Grab and Strip Tensile Strengths for Woven Fabrics: An Experimental Verification

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ABSTRACT

In the present study we have attempted to verify a theoretical model of grab versus strip strengths of fabrics [*Textile Research Journal*, 2003, 73(2), 165–171] through experimental investigation. Five different fabrics were included in this study, and three related parameters were investigated including the modulus ratio of the specimen (shear versus tensile moduli), the specimen gauge length and the ungripped specimen width. The ratios of grab versus strip tensile strengths were computed from the experimental results and compared with the values predicted from the theoretical model. The predicted results are compatible with the measured values, suggesting that the theoretical model is capable of estimating the tensile strength of a grab specimen.

Tensile strength is one of the most important mechanical properties for woven fabrics. To quantify the tensile strength of a piece of fabric, two testing methods are often used, namely the grab test and the strip test. Each testing method has its own advantages and drawbacks. Specimens in the grab test are easier to prepare, and the testing condition is closer to the load application on a fabric in practical use. However, the results of the grab test may not be as accurate and interpretable as those of the strip test, but the preparation of unraveled strip specimens usually takes up time [1, 2, 3]. Both testing methods have been standardized as the ASTM standard D5034-95 for the grab test and D5035-95 for the strip test, respectively. Given the wide application of both testing methods, it is desirable to establish the relationship between these two methods from both theoretical and experimental viewpoints.

A few studies have been reported work towards establishing the relationship between the grab and strip tests. These early investigations attempted to explore the relationship from empirical approaches [2, 5]. However, the breaking mechanisms and physical implications involved cannot be obtained from those studies.

Recently, Pan [3] conducted a theoretical investigation to relate the grab and strip tensile strengths of a fabric. In his model a grab specimen is basically divided into two portions, the gripped part held by the machine grips, acting essentially like a strip specimen, and the ungripped parts on each side of a grip, as shown by Figure 1a. A herringbone deformation mode as seen in Figure 1b was adopted for the ungripped portions caused by the tensile load during the test. According to continuum mechanics, the shear forces within the herringbone elements contribute to the generation of tensile stress in the ungripped portion. With the assumptions of roughly linear mechanical behavior of a fabric specimen as well as the negligence of the Poisson effect, the tensile stress in the ungripped portions can be expressed in terms of gauge length, ungripped specimen width, machine clamp width, and tensile and shear modulus of the specimen, among other variables. The overall tensile strength for a grab specimen can thus be calculated as the combination of the contributions from both ungripped and gripped parts. In other words, the tensile strength of the ungripped portions obviously determines the difference between the grab and the strip tensile strengths for a fabric specimen.

In the present study we attempted to verify the predictions of Pan's model [3] through experimental investigation. According to the theoretical predictions, we first studied the influence of the tensile and shear moduli by measuring five different fabrics with the sample size determined from the aforementioned two ASTM standards. Then, we chose one fabric type and investigated the effects of the specimen gauge length and the ungripped specimen width, respectively. The ratios of the grab versus strip tensile strengths were computed from the experimental results and finally compared with the values predicted from Pan's model [3].

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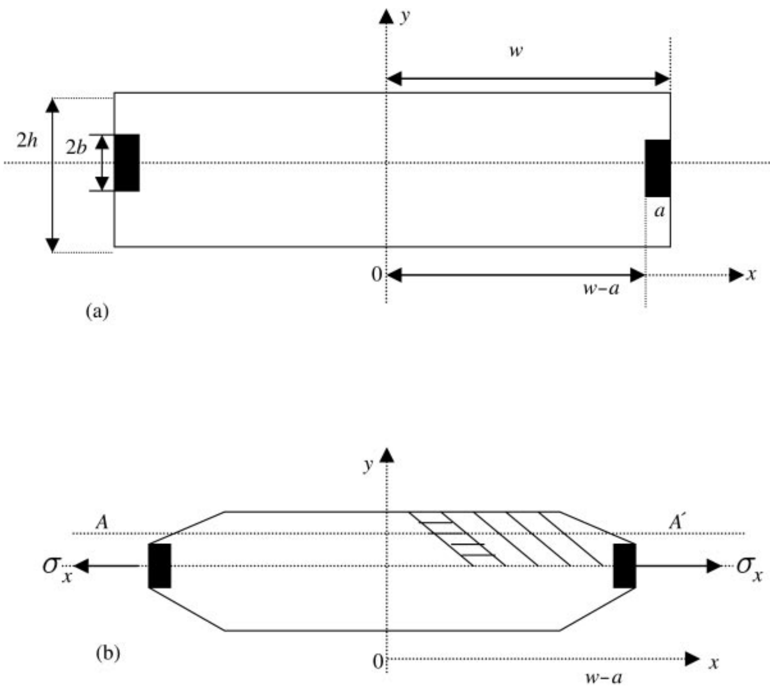


FIGURE 1. The schematic diagram of a grab specimen.

Predictions from the Theoretical Model

Figure 1a shows the schematic diagram of a grab specimen with the length of $2w$ and the width of $2h$. The machine clamps holding the specimen are $2b$ wide and a long. The overall tensile strength for the specimen is contributed from both the gripped portion held by the machine clamps and the ungripped portions including both top and bottom parts. The herringbone deformation is assumed for the ungripped portions of the specimen subjected to an external tensile load. The overall tensile force from both the top and bottom ungripped portions of the specimen was derived in detail by Pan in [3]

$$F_e = \sigma_x(h-b) \times \left[1 - (h-b) \frac{\tanh\left(\frac{2(w-a)}{h-b} \sqrt{\frac{G_{xy}}{E_x}} \right)}{2(w-a)\sqrt{\frac{G_{xy}}{E_x}}} \right] . \quad (1)$$

where σ_x is the external tensile stress applied directly on the entire width of the specimen through machine clamps; G_{xy} and E_x are the respective shear and tensile modulus of the specimen; w–a is the one-half of the specimen gauge length between two clamps, h–b is the width of the top or bottom ungripped portion of the specimen, respectively.

The overall tensile load applied to the grab specimen was hence given in [3] as

$$F_g = F_r + F_e = 2b\sigma_x + \sigma_x(h-b) \times \left[1 - (h-b) \frac{\tanh\left(\frac{2(w-a)}{h-b} \sqrt{\frac{G_{xy}}{E_x}} \right)}{2(w-a)\sqrt{\frac{G_{xy}}{E_x}}} \right] \quad (2)$$

where F_r is the tensile load applied to the gripped portion of the specimen through machine clamps, which is equal to $2b\sigma_x$.

Therefore, the ratio of the grab versus strip tensile breaking loads for a fabric specimen can be expressed as

$$\lambda = \frac{F_g}{F_r} = 1 + \frac{1}{2}\frac{(h-b)}{b} \times \left[1 - (h-b) \frac{\tanh\left(\frac{2(w-a)}{h-b} \sqrt{\frac{G_{xy}}{E_x}} \right)}{2(w-a)\sqrt{\frac{G_{xy}}{E_x}}} \right] \quad (3)$$

It is worth mentioning that although tensile breaking loads instead of strength were measured in the present experimental study because of the difficulty in accurately determining the cross-sectional areas of fabric specimens, equation (3) is valid for both breaking load and strength. For brevity, however, we still use the term strength rather than breaking load in the following discussion.

Experimental Investigation

As revealed by equation (3), the ratio λ of the grab versus strip strength for a fabric specimen is related to the modulus ratio G_{xy}/E_x, the ungripped specimen width *h–b*, and the tensile gauge length *w–a*. We first investigated the influence of the modulus ratio G_{xy}/E_x,; that is, the mechanical properties of fabrics, on the ratio λ. Five different fabrics were included in our experimental investigation, four of which were woven fabrics and one was a plastic film. Then, fabric 1 was chosen to study the influence of the specimen size on the ratio λ; that is, the tensile gauge length *w–a* as well as the ungripped specimen width *h–b*. Details of the fabric properties are given in Table I.

Table II shows the specification of all the tensile specimens. Specimens 1–10 were used to investigate the effects of modulus ratio G_{xy}/E_x. Specimens 1–5 were the raveled strip specimens from fabrics 1 to 5, respectively, with the specimen size of 25.4 mm × 152.4 mm (1 inch × 6 inches) according to the standard ASTM D5035-95. Specimens 6–10 were the grab specimens from fabrics 1 to 5, respectively, with the specimen size of 101.6 mm × 152.4 mm (4 inches × 6 inches) following the standard ASTM D5034-95. Specimens 11–15 together with specimen 6 were the grab specimens of fabric 1 with varied gauge length *w–a*, but a constant ungripped specimen width *h–b*. These six specimens were used to investigate the effect of specimen gauge length on the ratio λ. Specimens 16–19 plus specimen 6 were the grab specimens of fabric 1 with different ungripped specimen width *h–b* and a constant gauge length *w–a*. These five specimens were used to study the effects of ungripped specimen width *h–b* on the ratio λ.

The tensile tests were conducted on an Instron tester model 4465. The size of the clamps remained unchanged throughout the experimental study as 25.4 mm by 25.4 mm (1 inch × 1 inch), i.e., $a = 25.4$ mm and $b = 12.7$ mm. All the tensile tests were performed at the crosshead speed of 50 mm/min (2 inches/min). Data collection was conducted through a computerized data acquisition system, and a load–displacement plot was recorded to estimate the modulus of the specimen. When conducting a grab tensile test, a grab specimen was gripped in the center of the specimen width to ensure equal ungripped top and bottom portions. A custom-made apparatus [4] was used to conduct shear experiments, by being mounted on the Instron tester as shown in Figure 2. The shear specimens were cut to the size of 50.8 mm by 25.4 mm (2 inch × 1 inch). The crosshead speed was 10 mm/minute for all the shear experiments. The *nominal* tensile modulus E_x' and shear modulus G_{xy}' were calculated, respectively, as the slopes of the initial linear portion of the load–displacement plot. The values of E_x', G_{xy}' and the corresponding true modulus ratios G_{xy}/E_x are presented in Table I. The details of the measurement of E_x' and G_{xy}' and the calculation of the modulus ratio G_{xy}/E_x are referred to the Appendix.

TABLE II. Specifications of fabric specimens and the experimentally measured and theoretically predicted λ.

Type	Specimen no.	Fabric no.	*h–b* (mm)	*w–a* (mm)	λ_{exp}	λ_{pre}	$\lambda_{exp}/\lambda_{pre}$
Strip	1	1	0	38.1	–	–	–
	2	2	0	38.1	–	–	–
	3	3	0	38.1	–	–	–
	4	4	0	38.1	–	–	–
	5	5	0	38.1	–	–	–
Grab	6	1	38.1	38.1	1.142	1.013	1.13
	7	2	38.1	38.1	1.206	1.005	1.20
	8	3	38.1	38.1	1.505	1.021	1.47
	9	4	38.1	38.1	1.939	1.019	1.90
	10	5	38.1	38.1	2.704	1.257	2.15
	11	1	38.1	12.7	1.122	1.002	1.12
	12	1	38.1	25.4	1.094	1.006	1.09
	13	1	38.1	50.8	1.119	1.024	1.09
	14	1	38.1	76.2	1.095	1.052	1.04
	15	1	38.1	127.0	1.180	1.135	1.04
	16	1	12.7	38.1	1.083	1.037	1.04
	17	1	25.4	38.1	1.098	1.020	1.08
	18	1	50.8	38.1	1.039	1.010	1.03
	19	1	63.5	38.1	1.134	1.008	1.13

Note that λ_{exp} and λ_{pre} denote the experimentally measured and theoretically predicted ratio λ, respectively.

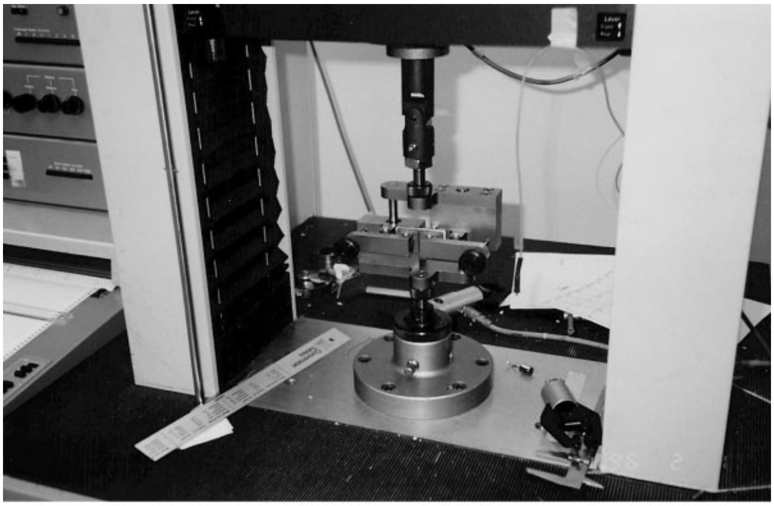
Results and Discussion

The experimental and predicted ratios λ for five different fabrics are presented in Table II. All λ values from both the

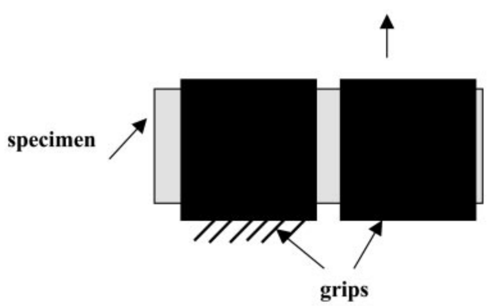
TABLE I. Details of fabric samples.

Fabric no.	Construction	Material	Type	Weight (g/m²)	Thickness (mm)	E_x' (N/mm)	G_{xy}' (N/mm)	$\frac{G_{xy}}{E_x}$	$\frac{\overline{G_{xy}}}{E_x}$
1	woven	cotton	plain (78x58)	125.81	0.38	36.75	19.02	0.0068	0.0012
2	woven	cotton	plain (76x46)	162.49	0.44	50.48	9.69	0.0025	0.0019
3	woven	wool	satin (38x28)	263.50	1.00	11.00	9.16	0.0109	0.0065
4	woven	polyester	plain (100x88)	59.30	0.11	21.78	15.56	0.0094	0.0274
5	film	polyethylene	-	487.55	0.71	31.29	384.98	0.1615	0.1405

Note that the calculations of G_{xy}', E_x' and G_{xy}/E_x are referred to the Appendix.



(a)



(b)

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

experiment and prediction are shown to be greater than 1, reflecting that the tensile strength of a grab specimen is always higher than that of a strip specimen [3]. Judging from the values of $\lambda_{exp}/\lambda_{pre}$, it seems that both experimental and theoretical results are in good agreement, and the discrepancies between them are probably attributable to the negligence of the stress variation along the *y*-axis and the frictions between the shear elements in the theoretical model, and the assumption of linear tensile behavior of the fabrics [3]. However, it is proved in a later section that the unusually high $\lambda_{exp}/\lambda_{pre}$ value for fabric 5 is caused by the experimental error.

EFFECTS OF GAUGE LENGTH *w–a*

The experimental and predicted ratios λ are presented against the specimen gauge length *w–a* for fabric 1 (specimens 6 and 11–15) in Table II, and is displayed in Figure 3. A similar trend can be observed between them, in which a longer specimen would yield a higher contribution from the ungripped portions of a grab specimen.

The experimental results differ most from the predicted values at short gauge lengths (Figure 3). This can be explained from the perspective of the breakage mechanism of a grab specimen. A grab specimen would break first at the gripped portion and then propagate to the ungripped portions. When $w–a = 0$, in theory the breakage of a grab specimen can only occur in the gripped portion and would not propagate to the ungripped portion

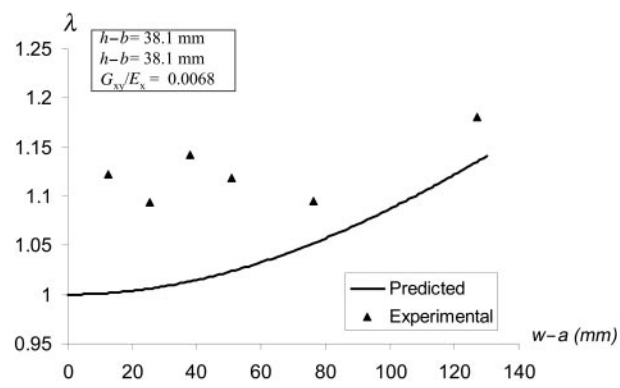


FIGURE 3. Comparison of experimental and predicted λ for fabric 1 with respect to gauge length *w–a*.

due to zero shear stress and strain on the ungripped portion. Therefore, no tensile strength would be generated within this region. However, as pointed out by Pan [3], in reality the breakage of the gripped portion would soon provide a non-zero gauge length for the grab specimen, which in turn would yield tensile strength within the ungripped portion. In other words, in reality the ratio λ would be greater than 1 even for $w–a = 0$, as verified by the experimental results in Figure 3.

Note that since we are comparing the grab and strip specimens at the same gauge lengths so the influence associated with the scale effect is non-existent here.

EFFECTS OF UNGRIPPED SPECIMEN WIDTH $h–b$

The experimental and predicted ratios λ are presented against the ungripped specimen width $h–b$ for fabric 1 (specimen 6 and 16–19) in Table II and Figure 4. Again, a similar trend can be observed between the experimental and predicted ratios λ such that the ratio λ first increases with the ungripped specimen width $h–b$ and then declines after it reaches the maximum. Yet, all the predicted ratios λ are less than those experimental ones. Moreover, the critical point the maximum λ is reached for the predicted results appears smaller and occurs at a lesser value of $h–b$ than that in the experimental result. Yarn jamming or fabric buckling, which becomes inevitable at large $h-–b$ values (wide grab specimen) is likely responsible for the high discrepancy at the point when $h–b = 60$ mm.

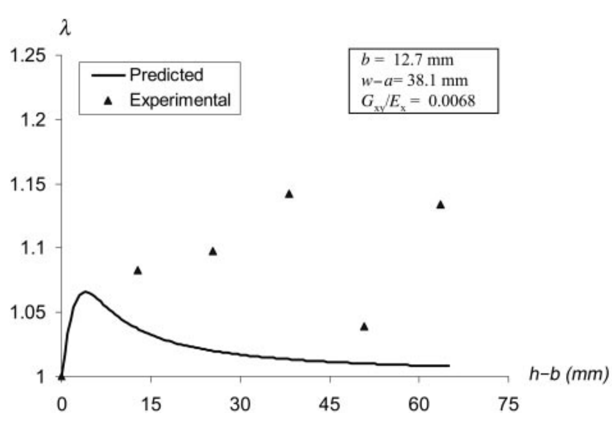


FIGURE 4. Comparison of experimental and predicted λ for fabric 1 with various un-gripped specimen width $h–b$.

EFFECTS OF MODULI RATIO G_{XY}/E_X

In fact, the modulus ratio $\frac{G}{E} = \frac{1}{2(1 + v)}$ in an isotropic material is directly related to its Poisson effect v in the material. A similar implication should be qualitatively true for G_{xy}/E_x value in relation to the tightness of a fabric. For a given fabric, a smaller G_{xy}/E_x indicates a looser connection between the deformations in y and x (or warp and weft) directions, and hence more likely justifiable for the negligence of the horizontal components of the tensions in the herringbone elements and frictions between these elements. For example, for fabric 4 (a tightly woven polyester fabric), the horizontal components of the tensions in the herringbone elements and frictions between these elements may be too large to be neglected. Next, as the theoretical model [3] is established on the assumption of linear mechanical behavior, some nonlinearity will more or less swing the prediction.

The relationship between the ratio λ and the modulus ratio G_{xy}/E_x is displayed in Figure 5 for both the experimental and predicted results. We have to admit that the consistency between the theoretical and experimental results is rather poor, and thus reveals the complex role G_{xy}/E_x plays here. It is actually not surprising to anticipate that this ratio G_{xy}/E_x must be changing during a specimen breakage, as the fabric structure is increasingly tighter.

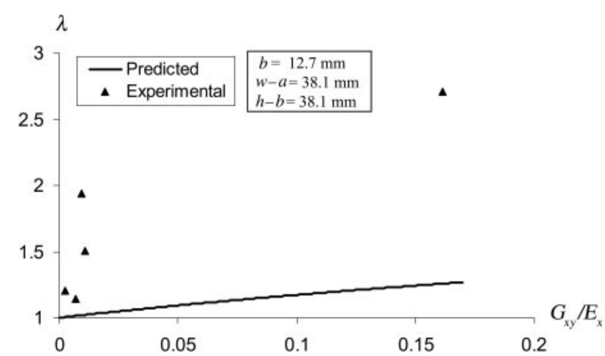


FIGURE 5. Comparison of experimental and predicted λ for five fabrics of various G_{xy}/E_x.

THE MODEL AT THE STANDARD SAMPLE SIZES

If choosing the standard sample and grip sizes, we have $2h = 101.6$ mm (4 inches), $2b = 25.4$ mm (1 inch), $2w = 127$ mm (5 inch), $a = 25.4$ mm (1 inch), or $h–b = 38.1$ mm (1.5 inch), $b = 12.7$ mm (0.5 inch), $w–a = 38.1$ mm (1.5 inch), then equation (3) reduces to

$$\lambda = \frac{F_g}{F_r} = 1 + 1.5\left[1 - \frac{\tanh\left(2\sqrt{\frac{G_{xy}}{E_x}}\right)}{2\sqrt{\frac{G_{xy}}{E_x}}}\right] \tag{3b}$$

and is a function of the moduli ratio G_{xy}/E_x alone. As seen in Figure 6 now, λ is monotonically increasing with G_{xy}/E_x, meaning that the strength difference between the grab and strip samples will be greater for a tighter fabric. As proposed in the theoretical model [3], the breakage of a grab specimen would in general originate at the center of the specimen and then propagate towards the edges, or from the gripped portion to the ungripped portions. A grab specimen with a higher shear modulus would generate a greater shear resistance at the ungripped portions after the gripped portion is broken, and impede the destruction within this region and finally result in a higher tensile strength.

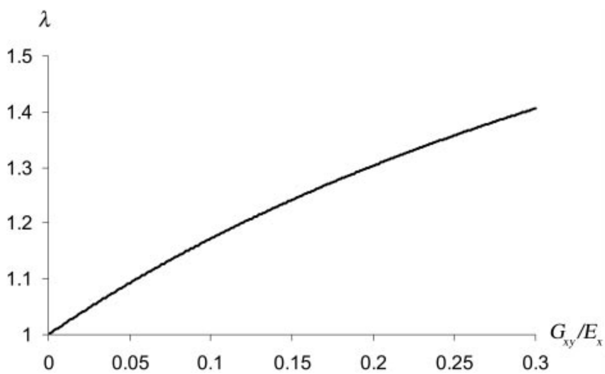


FIGURE 6. Theoretical predictions for λ for fabrics with standard size of grab specimens.

To reflect the fact that prior to the moment of breakage, the fabric structure becomes so much tighter that the ratio G_{xy}/E_x grows drastically. It can therefore be envisioned that a much greater G_{xy}/E_x value could greatly improve the prediction agreement. For instance by using equation 3(c)

$$\lambda = \frac{F_g}{F_r} = 1 + 1.5\left[1 - \frac{\tanh\left(2\sqrt{64\frac{G_{xy}}{E_x}}\right)}{2\sqrt{64\frac{G_{xy}}{E_x}}}\right] = 1 + 1.5\left[1 - \frac{\tanh\left(16\sqrt{\frac{G_{xy}}{E_x}}\right)}{16\sqrt{\frac{G_{xy}}{E_x}}}\right] \quad (3c)$$

Figure 7 can be constructed in place of Figure 5 and shows a much closer agreement with the experimental results. Furthermore, since in equation 3(b)

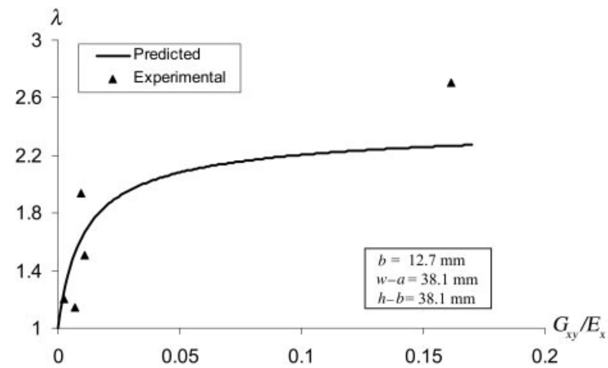


FIGURE 7. Revised theoretical predictions of λ and comparison with the experimental results.

$$\lambda = 1 \text{ when } G_{xy}/E_x \to 0$$

$$\text{and } \lambda = 2.5 \text{ when } G_{xy}/E_x \to \infty$$

that is, at the standard sample sizes, the parameter $\lambda < 2.5$ for any materials, the experimental value in Table II for the plastic film cannot be correct.

ANOTHER POTENTIAL APPLICATION

From the above discussion and our other publications, such as Pan [3], the moduli ratio G_{xy}/E_x has been shown to be a very effective parameter in characterizing the mechanical behavior of woven fabrics. In practice, however, this ratio, especially the fabric shear modulus G_{xy}, is not easy to determine experimentally as demonstrated in the Appendix, whereas the ratio $\lambda = F_g/F_\gamma$ is much more convenient to obtain through tensile test. Thus G_{xy}/E_x can be readily calculated by solving the equation 3(d) for a given λ value

$$\lambda - 1 - 1.5\left[1 - \frac{\tanh\left(16\sqrt{\frac{G_{xy}}{E_x}}\right)}{16\sqrt{\frac{G_{xy}}{E_x}}}\right] = 0 \quad (3d)$$

For differentiation, $\overline{\frac{G_{xy}}{E_x}}$ is used in Table I to represent the calculated results for each fabric, here we use $\lambda = 2.25$ for fabric 5 to correct the experimental error. As seen from the table, the predicted G_{xy}/E_x values show a fairly good agreement with the experimental data.

Conclusions

The predictions by Pan's model [3] are found to be consistent with the experimentally measured data for various fabrics. Pan's model thus can be used as a convenient tool in estimating the tensile strength applied on the ungripped portion of a grab specimen as well as the relationship between the tensile strengths of the grab and strip specimens. This study has confirmed the effects of important variables on the results; when all other corresponding variables are fixed, an increasing gauge length $w–a$ will lead to a higher $\lambda = F_g/F_\gamma$ value; the specimen width $h–b$ causes an initial increase in λ value, λ reaching a peak and then gradually leveling off as the width $h–b$ becomes larger. Further increase of $h–b$ will trigger sample buckling which will render the theoretical model no longer valid; fabric tightness or the ratio G_{xy}/E_x has a more profound effect on the λ value. In general, a tighter fabric leads to a higher λ value, but a correction factor has to be added into the model to improve the prediction agreement with the tested data.

Another perhaps more important application of the present model is to estimate the moduli ratio G_{xy}/E_x with a given $\lambda = F_g/F_\gamma$ value which is much easier to acquire experimentally. This could act as a very useful tool in characterizing the mechanical behavior of woven fabrics. Of course, the prediction accuracy of the model can be improved by taking the ignored factors including the vertical components of the tensions in the herringbone elements and frictions between these elements and fabric buckling if any during grab specimen test. However, it is our opinion that any small additional accuracy might not justify such a further complication of the model.

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Appendix

DETERMINATION OF THE TRUE MODULUS RATIO G_{XY}/E_X

Figure A1a and A1b are the schematic diagrams of tensile and shear tests, respectively. The thickness of the fabric is h. In Figure A1a, l is the gauge length, b is the specimen width and F is the external tensile forces. In Figure A1b, a is the gauge length, b is the specimen width, T is the external shear forces and θ is the deformation angle. In the present study the gauge length for the tensile specimens was 76.2 mm (l = 76.2 mm), whereas the gauge length for the shear test is very small

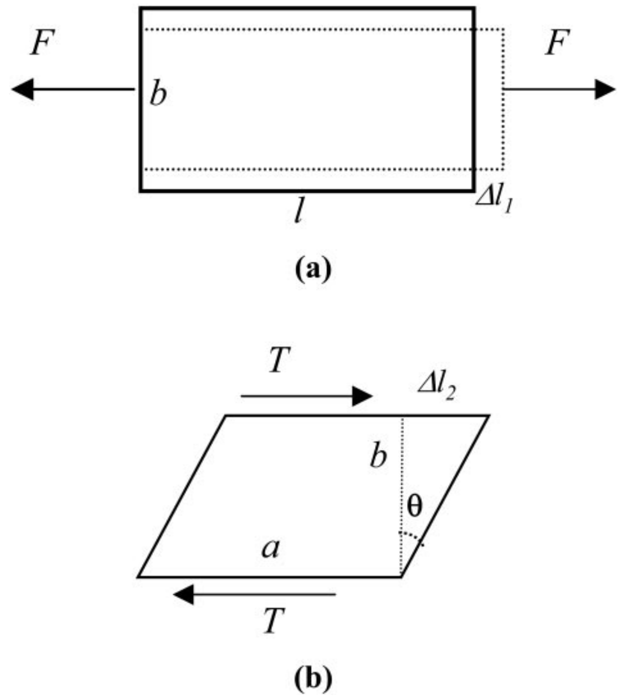

FIGURE A1. Schematic diagrams of tensile and shear tests. (a) tensile test and (b) shear test.

with respect to the custom-made shear apparatus (Figure 2), and can be estimated as 1 mm ($a \sim 1$ mm). Thus, the ratio l/a can be estimated to be close to 76.2 in this study.

By definition the tensile modulus is

$$E_x = \sigma/\varepsilon = \frac{F/(h \cdot b)}{\Delta l_1/l} \quad \text{(A1)}$$

and the shear modulus

$$G_{xy} = \tau/\theta = \frac{T/(h \cdot b)}{\theta} = \frac{T/(h \cdot b)}{\Delta l_2/a} \quad \text{(A2)}$$

where Δl_1 and Δl_2 are the displacement for the tensile and shear tests, respectively.

Hence

$$E_x/G_{xy} = \frac{F/(\Delta l_1/l)}{T/(\Delta l_2/a)} = \frac{F/\Delta l_1}{T/\Delta l_2} \cdot \frac{l}{a} = \frac{E_x'}{G_{xy}'} \cdot \frac{l}{a} \quad \text{(A3)}$$

where E_x' and G_{xy}' are the tangents obtained directly from the regular force–deformation curves, which were measured and calculated in the present study. In many cases, they have been treated as the tensile and shear moduli. However, as shown in equation (A3) that they are related to the genuine moduli by

$$\frac{E_x}{G_{xy}} = \frac{E_x'}{G_{xy}'} \cdot \frac{l}{a} \tag{A4}$$

The calculation of the modulus ratio G_{xy}/E_x thus followed this equation in the present study and the results are shown in Table I.

In standard tests, the gauge lengths $l > a$, which leads to

$$\frac{E_x}{G_{xy}} >> 1 \quad \text{or} \quad \frac{G_{xy}}{E_x} << 1 \tag{A5}$$

This of course is the result for fabrics, for it is much easier to shift yarns (shearing) than to extend them, which accounts for the excellent drape ability of fabrics.

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