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Estimation of the Initial Shear Modulus of Twill Woven Denim Fabrics Based on Fabric Mechanical and Geometrical Properties

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Abstract
A new theoretical analysis is presented which predicts the initial shear modulus of twill woven denim fabrics (T3/1) in terms of fabric mechanical and geometrical properties under conditions of small strain. The warp and weft yarn lengths in a unit repeat for a twill weave (T3/1) structure are theoretically estimated by using geometrical parameters including the contact angles between warp and weft yarns based on yarn crimp values. The values of initial shear modulus predicted are compared with experimental values obtained by a Sirofast Tester 3. The results show that the predicted and experimental shear modulus values are linearly correlated (R^2 = 0.904) with a performance factor (PF/3) value of 15%.

Key words: *twill woven fabric, bending rigidity, initial shear modulus, denim fabric, geometrical parameters.*

Introduction

Shear behaviour is one of the most important mechanical properties of fabrics that influence how the fabric will conform when subjected to a wide variety of complex deformations during use. It also affects the handling, crease resistance and drape behaviour of the final product [1 - 4].

Several researchers have considered the load - extension behaviour of woven fabric [5 - 8]. Some of the methods developed are quite general, mostly based on energy considerations. Lindberg et al. [9] investigated the shearing behaviour of various commercial woven fabrics in relation to plate and shell buckling. They showed that the shell-buckling load depends on both the plane-buckling load and shear angle in such a way that an increase in the shear angle leads to a decrease in the shell buckling load. Kilby [10] developed a formula for calculating the shear modulus of fabric based on the Young's modulus of fabric along the warp, weft and bias directions, and Poisson's ratio of fabric in the warp and weft directions. Grosberg et al [11] suggested a model to predict the mechanism of the deformation of woven fabric under shear stress in the elastic region. Leaf and Kandil [12] analysed the initial load-extension behaviour of plain–woven fabrics using Castigliano's theorem. The bending rigidity, yarn compression, and extension were taken into account. They compared experimental values with theoretical values of the initial tensile modulus (Young's modulus). The approach of their model could be extended to predict other mechanical properties of fabrics, particularly shear properties.

Leaf and Sheta [13] proposed a theoretical approach and derived an equation which described the initial shear modulus of plain-woven fabrics in terms of fabric geometrical parameters such as yarn spacing, the weave angle, the length of a unit repeat, and warp and weft yarn bending rigidities. Theoretical values of the initial shear modulus were then compared with the experimental results of several woven fabrics. Leaf [15] estimated the initial shear modulus of plain-woven fabrics along the warp and weft directions using KES-F equipment, which obeys the simple shear model. He used some equations based on geometrical parameters that were previously derived by leaf and co-workers [12 - 14]. Thus the shear modulus was predicted based on fabric bending rigidity in the warp and weft directions and on the length of warp and weft actually in contact with the region where the yarns cross each other.

Sun and Pan [16] developed a new mechanical method to evaluate the shearing properties of woven fabrics during the initial slip region. The approach for their model can be extended to predict other mechanical properties of fabrics. Radhalakshmi et al. [17] adopted a modification to simplify the conventional method of determining the low-stress mechanical properties of fabrics to make it applicable for finished silk fabrics.

Klevaitytė and Masteikaitė [18] developed an original method for evaluating the deformation anisotropy of fabrics under tension. The deformation of specimens was investigated after loading. The shear angles, elongation at a fixed load and other parameters were measured. Naujokaitytė et al [19] used the image analysis method in conjunction with an bias extension test for characterising the specimen buckling point and surface irregularity changes during uni-axial extension. The shear angle values were obtained by the optical method.

Kamali et al. [20] developed a method for detecting the exterior positions of yarns in a sheared fabric using a modification of the Fast Fourier Transform (FFT) technique. It was found that the modified FFT technique is valid for evaluating the exterior positions of yarns in fabrics. Moreover, it was observed that there is a critical state in the behaviour of woven fabric under shear deformation. In their subsequent work, Kamali and Kovar [21] proposed a 3D model of plain woven fabric before shear deformation by substituting a new concept of the yarn packing density inside a fabric, and then the geometrical specification of plain woven fabrics is successfully evaluated. In their later study [22], this model was utilised to predict the configuration of fabric and orientation of yarns under shear deformation. It was found that the model proposed is responsible for simulating fabric behaviour during shear deformation.

It may be considered that most of the theoretical works are concentrated on the shear behaviour of plain-woven fabrics. Recently, Özdil [23] compared the performance characteristics of different denim fabrics containing various percentages of elastane. The mechanical properties, such as the tensile and tearing strength, bending rigidity, stretching and bagging characteristics of the fabrics were tested. However, there is no research work available to predict the initial shear modulus of woven fabric with a twill weave struc-

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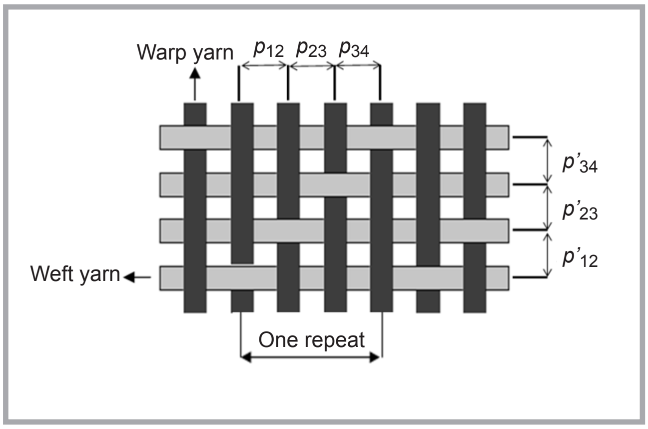

Figure 1. *Plan of twill voven fabric (T3/1).*

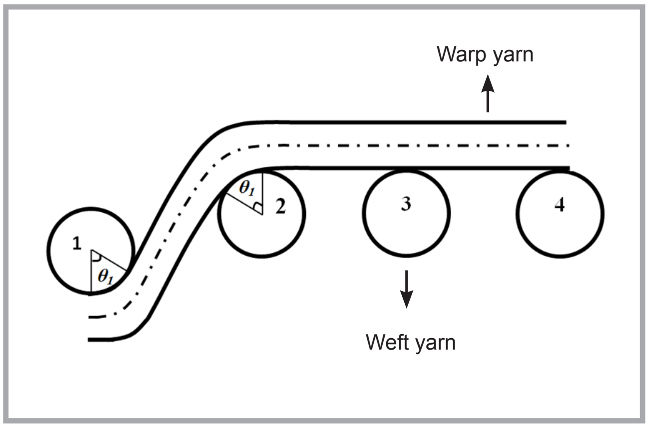

Figure 2. *Flexible thread model of twill woven fabric (T 3/1).*

ture and thus warrants further research. This study is an extended research work based on the theoretical analysis conducted by Leaf [15] in order to predict the shear modulus of twill structures (*T3/1*) in terms of their initial load extension behaviour and mechanical properties under conditions of small strain.

Theory

A plain model of the twill woven fabric

For modelling twill woven fabric (T 3/1), the basic repeat is shown in ***Figures 1 and 2.***

Peirce's assumptions [24] together with other assumptions are thus:

1. The yarn is perfectly flexible, i.e. their flexural rigidity = *0*.
2. The yarns have a circular cross-section.
3. The yarns are incompressible.
4. The yarns are inextensible.
5. The contact angle between the warp and weft at points 1 and 2 is Θ_1.
6. The spaces between warp yarns are $p_{12} = p_{23} = p_{34} = p_1$, and the spaces between weft yarns are $p'_{12} = p'_{23} = p'_{34} = p_2$.

Suffixes 1 and 2 refer to the warp and weft, respectively.

According to ***Figure 2*** and assumptions above, the fabric geometrical parameters can be written:

$$c_1 = \frac{l_{12} - p'_{12}}{p'_{12}} \Rightarrow l_{12} = p_2(1 + c_1) \quad (1)$$

$$l_{23} = l_{34} = p_2 \quad (2)$$

$$l_{1T} = l_{12} + l_{23} + l_{34} = \\ = p_2(1 + c_1) + 2p_2 = p_2(3 + c_1) \quad (3)$$

$$l'_{1T} = l'_{12} + l'_{23} + l'_{34} = \\ = p_1(1 + c_2) + 2p_1 = p_1(3 + c_2) \quad (4)$$

where, c_1, c_2 are the crimps of warp and weft yarns, l_{12}, l_{23}, l_{34} (l'_{12}, l'_{23}, l'_{34}): the length of warp (weft) yarn between points 1-2, 2-3, and 3-4 respectively.

l_{1T} and l'_{1T} - the length of warp and weft yarns between points 1 and 4, respectively (one complete repeat of the twill structure, see ***Figure 2***).

Important features of the model are the contact lengths '*ab*' and '*cd*' (***Figure 2***). These lengths are equal to $D\Theta_1/2$; therefore, the length of a straight section (l_{1S}) is:

$$l_{1S} = l_{1T} - D\theta_1 = p_2(3 + c_1) - D\theta_1 \quad (5)$$

D - fabric thickness, θ_1 is the angle in radians.

The distance between weft yarns (points 1 and 2) can be calculated as follows:

$$p_2 = (l_{12} - D\theta_1)\cos\theta_1 + D\sin\theta_1 \quad (6)$$

By using a Fourier series, the cosine and sine expansion against θ can be written:

$$\sin\theta = \frac{\theta^1}{1!} - \frac{\theta^3}{3!} + \\ + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + \cdots\cdots \approx \theta \quad (7)$$

$$\cos\theta = \frac{\theta^0}{0!} - \frac{\theta^2}{2!} + \frac{\theta^4}{4!} - \frac{\theta^6}{6!} + \cdots\cdots \approx \\ \approx 1 - \frac{\theta^2}{2} \quad (8)$$

Therefore, equation (6) can be rewritten:

$$p_2 = (l_{12} - D\theta_1)(1 - \frac{\theta_1^2}{2}) + D\theta_1 \approx \\ \approx l_{12}(1 - \frac{\theta_1^2}{2}) \quad (9)$$

Substitution ***Equation 9*** into ***Equation 3*** leads to:

$$c_1 = \frac{l_{1T}}{p_2} - 3 = \frac{l_{1T}}{l_{12}(1 - \frac{\theta_1^2}{2})} - 3 \quad (10)$$

Considering equations (2), (3) and (9), the total length in a unit repeat of the twill structure (*T3/1*) becomes:

$$l_{1T} = l_{12} + 2l_{12}(1 - \frac{\theta^2{}_1}{2}) = \\ = l_{12}(3 - \theta_1^2) \quad (11)$$

and from equations (10) and (11), the yarn crimp is obtained:

$$c_1 = \frac{l_{12}(3 - \theta_1^2)}{l_{12}(1 - \frac{\theta_1^2}{2})} - 3 = \frac{\frac{\theta_1^2}{2}}{1 - \frac{\theta_1^2}{2}} \quad (12)$$

Since, the value of θ_1^2 is very small, it can be neglected in the denominator; therefore, θ_1 is equal to:

$$\theta_1 \approx \sqrt{2c_1} \quad (13)$$

Similarly, for the weft yarns the following can be written:

$$\theta_2 \approx \sqrt{2c_2} \quad (14)$$

In real fabric, because of the yarn bending rigidity, the length of the contact region is likely to be different. Thus Leaf [15] supposed this length to be $k_1 D\Theta_1/2$. Therefore the straight length is changed accordingly:

$$l_{1S} = l_{1T} - k_1 D\theta_1 \quad (15)$$

and similarly,

$$l'_{1S} = l'_{1T} - k_2 D\theta_2 \quad (16)$$

Provided the values of k_1 and k_2 are chosen appropriately.

Estimation of shear modulus

In order to predict the shear modulus of twill woven denim fabrics (T3/1) based on geometrical and mechanical properties, the equation that was defined by Leaf [15] for plain-woven fabric (Equation 17) is modified as equation (18). The analyses assumed that the contact regions are rigid and that small fabric deformations occur through the bending of straight sections.

$$\frac{12}{G}=\frac{(l_1-k_1D\theta_1)^2}{B_1}+\frac{(l_2-k_2D\theta_2)^2}{B_2} \quad (17)$$

l_1 and l_2 - total length of warp and weft yarn in a unit repeat of plain structure (the length *abcd* in ***Figure 2***), respectively.

B_1 and B_2 - bending modulus of a unit width of fabric in the warp and weft direction, respectively.

G is the shear modulus of the fabric.

$$\frac{12}{G}=\frac{l_{1S}^{\,2}}{B_1}+\frac{l'^{\,2}_{1S}}{B_2} \quad (18)$$

The values of l_{1S} and l'_{1S} are estimated by equations (15) and (16) in the twill structure (*T3/1*). Expression (18) shows that the shear modulus can be considered as functions of the fabric bending rigidities and its geometrical parameters. By using ***Equation 18***, it is possible to predict the theoretical G of twill fabrics (*T3/1*); however, this prediction is not so easy, since it is necessary to estimate θ_1, θ_2, l_{1T}, and l'_{1T}.

Experimental

Fabric production

In this work, to evaluate the theoretical prediction of the shear modulus, 20 unfinished and finished woven fabric samples with a twill weave structure (*T 3/1*) were produced. The fabric properties are listed in ***Table 1***. Four samples *S1, S2, S3*, and *S4* of woven cotton fabrics with different weft densities were produced on a*SMIT TP400* Rapier loom. To produce other fabrics, the warp cotton yarns were dyed on a *RAMLLUMIN* dyeing machine using indigo dyes. Then ten unfinished Denim fabrics (*D5, D6…,* and *D14*) were woven on a *PICANOL OMNIPLUS 800* Air-jet loom with different warp yarn tension forces. Finally, six finished samples (*D15 ...,* and *D20*) were also produced using a *H.T.P UNITEX* finishing machine.

Table 1. *Physical and mechanical properties of fabrics.*

Sample code	Yarn count, tex		Yarn density, 1/cm		Fabric weight, g/m2	Fabric thickness, mm	Bending rigidities, µN·m	
	warp	weft	warp	weft			warp	weft
S1	49	49	20.0	12.0	172	0.930	19.1	12.5
S2				14.0	173	0.920	15.9	14.9
S3				16.0	196	0.990	28.7	23.4
S4				18.0	207	0.940	34.4	35.7
D5	74	74	26.7	18.3	366	1.313	251.8	179.4
D6			26.6	18.6	353	1.124	215.7	171.9
D7			26.6	19.3	353	1.093	245.8	167.0
D8			26.7	19.0	346	1.152	232.3	161.2
D9			26.9	19.8	382	1.191	303.2	241.3
D10			27.0	20.0	383	1.238	330.5	243.0
D11			27.1	20.0	384	1.193	313.0	231.7
D12			27.0	20.2	384	1.187	360.0	230.2
D13			27.0	20.2	381	1.163	373.7	267.1
D14			27.1	20.4	377	1.169	334.7	254.6
D15			31.2	21.1	392	1.162	88.8	90.4
D16			31.5	21.5	402	1.114	101.1	110.8
D17			31.3	21.3	399	1.100	100.5	118.5
D18			31.5	21.6	400	1.048	95.6	127.4
D19			31.2	21.2	395	1.069	98.4	116.1
D20			31.5	21.3	400	1.101	103.1	126.3

Testing of physical and mechanical properties

The fabric physical properties: the warp and weft yarn spacing in the fabrics, the fabric weight, and yarn crimp were measured according to ASTM Standard D 3775-98, D 3776-96, and D 3883-99, respectively.

Fabric thickness and fabric mechanical properties including the bending rigidity in the warp and weft directions, the shear rigidity, and the extensibility along the warp, weft and bias (45°) directions were measured with a SiroFAST Tester [25].

The fabric thickness was determined under a 2 g/cm2 load by a *FAST-1* tester (***Table 1***). The fabric-bending length was determined using a *FAST-2* tester, which is used for calculating the fabric-bending rigidity (***Table 1***), according to ***Equation 19:***

$$B = W \times C^3 \times 9.807 \times 10^{-6} \quad (19)$$

where, B - bending rigidity in µN.m, W - fabric weight in g/m2, and C - bending length in mm.

The percentage of fabric extension in the bias direction under a load of 5 g/cm was obtained by a *FAST-3* tester. The shear rigidity (G) is calculated as follows:

$$G\ (\text{N/m}) = 123/\text{Bias extensibility} \quad (20)$$

All tests were carried out under standard conditions (65 ± 2% RH and 20 ± 2 °C).

Prediction of initial shear modulus

In order to predict the shear modulus based on ***Equation 18***, it is essential to calculate l_{1S} and l'_{1S} . By using ***Equations 3*** and ***4***, the amount of l_{1T} and l'_{1T} were estimated. Moreover, using Equations 13 and 14, the values of θ_1 and θ_2 in terms of c_1 and c_2 were calculated. From ***Equations 15*** and ***16***, l_{1S}, and l'_{1S} were obtained (***Table 2***).

Table 2. *Estimated geometrical properties of fabrics.*

Sample No.	l_{1S}, mm	l'_{1S}, mm
S1	2.35	1.35
S2	1.98	1.35
S3	1.69	1.34
S4	1.48	1.34
D5	1.29	0.86
D6	1.33	0.90
D7	1.29	0.90
D8	1.30	0.90
D9	1.20	1.05
D10	1.18	0.90
D11	1.18	1.00
D12	1.18	0.90
D13	1.19	0.91
D14	1.17	1.00
D15	1.09	0.73
D16	1.07	0.74
D17	1.11	0.73
D18	0.99	0.68
D19	1.11	0.74
D20	1.10	0.74

Table 3. *Comparison between experimental and predicted values of shear rigidity.*

Sample code	Shear rigidities, N/m		Error, %
	experimental	predicted	
S1	27.6	27.7	0.2
S2	32.6	32.6	0.0
S3	62.4	68.6	9.9
S4	110.2	105.3	-4.4
D5	1481.9	1115.8	-24.7
D6	1230.0	930.8	-24.3
D7	1230.0	1024.7	-16.7
D8	1330.0	975.9	-26.6
D9	1230.0	1295.8	5.3
D10	1330.0	1589.0	19.5
D11	1481.9	1371.4	-7.4
D12	1835.8	1627.3	-11.3
D13	1230.0	1741.0	17.6
D14	1481.9	1499.0	1.2
D15	615.0	622.2	1.2
D16	615.0	726.9	18.2
D17	672.0	717.7	16.7
D18	672.1	691.5	2.9
D19	736.5	689.7	-6.4
D20	820.0	748.4	-8.7
Mean absolute error, %			11.16
Minimum absolute error, %			0.00
Maximum absolute error, %			26.6

In this study, according to the geometrical parameters of the twill structure (T3/1), the values of k_1 and k_2 are considered to be equal to 0.8.

By substituting the values of l_{1S}, l'_{1S}, B_1 and B_2 into ***Equation 18***, the values of (G) were predicted, as depicted in ***Table 3***.

Results and discussion

The shear modulus of fabrics predicted is calculated as discussed in section **Prediction of initial shear modulus**. The prediction accuracy of the shear rigidity was evaluated by applying '*PF/3*' (Performance Factor [26]), *Error* values (***Equation 21***), and the correlation coefficient (*R-value*) between the predicted and experimental values (***Table 3,*** and ***Figure 3***).

$$Error = \frac{G_P - G_E}{G_E} \times 100 \text{ in } \% \qquad (21)$$

where, G_E - experimental shear modulus, and G_P - predicted shear modulus.

It is observed that the 'R-value' is 0.951 (R^2 = 0.904), and the value of '*PF/3*' is 15.206. Therefore, it shows that the prediction accuracy is up to 85%. ***Figure 3*** shows the relationship between experimental and predicted shear modulus values. It may be seen that the accordance between these values is rather acceptable. Therefore, by using ***Equation 18***, the shear modulus of fabric with a twill structure could be predicted. However, in a few samples, the differences between predicted and experimental values are considerable which can be explained as follows:

1. In theoretical assumptions, the contact angles between warp and weft yarns at points 3 and 4 (***Figure 2***) were assumed to be zero, but in reality these angle values are not zero.
2. The value of *k* was supposed to be 0.9. However, this value of *k* can be different for fabric samples with different yarn density.
3. The load analysis was considered based on the theory of Leaf [15], being true for plain-woven fabrics. However, further force analysis is needed for the twill weave structure.
4. It is shown that denim fabric samples (*D5* to *D14*) with a higher bending rigidity along the warp and weft directions exhibit a much higher shear modulus, which in turn leads to a higher mean absolute error.
5. It is evident that fabric samples with a higher bending rigidity demonstrate a lower extensibility, particularly along the bias direction, as a result of which the *SiroFast Tester 3* may not estimate the exact value of bias extensibility and hence the shear rigidity.

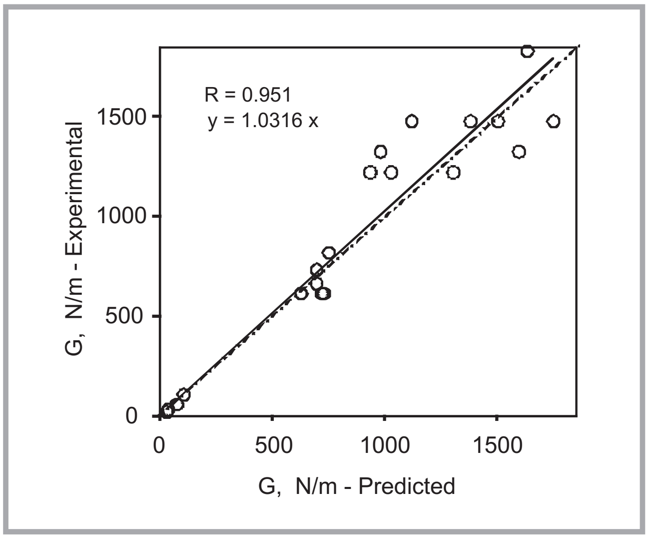

Figure 3*. Relationship between experimental and predicted values of shear rigidity.*

Conclusions

In this study, a new theoretical approach was developed based on the theory of Leaf for predicting the shear modulus of twill-woven Denim fabrics (*T3/1*) in terms of fabric bending rigidities along the warp and weft directions, as well as the total yarn length and straight yarn length in a unit weave repeat. These yarn length values are theoretically estimated by using geometrical parameters including the contact angle between the warp and weft, and yarn crimps. The values of shear modulus predicted are compared with the experimental values obtained by a Sirofast Tester 3.

The results show that the predicted and experimental shear modulus values is linearly correlated (R^2 = 0.904), and the value of performance factor (*PF/3)* shows that the prediction accuracy is up to *85%*. However, in order to obtain a better estimation of value *G*, it is necessary to theoretically investigate the force and undertake an energy analysis of the woven twill weave structure. The results of this research can be continued for light stretchable denim fabrics that demonstrate better shearing properties, particularly when undergoing complex 3-D deformations.

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The **Laboratory** is active in testing fibres, yarns, textiles and medical products. The usability and physico-mechanical properties of textiles and medical products are tested in accordance with European EN, International ISO and Polish PN standards.

Tests within the accreditation procedure:
■ linear density of fibres and yarns, ■ mass per unit area using small samples, ■ elasticity of yarns, ■ breaking force and elongation of fibres, yarns and medical products, ■ loop tenacity of fibres and yarns, ■ bending length and specific flexural rigidity of textile and medical products

Other tests:
- **for fibres:** ■ diameter of fibres, ■ staple length and its distribution of fibres, ■ linear shrinkage of fibres, ■ elasticity and initial modulus of drawn fibres, ■ crimp index, ■ tenacity
- **for yarn:** ■ yarn twist, ■ contractility of multifilament yarns, ■ tenacity,
- **for textiles:** ■ mass per unit area using small samples, ■ thickness
- **for films:** ■ thickness-mechanical scanning method, ■ mechanical properties under static tension
- **for medical products:** ■ determination of the compressive strength of skull bones, ■ determination of breaking strength and elongation at break, ■ suture retention strength of medical products, ■ perforation strength and dislocation at perforation

The Laboratory of Metrology carries out analyses for:
■ research and development work, ■ consultancy and expertise

Main equipment:
■ Instron tensile testing machines, ■ electrical capacitance tester for the determination of linear density unevenness - Uster type C, ■ lanameter