Investigation of the Impact of the Type of Weave on Shear Properties of Woven Fabrics in Various Directions

Penava[1*], Ž., Šimić Penava[2], D., Knezić[1], Ž.

[1]Faculty of Textile Technology, University of Zagreb, Pr. b. Filipovića 28a, Zagreb, Croatia
[2]Faculty of Civil Engineering, University of Zagreb, Kačićeva 26, Zagreb, Croatia
e-mail: *zpenava@ttf.hr, dianas@grad.hr, zknezic@ttf.hr

Abstract: Shear behavior is a very important mechanical property of woven fabrics. Shear properties of woven fabrics were tested in various directions because of anisotropy. This research was focused on the experimental study of shear properties of woven fabric for different types of weaves, when shear force acts on specimens that are cut at different angles to the weft direction. Tests were conducted on woven fabric specimens that were fastened in two parallel clamps that were placed in the tensile tester. Three cotton woven fabrics of different types of weave (plain, twill, and sateen) were used. Based on the diagram of the measured values of shear force and corresponding vertical displacement, shear angles and corresponding shear stresses were calculated. The initial shear modulus of woven fabrics was determined experimentally in the laboratory. Based on the experimentally obtained values, the theoretically calculated initial shear modulus of arbitrarily chosen fabric directions was calculated. The results of the conducted research show a very high degree of correlation between experimental and theoretical initial shear moduli only for the orthogonal plain weave fabric which represents a symmetrical weave.

Keywords: anisotropy, initial shear modulus, pure shear, shear angle, shear force, woven fabric, weave

1. Introduction

In practical use, textile fabrics are subjected to a wide range of complex deformations, so the shear properties of woven fabrics are important in many practical applications. During shear deformation, the woven fabric yarns experience a large angular variation between warp and weft yarns. Test methods of shear properties of woven fabrics are listed in the existing literature [1-3]. To understand the mechanisms of woven fabric shear behavior, shear apparatuses which measure woven fabric shear properties are described [4-8]. They indicated that the hysteresis produced during shearing is determined wholly by the frictional restraints arising in the rotation of the yarns from the intersecting points in the woven fabric. In addition, the existing literature proves that the shear mechanism is one of the important properties influencing the draping and pliability of woven fabrics [9].

Shear deformation of woven fabrics also affects their bending and tensile properties in various directions other than just in the warp and weft directions [10]. Kilby introduced the classical elasticity theory with the assumption of a woven fabric regarded as an anisotropic material with two planes of symmetry at right angles to one another [11]. He used a simple grid model for woven fabrics and analyzed the relationship between stress and strain in the plane and noted that there is a connection between the Poisson ratio, shear modulus and modulus of elasticity of the woven fabric. He showed that shear rigidity can be calculated from the tensile properties of the woven fabric at an angle of 45° in relation to the plane of the plate. Grosberg and Park [12] produced a mathematical analysis to determine the initial shear modulus, frictional shear stress, and shear rigidity. At the beginning, researches mainly focused on the shear behavior of woven fabrics in both principal directions because it affects much woven fabric behavior, and later their attention was directed at woven fabric shear properties in various directions. Therefore, the shear properties of woven fabrics should be determined in various directions. This engineering property has been studied by many researchers. Anisotropy is the characteristics of woven fabric that affects its physical and mechanical properties [13]. The determination of shear stresses and strains in various directions involves complex mechanisms that provide information about the shear properties of woven fabrics in various directions where the angles between two sets of yarns change in the intersecting points. Due to the inherent nature of woven fabrics an accurate and reliable determination of shear angle and shear stress is a difficult task.

The aim of this study was to determine the shear angle, shear forces and shear stresses of woven fabric using clamps that were specially designed in the laboratory for measuring shear forces. Shear force acts on woven fabric specimens that are cut at different angles to the weft direction. Also, the influence of anisotropy and type of weave to the initial shear modulus values of a woven fabric was analyzed. The degree of agreement between experimental results and calculated values of the initial shear modulus was determined. The structure of the apparatus and the measurement procedures are introduced and illustrated in this paper. Woven fabric specimens which are fastened in two parallel clamps that are placed in the tensile tester that will be used for the experimental determination of shear properties of the woven fabric.

2. Theory of pure shear

Woven fabrics are elastic orthotropic materials with a very small deformation which are defined as orthotropic plates with two mutually perpendicular planes of elastic symmetry [14]. These planes of elastic symmetry are planes of orthotropy. The x-axis represents the weft direction, and the y-axis represents the warp direction of woven fabric. In the arbitrary cross section of a woven fabric specimen under stress normal stresses σ_x, σ_y and shear stresses τ_{xy} or σ_k, σ_l, τ_{kl} generally act (Fig. 1a).

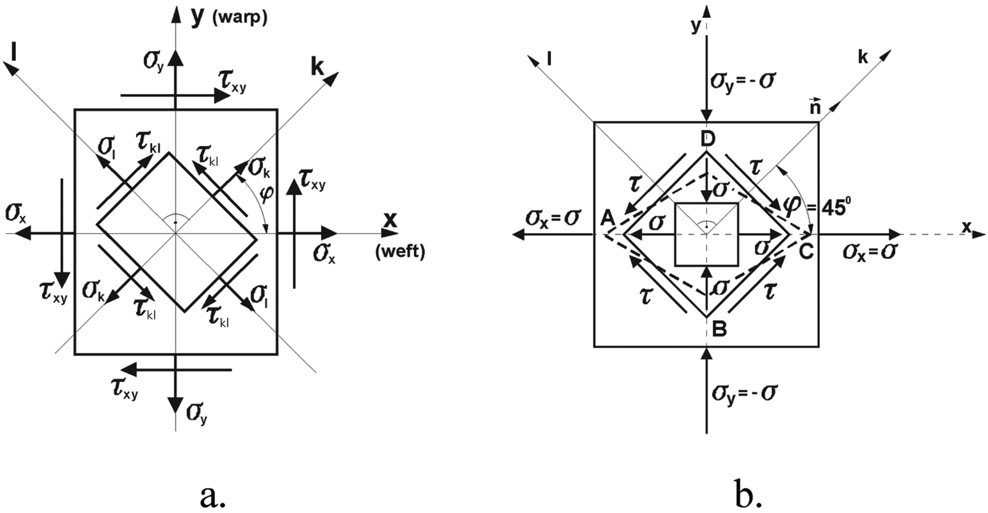


Fig. 1 – Woven fabric element: a) state of plane stress in woven fabric specimen, b) pure shear behavior

For a particular state of plane stress in an element we can determine the plane in which only shear stresses act and normal stresses are zero [15]. Parallelepiped forms of fabric specimens on whose sides only act normal stresses $\sigma_x = \sigma$ and $\sigma_y = -\sigma$ are observed, Fig. 1b. In the plane with an angle φ=45° with the x-axis according to Equation (1) normal stress is σ_k=0, and shear stress is $\tau_{kl} = \tau = -\sigma$. Such a case of stress is called a pure shear.

$$\sigma_k = \sigma_x \cdot \cos^2\varphi + \sigma_y \cdot \sin^2\varphi + \tau_{xy} \cdot \sin 2\varphi = \sigma \cdot \cos 2\varphi \quad (1a)$$

$$\tau_{kl} = \frac{\sigma_y - \sigma_x}{2} \cdot \sin 2\varphi + \tau_{xy} \cdot \cos 2\varphi = -\sigma \cdot \sin 2\varphi \quad (1b)$$

If a cube is cut with sides perpendicular to the x and y axes, on these sides only normal stresses which are equal in magnitude but in opposite direction, Fig. 1b, would act. Pure shear is equivalent to the simultaneous stretching and pressure with equal intensity in mutually vertical directions. In pure shear the relative change of volume is $\varepsilon_v=0$. Shear stress changes only the body shape, but does not change its volume. The isolated element of the woven fabric ABCD which is subjected to pure shear is shown in Fig. 2. During shear deformation, the woven fabric yarns experience a large angular variation between the warp and weft yarns.

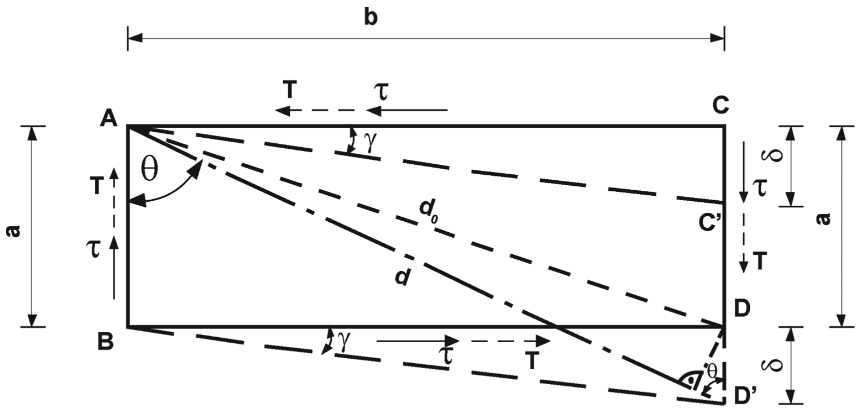


Fig. 2 – Woven fabric element subjected to pure shear – rectangular shape of the element

If side AB is motionless, then under the action of shear force T which acting in the plane of the element side shear stress τ will occur and it will come to the appearance of shearing side DC parallel with side AB for the amount CC'=DD'=δ (mm) which is called absolute shear (Fig. 2). Rectangle ABCD becomes a parallelogram ABC'D'. The side lengths of the woven fabric elements do not change, only the right angles between the element sides change, right angles become sharp or blunt angles. A change in the right angle is denoted with γ (rad) and is called relative shear, shear angle or relative angular (shear) strain. It is a measure of deformation. During the elastic deformation t shear angle γ is very small and it is equal to absolute shear divided by the spacing between the shear planes, Eq. (2):

$$\mathrm{tg}\,\gamma \cong \gamma = \frac{\delta}{b} \tag{2}$$

The value of the absolute shear δ depends not only on the value of shear stresses but also on the dimensions of the cut element. Shear stress τ (N/mm^2 = MPa) of the woven fabric can be directly calculated using shear forces. Shear strain is equal to the shear angle γ. It is assumed that the thickness of the woven fabric t (mm) is constant during shearing. Then the shear stress is calculated using Eq. (3)

$$\tau = \frac{T}{A} \tag{3}$$

where are: T (N) is a shear force acting on the side DC of the woven fabric element as a result of stress (assuming a uniform distribution of shear stresses on the surface side), A (mm^2) is a surface side DC of woven fabric element.

The connection between the shear angle γ and the shear stress τ is shown by Eq. (4) which represents the Hooke's law of shear and applies for elastic, homogeneous isotropic material in a linear region, i.e. where the relationship between shear stress and shear strain is linear. G (N/mm^2 = MPa) is shear modulus.

$$\tau = G \cdot \gamma \tag{4}$$

For an orthotropic and elastic material when the k- and l-axes do not coincide with the main x- and y-axes of orthotropy, the anisotropic behaviors of materials under loads can be written in matrix form according to Hooke's law [14]:

$$\begin{Bmatrix} \varepsilon_k \\ \varepsilon_l \\ \gamma_{kl} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_k} & -\frac{\nu_{lk}}{E_k} & \alpha_k \\ -\frac{\nu_{kl}}{E_l} & \frac{1}{E_l} & \alpha_l \\ \alpha_k & \alpha_l & \frac{1}{G_{kl}} \end{bmatrix} \cdot \begin{Bmatrix} \sigma_k \\ \sigma_l \\ \tau_{kl} \end{Bmatrix} \tag{5}$$

σ_k and σ_l are normal stresses, τ_{kl} is shear stress, ε_k, ε_l is normal strain (relative extension strain), γ_{kl} is shear strain (relative angle strain), E_k, E_l is modulus of elasticity, G_{kl} is shear modulus, α_k, α_l are elasticity coefficients, ν_{kl}, ν_{lk} is Poisson's ratio for arbitrary coordinate system k, l.

2.1. Shear modulus of woven fabrics

The functional relationship between stress and strain cannot be determined theoretically, but only by experimental tests of samples made of certain materials. Mechanical properties are mainly investigated within the area of elasticity which means in terms of low load [16]. Diagrams of shearing and diagrams of extension have a similar shape. It is assumed that force- shear angle curve of the woven fabric is an approximate straight line before the yield point. Therefore, elastic performance equation can be applied here. Shear modulus is the initial, linear elastic slope of the stress-strain curve in shear. It is the numerical constant that describes the elastic properties of a woven fabric under the application of shear forces. For orthotropic elastic materials, shear modulus G_{kl}, in various directions of cutting samples, i.e. in the coordinate system k, l whose axes do not coincide with the main axes x, y is obtained by using the expression for the transformation of the elastic constants, which states [14]:

$$\frac{1}{G_{kl}}=\left(\frac{1}{E_x}+\frac{1}{E_y}+\frac{2\cdot\nu_{xy}}{E_x}\right)\cdot 4\cos^2\varphi\cdot\sin^2\varphi+\frac{1}{G_{xy}}\cdot\left(\cos^2\varphi-\sin^2\varphi\right)^2=\frac{1}{G_\varphi} \quad (6)$$

φ is the cutting angle of the samples due to the weft (Fig. 1), E_x, E_y is the modulus of elasticity in two main directions (weft direction φ=0°, warp direction φ=90°); G_{xy} is the shear modulus between both principal directions; ν_{xy} is the Poisson's ratio. Shear modulus G_{kl} changes depending on the angle φ, and will be denoted as $G_\varphi=G_{kl}$.

Shear modulus G_φ in any given direction can be calculated by Eq. (6). The numerical values of E_x, E_y, G_{xy}, ν_{xy} are obtained by experimental tests of woven fabric samples in the laboratory. In standard conditions the value of ν_{xy} is very difficult to determine by experimental measurements. The theoretical treatment suggests that measurements of the modulus in two directions (weft and warp direction) are insufficient to define the shear modulus of a woven fabric. An investigation of the third direction is therefore necessary, and the most convenient direction is φ=45°. Therefore, measurements were carried out in three directions by considering samples cut along the warp, weft, and 45° directions. Therefore, when considering φ=45° values, Eq. (6) gives:

$$\frac{2\cdot\nu_{xy}}{E_x}=\frac{1}{G_{45^0}}-\frac{1}{E_x}-\frac{1}{E_y} \quad (7)$$

Substituting Eq. (7) into Eq. (6), we get

$$\frac{1}{G_\varphi}=\left(\frac{4}{G_{45^0}}\right)\cos^2\varphi\sin^2\varphi+\frac{1}{G}\left(\cos^2\varphi-\sin^2\varphi\right)^2 \quad (8)$$

Thus, woven fabric shear modulus in various directions can be predicted from Eq. (8) when its values in the warp or weft directions and under the angle of 45° are measured. Because shear modulus provides a measure of the resistance to rotational movements between the warp and weft yarns at the intersecting points when the woven fabric is subjected to small shear deformation, the relationship between both principal directions should be determined. However, if differences in the shear modulus values between the warp and weft directions are large, we take the average value in both principal directions to calculate the shear modulus in various directions given in Eq. (8). Eq. (8) indicates the mathematical relation between shear modulus G_φ in any given direction and values of G and $G_{45°}$.

3. Experimental testing

In the experimental part of the paper, the impact of anisotropy of woven fabrics and the impact of different types of weaves on shear properties were tested. The experimental study of shear properties of the woven fabric when shear force acts on the samples that are cut at different angles 0°, 15°, 30°, 45°, 60°, 75°, 90° in the direction of the weft was conducted. The values of the shear force in relation to the shear angle were measured, as well as breaking force and shear angle at break. Based on the experimentally obtained values, the initial shear modulus was calculated in various directions.

3.1. Test samples and the apparatus

To carry out this study, three cotton woven fabrics of different types of weaves (plain weave, twill and sateen) were available. Structural properties of the tested woven fabrics are shown in Table 1. Standard ISO 5084:1996 describes a method for the determination of the thickness of fabric.

Table 1 – Description of woven fabric

Fabric structure	Yarn fibers	Yarn count (tex)		Yarn density (cm^{-1})		Mass (g/m^2)	Thickness (mm)
		warp	weft	warp	weft		
Plain	Cotton	30	30	24	24	151	0.39
Twill	Cotton	30	30	24	24	150	0.39
Sateen	Cotton	30	30	24	24	148	0.38

Before testing all samples were conditioned under standard atmospheric conditions (relative humidity 65 ± 2%, temperature of 20 ± 2 ° C). Five tests were carried out on the tensile tester for each mentioned cutting direction of the specimen (0°, 15°, 30°, 45°, 60°, 75°, 90°), Fig. 3. For each cutting direction, the average values obtained from five measurements will be shown in diagrams and will be used to calculate the initial shear modulus.

To determine shear properties of the fabric, the clamps for shearing woven fabrics were designed, manufactured and schematically shown in Fig. 4a, and consist of the left (fixed) clamp and the right (movable) clamp. The force acting on the right clamp causes its vertical displacement. The left clamp is placed on the upper plate on which there is a measuring probe, and the right clamp to the lower plate on

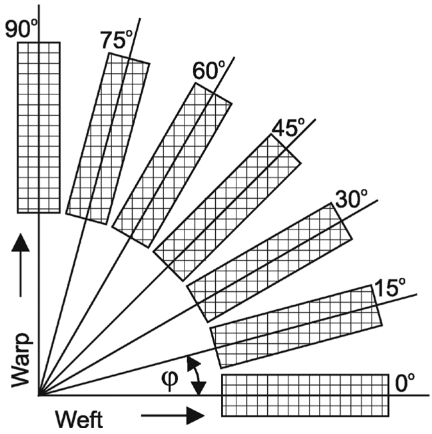
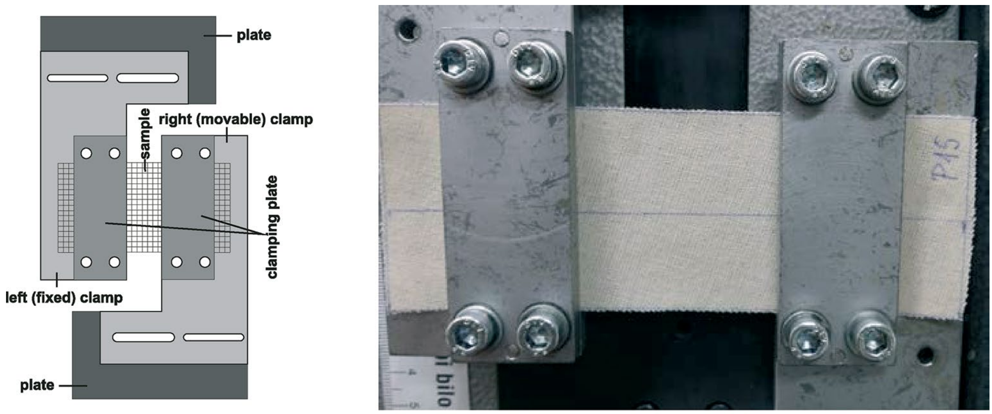


Fig. 3 – Schematic view of directions (angles) of cutting specimens

which the movable clamp is usually placed. The distance between the left and right clamp can be adjusted in a range from 0-50 mm. The maximum specimen size that can be fixed within the clamp is 75 mm.

For this testing, specimens were cut with dimensions 125 x 50 mm, fastened in the clamps of the instrument at a distance of b=50 mm, and subjected to the force acting in the plane of the fixed side of specimen till rupture (Fig. 4b). Sample dimensions are: a=50 mm and b=50 mm.



a) b)

Fig. 4 – Sample testing in the clamps: (a) schematic view, (b) photo

A tensile tester Statimat M of the German manufacturer "Textechno" was used for testing. This tensile tester is an automatic, microprocessor-controlled instrument operating on the principle of the constant deformation speed. Two parallel clamps at a distance of 25 mm are fixed on the tensile tester and the pulling speed of the right clamp is 100 mm/min. The action of an external force T causes the shearing of right fixed side of the specimen in relation to the left side for δ. Forces in parallel clamps causing the shear condition in the plane of the woven fabric specimen, whereby the state of deformation in the woven fabric are uniform. In this study the value of the pulling forces T in the right clamps and its corresponding vertical displacements δ were measured. The angle between the warp and weft yarns change and this leads to the appearance of shear strain in the woven fabric specimen.

4. Overview of test results and discussion

The Microsoft Excel software was used for statistical analysis of data at $p<0.05$ for five measurements. The diagrams (T- δ) of the average values of test results of force action T and the corresponding vertical displacements δ until breakage of samples that are cut at different angles to the direction of the weft are shown in Figures 5-7.

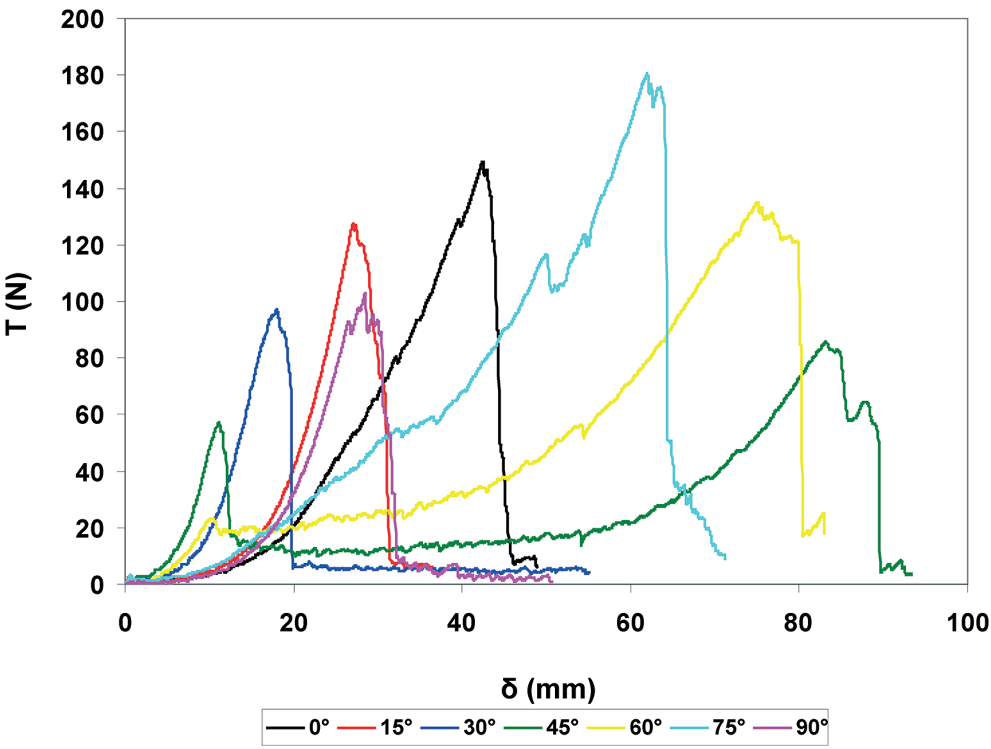


Fig. 5 – Diagram T- δ (force- vertical displacement) for plain weave

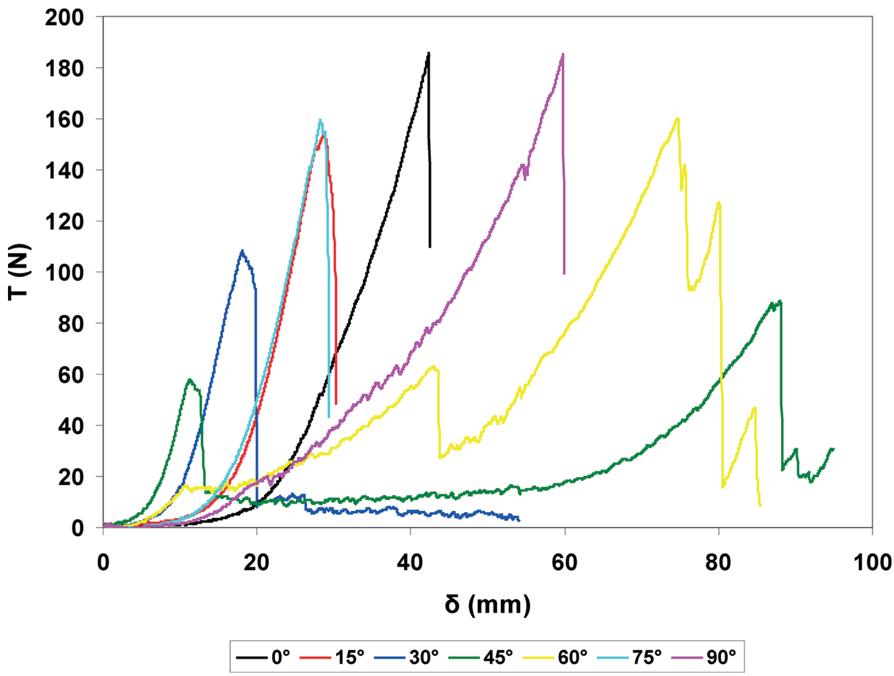


Fig. 6 – Diagram T- δ (force- vertical displacement) for twill weave

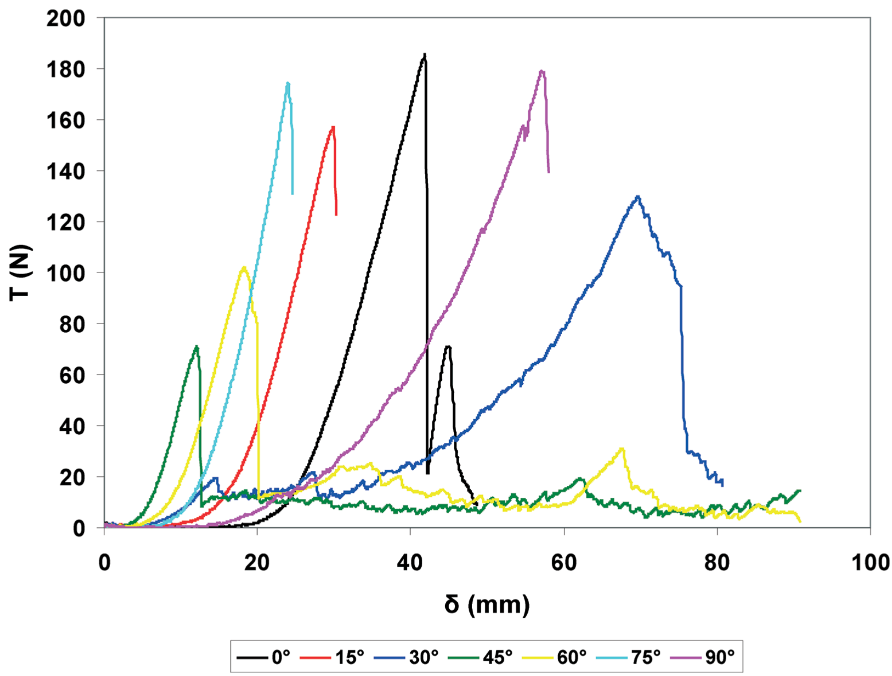


Fig. 7 – Diagram T- δ (force- vertical displacement) for sateen weave

Based on the diagrams of the measured values of force T and corresponding vertical displacement δ from Figures 5-7, the average values of the shear angle γ and the corresponding shear stress τ were calculated using Eq. (2) and Eq. (3). These values are shown in the diagrams in Figures 8-10, up to the value of the shear angle γ = 8°. The surface on which τ acts is A= t·a (mm^2). The related average values of breaking shear force $T_φ$ (N) and shear angles at break $γ_φ$ (rad) are given in Table 2 in all directions of cutting samples in plain, twill and sateen weave.

Table 2 – Average values of breaking shear force $T_φ$ corresponding shear angle at break $γ_φ$

$φ$(°)	Plain		Twill		Sateen	
	$γ_φ$ (rad)	$T_φ$ (N)	$γ_φ$ (rad)	$T_φ$ (N)	$γ_φ$ (rad)	$T_φ$ (N)
0	0.85	149.5	0.85	185.9	0.84	185.8
15	0.54	127.5	0.57	153.6	0.60	157.4
30	0.36	97.2	0.36	108.4	1.39	129.9
45	1.66	85.6	1.76	88.9	0.24	71.2
60	1.50	135.0	1.49	160.7	0.36	102.4
75	1.24	180.5	0.56	160.2	0.48	175.0
90	0.57	102.7	1.20	185.7	1.14	179.5

Shear forces $T_φ$ at break have maximum values for plain weave that were cut at an angle of 75°. Shear forces for twill and sateen weaves had the maximum value for the cutting angle 0°. All weaves reached the minimum value of $T_φ$ at an angle of 45°. Shear angle $γ_φ$ at break had the maximum value for plain and twill weave that were cut at an angle of 45°. For sateen weave, shear angle at break had the maximum value for the cutting angle 30°.

The values of shear forces on the complementary angles and from warp and weft directions varied with shear strain. When the vertical displacement or shear strain was very small, the values of shear forces from the warp and weft directions were very close. This also applied to the values of shear force for complementary angles However, at the later stage, the difference between above mentioned values increased when the strain increased.

During the woven fabric shearing, buckling in the woven fabric specimen occurred at a certain shear angle. According to Kawabata [17] woven fabric specimens which are subjected to the shear after exceeding the value of the shear angle γ = 8° tend to buckle. Shear angle γ = 8° corresponds to a vertical displacement of δ=6.98 mm. This value specifies the limit of in plane deformation after which a sample begins its out of plane deformation and it is called buckling zone. The appearance of buckling causes errors in the measurement results. The shear stress and shear angle curve up to the value of γ = 8° (until the beginning of buckling during the shear) is shown in Figures 8-10.

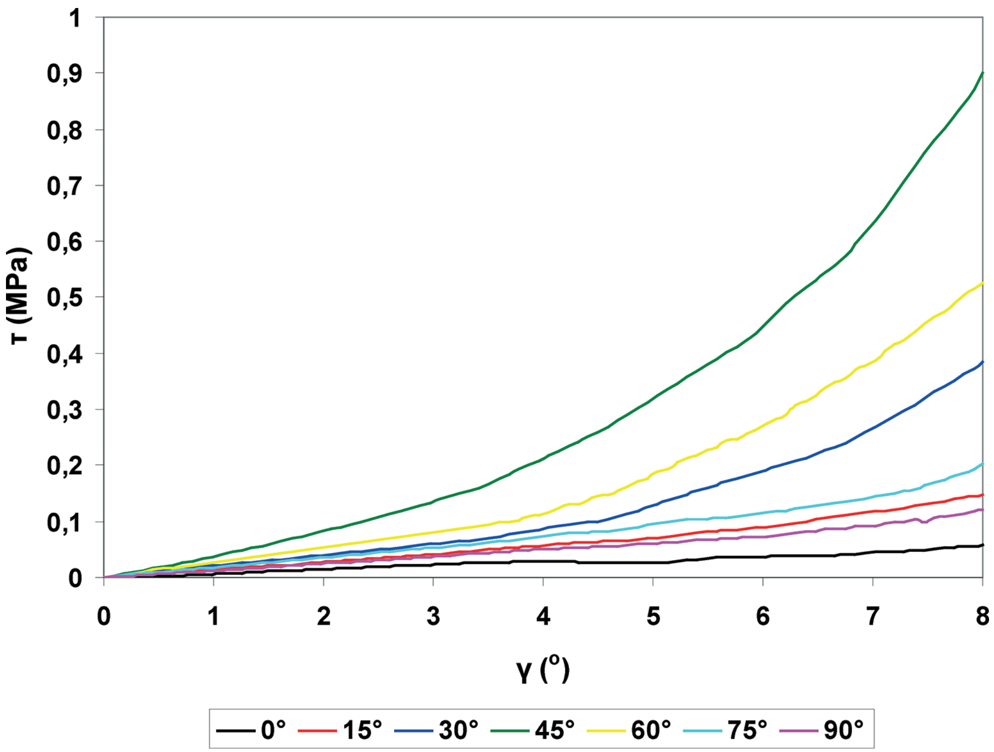


Fig. 8 – Diagram τ-γ (shear stress–shear angle) for plain weave

In Figures 8-10, at the same shear angle the highest value of shear stress τ appears in the samples which have been cut at angle of 45°. The values of shear stresses τ are very similar for complementary angles of the cutting samples. Shear stress τ takes on the minimum values for warp and weft directions. For samples that are cut in weft and warp directions at a very small increment of shear stress, values of shear angle are greatly increasing. Shear stress in relation to the shear angle has the highest increase at an angle of 45°. This applies only to area in which there is no buckling of woven fabric. When the fabric sample is subjected to the deformation imposed by pure shear test, in the initial stage, warp and weft yarns are perpendicular to each other, and the rotation relative to each other is limited by internal friction between the warp and weft. By contrast, in the later stage, the fabric structure changes from orthotropic to skewed structure, where the warp and weft yarns are no longer perpendicular to each other. The difference between warp and weft increases more and more as shear angle (shear strain) increases.

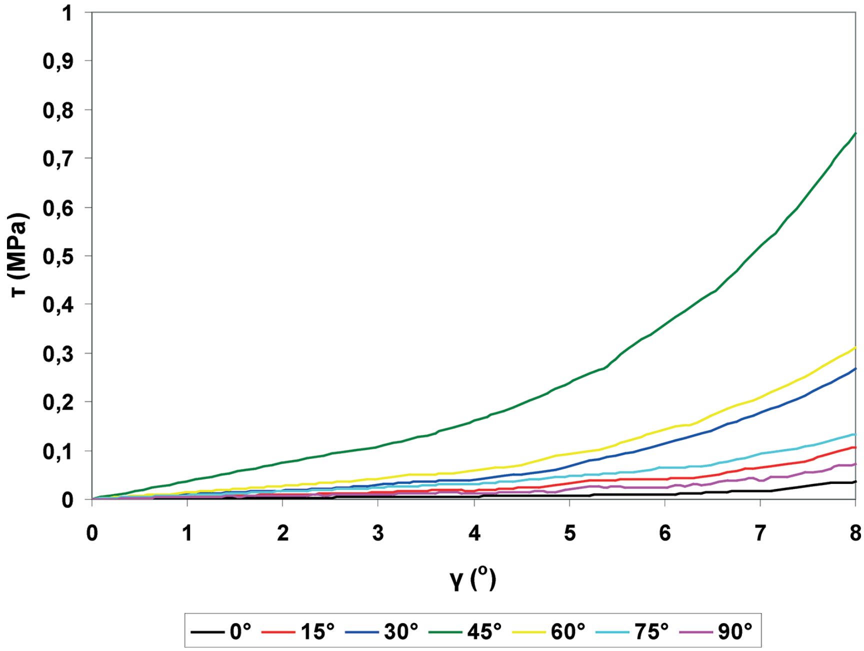


Fig. 9 – Diagram τ-γ (shear stress–shear angle) for twill weave

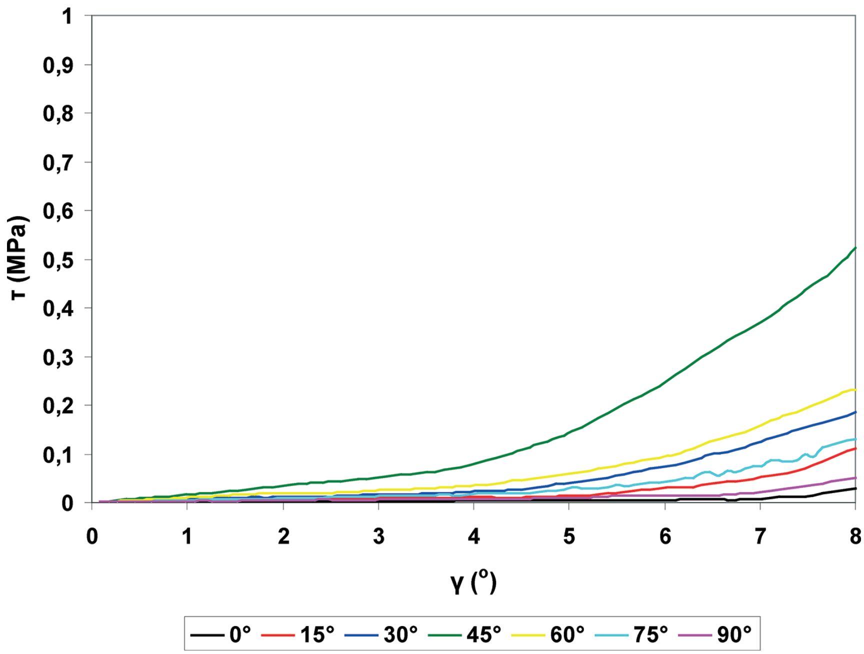


Fig. 10 – Diagram τ-γ (shear stress–shear angle) for sateen weave

5. Determining the initial shear modulus

Based on the experimentally obtained force-shear angles curves, the values of initial shear modulus were obtained and compared with the corresponding calculated values. Deviation in percentage between experimental and calculated values of initial shear modulus will also be calculated.

5.1. Experimental values of the initial shear modulus

From the presented diagrams, in Figures 5-7, the values of shear force in the elastic range are used. We determined shear modulus G_φ from a particular region on force – shear angle curve that is determined by monitoring the experimental data obtained from an experimental set-up with regression control chart [18]. In this area of the curve, the relationship between shear stress and shear strain is linear. The shear modulus G_φ is defined as a slope of its shear stress- shear strain curve (τ- γ) in the elastic deformation region. The Hooke's law for shearing can be applied:

$$G_\varphi = \mathrm{tg}\,\alpha = \frac{\tau}{\gamma} = \frac{T}{\gamma \cdot a \cdot t}(\mathrm{MPa}) \tag{9}$$

where A=a ·t is the area of the sample in which shear force acting.

Using values T and γ in elastic range and using Eq. (9), the average values of initial shear modulus G_φ in relation to an arbitrary direction of cutting of the woven fabric samples are calculated. Linear regression equations are placed on the shear stress-shear strain curves in the elastic range. In Figures 8-10, the slope of the curve, i.e. the coefficient of line direction represents the shear modulus G_φ for all samples. The curve τ- γ is shown up to value of the shear angle γ= 8° (0.14 rad). The shape of linear equation is: τ=G γ.

Table 3 – Experimentally obtained values of shear modulus G_φ (MPa)

Sample	$G_{0°}$	$G_{15°}$	$G_{30°}$	$G_{45°}$	$G_{60°}$	$G_{75°}$	$G_{90°}$
Plain	0.46	0.81	1.20	2.44	1.59	1.02	0.73
Twill	0.08	0.26	0.57	1.30	0.84	0.45	0.17
Sateen	0.05	0.15	0.29	1.08	0.45	0.23	0.09

The obtained experimental values of shear modulus G_φ in dependence on the change of the cutting angle of the samples are given in Table 3. The diagram of experimental values G_φ for each 15° is shown in Figure 11.

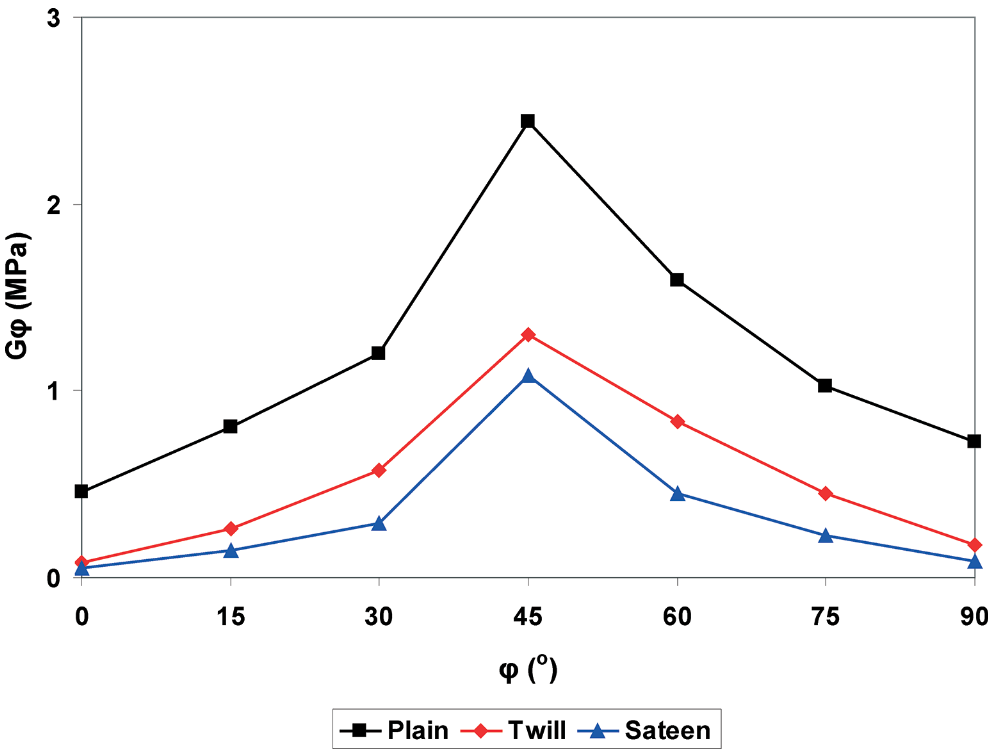


Fig. 11 – Diagram of experimental values of shear modulus G_φ (MPa) for each 15°

The diagram is almost symmetrical curve in relation to the angle of 45°. At that angle G_φ assumes the highest value for all woven fabric samples because initial slope of the stress-strain curve in shear is the biggest at that angle, Figure 8-10. When the samples are cut in the warp direction (φ=90°) and weft direction (φ=0°) shear modulus G_φ have the lowest value for all woven fabric samples because initial slope of the stress-strain curve in shear is the smallest at that angle, Figure 8-10. The values G_φ in the warp and weft direction are almost equal for each woven fabric sample or it is observable that shear modulus G_φ are almost equal for complementary angles.

5.2. Calculation of initial shear modulus in relation to an arbitrarily selected coordinate system

According to Eq. (8) and based on the experimental data $G_{0°}$ or $G_{90°}$ and $G_{45°}$ from Table 3, the values of initial shear modulus G_φ were calculated, depending on the change of the cutting angle of the samples. The calculated values of G_φ for each 15° are shown in Table 4.

Table 4. The theoretically calculated values of initial shear modulus G_φ (MPa)

Sample	$G_{0°}$	$G_{15°}$	$G_{30°}$	$G_{45°}$	$G_{60°}$	$G_{75°}$	$G_{90°}$
Plain	0.46	0.56	1.04	2.44	1.82	0.92	0.73
Twill	0.08	0.10	0.22	1.30	0.85	0.24	0.17
Sateen	0.05	0.07	0.16	1.08	0.38	0.12	0.09

The diagram of their calculated values G_φ (MPa) for each 5° is shown in Figure 12.

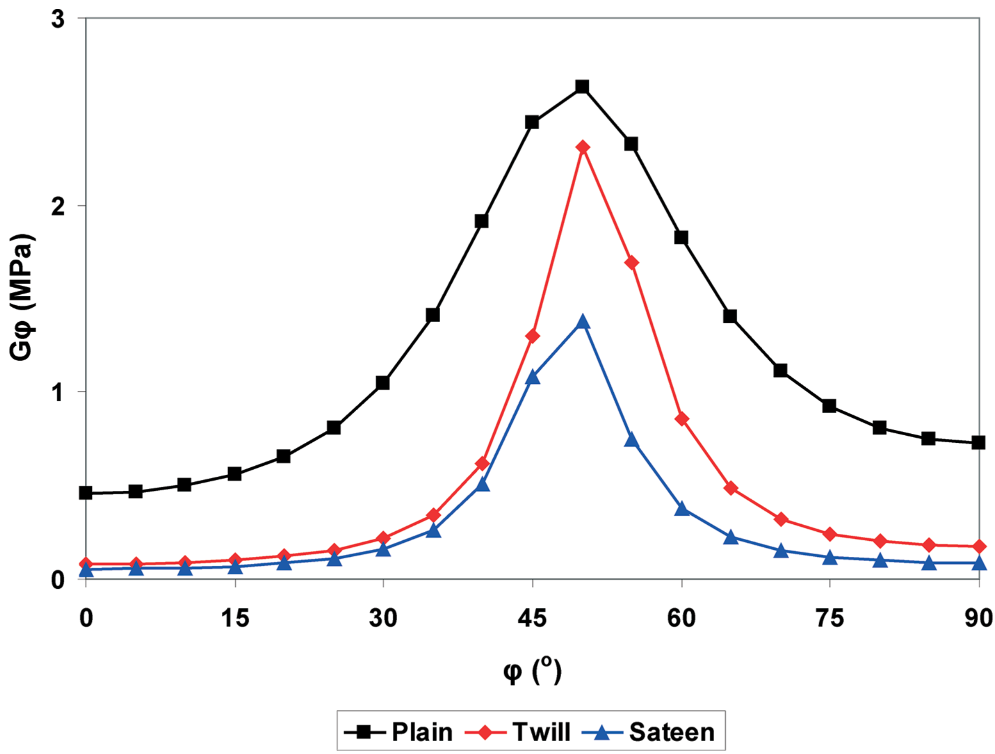


Fig. 12 – Diagram of calculated values of shear modulus G_φ (MPa) for each 5°

Table 5 shows percent deviations between experimental values G_φ in Table 3 and calculated values G_φ in Table 4. Deviations D (%) were calculated using the expression (10):

$$D = \frac{G_{\varphi,\exp} - G_{\varphi,\mathrm{calc}}}{G_{\varphi,\exp}} \cdot 100(\%) \tag{10}$$

Table 5 – Percent deviations D (%) between experimental and calculated values G_φ

Sample	0°	15°	30°	45°	60°	75°	90°
Plain	0	31.2	12.8	0	–14.6	10.0	0
Twill	0	62.2	61.8	0	–2.2	46.3	0
Sateen	0	53.8	45.6	0	16.2	47.2	0

In the warp (90°) and weft (0°) directions and under the angle of 45°, percent deviations between the experimental and calculated values of the initial shear modulus G_φ are 0%. It follows from Eq. (8) due to the periodicity of the sine and cosine functions for these values. Negative deviation values show that the obtained calculated values G_φ are higher than the experimental values of G_φ. Absolute values of deviations between the experimental and calculated values of the shear modulus are in a range from 0% to 62.2%. Deviations are maximal for twill weave, but minimal for plain weave.

6. Conclusion

Woven fabrics can be defined as orthotropic materials for which in the linear elastic range of the curve shear stress-shear angle Hooke›s law for anisotropic material behavior in calculating shear modulus when samples of woven fabric are cut in an arbitrary direction can be applied. Shear properties of the woven fabric are determined when shear force acts on woven fabric specimens which are cut at different angles to the weft direction. Due to the anisotropy of woven fabric its shear properties change in various directions. Shear modulus varies depending on the angle φ (cutting direction of the sample). Fundamental differences in shear properties in various directions between different fabrics will be present due to some inherent differences in their physical behavior, their finishes, and perhaps yarn or fiber stiffness, the contact area at the intersecting points of two yarn sets or the fiber packing density in the yarns. Any combination of these factors can confer different shear characteristics and shear modulus on woven fabrics, even when they are made from the same material. The shear modulus G_φ is almost symmetrical to the angle of 45° and the maximum value is reached exactly at that angle. Shear modulus values increase with increasing weft density for any cutting direction of the sample.

For the plain weave of the woven fabric, shear modulus values are from 0.46 MPa to 2.44 MPa. For twill weave shear modulus values are from 0.08 MPa to 1.30 MPa and for sateen weave shear modulus values are the lowest from 0.05 MPa to 1.08 MPa.

A good agreement between experimental results and the calculated values of the initial shear modulus was shown; thus, the theoretical equations can be used with high accuracy to calculate the initial shear modulus of the woven fabric in various directions only for symmetrical weaves. Hence, the balanced orthogonal plain weave fabric was considered. Thus, measurements had to be implemented when shear force acting only on the specimens that were cut in the warp and weft direction and at an angle of 45°. The theoretical equation for initial shear modulus cannot be used for unbalanced weaves such as twill and sateen. The woven fabric was subjected to shear up to $\gamma = 8°$ because after this point woven fabric specimens tended to buckle. The resulting buckling causes errors in measurement results and that requires attention. The woven fabric samples that are cut at an angle of 45° have the highest shear resistance. The lowest shear resistance had samples that were cut in the warp and weft direction. The same values of shear forces in woven fabrics cause the maximum shear deformation when the samples were cut in the warp and weft direction and minimum shear deformation when the samples were cut at an angle of 45°. This applies only to the area in which no buckling of the woven fabric occurred.

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