794. Characterization of mechanical properties by inverse technique for composite reinforced by knitted fabric. Part 1. Material modeling and direct experimental evaluation of mechanical properties

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Abstract. Polymer composites reinforced with knitted fabrics are materials with high potential in aerospace and machine building industries [1-6]. Such materials are mechanically non-linear with a high dynamic energy absorption capacity. Accurate prediction of mechanical properties is of great importance for these materials when considering their applications in novel structures. Three different approaches were implemented to this aim in the reported research work and the results are presented in: Part 1- numerical structural modeling (FEM using Solid Works) based on application of experimentally measured mechanical and geometrical properties of reinforcement and matrix, accompanied by direct measurements of mechanical properties; Part 2 - application of inverse method for characterization of mechanical properties by means of vibration modal analysis. The goal was to obtain and predict mechanical behavior of a weft knitted fabric reinforced multilayered composite plate. Results of all three approaches were compared and discussed.

Keywords: textile composites, weft knitted fabric, mechanical properties.

Introduction

Interest in polymer and brittle (concrete, ceramics) matrix composites, reinforced by knitted fabric, have increased in recent years [4-6]. Such materials are exhibiting attractive mechanical properties including high energy absorption and impact resistance.

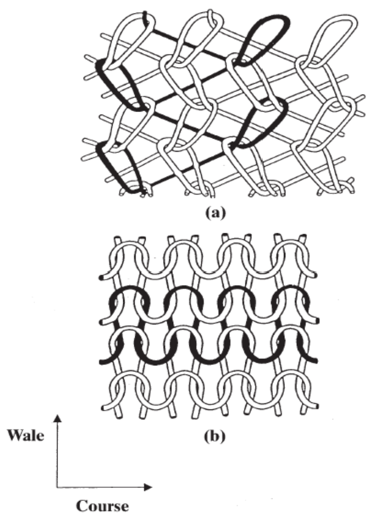


Fig. 1. Structure of warp (a) and weft (b) knitted fabrics (picture from [4])

Yarns loops are arranged in structures as shown in Fig. 1. In a woven fabric, threads traditionally are running horizontally and vertically. Contrary, in the case of knitted fabric, strands are forming loops. A knitted fabric is highly deformable in all directions. Depending on fibers used, some of them are more deformable than others. The reason is – yarns are not making any straight line anywhere in the knitted fabric. Looking at the Fig. 1 it is easy to recognize possible motions in the fabric – threads sliding, loops twisting, bending and stretching leading to technological advantage – excellent deformability, shape forming ability and flexibility, which allows it to be used in any complex shape mould without folds.

Natural fiber (cotton) and glass fiber yarns were investigated. Used in the experiments cotton yarn was more twisted in comparison with the glass fiber one, which was only easily twisted. Two differently made types of knitted fabrics - warp knit (produced by knitting in the lengthwise (wale) direction, Fig. 1a) and weft knit (produced by knitting in the widthwise (course) direction, Fig. 1b) are commercially produced by textile industry. In the framework of our investigation only weft knitted fabrics were created and used in the fabricated and investigated polymer matrix composites.

Mechanical properties of a cotton weft knitted fabric

Mechanical properties of a weft knitted fabric are determined by mechanical properties of the fibers included in the yarn as well as yarn thickness and its degree of twist, size of the loops in the fabric and by chemical and mechanical treatment that was applied to the yarn [7-9]. Fabric structural deformation modes can be recognized through the interaction of structured yarns within the fabric. Fig. 2a shows possible micro-level deformations in a single yarn span in the fabric. Yarn span bending or straightening occurs when the two threads are belonging to a two adjacent loops, are stretching in opposite directions. It is one of most important modes in knitted fabrics according to the knit loop geometry. Straightening also can be found in woven and braided fabrics. Inside-yarn slip shown in Fig. 2b is possible to be observed in the loop straight part during fabric stretching as well as it is coupling with yarn bending in the more curved loop part. In the last case the friction between the yarns becomes important. In this situation the matrix and fiber sizing usually lubricate the yarn to help this mode of deformation. Next is thread stretching (Fig. 2c) in longitudinal direction. This deformation mode is very important at fabric final deformation stage, when all geometrical (loops deformations) movements are hampered. Another deformation mechanism to consider is yarn twist (Fig. 2d), which has been observed in knitted fabrics and not so much in woven fabrics. Technologically the twist creates a resistance to the forming the looping structure of the knit. And in fabric deformation the twist creates a resistance to the increase in yarn curvature. Another deformation mechanism is a yarn transverse compression (Fig. 2e). This mode is realized where forces at yarn cross-over points compress it and cause the yarn to flatten out and conform to the curvature of perpendicular yarns (if it is combined with bending).

Finally, longitudinal compression of the yarn span (Fig. 2f) is leading to its buckling. Buckling can be realized in a form of buckled cylindrical shape of the yarn as well as buckling in a form of "china flashlight".

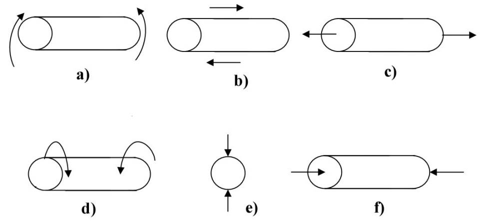


Fig. 2. Micro-level deformation modes of single yarn spans: a) bending; b) inside yarn sliding; c) stretching in longitudinal direction; d) twisting; e) compression in transverse direction; f) compression in longitudinal direction

Mechanical properties of a yarn

Cotton [10] fiber yarn testing by tension. Cotton yarns, produced by Juglas Manufaktura (Latvia) were used. Linear density of the cotton yarn was calculated according to ASTM D 2591-01:

$$T_d = 10000 \times (M / L), \quad (1)$$

where T_d is linear density (dtex), M is specimen mass (g) and L is specimen length (m). The length of the investigated cotton yarn specimen was 50 m, specimen mass 1 g and obtained linear density 200 dtex or 20 tex, density of the cotton ρ = 1510 kg/m^3, diameter of the yarn d was determined as:

$$d = \sqrt{\frac{4m}{L\pi\rho}}, \quad (2)$$

where m is the specimen mass (kg). In our case d = 1,3×10^{-4} m. Simultaneously the yarn diameter was measured using microscope. The yarns were stored and tested at room conditions. Yarn samples were tested according to the preparation procedure described in ASTM D 2256-02. Gage length was 500 mm. The tests were carried out on a computer-driven electromechanical testing machine Zwick Z150. The load–displacement curve was recorded during the test. Loading rate was 500 mm/min. During the experiment the data were transferred to the PC. Assuming the yarn diameter is a constant the stress–strain curves were obtained (some of them are shown in the Fig. 3). We may observe that the scatter of results is quite low (Table 1). Averaged elastic modulus was 3.68 GPa.

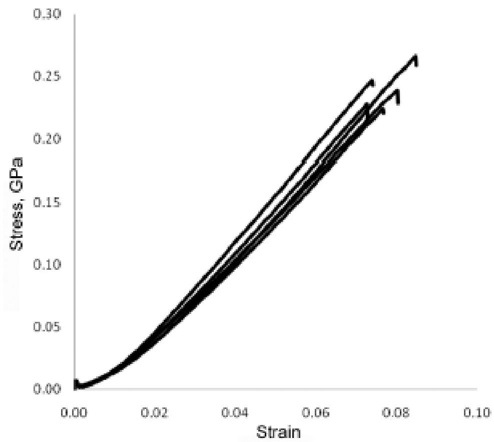


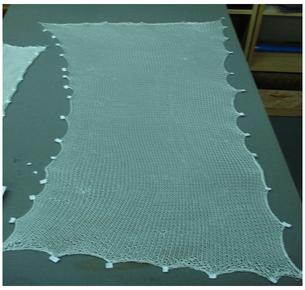
Fig. 3. The stress-strain curves for cotton yarn

Table 1. Cotton yarn elastic modulus (GPa)

Yarn gage length	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Averaged
500 mm	3.849	3.683	3.754	3.496	3.635	3.683

Glass fiber yarn testing by tension. Type E glass fiber yarns, produced by JSC “Valmieras stikla šķiedra” (Latvia), were used. Density of the glass was ρ = 2540 kg/m^3, diameter of the yarn d was determined according the formula (2) and equals 0.37×10^{-3} m. Linear density of the glass yarn was calculated and equals to 275.6 tex. Value of elastic modulus for glass yarn was obtained from manufacturer and is equal to 73.4 GPa.

Knitted fabric preparation. Cotton and glass yarns were used for knitted fabric preparation. Cotton knitted fabric was prepared by “Juglas manufaktūra”, glass knitted fabric was prepared by ourselves in Riga Technical University (using knitting machine Neva-5). Prepared samples of the knitted glass fiber fabrics are shown in the Fig. 4.



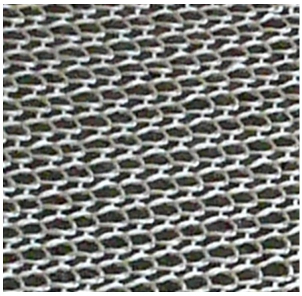


Fig. 4. Custom made glass fiber knitted fabric sample is ready for composite reinforcement (left picture); fabric’s structure (right picture)

Mechanical properties of a knit fabric

The ways of textile material deformation under applied stresses plays an important role in the understanding of textile behavior in mechanically loaded composite material. Prepared fabrics were tested experimentally. Two opposite sides of each fabric were clamped in testing machine grips and growing tensile load was applied. Yarns in material start to move with a friction, between adjacent yarns, in the places of contact and inside each yarn, between adjacent fibers, as a result, fabric’s loops stretched and start to change their geometry until they jam. After that yarns started to elongate until they breaks. Under applied load, the plain knitted fabric has less elongation in the wale wise direction than in the course wise direction due to the widthwise jamming occurring sooner than the course wise jamming [10-11]. Cotton and glass fiber knitted fabric specimens were prepared and tested according to ASTM D 2594-99 Standard. From each laboratory sampling unit 5 wale wise (0° angle) and 5 course wise (90° angle) test specimens 125 mm × 500 mm were cut. The longitudinal direction of the wale wise specimens is parallel to the wale direction and that of the course wise specimens parallel to the course direction. Each specimen was folded in half lengthwise forming a loop, sewed and fixed into the frame (hanger assembly). Weights of 22.27 N and 44.54 N were attached to specimens and exercised the specimen loop by cycling four times. Knitted fabric stretch was calculated as:

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

where S is the fabric stretch (%), A is the original gage length (mm), D is specimen length under tension (mm). Additionally, 5 specimens of the knitted fabric were tested (cut at 45°). The results are listed in Table 2 for cotton and in Table 3 - for glass knitted fabric. Additionally, the tensile tests under increasing applied load were carried out for the same specimens for cotton knitted fabric on an electromechanical testing machine Zwick Z150. All tests were performed under displacement control with the rate of 2 mm/min. Load–displacement curves were obtained. The curves for different directions demonstrate highly non-linear behavior (Fig. 5). Each curve can be divided into two typical zones: the first zone (with low elastic modulus) 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. Cotton knitted fabric stretch

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

Table 3. Glass knitted fabric stretch

Load	0°	45°	90°
22.27 N	57.14%	169.71%	250.85%
44.54 N	78.57%	190.35%	298.57%

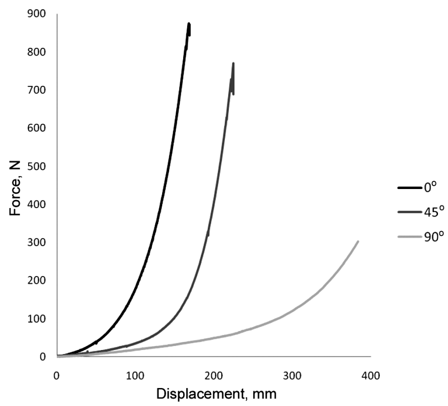


Fig. 5. Load-displacement curves for knitted fabric samples cut under different angles (cotton)

Mechanical properties of the composite material (reinforced by the knitted fabric)

Majority of the production processes used in the manufacture of ordinary fiber reinforced composites may be used and applied to textile composites. Main reason here is that in many cases manufacturers are looking at existing manufacturing methods and equipment. 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. Thermoset matrix composite plates (4 layers, 2.1×10^{-3} m thick), reinforced by the glass fabric, were manufactured using epoxy resin. Epoxy resin parameters: elastic modulus 3.3 GPa, density 1360 kg/m^3, Poisson's ratio was 0.22. 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°) (see Fig. 6).

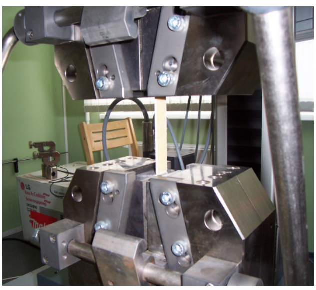
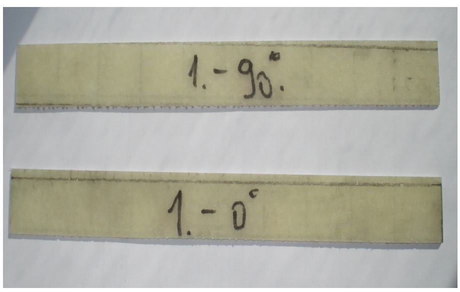



Fig. 6. Composite material sample during the test. Photo of test samples

Tensile test. Mechanical tests were performed on composites with fiber weight fraction 27 % for cotton fabric and 11 % for glass fabric. Knitted fabric samples were tested according to the preparation procedure described in ASTM D 5083-02. Tensile tests were executed on the 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.

Numerical simulation of composites, reinforced by the knitted fabric

It was supposed that the knitted fabric composite consist of multiple plain weft knitted fabric laminas, each of which can be oriented under different angle to material common axis [12]. The 3D geometrical modeling 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. 7. According to Leaf and Glaskin, fabric 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. 7 [12]. Elastic properties of the composite material can be calculated using material's representative volume or unit cell (shown in Fig. 7). All numerical simulations were carried out for a 3D unit cell of the cotton and glass fabric composite shown in Fig. 8. For the first yarn we have [10]:

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

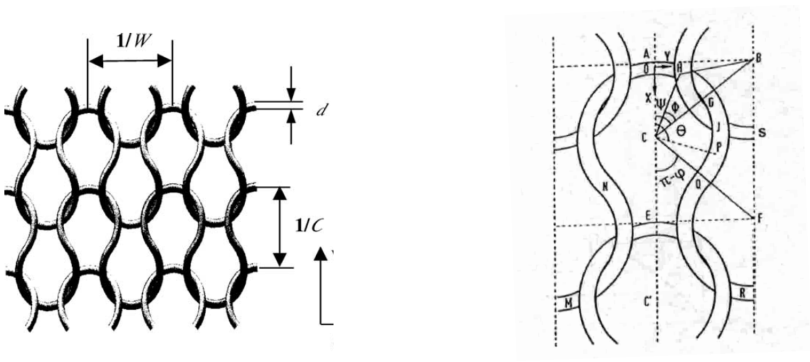
where:

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

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

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

where the superscripts 1 and 2 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. The yarn was considered as a homogeneous elastic rod and for elastic modulus of the yarn we used the experimental value of 3.7 GPa for cotton yarn (Table 1) and 73.4 GPa for glass yarn. The elastic modulus of the acrylic and epoxy resins were indicated earlier and are equal to 3.3 GPa. 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 as follows: wale number W = 13 loops/cm, course number C = 20 loop/cm, yarn diameter d = 0.013 cm. The parameters for glass knitted fabric are as follows: wale number W = 1.05 loops/cm, course number C = 2 loops/cm, yarn diameter d = 0.037 cm.



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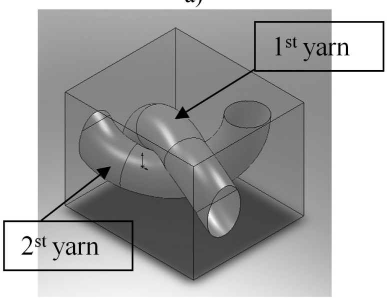


b)

Fig. 7. a) Schematic diagrams of knitted fabric structure [10]; b) fabric's unit cell

In Solid Works a 3D model was prepared, inputting x, y and z coordinates for both yarns after they were connected by 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 plain weft knitted fabric lamina was created as cube with holes for yarn by using sweep cut function. Finally, an assembly between yarns and matrix was created (Fig. 8).

One butt-end surface of unit cell was fixed, while pressure loads was applied to another butt-end surface. Side surfaces were imposed with symmetry conditions. Finite element analysis was carried out for this elastic model. Strain value was averaged over the butt-end surface, under applied loads and ratio between applied pressure and average strain values was calculated. Similarly, unit cell models for another directions corresponding to reinforcement were constructed. Obtained elastic modulus for different directions of knitted fabric composite are provided in Tables 4-5.

The elastic modulus was determined analyzing 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. The computer simulation data was compared with experimental results for samples cut under different directions and are shown in Fig. 9a-c, 10a-b.

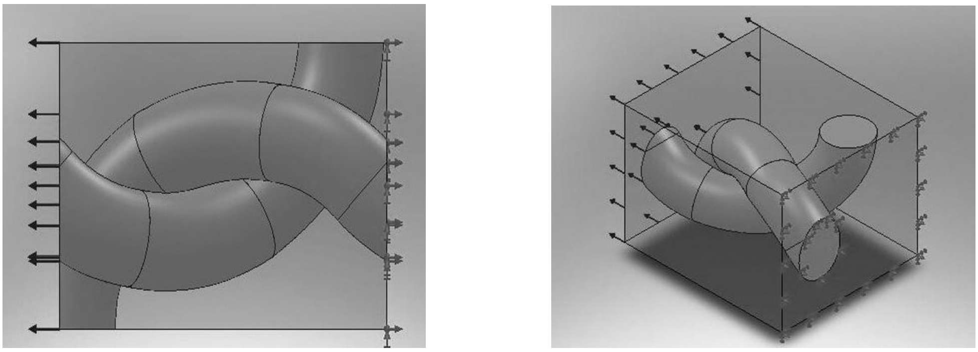


Fig. 8a. Unit cell Solid Works 3D model, used in our calculations for cotton knitted fabric (orientation 0°): 1) Side view; 2) 3D view

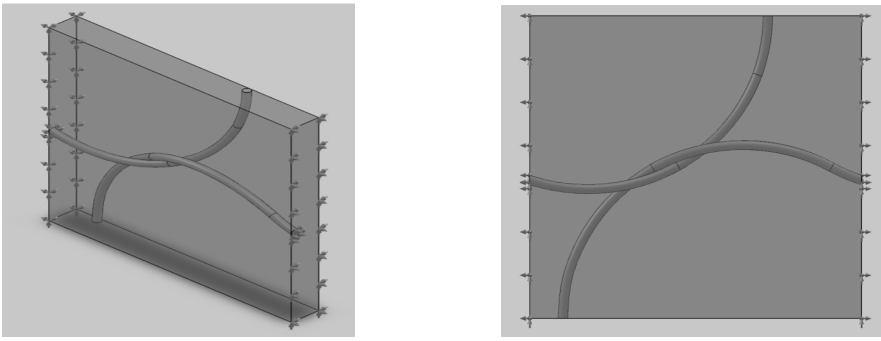


Fig. 8b. Unit cell Solid Works 3D model, used for glass knitted fabric (orientation 0°): 1) 3D view; 2) Side view

Table 4. Elastic moduli for cotton knitted fabric composite

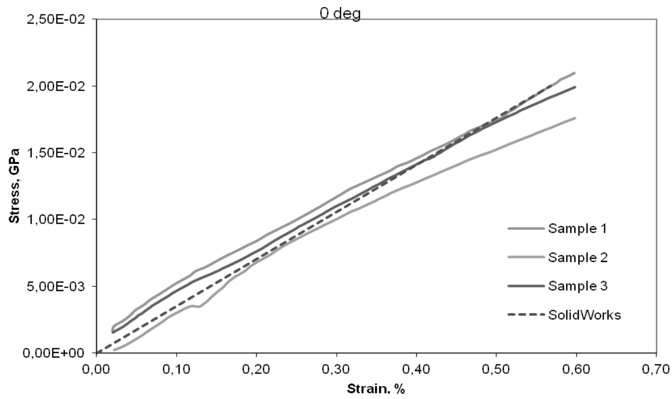
	0°	45°	90°
Experimental *E*, GPa	3.259	3.154	3.111
Solid Works *E*, GPa	3.521	3.384	3.333

Table 5. Results for glass knitted fabric composite

	0°	90°
Experimental *E*, GPa	5.46	3.95
SolidWorks *E*, GPa	5.825	4.555

Conclusions

Two different approaches were implemented in the presented study: a) structural modeling applying FEM simulations within Solid Works environment based on mechanical and geometrical properties of reinforcement and matrix that were measured experimentally and b) experimental characterization of mechanical properties with the goal to obtain in plane elastic properties of polymer composite reinforced by knitted fabric. Results on elastic properties were obtained for two types of composite materials, reinforced by cotton and glass knitted fabrics. A FEM model was developed with the goal to predict elastic properties of the knitted fabric layered composite. Obtained simulation results are in good agreement with the experimental data.



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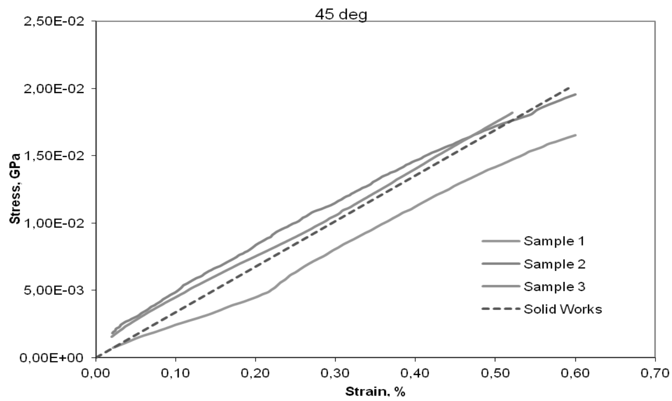

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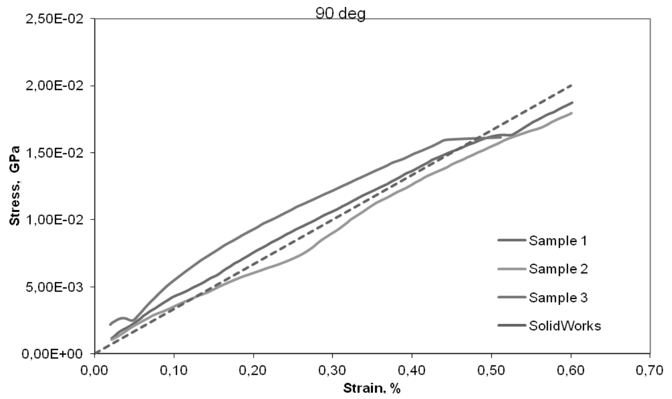

c)

Fig. 9. Stress-strain curve of cotton knitted fabric composites at: a) 0 deg; b) 45 deg; c) 90 deg

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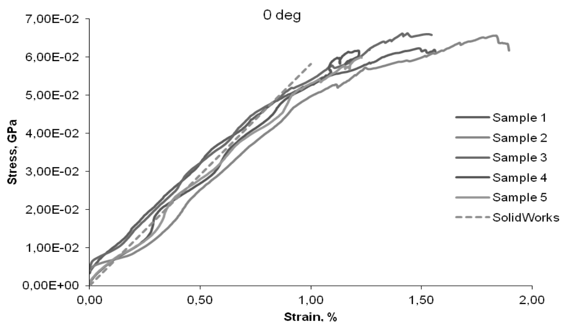

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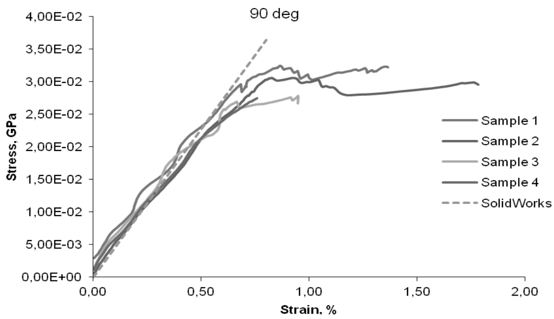

b)

Fig. 10. Stress-strain curve of glass knitted fabric composites at: a) 0 deg; b) 90 deg

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