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Determination of Elastic Modulus of Woven Fabrics under Uniaxial Tension in Arbitrary Direction

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Abstract. Anisotropy is the characteristic which is typical for most materials, especially woven fabrics. Influence of direction of tensile force action on the properties of the fabric is big and frequently tested. The woven fabric can be defined as orthogonal elastomer. The values of elastic modulus of woven fabrics for different angles of extension direction were analyzed. Three types of fabric samples of different weaves (plain, twill, sateen) and the same raw material composition were tested under tensile forces in seven directions oriented with 15° increment with respect to the weft direction. Elastic modulus of woven fabrics was determined experimentally in the laboratory. Based on the experimentally obtained values, theoretically calculated elastic modulus for arbitrarily chosen fabric directions was calculated. A good agreement between experimental results and the calculated obtained values of the elastic modulus was shown, so the theoretical equations can be used with high accuracy to calculate the elastic modulus of the fabric in various directions. Therefore, the measurements need to be implemented when the tensile force acting on the fabric only in the warp (90°), weft (0°) and at angle of 45°.

Introduction

Woven fabrics and textile materials are generally non homogeneous, anisotropic and discontinuous objects. Special types of anisotropic materials having two mutually perpendicular planes of elastic symmetry are called orthotropic materials. These planes of elastic symmetry are planes of orthotropy, and their cross sections are axes of orthotropy (*x* and *y*) [1]. So the woven fabric is elastic orthotropic material and the element of an orthotropic plate (woven fabric) with plane state of stress is shown in Figure 1. In a biaxial woven structure two main directions are defined: longitudinal (warp) and transverse (weft).

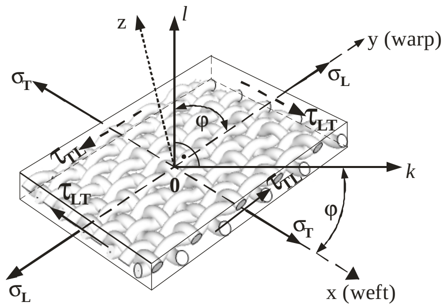


Fig. 1. Element of an orthotropic plate - woven fabric.

Theoretical analysis of fabric behaviour is often very complex, so that the experimental verification of theoretical predictions for them is more important than for other materials. The method for measuring anisotropic tensile properties of fabrics is called "uniaxial test method" or the method of force action in only one direction [2]. When the angle of an external load (tensile force) changes, elastic modulus change too. The aim of this work is to analyse the impact of anisotropy and different weaves on the elastic modulus of woven fabrics in various directions and to determine the degree of agreement between experimental results and calculated obtained values.

Elastic Modulus of Anisotropic Material for Arbitrarily Oriented Axes

Hooke's law can be applied for an anisotropic material when a tensile force acts in an arbitrary directions and the *k*- and *l*-axes do not coincide with the axes of orthotropy, Figure 1. It is assumed that load-strain curve for woven fabrics is approximate straight line before yield point. The elastic modulus E_φ in any given stretching direction can be calculated through the following equation [3]:

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

where φ is angle between tensile force direction and main axis x (Fig. 1), E_x, E_y are elastic modulus in two main direction (weft direction φ = 0°, warp direction φ = 90°), G_{xy} is shearing modulus, ν_{xy} is longitudinal Poisson ratio. The numeral value of E_x, E_y, G_{xy} and ν_{xy} can be obtained by experimental measurement. However, G_{xy} and ν_{xy} are too complicated to measure in normal experimental condition. It is proposed that G_{xy} and ν_{xy} can be replaced by elastic modulus $E_{45°}$ in direction φ = 45° which is easy to measure with E_x and E_y during uniaxial stretching. Eq. 2 indicates the mathematical relation between elastic modulus in any given tensile force direction and $E_x = E_{0°}$, $E_y = E_{90°}$ and $E_{45°}$.

$$\frac{1}{E_\varphi} = \frac{\cos^4\varphi}{E_x} + \frac{\sin^4\varphi}{E_y} + \left(\frac{4}{E_{45^0}} - \frac{1}{E_x} - \frac{1}{E_y}\right)\cdot\cos^2\varphi\cdot\sin^2\varphi. \tag{2}$$

Experiment

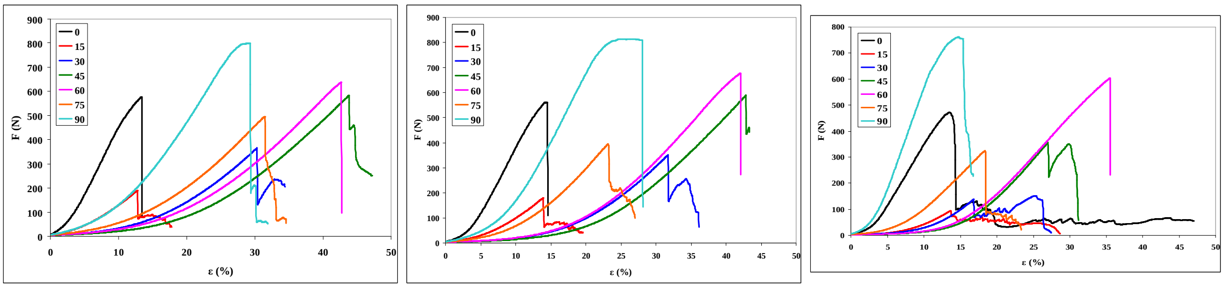
The experiment was carried out by measuring fabric spatial deformation under the action of tensile force till rupture, specifically in: warp direction, in weft direction, and under angles of 15°, 30°, 45°, 60°, 75° to the weft. Three different fabrics of different weaves (plain, twill and sateen) and the same raw material composition were used. Their structural properties are shown in Table 1. Width of the each specimen is b = 50 mm.

Table 1. Description of fabrics.

	Warp			Weft				
Fabric structure	Yarn fibres	Yarn linear density (tex)	Density (cm^{-1})	Yarn fibres	Yarn linear density (tex)	Density (cm^{-1})	Weight (g/m^2)	Thickness t (mm)
Plain	cotton	20	50	cotton	20	30	200.9	0.34
Twill	cotton	20	50	cotton	20	30	199.8	0.35
Sateen	cotton	20	50	cotton	20	30	199.4	0.37

Yarn linear density was determined by the gravimetric method according to standard ISO 2060:1994. Number of threads per unit length was determined according to standard ISO 7211-2:1984. Standard ISO 5084:1996 describes a method for the determination of the thickness of fabric. Before testing all specimens were conditioned under the conditions of standard atmosphere (relative air humidity 65 ± 2%, at a temperature of 20 ± 2°C). For the purposes of this testing standard specimens with dimensions 250 x 50 mm were clamped in clamps of the tensile tester at a distance of 200 mm and pulling speed: 100 mm/min and subjected to uniaxial tensile load till rupture. The specimens were cut in seven different directions: warp direction (φ = 90°), weft direction (φ = 0°), and at angles 15°, 30°, 45°, 60°, 75° to the weft. Three tests were done for each mentioned direction of force action on the fabric specimen. Tensile properties of all specimens were tested according with standard ISO 13934-1:1999 using the strip method for measuring fabric strength on a tensile strength tester Textechno Statimat M.

Diagrams of mean values of test results of action of tensile force F and the corresponding longitudinal strain (elongation) ε on specimens when the force acts in the warp (φ = 90°) and weft direction (φ = 0°) and under the angles 15°, 30°, 45°, 60° and 75° are shown in Fig. 2.



a) b) c)

Fig. 2. Tensile force- elongation diagram (F-ε): a) plain, b) twill, c) sateen.

From the presented diagrams, in Fig. 2, the values of tensile force in the elastic range are used. We determined elastic modulus (Young’s modulus) from a particular region on force – elongation curve that is determined by monitoring the experimental data obtained from an experimental set-up with regression control chart [4]. The mean values of initial elastic modulus E_φ are shown in Table 2.

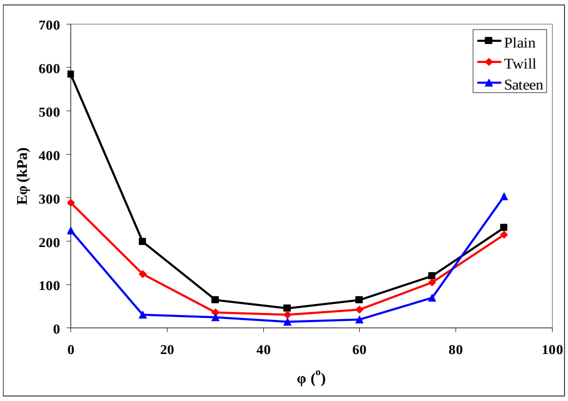
Table 2. Experimentally obtained values of elastic modulus E_φ [kPa]

	E_φ = F/ ε·b·t [kPa]						
Specimen	0°	15°	30°	45°	60°	75°	90°
Plain	583.12	199.01	64.92	45.64	64.63	119.79	231.41
Twill	289.04	124.24	35.41	31.45	42.36	104.63	214.75
Sateen	224.10	30.87	24.09	14.28	19.56	68.95	303.49

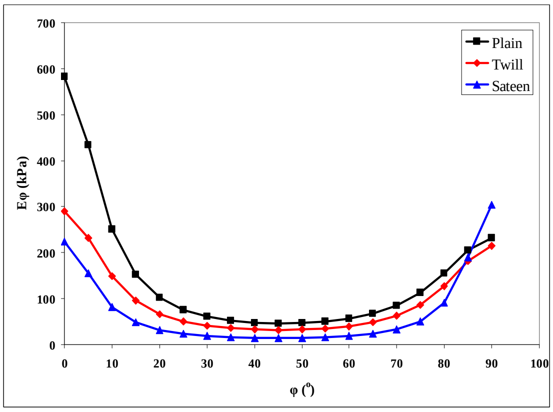
According to Eq. 2 and based on the experimental data $E_{0°}$, $E_{90°}$, $E_{45°}$ in Table 2, the values of elastic modulus E_φ were calculated for various angles of tensile force action. The calculated values E_φ are shown in Table 3. The diagram of experimental values of elastic modulus E_φ for for each 15° is shown in Fig. 3a. The diagram of calculated values of elastic modulus E_φ for each 5° is shown in Fig. 3b.

Table 3. The calculated values of elastic modulus E_φ [kPa].

	E_φ [kPa]						
Specimen	0°	15°	30°	45°	60°	75°	90°
Plain	583.12	151.22	60.47	45.64	56.06	112.74	231.41
Twill	289.04	95.46	40.71	31.45	39.74	86.87	214.75
Sateen	224.10	47.80	18.60	14.28	18.80	50.23	303.49



a)



b)

Fig. 3. Elastic modulus E_φ: a) experimental values, b) calculated values.

The values of the elastic modulus E_φ decrease from the weft direction ($\varphi = 0°$) seen in the angles 15° and 30°, while at the angle of 45° they assume the lowest value, and it increases towards 90° (warp direction).

Conclusion

Elastic modulus E_φ vary depending on the angle φ (direction of action of force). E_φ assume the highest values when the tensile force acts at angles of 0° and of 90° (weft and warp direction), and the minimum value is reached at an angle of 45°. Elastic modulus E_φ has the highest values for the plain weave, followed by the twill and the sateen weave has the lowest value. A good agreement between experimental results and the calculated obtained values of the elastic modulus E_φ was shown. Theoretical equation with high accuracy can be used to calculate the elastic modulus of fabrics for an arbitrarily chosen direction of action of tensile force. Therefore, the measurements need to be implemented when the tensile force acting on the fabric only in the warp, weft and at an angle of 45°.

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