7th International DAAAM Baltic Conference
"INDUSTRIAL ENGINEERING"
22-24 April 2010, Tallinn, Estonia

MECHANICAL PROPERTIES OF COMPOSITES REINFORCED BY COTTON KNITTED FABRIC

Kononova, O.; Krasnikovs, A.; Dzelzitis, K.; Kharkova, G.; Vagel, A. & Eiduks, M.

Abstract: *This paper presents analytical and experimental procedures for estimating the elastic properties of plain-weft-knitted-fabric-reinforced polymer-composite material. The composite material under study is assumed to have mainly reinforcement-fiber yarns and polymer matrix. Cotton yarn and fabrics are being considered as an environmentally friendly alternative to synthetic reinforcement in polymer composites. In present investigation cotton yarn of different length were tested by tension in order to obtain the stress-strain dependence. Also cotton knitted fabric specimens of different knitting directions were tested by tension in order to obtain the stress-strain response. Elastic moduli of cotton yarn and knitted fabrics having different load span and knitting direction were obtained. Cotton knitted fabric composites with thermoset polymer matrices were manufactured and tested by tension for stiffness and strength determination. Analytically predicted using effective modulus method composite material elastic properties were compared with experimentally obtained.*
Key words: Cotton yarn, cotton knitted fabric, method of effective modulus.

1. INTRODUCTION

Using knitted fabrics in composites are gaining much interest because of their excellent flexibility and mechanical properties in the through the thickness direction so they are most suitable for the production of 3D fabrics for complex shape.

Textiles and textile composites are hierarchical structured materials. Predictive models are complicated; it's hard to specify such mechanical properties like transversal elastic modulus and Poisson's ratio. The large variety of possible textile performs presents a challenge for composite materials science. In order to effectively predict the properties of a composite, it is often useful to know the properties of reinforcement.

2. MECHANICAL PROPERTIES OF YARN

Knitted fabric properties are determined by the yarn and fabric construction and any chemical and mechanical treatment applied to the yarn or fabric. Fabric thickness depends mostly on yarn diameter and little on stitch length and yarn twist due to loop curvature. The behavior of knitted fabrics under tensional loads depends on several factors such as fabric design, fabric tightness, yarn type and applied load [1,2].

2.1. Yarn tensile test

A common feature of natural yarns is a much higher variability of mechanical properties. Although yarn thickness varies along the yarn, we accepted each yarn perfectly round and having constant diameter.

Knowing the yarn number of explored cotton yarn, it is possible to determine the diameter of yarn. Number of yarn - 50, it means that 50 meters of cotton yarn's has 1 gram in weight. Knowing the density of cotton ρ = 1,51 g/cm^3 and using simple formulas diameter of yarn was determined and equal 130 mkm. Yarns diameters were evaluated from optical observation under microscope too.

Cotton yarns delivered by Juglas manufaktura (Latvia) were used. The yarns were stored and tested at ambient conditions. Yarn ends were glued onto a paper frame. During mounting the specimens were handled only by the paper frame. Yarn length outside the frame was 10, 15 and 20 cm.

The tests were carried out on an electromechanical tensile machine Zwick Z150 equipped with mechanical grips. Load-displacement curve was recorded during the test. Upper grip of the machine was attached through a hinge and thus allowed to self-align. All tests with yarns were displacement controlled with the loading rate of 10 mm/min. During the experiment the data were transferred to the PC.

2.2. Determination of elastic modulus of yarn

The diagrams of stress-strain curve were obtained from load-displacement curves taking into consideration that yarn diameter is a constant. The elastic modulus was found from experimental dates as a tangent of angle of slope of stress-strain curve to horizontal.

As demonstrated in Fig. 1 stress-strain curves being rather linear. Curves for three specimens at 10 cm length are presented showing remarkable stability of results. The obtaining stress-strain curves were linearized for the elastic modulus determination. The average values of the elastic modulus for different length of specimens are provided in Table 1. These results show that the elastic modulus is not significantly different, but with increasing length of the yarn - value of the elastic modulus also increases.

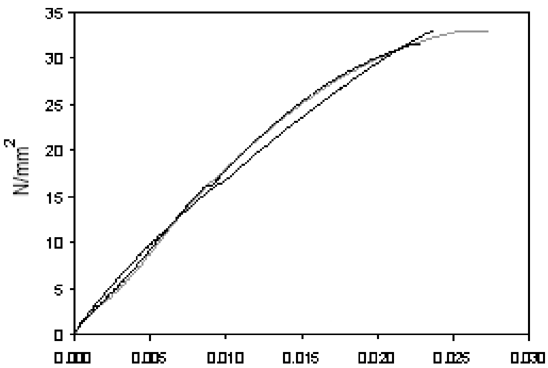


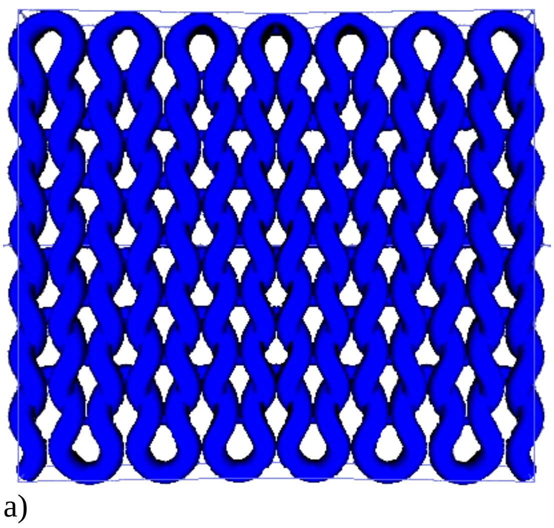
Fig. 1. The stress-strain diagrams of yarns at 10 cm length

Yarn length	10 cm	15 cm	20 cm
E (GPa)	3.606	3.761	4.230

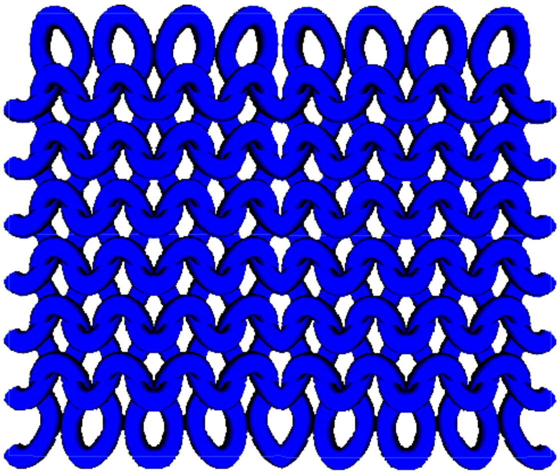
Table 1. Elastic modulus of cotton yarn

3. MECHANICAL PROPERTIES OF KNITTED FABRIC

The ways in which textile materials deform under application of axial stress play an important role in their processing and use. When tensile loading is applied to the knitted fabric (Fig. 2.), the yarn within the structure moves until it jams and then the yarn elongates until it breaks. Under an applied load, plain knitted fabric has less elongation in the walewise direction than in coursewise direction due to widthwise jamming occurring sooner than coursewise jamming [3].



a)



b)

Fig. 2. Knitted fabric, modelled in WiseTex, presented in Cortona 3D software [4]; a) the front side; b) the back side

3.1. Knitted fabric tensile test

Tensile tests were carried out on an electromechanical tensile machine Zwick Z150 machine equipped with mechanical grips. All tests with knitting fabric were displacement controlled with the loading rate of 40 mm/min. The specimens are cut to a size of 10 × 100 mm. The thickness of investigated cotton plain-knit fabrics was assumed equal $8.278 \cdot 10^{-5}$ m. The textile thickness was obtained from linear density of fabric 125 g/cm^2. Knitted fabrics samples are extended in different directions: in the walewise direction (0^0 angle), in coursewise direction (90^0 angle) and at 45° angle. Load-displacement curve was recorded during the test. During the experiment the data were transferred to the PC.

3.2. Determination of elastic modulus of knitted fabric

The diagrams of stress-strain curve were obtained from load-displacement curve. Stress-strain diagrams of knitted fabric in different direction demonstrate high nonlinearity of curves (Fig. 3). Stress-strain curve can be replaced by bilinear characteristic as it shown in Fig. 4 for diagram in the walewise direction (0^0 angle).

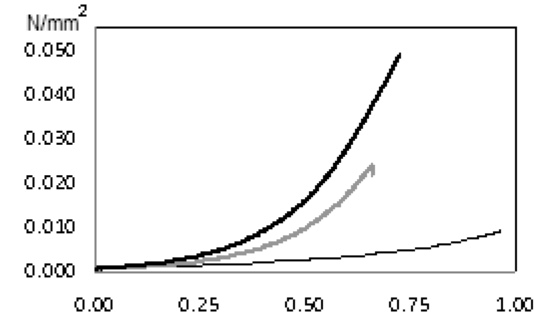


Fig. 3. The stress-strain diagrams of knitted fabric in directions:
0^0, 90^0, 45^0

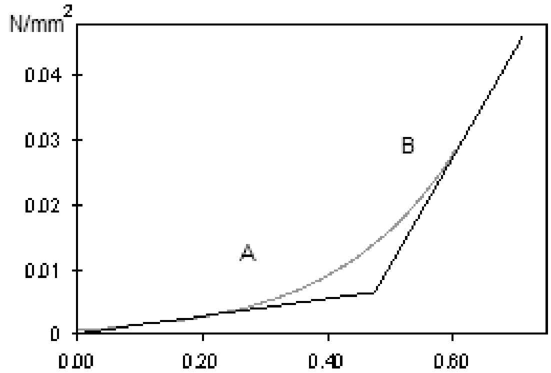


Fig. 4. The stress-strain diagram of knitted fabric in the walewise direction ;
bilinear aproximation .

Diagram in Fig. 4 has two typical zones: the yarn within the structure moves (zone A) and the yarn elongates until it breaks (zone B). Elastic moduli are obtained for both zones: 13.7 MPa (zone A) and 168.1 MPa (zone B).

4. MECHANICAL PROPERTIES OF COMPOSITES REINFORCED BY KNITTED FABRIC

4.1. Composites tensile test

Plates (of 2.2 mm thickness) of thermoset cotton fabric composites were manufactured by using acrylic resin. Acrylic resin parameters: elastic modulus E=3.3 GPa, density 1.12 g/cm^3, Poisson's ratio η=0.35. Rectangular specimens (5 layer) 25 x 100 mm were cut from the plates for tensile test with different directions of knitted fabric orientation (angles 0^0, 90^0, 45^0). Mechanical tests were performed on composites with fiber weight fraction W_f=27%. Volume fractions of fibers which are most suitable for theoretical analysis can be calculated using densities. Using densities of constituents ρ_f=1.51 g/cm^3 ρ_m=1.12 g/cm^3 and standard micromechanics expressions [5] we calculate the corresponding fiber volume fractions V_f=21.5%.

$$\frac{1}{\rho_c} = \frac{W_f}{\rho_f} + \frac{W_m}{\rho_m} \tag{1}$$

$$V_f = \frac{W_f \cdot \rho_c}{\rho_f} \tag{2}$$

Tensile tests were carried out on an electromechanical tensile machine Zwick Z150 machine equipped with mechanical grips. All tests with composite specimens were displacement controlled with the loading rate of 10 mm/min. Load-displacement curve was recorded during the test. During the experiment the data were transferred to the PC.

4.2. Determination of elastic modulus of composites

The diagrams of stress-strain curve were obtained from load-displacement curves. As demonstrated in Fig. 5 the stress-strain curves with different directions of knitted fabric appears close to one other.

The elastic moduli were determined analyzing data with the maximum strain value of about 0.2%. This level was used expecting that damage will not develop in this relatively low strain region [6]. The theoretical stress-strain curve is obtained in the same region using the parameters of both constituents:

$$E_L = E_f V_f + E_m \left(1 - V_f\right) \tag{3}$$

where E_L – longitudinal elastic modulus of composite; E_f – fiber (textile) elastic modulus; E_m – matrix (acrylic resin) elastic modulus.

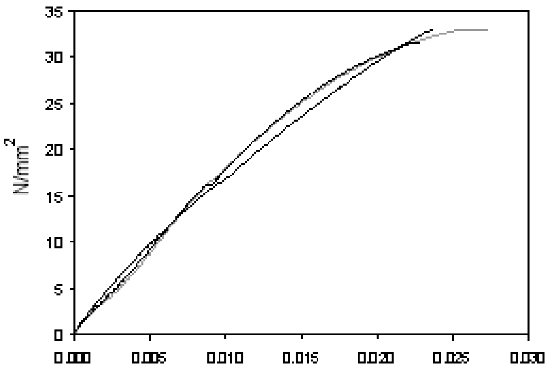


Fig. 5. The stress-strain diagram of composites reinforced by knitted fabric in different directions: at 0^0 ▬▬▬, 90^0 ——, 45^0 ▬▬▬ .

The comparison of experimental and theoretical stress-strain curves is shown in Fig. 6. The experimental and theoretical curves have different slopes and different values of elastic modulus. It means that the indicated above method of determination of knitted fabric elastic modulus is not correct. Primary cause of differences in real and obtained curves is rigidity of matrix that not allows considerable deformation of textile. Therefore the elastic modulus of composite was obtained experimentally for fabric direction 0^0 and evaluated for other directions.

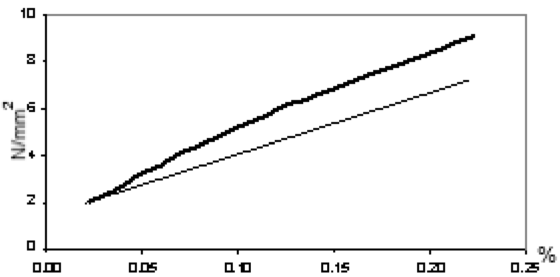


Fig. 6. The stress-strain diagram of composite at 0^0: experimental ▬▬▬, theoretical ——

The elastic modulus of composite is obtained by linearization of experimental curve (see Fig. 7) and equal 3.7 GPa.

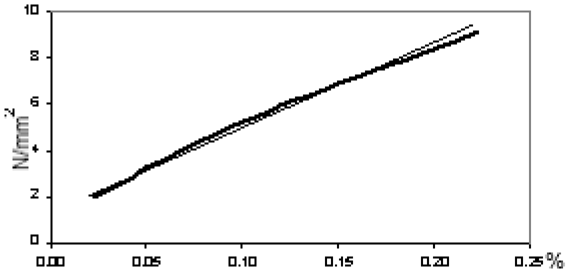


Fig. 7. The stress-strain diagram of composite at 0^0: experimental ▬▬▬, linearization ───

The fiber (textile) elastic modulus was obtained from (3) and is equal to 5.158 GPa. The longitudinal and transverse elastic moduli, Poisson's ratios were obtained:

$$
\begin{aligned}
E_T &= \frac{E_m\left(1+\xi_1\eta_1 V_f\right)}{1-\eta_1 V_f}\\
\eta 1 &= \frac{\frac{E_f}{E_m}-1}{\frac{E_f}{E_m}+\xi 1}\\
G_m &= \frac{E_m}{2\cdot(1+\nu_m)}\\
G_f &= \frac{E_f}{2\cdot(1+\nu_f)}\\
\eta 2 &= \frac{\frac{G_f}{G_m}-1}{\frac{G}{G_m}+\xi 2}\\
G_{lt} &= \frac{G_m\,(1+\xi 2\cdot\eta 2\cdot V_f)}{1-\eta 2\cdot V_f}\\
\nu_{lt} &= \nu_f\cdot V_f+\left(1-V_f\right)\cdot\nu_m
\end{aligned}
\tag{4}
$$

where E_T – transverse elastic modulus, G_m - matrix shear modulus, G_f – fiber shear modulus, G_{lt} –shear modulus of composite, ν_{lt} - Poisson's ratio of composite, constants $\xi 1$=2, $\xi 2$=1.

The effective modulus method (laminate plate theory) was used [7] and obtained inplane stiffness matrix for laminate in direction 45° (in N/m):

$$
A = \begin{pmatrix} 7.411\times10^{6} & 2.218\times10^{6} & 2.787\times10^{4}\\ 2.218\times10^{6} & 7.411\times10^{6} & 2.787\times10^{4}\\ 2.787\times10^{4} & 2.787\times10^{4} & 3.219\times10^{6} \end{pmatrix}
$$

And effective engineering properties for laminate are determined from stiffness constants including the longitudinal elastic modulus 3.359 GPa. The comparison of experimental and theoretical stress-strain curves for direction 45° is shown in Fig. 8.

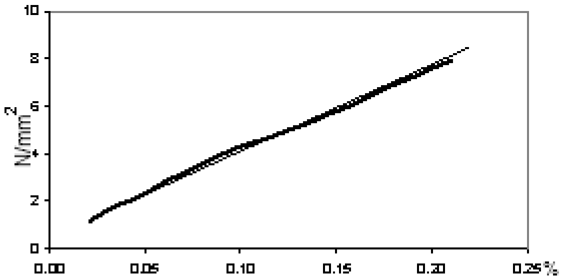


Fig. 8. The stress-strain diagram of composite at 45°: experimental ▬▬▬, theoretical ───

The inplane stiffness matrix (in N/m) and longitudinal elastic moduli were determined for fabric direction 90° and equal 3.649 GPa

$$
A = \begin{pmatrix} 8.409\times10^{6} & 2.523\times10^{6} & -4.247\times10^{-11}\\ 2.523\times10^{6} & 8.527\times10^{6} & 4.967\times10^{-11}\\ -4.247\times10^{-11} & 4.967\times10^{-11} & 2.596\times10^{6} \end{pmatrix}
$$

The comparison of experimental and theoretical stress-strain curves for direction 90^0 is shown in Fig. 9.

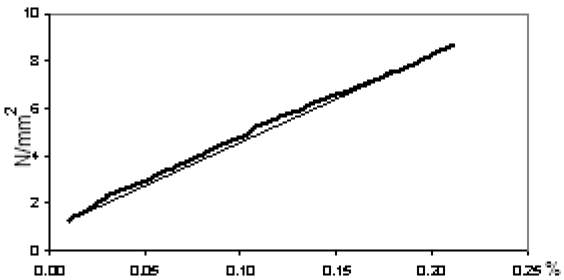


Fig. 9. The stress-strain diagram of composite at 90°: experimental ▬▬▬, theoretical ───

Figures 8 - 9 show the good coincide between experimental and theoretical data.

5. CONCLUSIONS

Cotton yarn elastic modulus was determined experimentally. Scale factor was investigated testing yarn pieces having different load span.

Cotton knitted fabric composites with thermoset polymer matrices were manufactured and tested (by tension) for stiffness determination. Observed composites show almost isotropic behavior at any knitted fabric orientation.

The elastic modulus of cotton fabric was obtained experimentally. Simultaneously analytical material stiffness prediction was done using effective modulus method for laminated composites. Results comparisons are shown good agreement.

6. ACKNOWLEDGEMENTS

This work has been supported by the European Social Fund within the project “Nanotechnological research of the mechanical element surface and internal structure in mechanical engineering”.

7. REFERENCES

1. Saville, B.P. *Physical testing of textiles*, CRT Press LLC, USA, 2000.
2. Ramakrishna, S.; Huang, Z.M.; Teoh, S.H.; Tay, A.A.O. and Chew, C.L. Application of the model of Leaf and Glaskin to estimating the 3D elastic properties of knitted-fabric-reinforced composites *Journal of the Textile Institute*, 2000, 91: 1, 132 — 150.
3. *Cotton: Science and technology*, edited by S.Gordon and Y-L.Hsieh, Woodhead Publishing Limited, USA, 2007.
4. Verpoest, I. and Lomov, S. V. Virtual textile composites software WiseTex: Integration with micro-mechanical, permeability and structural analysis *Composites Science and Technology* **65**, December 2005, 2563-2574.
5. Reddy, J.N. *Mechanics of laminated composite plates and shells: theory and analysis* - CRC Press, 2004.
6. Andersons, A., Joffe, R., Spārniņš, E. Stiffness and strength of flax fiber/polymer matrix composites *Polymer Composites* 2007, **27**, 221-229.
7. Halpin, J. *Primer on composite materials analysis*. USA: Technomic, 1992.

8. ADDITIONAL DATA ABOUT AUTHORS

Andrejs Krasnikovs
Riga Technical University, Institute of Mechanics, akrasn@latnet.lv

Olga Kononova
Riga Technical University, Institute of Mechanics, olga.kononova@gmail.com

Karlis Dzelzitis
Riga Technical University, Institute of Materials and Constructions, karlis.dzelzitis@rtu.lv

Galina Kharkova
Riga Technical University, Institute of Mechanics, kenji@inbox.lv

AngelinaVagel
Riga Technical University, Institute of Mechanics, shapulja@inbox.lv

Maris Eiduks
Riga Technical University, Institute of Mechanics, maris.eiduks@rtu.lv