MECHANICAL PROPERTIES CHARACTERIZATION BY INVERSE TECHNIQUE FOR COMPOSITE REINFORCED BY KNITTED FABRIC

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Abstract

Polymer composites reinforced by knitted fabric are materials with high potential in aerospace and machine building industries. In the same time such materials are mechanically non-linear with a high dynamic energy absorption possibility. Precise mechanical properties prediction has a great importance for such materials use in the novel structures. In present investigation results of three different approaches are rendered: a) elastic properties averaging based on structural reinforcement, matrix and geometry modeling (using Leaf and Glaskin fabric's structural model in combination with FEM calculations); b) direct experimental mechanical properties measuring – glass fiber knitted fabric composites with thermoset polymer matrices were manufactured and tested for stiffness and strength and c) inverse method execution, based on composite plate vibrations modal analysis. All three approaches results were compared and comparison results were discussed.

1 Introduction

Interest to knitted fabric reinforced composites has increased in recent years [1-3]. These kinds of materials are exhibiting attractive mechanical properties – excellent shape forming ability, high energy absorption and impact resistance. Knitted fabric has organized hierarchical structure (see Fig. 1). In contrast to "classical" woven fabrics, where threads (almost straight) traditionally are oriented horizontally and vertically, in the case of the knitted fabric, strands are forming loops, because that fabric is highly deformable in all directions. Depending on fibers are used, some of them are more deformable than others. The reason is – yarns are not making any straight line anywhere in the knitted fabric.

Precise evaluation of the in plane elastic properties for all orthotropic composite plates is very important and still not easy problem, especially if we have material with high damping performance.

In this paper mechanical properties of weft-knitted fabric reinforced laminates are being investigated, using different methods. Knitted reinforcement was produced using glass fibers and then was impregnated by polymer matrix.

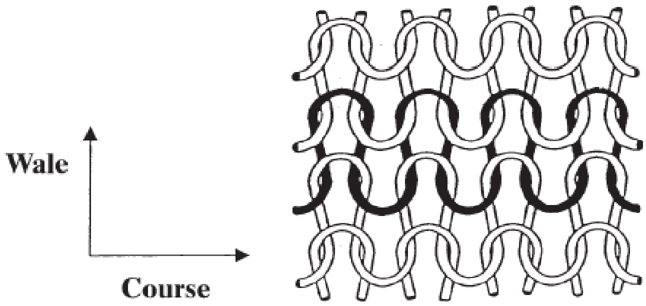

Figure 1. Structure of weft-knitted fabric (picture from [1]).

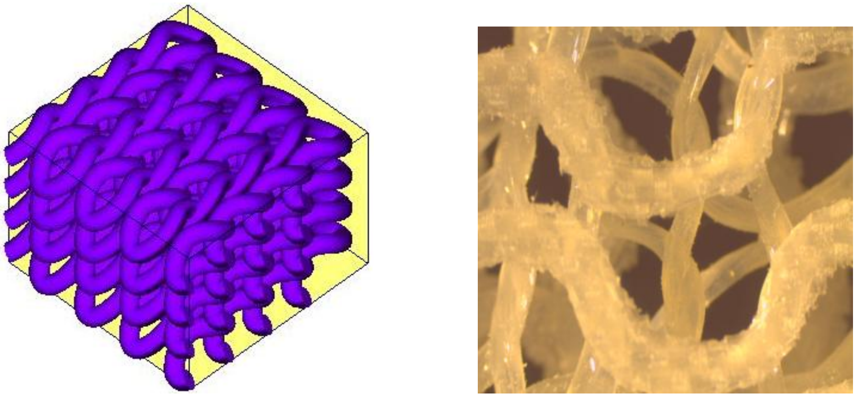

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Figure 2. Structure of the weft knitted fabrics laminate (a); glass fiber threads impregnated by epoxy resin (picture obtained using microscope) (b).

2 Materials and testing methods

For obtaining elastic properties of the glass fiber laminates, that were produced using weft-knitted fabrics, three different approaches were executed: a) structural composite unit cell model was geometrically created, meshed and numerically calculated using SolidWorks software; b) mechanical properties were measured directly in tensile tests; c) inverse method using modal analysis was executed.

Materials: E glass fiber yarns, produced by JSC "Valmieras stikla šķiedra" (Latvia), were used. Density of the glass fibers was ρ=2540 kg/m^3, diameter of the yarn d was determined according to the formula (1) and was equal to 0.37×10^{-3} m. Linear density of the glass yarn was calculated and was equal to 275.6 tex. Value of elastic modulus for glass yarn was adjusted by manufacturer and equal 73.4 GPa.

$$d = \sqrt{\frac{4 \cdot m}{L \cdot \pi \cdot \rho}} \tag{1}$$

where m is the specimen mass (kg), *L* is the specimen length (m).

Glass yarns were used for knitted fabric preparation. Glass knitted fabric was prepared in Riga Technical University using knitting machine Neva-5.

Fabrics were stacked and impregnated by polymer thermoset resin at room temperature. Epoxy resin was used. The laminate lay-up was $[0]_4$ (see Fig. 2). Glass fiber epoxy matrix composite two plates (SP1 and SP2) were fabricated. Each plate dimensions, as well as matrix and fibers properties are shown in the Table 1. These plates were experimentally tested using modal analysis (Section 2.3) and then were cut into pieces (specimens) for further tensile testing.

	Laminated composite plate with knitted glass fiber fabric reinforcement	
Number of layers	4	
Plates dimensions, mm	SP1: 280×380, thickness - 0.176; SP2: 280×380, thickness - 0.202.	
Stitch density in the fabric	W=1.053 loops/cm, C=2 loops/cm	
Yarn diameter, mm	0.37	
Fiber-weight fraction W_f, %	11	
	matrix (epoxy resin)	**reinforcement**
Density ρ, g/cm^3	1.36	2.54
Young modulus E, GPa	3.3	73.4
Poisson ratio ν	0.22	0.35

Table 1. Matrix/fibers properties and composite plates dimensions

2.1. Numerical simulation of composite in SolidWorks

Was supposed that knitted fabric composite consist of multiple plain weft-knitted fabric laminas, each of which can be oriented under different angle to material common axe [6]. In our case we had 4 layers oriented in 0^o direction. 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. 3. 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. 3 [6].

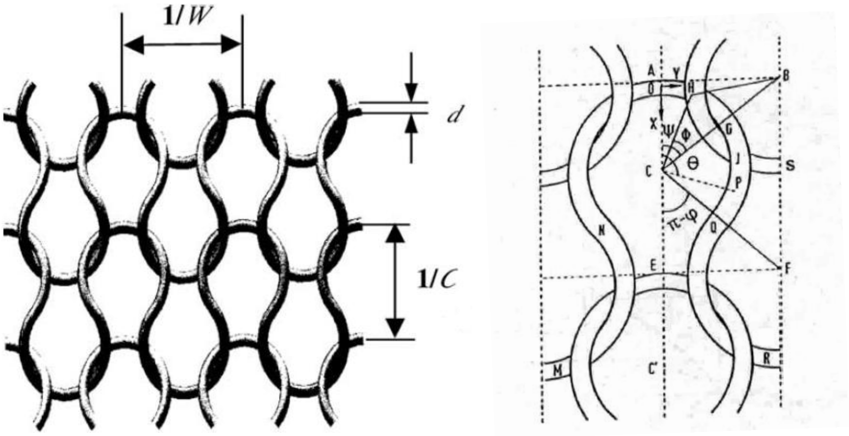

Figure 3. Weft knitted fabric geometry.

According to Figure 3, for the first yarn we have [5,6]:

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

where

$$a = \frac{1}{4Wd\sin\xi},$$

$$\phi = \arccos\left(\frac{2a-1}{2a}\right)$$

and

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

$$h = \left[\sin\left(\pi\frac{\psi}{\xi}\right)\sin\left(\pi\frac{\phi}{\xi}\right)\right]^{-1} \quad (3)$$

$$\psi = \arcsin\left(\frac{2a}{2a-1}\sin\xi\right)$$

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

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

$$x_n^{2nd} = x_1^{2nd} - x_n^{1st}$$

$$y_n^{2nd} = y_1^{2nd} - y_n^{1st} \quad (4)$$

$$y_1^{2nd} = \frac{1}{2W}$$

$$z_1^{2nd} = z_1^{1st},\; z_n^{2nd} = z_n^{1st},\; n \geq 2,3,...$$

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. The yarn was considered as a homogeneous elastic beam. Elastic modulus of the yarn was 73.4 GPa and elastic modulus of the epoxy resins was equal to 3.3 GPa (values used in our calculations). At first, coordinates, *x y* and *z* for the first and the second yarn were obtained by using formulas (2)–(4). The parameters for glass knitted fabric are the following (were measured experimentally): wale number W =1.053 loops/cm, course number C= 2 loops/cm, yarn diameter d =0.037 cm.

Elastic properties of the composite material can be calculated using material's representative volume or "unit cell" (is shown in Fig. 4).

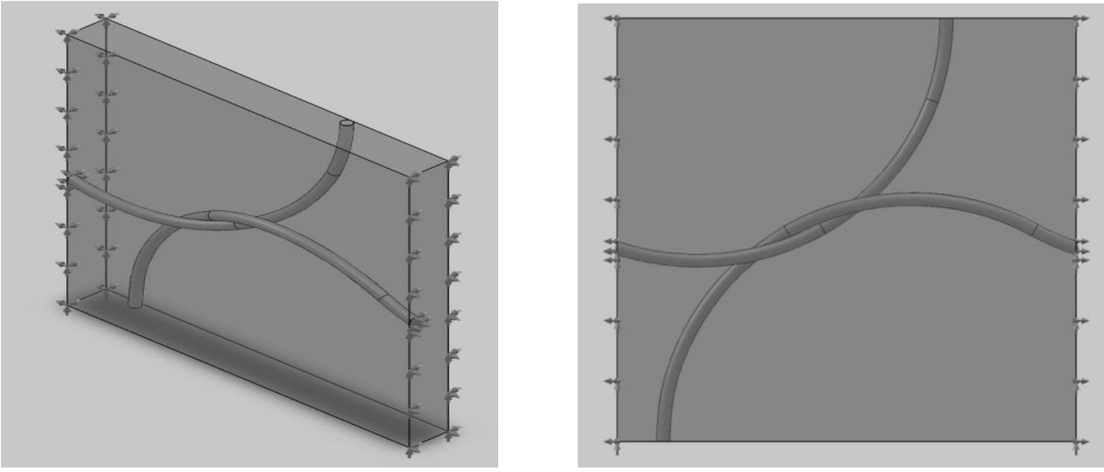

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Figure 4. Unit cell Solid Works 3D model, used in our calculations for glass knitted fabric. 1) 3D view; 2). Side view.

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.

2.2. Tensile test

Mechanical tests were performed on composites with fiber weight fraction 11%. 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 and compared with numerical simulations results (see Fig. 6,7).

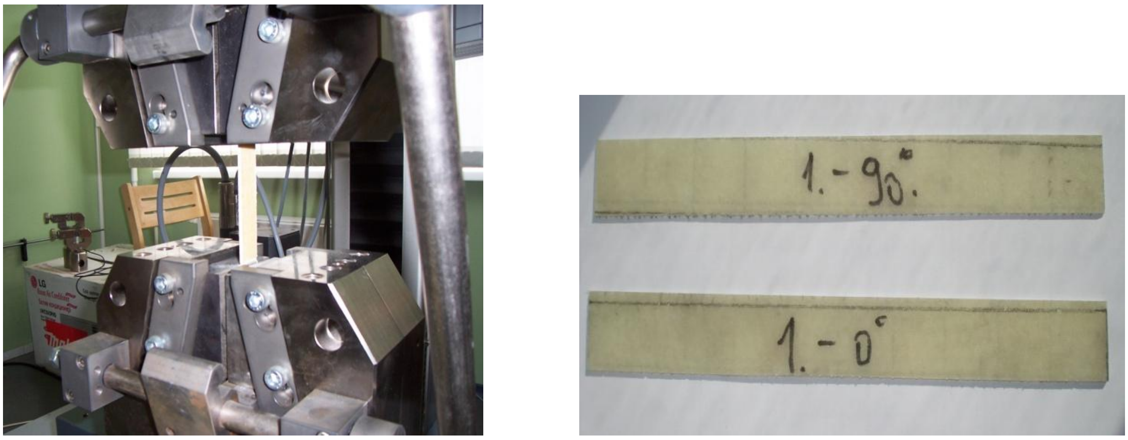

Figure 5. Composite material sample during the test. Testing samples view.

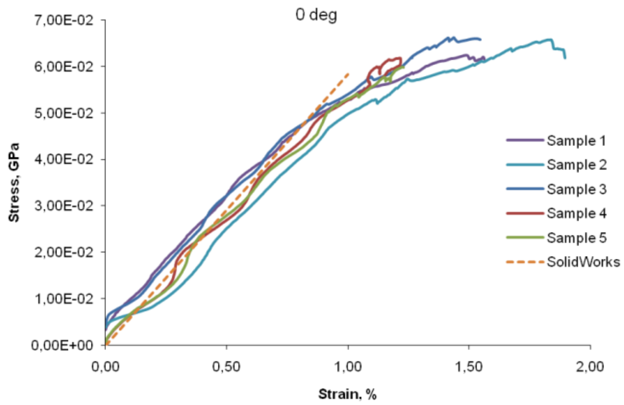

Figure 6. The experimental and modeled in SolidWorks stress-strain curves of glass fiber knitted fabric composites at 0°

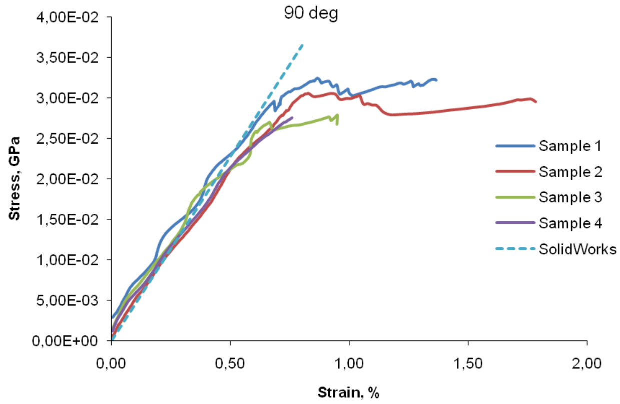

Figure 7. The experimental and modeled in SolidWorks stress-strain curves of glass fiber knitted fabric composites at 90°

2.3. Modal analysis

The given technique is using the test data of sample vibrating with a final goal to define material's elastic constants [7-9]. The method consists of 6 steps. At the first step the modal analysis of the sample is carried out and its eigenfrequencies and corresponding vibration shape modes are defined. Further limits of the search region for material properties are defined and the plan of numerical experiments is produced. Next step is finite-element modeling of the sample and its modal analysis. Material properties are varying according to the plan of experiments. At the fourth step the received results are approximated separately for each eigenfrequency. Further it is defined an error functional, which joins both experimentally obtained values of eigenfrequencies and the values received by numerical experiment in the form of eigenfrequency value dependences on material properties. Given error functional characterizes discrepancy between experimental and numerical values of eigenfrequencies. Spending minimization of a given functional, finally, the values of material properties are obtained.

The general experiment set-up of the POLYTEC PSV-400-B Scanning Laser Vibrometer consists of a PSV-I-400 LR optical scanning head equipped with high sensitivity vibration sensor (OFV-505), an OFV-5000 controller, PSV-E-400 junction box, an amplifier Bruel&Kjaer type 2732, and a computer system with data acquisition board and PSV Software. The system requires geometry defining of an object and set up scanning grid. Symmetrical points have been taken to cover a rectangular panel with regular grid. Free-free boundary conditions have been simulated by hanging up the panel with two thin threads bonded in two top corners of the plate. The test panel has been excited by a piezoelectric actuator (PZT), placed in the bottom of the composite plate. As a result of this excitation, the plate starts to vibrate within the frequency band of the input signal. After the measurement if performed in one point, the vibrometer automatically moves the laser beam to another point at the scan grid measures the response using the Doppler principle and validates the measurement with the signal-to-noise ratio. The procedure is repeated until all scan points have been measured. The frequency spectrum of the panel is then obtained by taking the Fast Fourier Transform of the response signal. Fig. 8 and 9 shows experimental set-up for modal test of the laminated composite plate.

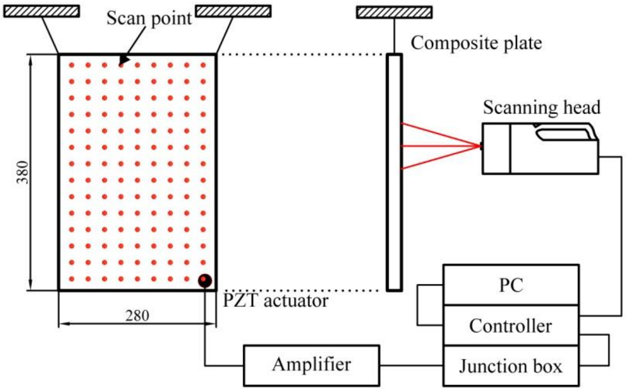

Figure 8. Signal acquisition system for detailed plate vibration analysis.

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Figure 9. Plate free vibration modal analysis experimental system: a) scanning laser system; b) hanged plate with connected piezoactuator.

Frequency response functions were obtained and were analyzed [4-5].

3. Results

Elastic modulus in longitudinal and transverse directions were obtained by all three methods are shown in Table 2.

Method	E_L, [GPa]	E_T, [GPa]
SolidWorks	5.825	4.555
Experimental tensile test	5.46	3.95
Modal analysis	5.93/6.23	4.92/4.96

Table 2. Results for glass knitted fabric composite. In modal analysis method are shown results obtained for both two fabricated plates.

4. Conclusions

Three different approaches were executed: a) structural modeling based on reinforcement and matrix mechanical and geometrical properties (using Leaf and Glaskin fabric's structure model) in combination with numerical (FEM using SolidWorks software) elastic properties averaging; b) direct experimental testing and c) inverse modal analysis method. Results were obtained for glass knitted fabrics reinforced polymer laminates. Results were compared with experimental data showing high level of coincidence. Inverse modal analysis method exposed high prediction ability for material with high damping behavior.

Acknowledgements

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