

ELASTIC PROPERTIES OF COTTON FABRIC BASED POLYMER COMPOSITES

**Galina Kharkova, Olga Kononova, Andrejs Krasnikovs, Maris Eiduks,
Edgars Machanovskis, Karlis Dzelzitis**
Riga Technical University, Latvia
akrasn@latnet.lv

Abstract. The paper presents analytical and experimental procedures for estimating elastic properties of a plain weft-knitted fabric and of polymer composite materials reinforced by it. Cotton yarn and fabrics are being considered as an environmentally friendly alternative to synthetic reinforcement in polymer composites. In the present investigation, cotton yarn of different length and cotton knitted fabric specimens of different knitting directions were tested by tension in order to obtain the stress-strain response. Elastic modulus of the cotton yarn and knitted fabrics, having different load span and knitting directions, were obtained. Cotton knitted fabric composites with thermoset polymer matrices were manufactured and tested for stiffness and strength. Based on the Leaf and Glaskin model, a numerical (FEM) elastic properties averaging model was elaborated. Calculated elastic properties of composite materials have shown high compatibility with experimentally obtained values.

Keywords: cotton yarn, cotton knitted fabric, elastic modulus, textile composites.

Introduction

Using knitted fabric as polymer composite reinforcement is gaining much interest during the last decades because of its attractive mechanical properties, energy absorption, impact resistance, etc. and technological advantages – excellent stretch ability, shape forming ability and flexibility, which allows it to be used in any complex shape mould without folds [1-5]. Yarns curvature through the thickness direction means that they are most suitable for the production of 3D fabrics of complex shape. At the same time, textiles and textile composites are hierarchical, structured materials; the large variety of possible textile preforms leads to sophisticated forms of predictive models of elastic properties. Investigation of textile composites behaviour traditionally is separated into two stages: first – investigation of mechanical properties of fibres, yarn and fabric, and second – experimental investigation of the knitted fabric composite material and prediction (creating some theoretical model) of the elastic properties [2; 4; 6].

In order to effectively predict the properties of a composite, it is necessary to know the properties of the reinforcement. Mechanical properties of the yarn are traditionally measured experimentally.

For the knitted fabric geometrical modelling is important [7; 8]. In papers [9; 10] also the plain knitted fabric was investigated and geometrical models were created. In the recent papers a new model was created by assuming that the orthogonal projection of the yarn path is formed of smoothly connected arcs. Different modelling of the geometrical structure of the knitted fabric is considered in [11; 12].

Knitted fabric reinforced composites have been investigated experimentally (for different fibres and matrices) and theoretically (elaborating analytical or numerical models) [2; 4; 6; 13-16]. Theoretical investigation of mechanical properties is based on averaging procedures used in combination with some assumptions about the internal geometry of the reinforcing fabric.

Mechanical properties of composites reinforced by knitted fabric

Properties of a knitted fabric are determined by the internal geometrical construction of the yarn and fabric, as well as by chemical and mechanical treatment applied to the yarn. Fabric thickness depends mainly on the yarn diameter; stitch length and yarn twist due to the loop curvature. The behaviour of the knitted fabric under the applied tensional load depends on several factors such as the fabric design, fabric tightness, yarn type and applied load [17-19]. The mechanical properties of a cotton yarn and knitted fabric have been investigated in ref. [24].

The ways how textile materials deform under applied stresses play an important role in their processing and use. When the tensile load is applied to the knitted fabric (shown in Fig. 1) and is increased, the yarn within the structure is moving with friction, changing loops geometry until it jams and then it elongates until it breaks. Under the applied load, the plain knitted fabric has less elongation

in the walewise direction than in the coursewise direction due to the widthwise jamming occurring sooner than the coursewise jamming [20].

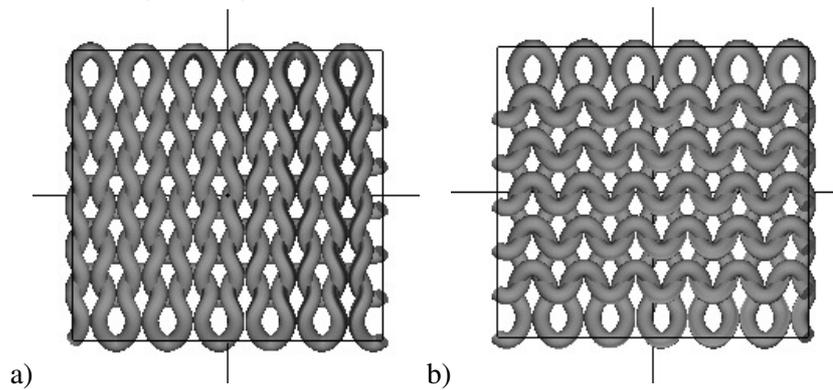


Fig. 1. Knitted fabric modelled in WeftKnit program:
a) the front side; b) the back side

Composites tensile test

Thermoset matrix composite plates (5 layers, $2.2 \cdot 10^{-3}$ m thick), reinforced by the cotton fabric, were manufactured using acrylic resin. Cotton yarns, delivered by Juglas Manufaktura (Latvia), were used. Acrylic resin parameters: elastic modulus 3.3 GPa, density $1120 \text{ kg} \cdot \text{m}^{-3}$, Poisson's ratio 0.35. Rectangular specimens 25-250 mm were cut out of the plates for tensile tests under different directions to knitted fabric orientation (angles 0° , 45° , 90°). Mechanical tests were performed on composites with fibre weight fraction 27 %. Knitted fabric samples were tested according to the preparation procedure described in ASTM D 5083-02.

Tensile tests were executed on an electromechanical testing machine Zwick Z150. All tests with composite specimens were displacement-controlled with the loading rate of $5 \text{ mm} \cdot \text{min}^{-1}$. Load-displacement curves were recorded during the tests. Experimental data in real time regime were transferred to the PC.

The stress-strain curves were obtained. As demonstrated in Fig. 2, the stress-strain curves with different directions of the knitted fabric area close to each other, which can be explained by peculiarities of the fabric used in sample preparation.

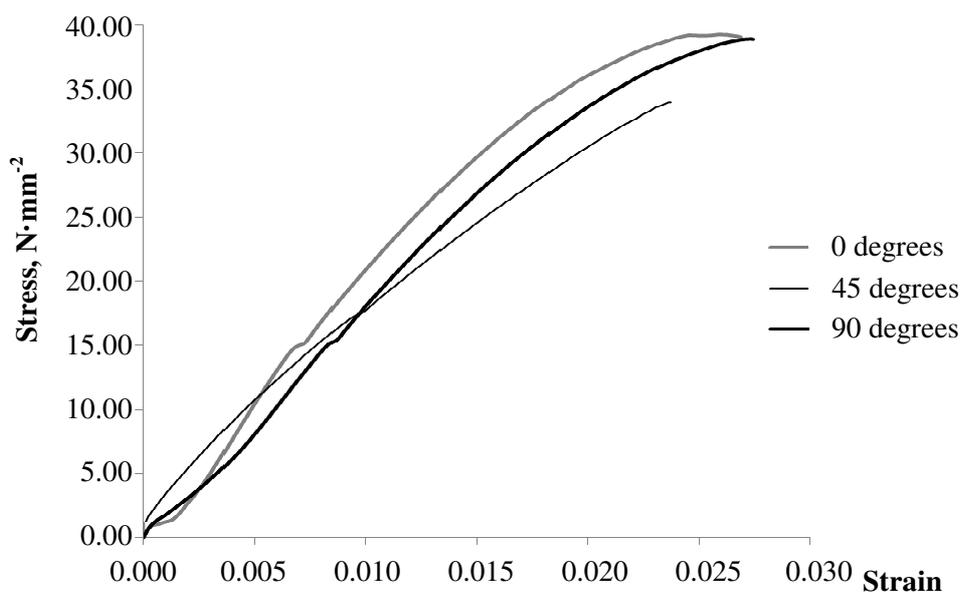


Fig. 2. The stress-strain curve of composites, reinforced by the knitted fabric

Numerical simulation of composites, reinforced by the knitted fabric

It was supposed that cotton fabric composites consist of multiples of plain weft-knitted fabric laminas, each of which can be arranged differently [22].

The 3D geometrical modelling of the knitted fabric was based on the Leaf and Glaskin model. A schematic diagram of an idealized plain weft-knitted fabric structure is shown in Fig. 3. According to Leaf and Glaskin, the structural geometry of the fabric is completely defined if three geometric parameters, the wale number W , the course number C and the yarn diameter d are provided. The wale number is defined as the step of loops of the fabric per unit length along the width (in the course) direction, whereas the course number is defined as the step along the length (in the wale) direction, as indicated in Fig. 3 [22].

For the first yarn we have [22]:

$$x = ad(1 - \cos\theta), \quad y = ad \sin\theta, \quad z = \frac{hd}{2} \left(1 - \cos\left(\pi \frac{\theta}{\xi}\right) \right) \tag{1}$$

where

$$a = \frac{1}{4Wd \sin\xi}, \quad \phi = \arccos\left(\frac{2a-1}{2a}\right)$$

$$\xi = \pi + \arcsin\left(\frac{C^2 d}{(C^2 + W^2(1 - C^2 d^2)^2)^{1/2}}\right) - \arctan\left(\frac{C}{W(1 - C^2 d^2)}\right), \tag{2}$$

$$h = \left[\sin\left(\pi \frac{\psi}{\xi}\right) \sin\left(\pi \frac{\phi}{\xi}\right) \right]^{-1}, \quad \psi = \arcsin\left(\frac{2a}{2a-1} \sin\xi\right).$$

Elastic properties of the composite material can be calculated using the representative volume of the material or unit cell (shown in Fig. 3). All numerical simulations were carried out for a 3D unit cell of the cotton fabric composite shown in Fig. 4.

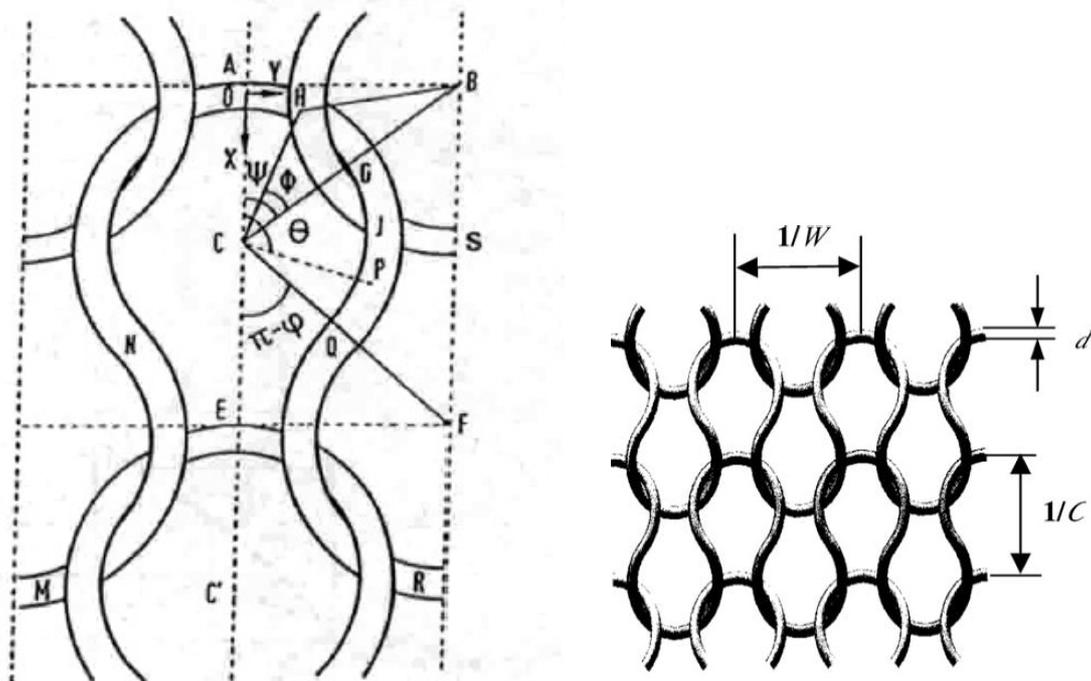


Fig. 3. Schematic presentation of the knitted fabric structure [22]

By using a symmetric condition, the coordinates of discretized points on the second yarn are derived as:

$$x_1^{2nd} = 2ad - \frac{1}{2W \tan(\psi)}, \quad x_n^{2nd} = x_1^{2nd} - x_n^{1st},$$

$$y_1^{2nd} = \frac{1}{2W}, \quad y_n^{2nd} = y_1^{2nd} - y_n^{1st}, \quad (3)$$

$$z_1^{2nd} = z_1^{1st}, \quad z_n^{2nd} = z_2^{2nd}, \quad n \geq 2, 3, \dots,$$

where the superscripts 1st and 2nd refer to the first and the second yarn, respectively.

The visual unit cell model (geometry) of the weft-knitted fabric composite was created using CAD software. The numerical model (based on FEM) was created using Solid Works code. Cotton yarn was considered as a homogeneous elastic rod and as elastic modulus of the yarn the experimentally obtained value was used, equal to 3.7 GPa, elastic modulus of the acrylic resin was indicated earlier [24] and was equal to 3.3 GPa.

At first, coordinates x , y and z for the first and the second yarn were obtained by using formulas (1)-(3). The parameters of the considered cotton knitted fabric are the following: wale number $W=13 \text{ loop}\cdot\text{cm}^{-1}$, course number $C=20 \text{ loop}\cdot\text{cm}^{-1}$, yarn diameter $d=0.013 \text{ cm}$.

In SolidWorks code the 3D sketch was obtained, inputting x , y and z coordinates for both yarns after that they were connected by a spline function. Yarn was simulated as a homogeneous elastic rod by using sweep function that creates a base by moving a profile (diameter of yarn in our case) along a spline curve. The matrix of the plain weft-knitted fabric lamina was created as a cube with holes for yarn by using the sweep cut function. And at last, the assembly between yarns and matrix was created (Fig. 4).

One butt-end surface of the unit cell was fixed; to another butt-end surface pressure loads were applied; to side surfaces symmetry conditions were applied.

Results and discussion

Finite elements analysis was carried out for this elastic model (Fig. 4). Strain value was averaged over the butt-end surface under applied loads and the ratio of applied pressure and average strain value was calculated. Similarly the unit cell models for other directions, corresponding to reinforcement, were created. The obtained elastic moduli for different directions of the knitted fabric composite are:

	0°	45°	90°
E , GPa	3.521	3.384	3.333

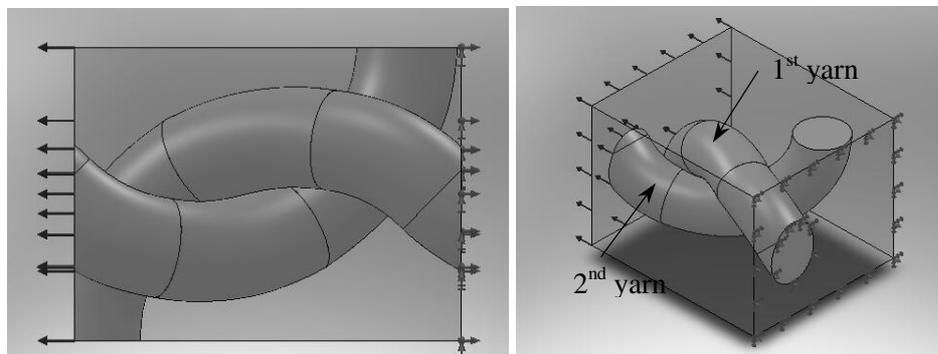


Fig. 4. SolidWorks 3D model for unit cell (knitted fabric orientation 0°)

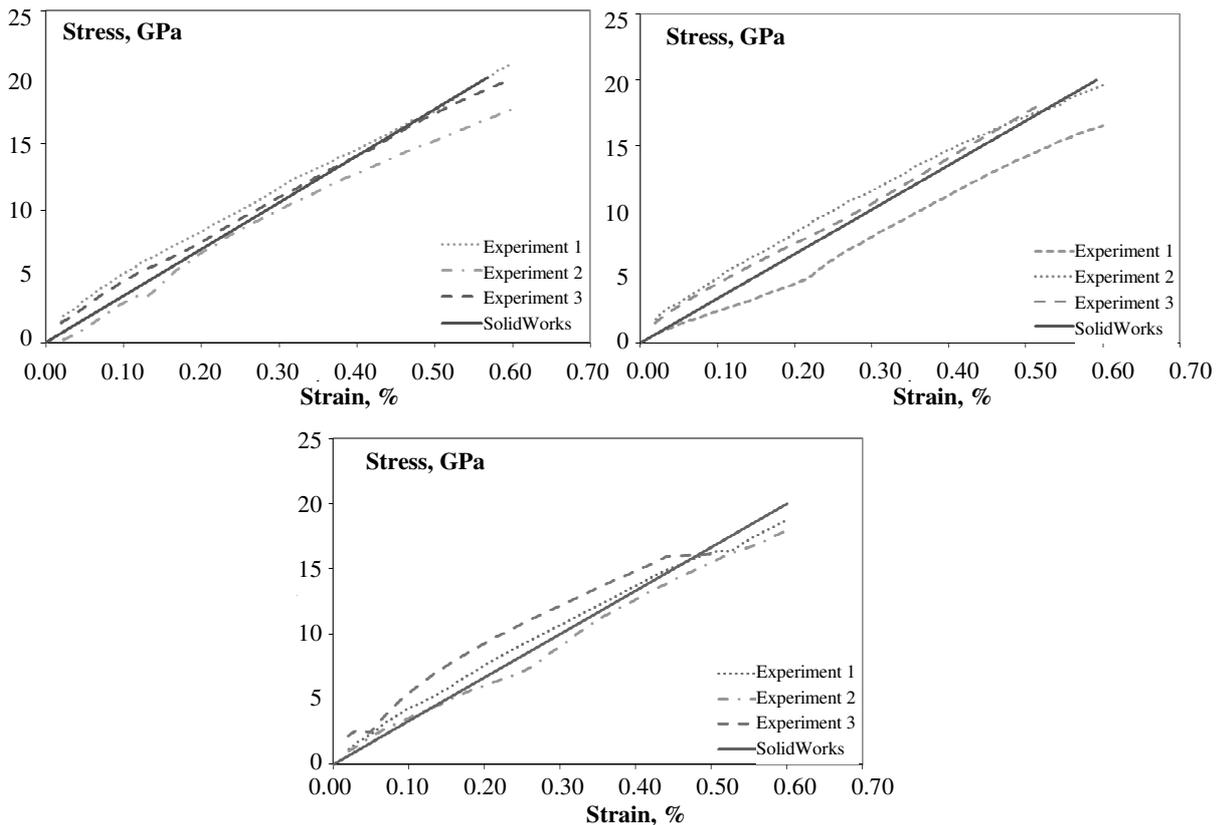


Fig. 5. The stress-strain curve of composites:
 (a) – direction 0°; (b) – direction 45°; (c) – direction 90°

The elastic modulus was determined analysing the data with the maximum strain value of about 0.6 %. This level was used expecting that damage will not develop in this relatively low (for our textile composite) strain region [23]. The computer simulation data were compared with the experimental results for samples, cut under different directions and are shown in Fig. 5.

Conclusions

Elastic properties of the cotton yarn and fabric were determined experimentally. Cotton knitted fabric composites with thermoset polymer matrix were manufactured and tested (by tension) for stiffness determination. The observed composites show almost isotropic behaviour at any knitted fabric orientation. A geometrical–numerical (FEM) model was created with the goal to predict elastic properties of the knitted fabric layered composite. The model is structural with high potential of predicting the elastic properties for diverse knitted fabric layered composites. The numerical simulation results were compared with the experimental data showing a high level of coincidence.

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