)	5.00 (90°)	8.24	51.16	4.71	10.86	58.22	0.88
7	147.78 (0°)	88.00 (75°)	1.68	58.11	59.21	0.98	59.68	0.97
8	216.38 (0°)	66.25 (75°)	3.27	152.19	79.16	1.92	155.31	0.98
9	40.28 (30°)	30.18 (75°)	1.33	83.40	19.35	4.31	64.34	1.30
10	25.68 (0°)	17.74 (75°)	1.45	31.26	9.74	3.21	35.31	0.89

[a] Numbers in parentheses indicate the direction sample was cut relative to the longitudinal direction.

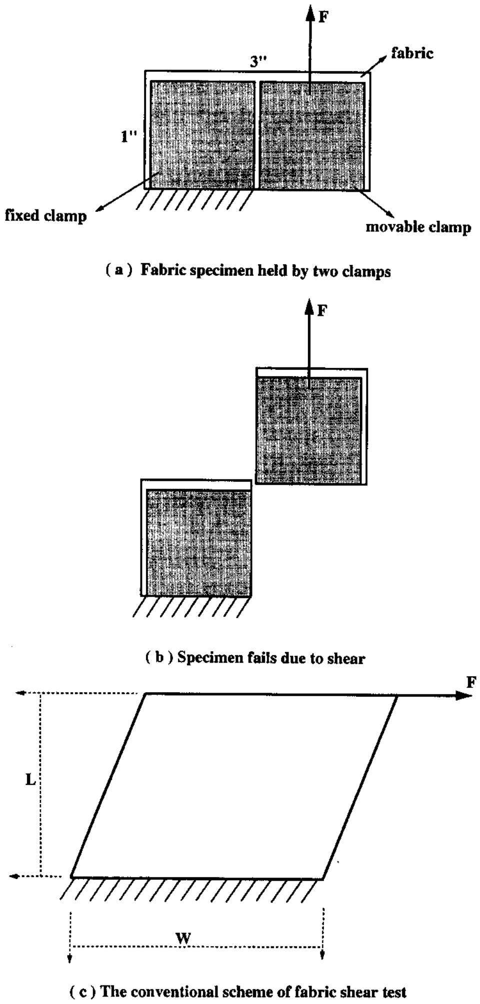

FIGURE 1. The principle and apparatus of the fabric in-plane shear test: (a) fabric specimen held by two clamps, (b) specimen fails due to shear, (c) the conventional scheme of fabric shear test.

all the tests is set at 10 mm/min. Figure 2 shows a photo of the actual apparatus, the sample clamps, and how it is installed on the Instron. A computer-controlled data acquisition system is used to collect data, plot load-displacement curves, and carry out some simple statistical analyses. The test results of shear strengths τ_{Ltest} for all ten samples can be found in Table II as well. This τ_{Ltest} is the shear strength in the longitudinal direction, *i.e.*, the direction across which a specimen fails.

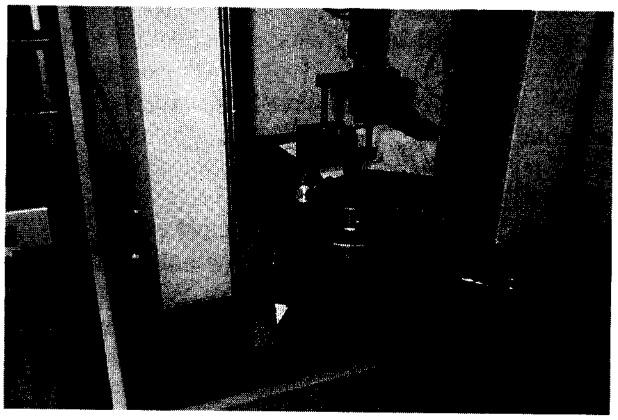

FIGURE 2. The apparatus mounted on an Instron for fabric shear test.

We have also tested the tensile strength of all samples. Specimen size, preparation, and actual testing all follow the ASTM 1682-65 cut strip method at the same crosshead speed of 10 mm/min. Results for selective samples are given in Table III.

Results

COMPARING TENSILE AND SHEAR BEHAVIOR

We chose two samples, 4 and 6, to compare their behavior in tension and shearing by examining their load-displacement curves. Figure 3a shows that sample 4, a woven fabric, has a higher strength but a smaller breaking elongation in the tensile case than for shearing. It is not difficult to conceive that although all the

TABLE III. Comparison of tested tensile strength anisotropy (N).

0° (*L*)	15°	30°	45°	60°	75°	90° (*T*)
Sample 5						
207.47	97.71	147.29	173.85	123.28	78.99	196.69
Sample 6						
41.19	27.86	13.87	9.41	7.09	5.45	5.04
Sample 7						
147.78	140.53	124.66	113.58	103.78	87.99	91.86
Sample 9						
35.48	38.33	40.27	38.52	34.32	30.18	21.00
Sample 10						
25.70	24.15	21.84	19.45	17.89	17.69	18.38

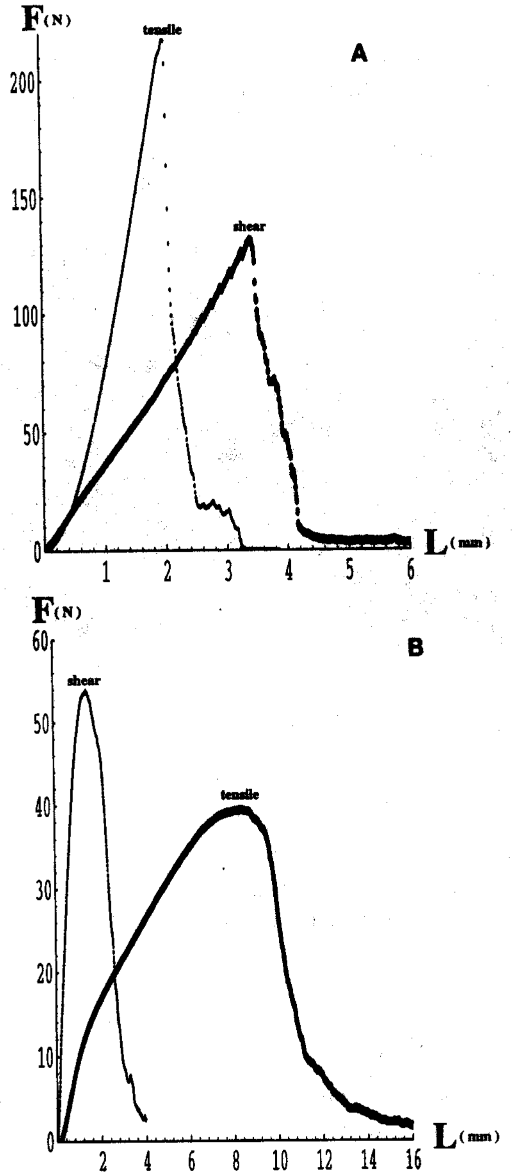

FIGURE 3. Comparison of tensile and shear behavior: (a) for sample 4, (b) for sample 6.

yarns are carrying the load during shearing deformation, the distribution of the load is not as uniform as in the tensile case. This explains the lower shear strength, and the greater breaking elongation reveals that more significant yarn movement took place during shearing.

The reverse is true for sample 6 in Figure 3b, which is a nonwoven of randomly distributed fibers hydroentangled with each other to form the structure. During a tensile test, fibers are being pulled out of the structure, whereas in a shearing test, fibers are being forced to move in the direction across the specimen width, which is more difficult than being pulled out. This leads to a lower strength and higher breaking elongation in tension, but an opposite result in shearing.

Between these two samples, as the figures reveal, the woven fabric possesses greater strength in both tensile and shearing cases and lower tensile breaking elongation but greater shearing elongation than those of the nonwoven sample.

Note the different deformation mechanism in both tensile and shear cases for the two samples. For nonwoven materials, fibers can either be pulled out or break, but for a woven fabric, yarn breakage is almost the only failure mode, and pull-out rarely occurs.

We also compared samples 6 and 9, both nonwovens with similar load-elongation curves for shear, as Figure 4a shows. But if we look at their tensile behavior in Figure 4b, sample 6 shows considerably higher strength and breaking elongation. This indicates that materials behaving similarly in one deformation mode may behave very differently in another.

COMPARING TESTED AND PREDICTED SHEAR STRENGTHS FROM THE ORIGINAL THEORY

It is evident from Table II that, except for sample 7, shear strength predictions for all the samples are disappointingly lower than the tested results. The most extreme case is for sample 6, a high loft hydroentangled nonwoven material, for which the predicted shear strength is less than one-tenth of what was tested.

To further study the discrepancies, we calculated a ratio for all the fabrics,

$$b = \frac{\tau_{L\text{test}}}{\tau_{L\text{pre1}}} , \qquad (6)$$

and included the values in Table II. Obviously, this *b* ratio indicates the closeness or accuracy of the predictions relative to the experimental results. We can easily see that the worst predictions are those for samples 6, 9, and 10, all three being nonwoven materials. The best agreement between the predicted and tested values occurs for sample 7, which is a paper napkin made of fine

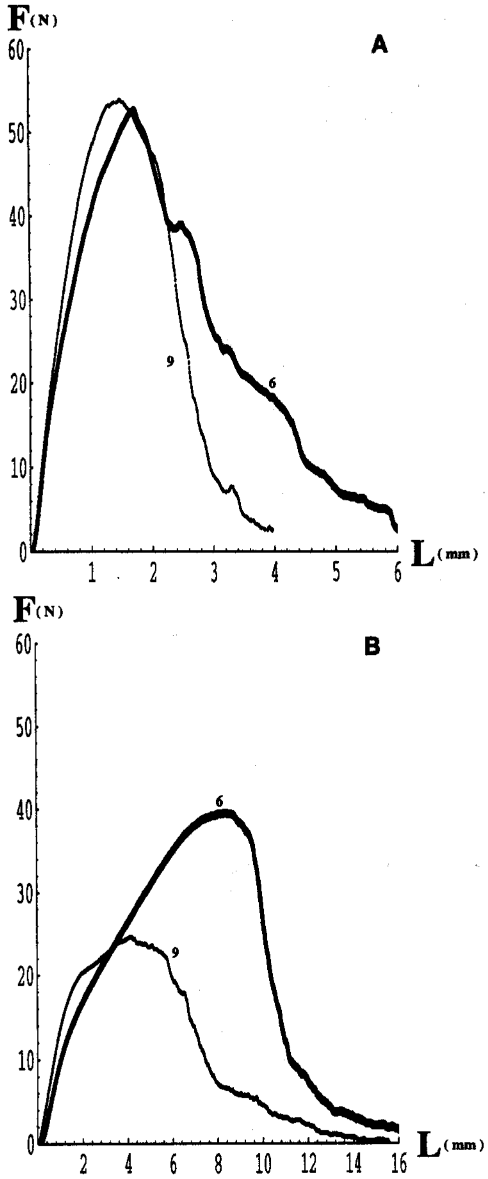

FIGURE 4. Comparison of tensile and shear behavior: (a) shear load-deformation curves for samples 6 and 9, (b) tensile load-deformation curves for samples 6 and 9.

pulp with much shorter fibers, leading to a more random fiber orientation and hence a more uniform structure. The accuracy of predictions for all the woven samples is in between the two extreme cases.

The main problem, which is responsible for the discrepancies, is the validity of Equation 5 in calculating the coefficient F_{12}. The various Tsai-Wu-type failure criteria differ from one another by the manner in which the coefficient F_{12} is determined [9]. Here, we chose Norris' result [4], which may not be entirely applicable to some of the fibrous sheets, such as textiles, in which the restrictions for the constituent fibers or yarns are relatively weak, allowing them to slip and move upon loading. This will contribute some prediction error. Evidence supporting this explanation is the accurate prediction for sample 7, a paper product in which fibers are tightly bonded together, and extremely poor predictions for the loosely formed nonwovens like samples 6, 9, and 10. We will discuss this effect in detail in the next section.

For simplicity, from now on, whenever we mention fiber movement in a structure under loading, it will include all the fiber (or yarn in the case of woven fabrics) movements such as slippage and reorientation in the structure.

MODIFYING THE THEORY AND THE NEW PREDICTIONS

It is now clear that in order to develop a theoretical tool to determine the shear strength of the fibrous sheet in place of a tedious experimental approach, we need to modify the original theory introduced earlier. To do that, we have to take into account the important factors that influence the accuracy of the theoretical predictions.

Of the possible sources for errors in the predictions we pointed out in the last section, fiber movement is the key factor. First of all, although the Tsai-Wu failure criterion is for anisotropic materials, to which textiles obviously belong, the fiber movement of textiles during deformation will augment this anisotropy, since fibers will slip or move differently according to their own orientation and location in the structure. This augmented or additional anisotropy caused by fiber movement is likely to be the primary reason that Equation 1 is not valid for textiles.

To demonstrate the tensile strength anisotropy, we have tested the samples at seven different directions as introduced in reference 6, and the results for some of the representative samples are given in Table III. Next, for each sample, we find the maximum σ_{max} and minimum σ_{min} tensile strengths and their corresponding directions, as shown in Table II. We then calculate another ratio a,

$$a = \frac{\sigma_{max}}{\sigma_{min}} \quad . \tag{7}$$

This a value offers us an indicator of the degree of anisotropy of the material, including both the inherent and augmented anisotropy.

As a demonstration that the ratio a can indeed represent the strength anisotropy of the materials, we have constructed Figure 5 to compare the tensile strengths tested at different directions for three samples, employ-

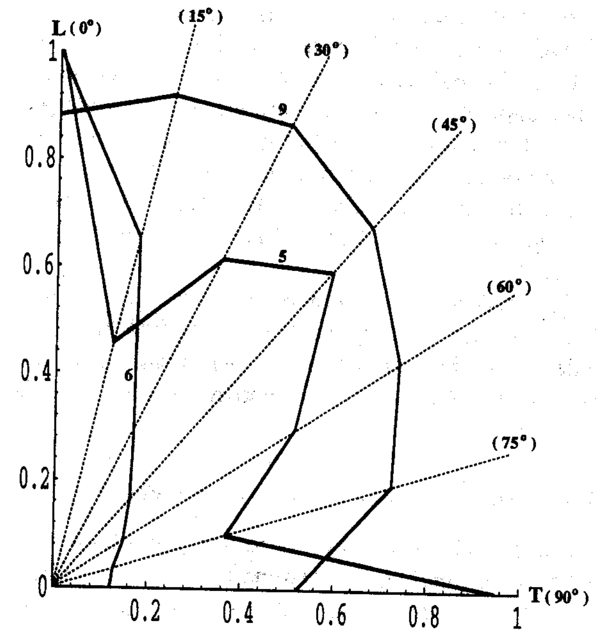

FIGURE 5. The tensile strength anisotropy of sample 5, 6, and 9.

ing the data from Table III normalized using their maximum values. Of the three samples in the figure, it is evident that sample 9 is the closest to an isotropic material, and sample 6 is the most anisotropic one. The *a* values in Table II for the three samples show the same trend.

To study the relationship between the prediction accuracy of shear strength and the augmented anisotropy of the material, we plot the two ratios, $\tau_{Ltest}/\tau_{Lpre1}$ versus $\sigma_{max}/\sigma_{min}$, in Figure 6. Note again that the ratio $\sigma_{max}/\sigma_{min}$ is an indicator of the sample tensile strength anisotropy, and $\tau_{Ltest}/\tau_{Lpre1}$ measures the accuracy of the prediction for the sample shear strength. As the figure shows, the ten samples can be approximately categorized into three groups. Group 1 includes samples 9 and 10, characterized by low $\sigma_{max}/\sigma_{min}$ and relatively high $\tau_{Ltest}/\tau_{Lpre1}$ ratios. Group 2 consists of sample 6 alone, a lofty and loosely entangled fiber sheet with extremely high anisotropy and inaccuracy of shear strength prediction. Note that the samples in these two groups are all nonwoven materials. In between the two groups, we find the rest of the samples fall into Group 3, all woven fabrics except sample 7, which is paper. The level of anisotropy for this group is moderate, and shear strength prediction accuracy is relatively high. Furthermore, we find that the effect of $\sigma_{max}/\sigma_{min}$ on the prediction accuracy of shear strength represented by the ratio $\tau_{Ltest}/\tau_{Lpre1}$ is roughly linear. This suggests that there may exist a relationship,

$$\frac{\tau_{Ltest}}{\tau_{Lpre1}} = \kappa \frac{\sigma_{max}}{\sigma_{min}} = \kappa a \quad , \tag{8}$$

where κ is a factor to be determined. Apparently, because κ will take different values for different materials, as revealed in Figure 6, it is a variable related to material properties. A simple statistical treatment will help us determine κ values for the three groups of fabrics. We obtain results of $\kappa_1 = 2.5$, $\kappa_2 = 1.5$, and $\kappa_3 = 0.6$, where the subscripts represent the three groups.

Once we know κ_i we can rearrange Equation 8 into

$$\tau_{Ltest} = a\kappa\tau_{Lpre1} \quad . \tag{9}$$

Bringing Equation 1 into it, we obtain a new equation to predict the tested shear strength τ_{Ltest} by

$$\tau_{Lpre2} = \frac{a\kappa}{\sqrt{F_{66}}} \quad . \tag{10}$$

This is the modified version for Equation 1, which we expect to yield more accurate shear strength predictions for fibrous sheets.

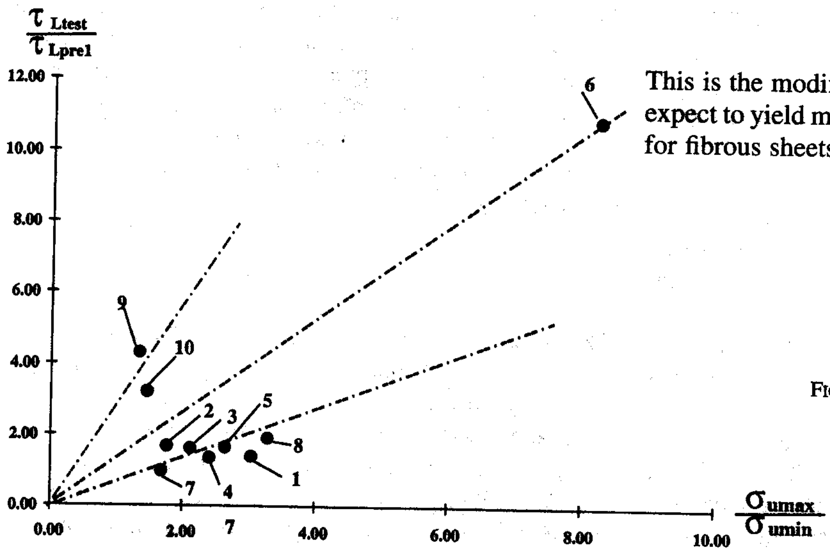

FIGURE 6. The ratio $\tau_{Ltest}/\tau_{Lpre1}$ versus $\sigma_{max}/\sigma_{min}$.

The new predictions using Equation 10 and incorporating different κ_i values for corresponding samples are also provided in Table II. Notice Table IV gives all the related factors as well as the values of σ_ϕ, where $\phi = 45°$. For easy comparison, we again calculate a ratio,

$$b_{\text{new}} = \frac{\tau_{L\text{test}}}{\tau_{L\text{pre2}}} \quad . \tag{11}$$

Judging from the values of b_{new} in Table II, we can conclude that the predictions using the modified theory, Equation 10, have improved considerably compared with the old results.

From the modified theory in Equation 10, we believe there are two major factors that make the Tsai-Wu failure criterion invalid for fibrous sheets. The first one is what we called the augmented anisotropy in this study, which is caused by fiber movement during material deformation. Reorientation, movement, and possible slippage of the constituent fibers or yarns in a textile structure will induce additional property anisotropy in the material, which leads to deviation of the predictions from the tested results of shear strength. This effect, however, can be rectified by the ratio a used in Equation 10.

Besides the anisotropy of the material, the intrinsic structure of a sample will also significantly affect the prediction accuracy of shear strength. For example, judging from the a values, samples 7, 9, and 10 are among those most close to being isotropic. However, the accuracy of the shear strength predicted using Equation 1 for the three samples varies enormously, as shown in Table II; among all the predictions, that for sample 7 is the most accurate, and those for samples 9 and 10 are the least accurate. This is also shown clearly in Figure 6, where a lower anisotropy value (a smaller $\sigma_{\max}/\sigma_{\min}$) does not necessarily lead to a better shear strength prediction (a smaller $\tau_{L\text{test}}/\tau_{L\text{pre1}}$). The explanation for this is due to the nature of the structure, for instance, the fiber and yarn properties and the different ways the constituents are assembled into various structures. This influence has been taken into account by the coefficient κ in the modified theory.

Conclusions

The Tsai-Wu failure criterion is not valid for textiles, mainly because of fiber slippage and movement during loading, which leads to a much lower prediction of shear strength. Yet for fibrous sheets like paper, with negligible fiber movement or slippage, the prediction using Tsai-Wu's theory is accurate.

The new apparatus introduced in this study for measuring the in-plane shear strength of fibrous sheets is effective. From the test results, we conclude that fiber movement during deformation of the samples is largely responsible for the difference in tensile and shear behavior of the materials. Fiber movement also induces additional structural anisotropy or property-direction dependence, which makes most fibrous sheets unique in comparison with other ordinary anisotropic solids, whose failure criterion forms an elliptic shape in a planar coordinate system.

For fibrous sheets to which the original Tsai-Wu theory is not applicable, we have developed a modified theory in this study by considering two factors: one is the augmented anisotropy caused by fiber movement in a fibrous sheet under deformation, and the other is due to structural differences. We therefore introduce two coefficients in the modified theory—coefficient a can be calculated from fabric tensile strength, and $\kappa = 0.6$ is found here for woven fabrics. More samples are needed to determine κ values for other fabric types, and even for woven fabrics if a higher reliability is required.

Compared with the original predictions, the results from the modified theory are in much better agreement with the tested values. The prediction error is within the generally accepted allowance for engineering applications.

TABLE IV. Coefficients of the strength tensor of fabrics.

Fabric	F_{11}, 10^{-6}	F_{22}, 10^{-6}	F_{12}, 10^{-6}	F_{66}, 10^{-6}	$\sigma_{45°}$, N
1	5.39	7.90	−3.26	56.23	226.18
2	27.52	25.67	−13.29	157.87	147.98
3	14.61	13.64	−7.06	68.93	206.58
4	24.56	39.43	−15.56	131.57	159.94
4	23.23	25.85	−12.25	107.55	173.85
6	590.27	40000.00	−2429.54	45148.40	9.41
7	45.79	118.59	−36.84	285.27	113.58
8	21.36	27.81	−12.19	15.96	147.29
9	794.39	2274.07	−672.03	2671.00	38.52
10	1516.39	2947.28	−1057.03	10548.80	19.45

Literature Cited

1. Asvadi, S., and Postle, R., An Analysis of Fabric Large Strain Shear Behavior Using Linear Viscoelasticity Theory, *Textile Res. J.* **64**, 208 (1994).
2. Hearle, J. W. S., Grosberg, P., and Backer, S., "Structural Mechanics of Yarns and Fabrics," vol. 1, Wiley-Interscience, NY, 1969, p. 372.
3. Kawabata, S., "The Standardization and Analysis of Hand Evaluation," 2nd ed., The Textile Machinery Society of Japan, Osaka, Japan, 1980.
4. Norris, C. B., Strength of Orthotropic Materials Subjected to Combined Stress, Report No. 1816, USDA Forest Service, Forest Products Laboratory, Madison, WI, 1950.
5. Pan, N., An Analysis on Woven Fabric Strength: Prediction of Fabric Strength Under Uniaxial and Biaxial Extensions, *Composites Sci. Technol.* **56**, 311 (1996).
6. Pan, N., and Yoon, M. Y., The Structural Anisotropy, Failure Criterion, and Shear Strength of Woven Fabrics, *Textile Res. J.* **66**, 238 (1996).
7. Postle, R., Carnaby, G. A., and de Jong, S., "The Mechanics of Wool Structure," Ellis Horwood Limited, England, 1988, p. 340.
8. Pouyet, J., Huchon, R., and Vidal, F., Predicting Compressive and Shear Strengths of Polymer or Paper Sheets from Off-axial Tensile Tests, in "Mechanics of Wood and Paper Materials," Proc. Winter Annual Meeting of ASME, AMD-V. 112, MD-V. 23, R. W. Perkins, Ed., 1990, p. 99.
9. Rowlands, R. E., Gunderson, D. E., Suhling, J. C., and Johnson, M. W., Biaxial Strength of Paperboard Predicted by Hill-type Theories, *J. Strain Anal.* **20**, 121 (1985).
10. Subramaniam, V., Sivakumar, M., Srinivasan, V., and Sasikala. M., Determining Factors that Affect Fabric Shear Behavior with the Twist Method, *Textile Res. J.* **60**, 368 (1990).
11. Sinoimeri, A., and Drean, J. Y., A Study of the Mechanical Behavior of the Plain-weave Structure by Using Energy Methods—Fabric Shear, *J. Textile Inst.* **87**, 120 (1996).
12. Treloar, L. R. C., The Effect of Test-piece Dimensions on the Behavior of Fabrics in Shear, *J. Textile Inst.* **56**, T533 (1988).
13. Tsai, S. W., and Wu, E., A General Theory of Strength for Anisotropic Materials, *J. Compos. Mater.* **5**, 58 (1971).

Manuscript received February 26, 1996; accepted October 29, 1996.