Relationship Between Grab and Strip Tensile Strengths for Fabrics with Roughly Linear Mechanical Behavior

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Relationship Between Grab and Strip Tensile Strengths for Fabrics with Roughly Linear Mechanical Behavior

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ABSTRACT

A theoretical analysis is presented here to study the relationship between strengths tested using grab and strip specimens. The shear and tensile stress distributions at the portion of the grab specimen not directly stretched are derived. The total force carried by this portion is calculated, providing the difference between the test results of the two specimen types. Although the analysis is still primitive, the results nonetheless establish a foundation for a parametric analysis to show the effects of the factors.

In terms of specimen shapes, there are mainly two different kinds of tensile strength tests for woven fabrics, *i.e.*, grab and ravelled strip specimens. Although both specimens are designated as the ASTM standard (ASTM D 1682), because the dimensions of the grab specimen are larger, its breaking load is consequently greater than that for the strip method for the same fabric with an equal width inserted in the grips.

There are some advantages to using the grab specimen. First, it is much simpler to prepare the samples in comparison with the strip, especially the ravelled strip. Second, the test results of the grab method correspond more closely to load applications in practical use. It is usually true that accidental stretching of fabric occurs on a portion of a garment, similar to the grab test. The strip or ravelled strip tests usually provide more accurate results, which are easier to interpret. The grab specimen is extensively used by the textile industry, and the strip method is preferred by the research community. It is highly desirable, therefore, to establish the relationship between test results for two different specimens of the same fabric.

There have been at least two attempts to accomplish this task, *i.e.*, by Walen in 1916 [4] and by Eeg-Olofsson and Bernskiold [3]. However, both methods are largely empirical, and the physical implications are not clear in their treatments. Thus, our purpose in this study is to develop a more rigorous theoretical analysis to establish the relationship between the test results of the two sample types.

Theoretical Analysis

Our analysis should reveal the physics and the factors involved. A more accurate result can always be obtained with a finite element technique. Actually, since this problem is very similar to the one involving grip point spacing in a biaxial test of fabric dealt with by us (Bassett *et al.* [1]), we use the same mathematical approach here with some alterations wherever necessary.

Figure 1a is a schematic diagram of a grab specimen, which is held along the specimen ends by machine grips of width $2b$ and length a. The specimen is $2w$ long and $2h$ wide. The mean value σ_x of the uniaxial stress applied to the specimen through the grips as seen in Figure 1b equals the sum of forces divided by the specimen width held, assuming a unit thickness. The coordinate system in x refers to the unstrained state of the specimen. Since the specimen is symmetrical about the grips or the x direction, we need analyze only the top half of the specimen.

The portion of the fabric strip of width b held directly by the two grips should have a uniform tensile stress σ_x throughout the entire length of the specimen. While the tensile stress in the horizontal x direction at points along and above section AA' will, by intuitive reasoning, be smaller by being closer to the edges (designated as subscript e below) of the specimen and will approach the average stress σ_x toward the center (designated as c), both edges in the width (y) direction are obviously stress-free.

For simplicity, the fabric is assumed to be a continuum sheet made of closely packed yarns, initially straight in the y direction, which then deform into the herringbone pattern of straight segments shown in Figure 1b, and no yarn jamming or specimen buckling occurs prior to failure. Also, the effects of the fabric weave structure are not explicitly included (see later discussion).

Now consider the narrow strip above the line AA'. In a continuum, the only way tensile stress can be applied to

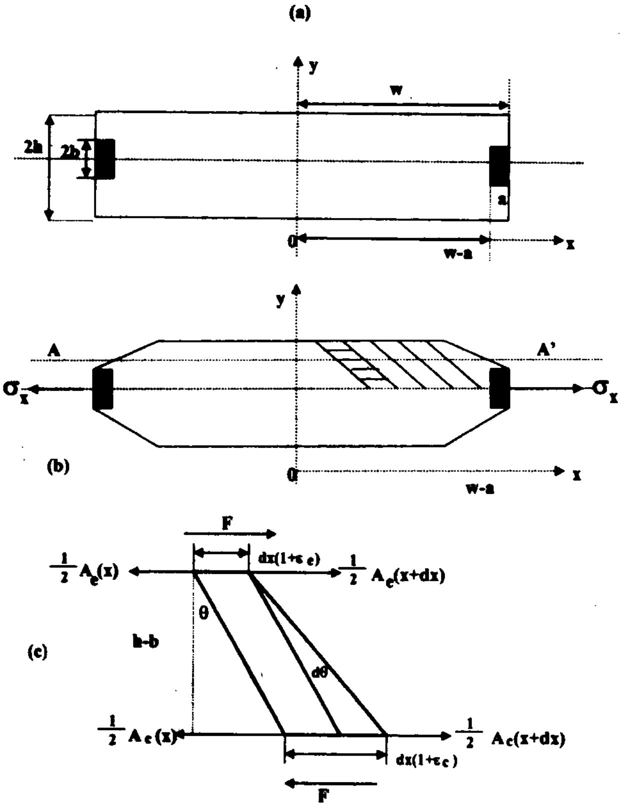

FIGURE 1. Illustration of fabric specimens and deformation: (a) fabric dimension and the coordinate system, (b) deformed fabric, (c) an element from the deformed fabric.

this strip is by reaction to the shear stress within the specimen. More specifically, the tensile stress in the ungripped parts of the specimen is generated by shear forces due to shear in the herringbone elements, and the horizontal components of the tensions in the inclined directions of the herringbone elements. The latter effect is neglected in this analysis. The effect of this assumption will be that the predicted stress distribution is more uneven than it would be otherwise.

The shear strain θ varies from zero at $x = 0$ (by symmetry) to some positive value at the ends in the x direction, due to the cumulative difference in tensile strain in the specimen. Figure 1c illustrates an element and its increment $d\theta$ in θ. We assume that θ is small, so that $\cos\theta \approx 1$. It follows that

$$d\theta = dx\,\frac{\epsilon_c - \epsilon_e}{h - b} \quad , \tag{1}$$

where ϵ_c and ϵ_e are the tensile strains closer to the center and to the edges, respectively.

It is possible that θ in a real fabric will become large, so that fabric jamming may occur, which would help the stress transfer. Additionally, the tension in the element in the y-direction would then have significant effects.

Assuming the material has linear stress-strain properties and the Poisson effects are negligible, the value of the forces F due to the shear of the element in Figure 1c is

$$F = \tau dx = G_{xy}\theta dx \quad , \tag{2}$$

where τ is the shear stress and G_{xy} is the fabric shear modulus.

Let the axial forces in the horizontal lines be given by some functions $A_e(x)$ and $A_c(x)$. The equations of equilibrium in the x-direction of the ends of the element in Figure 1c are as follows:

Close to the edges:

$$\frac{1}{2}A_e(x + dx) = \frac{1}{2}A_e(x) - F \quad , \tag{3}$$

Close to the center:

$$\frac{1}{2}A_c(x + dx) = \frac{1}{2}A_c(x) + F \quad , \tag{4}$$

i.e.,

$$A_c(x + dx) - A_c(x) = 2G_{xy}\theta dx \quad , \tag{5}$$

or

$$dA_c = 2G_{xy}\theta dx \quad . \tag{6}$$

Integrating,

$$A_c = 2G_{xy}\int \theta dx \quad , \tag{7}$$

where A_c represents the tensile force in a strip of width $h - b$, so that the tensile stress is

$$\sigma_c = 2\,\frac{G_{xy}}{h - b}\int \theta dx \quad . \tag{8}$$

Applying Hooke's Law,

$$\epsilon_c = 2\,\frac{G_{xy}}{(h - b)E_x}\int \theta dx \quad . \tag{9}$$

Similarly,

$$\epsilon_e = -2\,\frac{G_{xy}}{(h - b)E_x}\int \theta dx \quad , \tag{10}$$

where E_x is the tensile modulus of the fabric in x direction. Substituting into Equation 1,

$$\frac{d\theta}{dx} = \frac{4G_{xy}}{(h-b)^2E_x}\int \theta dx \quad , \tag{11}$$

or, differentiating,

$$\frac{d^2\theta}{dx^2} = \frac{4G_{xy}}{(h-b)^2E_x}\theta \quad . \tag{12}$$

Putting

$$k = \frac{4G_{xy}}{(h-b)^2E_x} \quad ,$$

and noting the boundary condition $x = 0$, $\theta = 0$, the solution to this equation can be found using standard methods:

$$\theta = c_1(e^{\sqrt{k}x} - e^{-\sqrt{k}x}) = 2c_1 \sinh(\sqrt{k}x) \quad , \tag{13}$$

and differentiating Equation 13 and equating it to Equation 1 yields

$$c_1 = \frac{\sigma_x}{2(h-b)E_x\sqrt{k}\cosh(\sqrt{k}(w-a))} \quad . \tag{14}$$

Substituting in the expressions of the constants and canceling the common terms, Equation 15 gives the shear strain distribution:

$$\theta = \frac{\sigma_x \sinh\left(\dfrac{2x}{(h-b)}\sqrt{\dfrac{G_{xy}}{E_x}}\right)}{\sqrt{E_xG_{xy}}\cosh\left(\dfrac{2(w-a)}{(h-b)}\sqrt{\dfrac{G_{xy}}{E_x}}\right)} \quad . \tag{15}$$

The shear stress follows:

$$\tau = G_{xy}\theta = \sqrt{\frac{G_{xy}}{E_x}}\,\frac{\sigma_x \sinh\left(\dfrac{2x}{(h-b)}\sqrt{\dfrac{G_{xy}}{E_x}}\right)}{\cosh\left(\dfrac{2(w-a)}{(h-b)}\sqrt{\dfrac{G_{xy}}{E_x}}\right)} \quad . \tag{16}$$

Substituting Equation 13 into Equation 8 and integrating, the tensile stress can be expressed finally as

$$\sigma_c = \sigma_x\left[1 - \frac{\cosh\left(\dfrac{2x}{(h-b)}\sqrt{\dfrac{G_{xy}}{E_x}}\right)}{\cosh\left(\dfrac{2(w-a)}{(h-b)}\sqrt{\dfrac{G_{xy}}{E_x}}\right)}\right] \quad . \tag{17}$$

Here, the boundary condition $x = w - a$, $\sigma_c = 0$ is used.

During a grab test, the grabbed and ungripped portions of the fabric specimen interact, causing a distribution of shear strain in the ungripped portions, as shown in Equation 15. Tensile stress in these portions builds up gradually, depending on the mechanical and geometric parameters.

The average tensile stress carried by the ungripped part of the fabric specimen is

$$\langle\sigma_c\rangle = \frac{1}{w-a}\int_0^{w-a}\sigma_c dx = \sigma_x\left[1 - (h-b)\frac{\tanh\left(\dfrac{2(w-a)}{(h-b)}\sqrt{\dfrac{G_{xy}}{E_x}}\right)}{2(w-a)\sqrt{\dfrac{G_{xy}}{E_x}}}\right] \quad , \tag{18}$$

and the load F_c is

$$F_c = 2\langle\sigma_c\rangle(h-b) = 2\sigma_x(h-b) \times \left[1 - (h-b)\frac{\tanh\left(\dfrac{2(w-a)}{(h-b)}\sqrt{\dfrac{G_{xy}}{E_x}}\right)}{2(w-a)\sqrt{\dfrac{G_{xy}}{E_x}}}\right] \quad , \tag{19}$$

noting that there are two parts of the ungripped portions in the fabric specimen.

The overall tensile load F_g applied to the grab specimen is

$$F_g = F_r + F_c = 2b\sigma_x + 2\sigma_x(h-b) \times \left[1 - (h-b)\frac{\tanh\left(\dfrac{2(w-a)}{(h-b)}\sqrt{\dfrac{G_{xy}}{E_x}}\right)}{2(w-a)\sqrt{\dfrac{G_{xy}}{E_x}}}\right] \quad , \tag{20}$$

where $F_r = 2b\sigma_x$ equals the overall tensile load applied to a strip specimen. When $h - b = 0$, we can easily show that $F_c \to 0$, so that the grab specimen case becomes a ravelled strip one. The ratio λ of the two loads corresponding to the two specimen types is

$$\lambda = \frac{F_g}{F_r} = 1 + \frac{h-b}{b} \times \left[1 - (h-b)\frac{\tanh\left(\dfrac{2(w-a)}{(h-b)}\sqrt{\dfrac{G_{xy}}{E_x}}\right)}{2(w-a)\sqrt{\dfrac{G_{xy}}{E_x}}}\right] \quad . \tag{21}$$

Note that the preceding analysis is in essence an approximation of a very complex problem. Consequently, we adopt some crude but necessary assumptions including the linear behavior of the specimen, the yarn herringbone deformation, and the negligence of the stress variations along the y-axis as well as the Poisson effect.

Also, the nonlinearity of a fabric is most significant when deformation developed within is largely caused by internal friction, fiber slippage, and yarn uncrimping.

Yet the linearity is less unacceptable for tight fabrics and fabrics made of more brittle fibers such as glass, Kevlar, or maybe cotton. Moreover, if we examine the complete stress-strain curves of either individual yarns or fabrics, we will find that at the moment prior to specimen failure, some of the assumptions such as linearity and yarn herringbone deformation are actually not too far from reality, provided fabric buckling doesn't occur.

Moreover, as shown above, the mathematical relationships thus obtained shed significant light on the effects of the related factors, and are much more robust than those from the previous studies. In fact, it would be interesting to compare Equation 21 with the empirical result by Eeg-Olofsson and Bernskiold [3], which can be expressed, using our symbols, as

$$F_g = \frac{b}{b_R} F_r + g_a \quad , \tag{22}$$

where the grab and strip tests were done at the grip width b and b_R, respectively, and g_a was termed the power absorption of the side yarns over the specimen gauge length. In our case, $b = b_R$ so that

$$F_g = F_r + g_a, \; \lambda_e = \frac{F_g}{F_r} = 1 + \frac{g_a}{F_r} \quad . \tag{23}$$

Since $\lambda_e = 1$ when $h = b$, the term g_a must diminish, which implies g_a has to be a function of h and b. Also, as stated in reference 3, g_a is dependent on the gauge length $w - a$. Furthermore, the moduli ratio of the fabric $\frac{G_{xy}}{E_x}$ is in fact a reflection of overall fabric mechanical behavior, so it also has to be included in g_a.

The immediate difference between the two results in Equations 21 and 23 is that in our model, λ is independent of the load F_r, unlike in Equation 23. We will compare the two models further in our later discussions.

Predictions and Discussion

From these results, we know that overall tensile loads and stress distributions at the regions of a grab sample not directly gripped are the functions of fabric mechanical properties, the dimensions of the specimen, and the grip size. The ranges of these related parameters, used in the following study, are provided in Table I.

SHEAR STRESS DISTRIBUTION IN THE SPECIMEN

Shear stress τ at the portion of the specimen indirectly stretched is given in Equation 16 as a function of the

TABLE I. Parameters for calculation.

Parameter	Range	Typical value
b, mm	0–50 (assumed)	25.4
$w - a$, mm	0–40 (assumed)	40
$h - b$, mm	0–20 (assumed)	5
$\frac{G_{xy}}{E_x}$	1/120–1/500 [2]	1/214

location x, specimen mechanical properties $\frac{G_{xy}}{E_x}$, sample length $2w$, and grip length a, fabric width $2h$, and grip width $2b$ at a given external tensile stress σ_x. Note that all the figures of stress distributions are plotted relative to the original tensile stress σ_x applied.

Figure 2a illustrates the distribution of shear stress along the fabric sample length and the effect of the moduli ratio $\frac{G_{xy}}{E_x}$, while the parameters $h - b$ and $w - a$ remain constant. The shear stress is at a maximum at both ends of the sample, descending inward until the center where it diminishes. A fabric sample with a higher

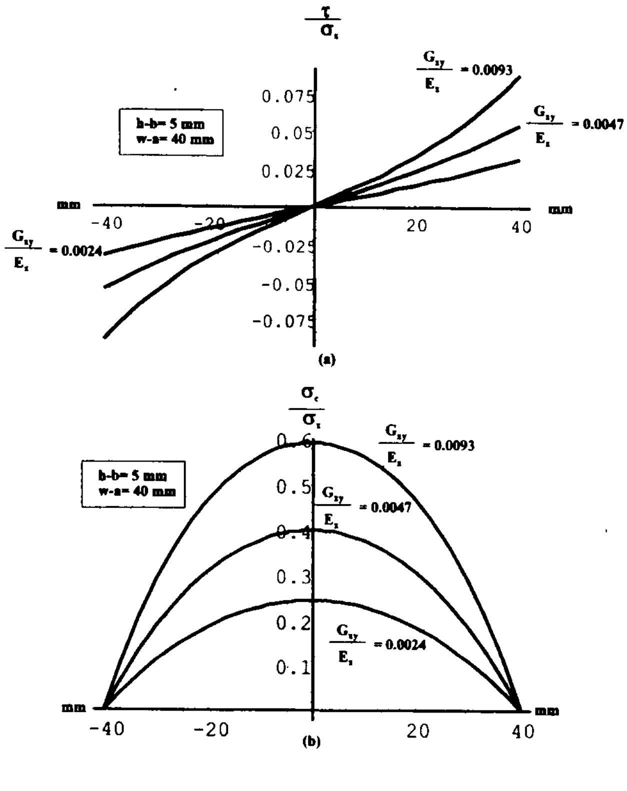

FIGURE 2. Stress distributions in the portions of fabric not directly stretched: (a) shear stress τ distribution and influence of the moduli ratio $\frac{G_{xy}}{E_x}$; (b) tensile stress σ_c distribution and influence of the moduli ratio $\frac{G_{xy}}{E_x}$.

$\frac{G_{xy}}{E_x}$ value, usually meaning a tighter fabric structure or higher inter-yarn friction, will have a shear stress of greater magnitude at the specimen ends and a steeper descending process.

TENSILE STRESS DISTRIBUTION IN THE SPECIMEN

Tensile stress in the ungripped areas is built up with the assistance of shear stress. The effects of important parameters on its distribution can be seen from Figure 2b for the tensile stress σ_c in Equation 17 in relative scale.

The figures show that the tensile stress is zero at the both ends of the sample and ascends to the maximum value at the center of the sample. We can also conclude from the figures that a tighter fabric with a greater modulus ratio $\frac{G_{xy}}{E_x}$ will generate a tensile stress distribution with greater magnitude along a cross section of specimen length such as marked by line AA' (see Figure 1b). Also, it indicates that even at the center where the tensile stress σ_c reaches a maximum, it may still be smaller than the external stress σ_x. This explains the often less tightened fabric portions at the ungripped parts of a specimen during a grab test, and this effect will be less apparent for a tighter fabric according to the prediction.

Furthermore, Equation 17 shows that for a grab test, when the external tensile stress σ_x reaches the breaking strength of the fabric, the directly grabbed portion of the specimen will break. However, the rest or the ungripped portions of the specimen have not yet broken, for σ_c in Equation 17 is always lower than σ_x, or the terms in the square brackets are always <1. This may explain why failure in a grab tensile test always occurs at the center of the specimen, and is always a gradual process. The stress in the center creates a break, and the break propagates on both sides into the ungripped portions of the specimen due to the stresses within. These stresses are smaller than the value required to initiate a break in the specimen, but they are able to propagate an existing one. A strip specimen breaks in a much shorter time, almost instantaneously if we ignore the viscoelasticity of the material.

Note also in the theoretical results that in the case when $w - a = 0$ or at the zero gauge length test $x = 0$, the shear strain and stress are both zero, which leads to zero tensile stress in the ungripped portions of the specimen. This may reveal that at zero gauge length, we could only create a break in the gripped portion of a grab specimen, but this crack would not develop into the ungripped portions. That is, in theory the grab specimen cannot be broken completely at a true zero gauge length because the shear mechanism no longer exists to generate tensions in the ungripped portions. Of course, in practice, there is no such thing as a true zero gauge length: as soon as a break occurs in the specimen, the associated elongation will provide a non-zero gauge length for the whole failure process to proceed. Further, for a ravelled strip test $h = b$, we will have $\sigma_c = \sigma_e = 0$, and the shear stress and strain in the fabric are nonexistent as well, as reflected by Equations 15, 16, and 17.

DIFFERENCE ANALYSIS AND PARAMETRIC STUDY

It is clear from our analysis that the fabric strength tested using the grab specimen is higher than that of a strip specimen. The difference is represented by the ratio λ in Equation 21.

From the equation, it is obvious that $\lambda > 1$, meaning again the breaking load for a grab specimen is always greater than that for the strip one. For the two extreme cases, including when $h - b = 0$ so that $\lambda = 1$, it becomes a strip specimen test and $F_c = 0$, whereas when $w - a = 0$, $\lambda = 1$ and $F_c \neq 0$ also, representing the true zero gauge length case discussed before.

The effect of fabric mechanical properties $\frac{G_{xy}}{E_x}$ on the ratio λ can be seen in Figure 3a. When other variables are fixed, a greater $\frac{G_{xy}}{E_x}$, or a tighter fabric, will lead to a higher λ value; the limit of the λ value is 1.2 when $\frac{G_{xy}}{E_x}$ approaches infinity. However, since the highest possible value for any material $\frac{G_{xy}}{E_x} = \frac{1}{3}$, $\lambda = 1.175$ only.

Since the whole term in the square brackets in Equation 21 is in the range of $[0,1]$, the value of λ is largely determined by the ratio $\frac{h-b}{b}$, as seen in the equation. When all other parameters are given as in Figure 3b, the influence of the grip width b is profound when its value is small, yet this influence levels off abruptly once b exceeds a certain value, *e.g.*, $b > 10$ mm in this case.

According to the plot by Eeg-Olofsson and Bernskiold, Figure 3 in reference 3, F_g and F_r versus b are both straight lines parallel to each other. We would argue that given the analysis in this work, it is unlikely that a linear relationship exists between the grip width b and the breaking load, for it is impossible to increase the breaking load of a fabric by widening the grip width without limit. Our study shows that $\lambda \to 1$ when $b \to \infty$, *i.e.*, a strip specimen case where the fabric ends are entirely gripped. Furthermore, the two parallel straight lines mean $F_g - F_r =$ a constant, as indicated in Equation 23,

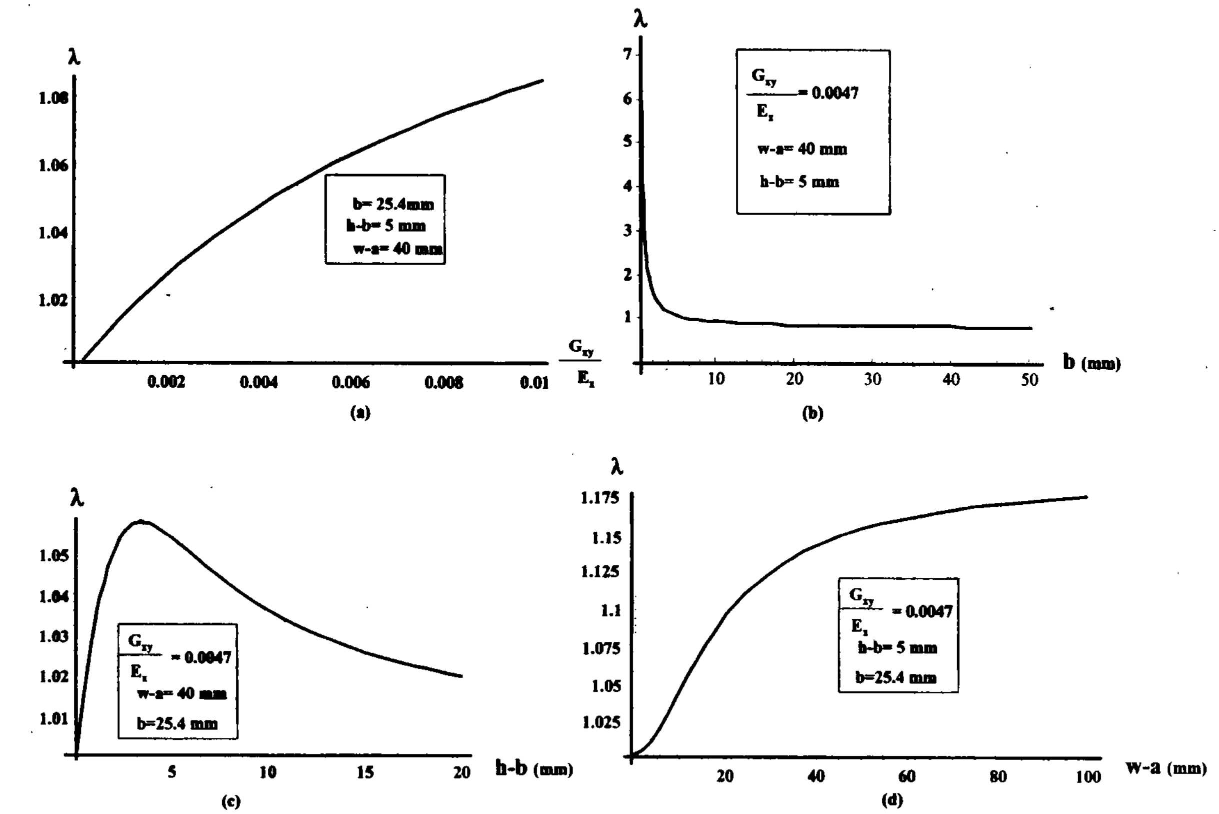

FIGURE 3. Parametric study of ratio $\lambda = \frac{F_g}{F_r}$: (a) influence of the moduli ratio $\frac{G_{xy}}{E_x}$, (b) influence of the factor b, (c) influence of the factor $h - b$, (d) influence of the effective gauge length $w - a$.

whereas our result shows that $\lambda = \frac{F_g}{F_r}$ = a constant only when $b > 10$ mm.

Next, the λ value is slightly affected by the parameter $h - b$, the width difference between the grab and strip samples, as shown in Figure 3c, and the relation is not monotonic, when $h - b$ increases to a critical value (≈4 mm here), λ will grow to its maximum value, and it will decrease with further increases of $h - b$. When all other parameters are as given in Figure 3c, $\lambda \rightarrow 1$ as $h - b \rightarrow \infty$.

The effective gauge length $w - a$ also influences the λ value, as seen in Figure 3d, and the relation is again nonlinear. When the gauge length $w - a = 0$, $\lambda = 1$ or $F_g = F_r$ just as speculated by Eeg-Olofsson and Bernskiold [3]. As $w - a$ increases, so does λ. Finally, when $w - a \rightarrow \infty$, $\lambda \rightarrow 1.2$.

So from this discussion, we can say that the grip width b is the most important parameter that can lead to a big difference between the tested breaking loads of the two specimen types. Other parameters including fabric tightness reflected by $\frac{G_{xy}}{E_x}$, the width difference of the specimens $w - a$, and the effective gauge length $w - a$ have only marginal effects.

Again, our theoretical analysis is based on a simplified approach with several rough assumptions. Nevertheless, the explicit results clearly represent an advance on the previous studies, and the discussions of these results are consistent with our empirical knowledge. More importantly, if we examine the stress-strain curves of either individual yarns or fabrics, we find that at the moment prior to specimen failure, our assumptions are actually less unrealistic. An experimental work is currently in progress to verify the results. In addition, one can always resort to the numerical approach if such accuracy is indeed required.

Conclusions

Our theoretical analyses of the tests of two different specimen types lead to the following conclusions: For the grab specimen test, shear and tensile stresses in the ungripped areas, as well as the total tensile breaking load, are all functions of the moduli ratio $\frac{G_{xy}}{E_x}$, the difference between the widths of the specimen $h - b$, and the effective gauge lengths $w - a$.

The shear and tensile stress distributions at the portions of the grab specimen not directly stretched are nonlinear. Shear stress is at a maximum at both ends of the fabric and decreases gradually to zero toward the center; the tensile stress is generated by means of the shear stress, is zero at the fabric ends, and reaches the maximum at the fabric center. This maximum tensile stress value, however, can never reach the value of the original tensile stress σ_x applied before specimen failure. This explains why the break always occurs in the grabbed portion of the specimen. Since the break will gradually develop into the ungripped portions due to the stresses within, the grab tensile test is a gradual process, whereas strip specimen failure is much quicker.

The ratio of the breaking loads of the two specimens, $\lambda = \frac{F_g}{F_r}$, is always greater than 1, meaning that the breaking load for the grab test F_g is always greater than that for the strip test F_r. In terms of the influence of the related parameters, the grip width b is the most important parameter and may cause big differences in the tested breaking loads between the two specimen types if b is too small. Other parameters including the fabric tightness reflected by $\frac{G_{xy}}{E_x}$, the specimen width difference $h - b$, and the effective gauge length $w - a$ have only marginal effects.

Further study of this problem should include the effects of the stress variations in the y-axis and the Poisson ratio of the fabric.

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