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Modelling and experimental verification of mechanical properties of cotton knitted fabric composites

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Abstract. This 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 moduli 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.

Key words: cotton yarn, cotton knitted fabric, elastic modulus.

1. INTRODUCTION

Using knitted fabric as polymer composite reinforcement is gaining much interest during the last decades because of it 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 in the 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 important is geometrical modelling [7,8]. In papers [9,10] also the plain knitted fabric was investigated and geometrical models were created. In the last 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.

2. MECHANICAL PROPERTIES OF A YARN

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 applied tensional load depends on several factors such as the fabric design, fabric tightness, yarn type and applied load [17–19].

2.1. Tensile test of the yarn

Cotton yarns, delivered by Juglas Manufaktura (Latvia), were used. Linear density of the cotton yarn was calculated by the formula, described in ASTM D 2591-01 Standard:

$$T_d = 10\,000 \times (M/L), \tag{1}$$

where T_d is linear density (dtex), M is specimen mass (g) and L is specimen length (m). For example, the length of the investigated cotton yarn specimen was 50 m, specimen mass 1 g and obtained linear density 200 dtex or 20 tex. A common feature of natural yarns is a high variability of mechanical properties. Although the yarn thickness varies along the yarn, similarly to the majority of authors we supposed that the yarn is perfectly round and has a constant diameter. Knowing the density of cotton ($\rho = 1510$ kg/m^3), diameter of the yarn d was determined as

$$d = \sqrt{\frac{4m}{L\pi\rho}}, \tag{2}$$

where m is the specimen mass (kg). In our case $d = 1.3\times10^{-4}$ m. Simultaneously the yarn diameter was evaluated from optical measurements with a microscope.

The yarns were stored and tested at ambient conditions. Yarn samples were tested according to the preparation procedure described in ASTM D 2256-02. Gauge lengths of specimens were 500 mm.

The tests were carried out on a computer controlled electromechanical testing machine Zwick Z150, equipped with mechanical grips. The load–displacement curve was recorded during the test. The displacement was controlled with the loading rate 500 mm/min. During the experiment the data were transferred to the PC.

2.2. Determination of the elastic modulus of the yarn

The stress–strain curves were obtained from the load–displacement curves under the assumption that yarn diameter is a constant. The elastic modulus was found as the angle of the tangent to the stress–strain curve. As is shown in Fig. 1, after pre-tension, the slope can be successfully approximated by a linear function. Curves for five specimens are presented showing remarkable stability of the results. Elastic modulus was determined using the linear part of the curves (Table 1).

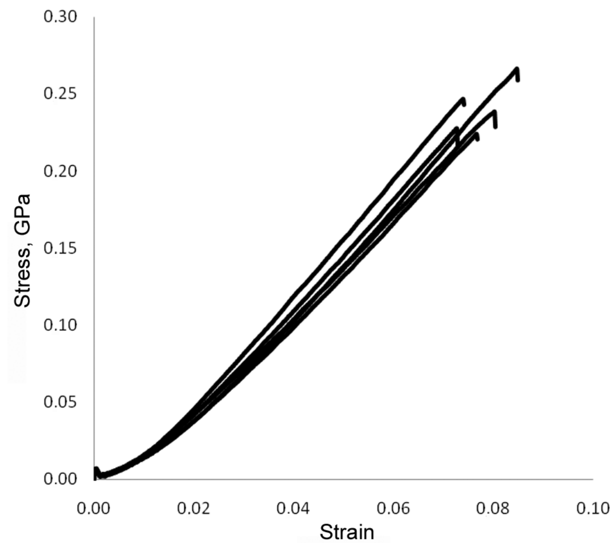

Fig. 1. The stress-strain curves for 5 samples of the yarn.

Table 1. Elastic modulus of the yarn in GPa, gauge length is 500 mm

Samples					Average
1	2	3	4	5	
3.849	3.683	3.754	3.496	3.635	3.683

3. MECHANICAL PROPERTIES OF THE KNITTED FABRIC

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. 2) 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].

3.1. Tensile test of the knitted fabric

Cotton knitted fabric specimens were prepared and tested according to ASTM D 2594-99 Standard. From each laboratory sampling unit 5 walewise (0° angle) and 5 coursewise (90° angle) test specimens 125 × 500 mm were cut. The long dimension of the walewise specimens is parallel to the wale direction and that of the coursewise specimens parallel to the course direction. Consider the long direction as the direction of the test. Each specimen was folded in half lengthwise forming a loop, sewed and fixed into the frame (hanger assembly). Weights of 22.27 and 44.54 N were attached to specimens and exercised the specimen loop by cycling four times. Knitted fabric stretch was calculated as

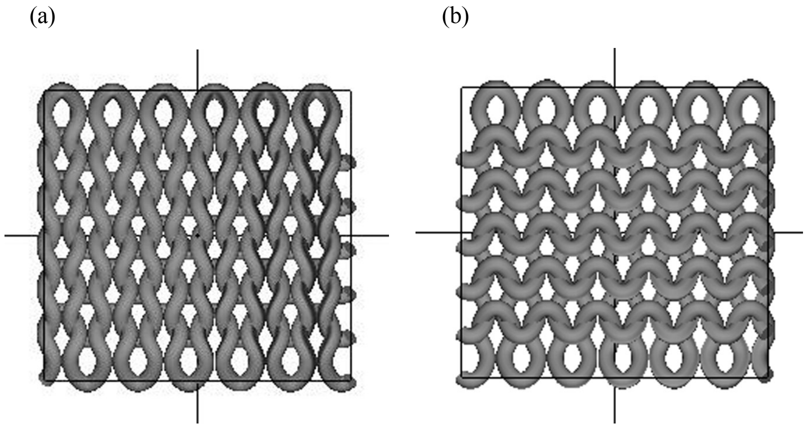

Fig. 2. Knitted fabric, picture from [21]: (a) the front side; (b) the back side.

$$S = 100(D - A)/A, \tag{3}$$

where S is the fabric stretch (%), A is the original gauge length (mm), D is specimen length under tension (mm). Additionally were tested 5 specimens of the knitted fabric, which were cut at 45°. The results are shown in Table 2.

Additionally the tensile tests under increasing applied load were carried out for the same specimens on an electromechanical testing machine Zwick Z150. All tests were carried out under displacement control with the rate of 2 mm/min. Load–displacement curves were obtained. The curves for different directions demonstrate highly non-linear behaviour (Fig. 3). Each curve can be divided into two typical zones: the first zone (with low elasticity module) corresponds to situation when the yarn within the structure moves with friction deforming the loops and the second zone (with high elastic modulus) when each yarn elongates until it breaks.

Table 2. Knitted fabric stretch, %

Load, N	0°	45°	90°
22.27	15.60	46.40	68.40
44.54	26.13	55.20	99.20

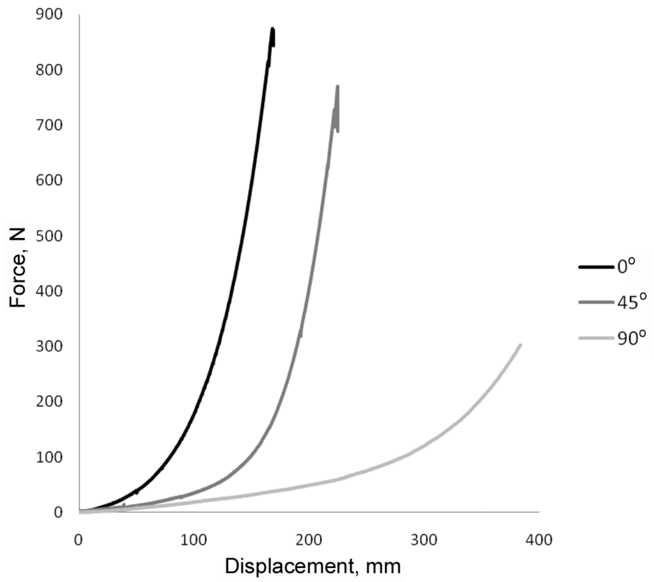

Fig. 3. Load–displacement curves for knitted fabric's samples cut under different angles.

4. MECHANICAL PROPERTIES OF COMPOSITES REINFORCED BY THE KNITTED FABRIC

4.1. Tensile test

Thermoset matrix composite plates (5 layers, 2.2×10^{-3} m thick), reinforced by the cotton fabric, were manufactured using acrylic resin. Acrylic resin parameters: elastic modulus 3.3 GPa, density 1120 kg/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 mm/min. 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. 4, the stress–strain curves with different directions of the knitted fabric area close to each other, what can be explained by peculiarities of the fabric used in sample preparation.

4.2. 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].

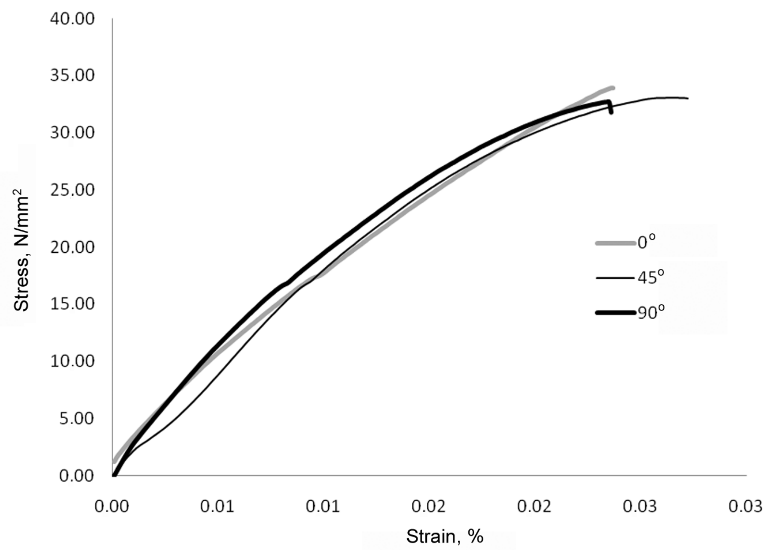

Fig. 4. The stress–strain curves of composites, reinforced by the knitted fabric.

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. 5. According to Leaf and Glaskin, the fabric's structural geometry 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 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. 5 [22].

Elastic properties of the composite material can be calculated using material's representative volume or unit cell (shown in Fig. 5). All numerical simulations were carried out for a 3D unit cell of the cotton fabric composite shown in Fig. 6.

For the first yarn we have [22]:

$$x = ad(1-\cos\theta), \quad y = ad\sin\theta, \quad z = \frac{hd}{2}\left(1-\cos\left(\pi\frac{\theta}{\xi}\right)\right), \tag{4}$$

where

$$\begin{gathered} a = \frac{1}{4Wd\sin\xi}, \quad \phi = \arccos\left(\frac{2a-1}{2a}\right), \\ \xi = \pi + \arcsin\left(\frac{C^2 d}{(C^2 + W^2(1-C^2d^2)^2)^{1/2}}\right) - \arctan\left(\frac{C}{W(1-C^2d^2)}\right), \\ h = \left[\sin\left(\pi\frac{\psi}{\xi}\right)\sin\left(\pi\frac{\phi}{\xi}\right)\right]^{-1}, \quad \psi = \arcsin\left(\frac{2a}{2a-1}\sin\xi\right). \end{gathered} \tag{5}$$

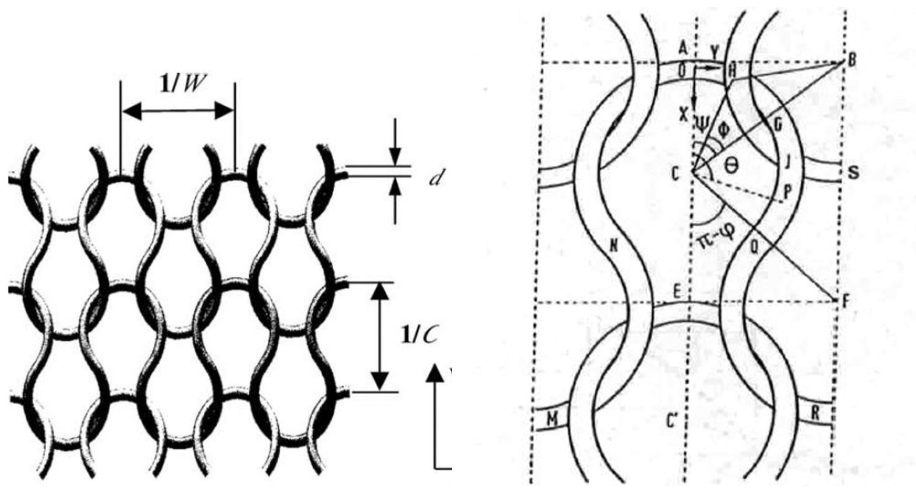

Fig. 5. Schematic presentation of the knitted fabric structure [22].

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

$$
\begin{gathered}
x_1^{2\text{nd}} = 2ad - \frac{1}{2W\tan(\psi)}, \quad x_n^{2\text{nd}} = x_1^{2\text{nd}} - x_n^{1\text{st}}, \\
y_1^{2\text{nd}} = \frac{1}{2W}, \quad y_n^{2\text{nd}} = y_1^{2\text{nd}} - y_n^{1\text{st}}, \\
z_1^{2\text{nd}} = z_1^{1\text{st}}, \quad z_n^{2\text{nd}} = z_2^{2\text{nd}}, \quad n \geq 2, 3, \ldots,
\end{gathered}
\tag{6}
$$

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. 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 was used the experimentally obtained value, equal to 3.7 GPa (Table 1), elastic modulus of the acrylic resin was indicated earlier and was equal to 3.3 GPa (Section 4.1).

At first, coordinates x, y and z for the first and the second yarn were obtained by using formulas (4)–(6). The parameters of the considered cotton knitted fabric are the following: wale number $W = 13$ loop/cm, course number $C = 20$ loop/cm, yarn diameter $d = 0.013$ cm.

In Solid Works 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. 6).

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. Finite elements analysis was carried out for this elastic model (Fig. 6). Strain value was averaged over the butt-end surface under applied loads and the ratio of

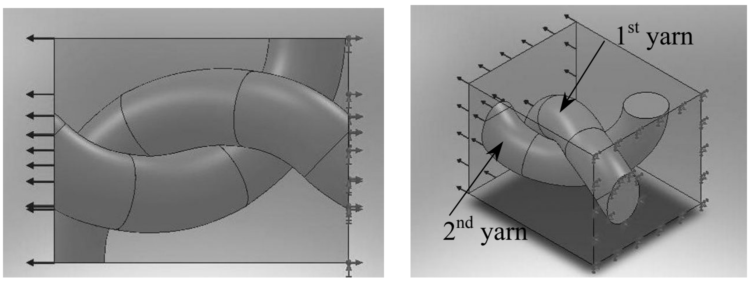

Fig. 6. SolidWorks 3D model for the unit cell (knitted fabric orientation 0°).

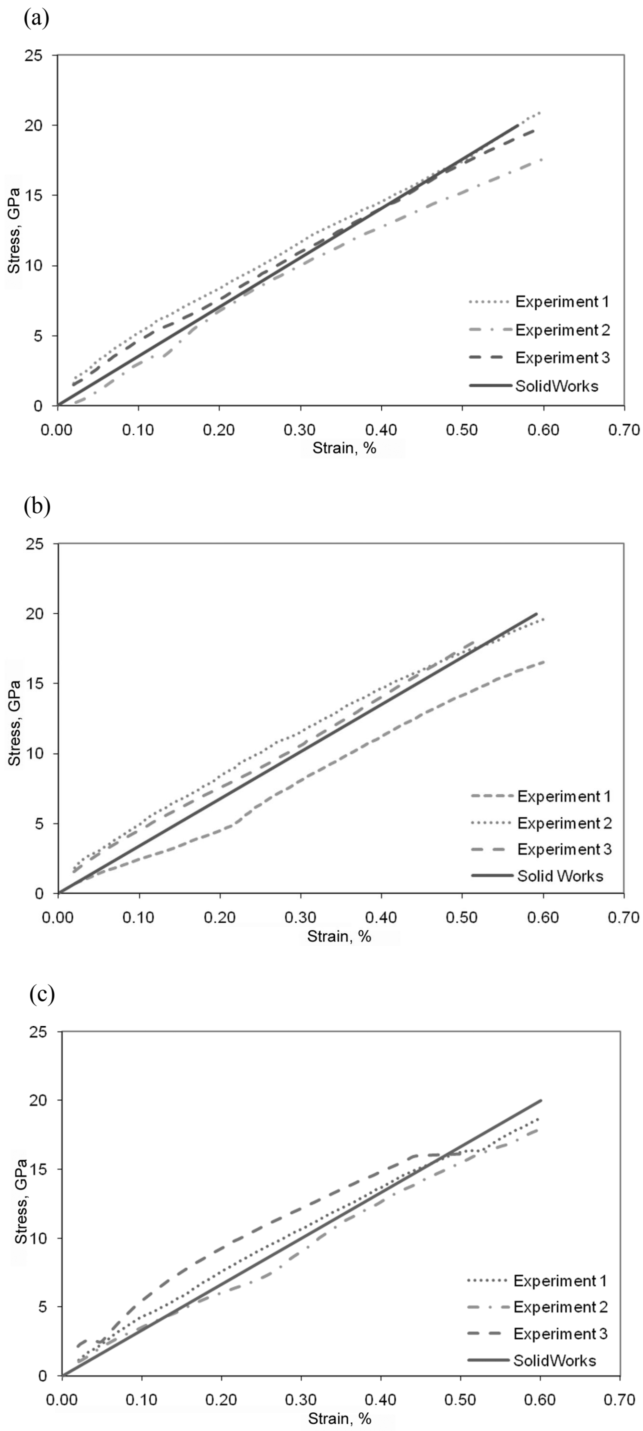

Fig. 7. The stress–strain curve of composites: (a) – direction 0°; (b) – direction 45°; (c) – direction 90°.

Table 3. Elastic moduli of composites, reinforced by knitted fabric (numerical modelling)

	0°	45°	90°
E, GPa	3.521	3.384	3.333

applied pressure and average strain value was calculated. Similarly the unit cell models for another directions, corresponding to reinforcement, were created. Obtained elastic moduli for different directions of the knitted fabric composite are shown in Table 3.

The elastic modulus was determined analysing 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 was compared with experimental results for samples, cut under different directions and are shown in Fig. 7.

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. 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. Model is structural with high potential of predicting the elastic properties for diverse knitted fabric layered composites. Numerical simulation results were compared with experimental data showing high level of coincidence.

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Silmuskootud puuvillakangast komposiitide mehaaniliste omaduste modelleerimine ja võrdlemine katsetulemustega

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On käsitletud tasapinnalise põikikiulise kanga ja sellega tugevdatud komposiitmaterjali elastsusomaduste hindamise arvutuslikke ning katselisi metoodikaid. Puuvillaniiti ja kangaid peetakse keskkonnasõbralikuks alternatiiviks polümeerkomposiitides kasutatavatele sünteetilisest kiust sarrustele. Käesolevas uuringus määrati erineva pikkusega puuvillakiudude ja erinevate silmuskudumise suundadega puuvillakanga näidiste pinge ning deformatsioon tõmbetingimustes. Määrati puuvillakiu ja erineva koesuuna ning venivusega kangaste elastsusmoodulid. Töötati välja reaktoplastse polümeermaatriksiga puuvillakangast sarrusega komposiidid ja testiti nende jäikust ning tugevusomadusi. Leafi ja Glaskini mudelile toetudes töötati välja arvutuslik mudel elastsusomaduste keskmistamiseks. Komposiitmaterjali elastsusomaduste arvutuslikud katsetulemused on lähedased.