COMPOSITE MATERIAL TEST RESULTS AND FINITE ELEMENT ANALYSIS: ITS CORRELATION

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INTRODUCTION

Fiber-reinforced composite materials have gained popularity (despite their generally high cost) in high-performance products that need to be lightweight, yet strong enough to take harsh loading conditions such as aerospace components (tails, wings, fuselages, propellers), wind rotors, boat and scull hulls, bicycle frames and racing car bodies. Other uses include fishing rods, storage tanks, swimming pool panels, and baseball bats. The new Boeing 787 structure including the wings and fuselage is composed largely of composites. Composite materials are also becoming more common in the realm of orthopedic surgery.

In order to study the structures of composite materials, as for classic materials, two calculation methods are used: analytical methods and numerical methods.

For composite material strength structure modelling both theoretical models and real models are used. Theoretical models are an intermediate link between experience and theory referring to these structures, comprehensive and accurate but laborious. These are often sets of hypotheses based on the analogy with structures whose theory is well known.

Real models allow experimental way of solving problems that cannot be solved analytically or numerically, either because there are no appropriate calculation methods or because existing methods are too laborious and expensive.

There are no general algorithms and methods to ensure transition from real structure to its model which approximates, with predetermined error, the structure that will be calculated. There are several models developed, all correct, but with different performance. But modelling of composite structures is very difficult. To obtain data closer to reality, composite materials are modelled on level of the lamine. This clearly shows the main damages occurring in the fibre reinforced laminate (matrix cracks, delamination, fibre failure etc.).

Because of the high degree of complexity of analytical methods and limitation of their application for a wide variety of structures there were developed very much the numerical methods. Currently, the most widely used numerical method of calculation applied in field of analysis of composite structures is the finite element method (FEM).

Finite element analysis software are continuously improved thereby in their library are included finite elements for analysis of composite structures. Currently, research on the FEM takes the form of laborious theoretical and applicative studies, pursuing a variety of directions:

- setting up and developing of modern computing software for these structures, by facilitating of composite material modelling architecture and visualization of stresses that occur in it, modernization of data input (automatic generation of nodes and elements, suitable and easy to use menus, etc.), creation of facilities related data preprocessing and postprocessing analysis results, coupling with general interest programs etc.;
- creation of software products including opportunities for optimization of composite structures using the criteria of weight, stiffness, strength, price etc.

MATERIALS AND TESTING METHOD

Composite material samples were manufactured in the laboratory "*Composite Technologies"* within the Scientific Technical Center of Advanced Technologies Implementation "*Etalon*" of the Technical University of Moldova. The samples were made from polyester resin reinforced with fiberglass using technology of vacuum assisted resin transfer moulding (Fig. 1). This method is most prevalent due to its advantages: it is ecological (the whole process takes place under vacuum and thus totally eliminates exposure to pollutants), hardening resin occurs at ambient temperature and can be obtained very good quality parts. The same time by this method can be obtained higher percentage of fiber (60% - 70%) compared to hand molding (30% - 40%). Fabrics characteristics are shown in Table 1.

Laminates obtained by overlapping fabrics are described by the type of the fabric, the number of layers and the angle of fiber orientation. These parameters are included in laminate notation [1] Table 2. In order to facilitate uniform penetration of

Figure 1. Composite material samples.

the resin among laminates a layer of chopped strand mat (CSM) was used.

For analysed plates the volume fraction of fibers was determined by expression:

$$V_f = \frac{\dfrac{m_f}{\rho_f}}{\dfrac{m_f}{\rho_f} + \dfrac{m_m}{\rho_m}}, \tag{1}$$

where the m_f and m_m is the mass of fibres and matrix respectively;

ρ_f and ρ_m - density of fibres and matrix respectively.

The fiber content by weight was obtained about 66% for unidirectional laminate and 43% for bidirectional laminate.

The samples were cut using a cutting disc device then finished according to standard ASTM D3039.

Table 1. Characteristics of fabrics.

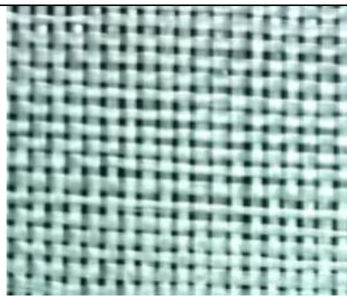
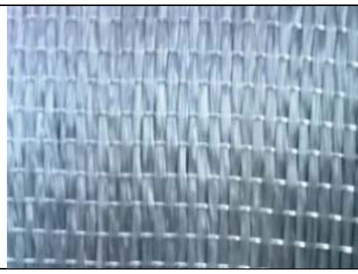
Fabric type	Number of fibres in bundle		Details
E glass woven roving (WR) 300 g/m^2	Warp	600	
	Weft	600	
E glass unidirectional UD 600 g/m^2	Warp	2400	
	Weft	300	

Table 2. Characteristics of laminates.

Nr. of specimens	**Notation**	**Type of tests**	**Plate thickness, mm**
5	[0$_2$/CSM/0$_2$]	tensile x	2,9
5		tensile y	2,9
5	[WR 0-90$_{13}$/CSM/ WR 0-90$_{13}$]	tensile x	7,2
5		shear	7,2

ASPECTS REGARDING REQUIRED MECHANICAL PROPERTIES OF COMPOSITE MATERIAL

Because unidirectionally reinforced composite materials are part of orthotropic materials that admit three orthogonal planes of symmetry for physical characteristics, the study of a structure having some form made of laminated composite materials and reinforced with continuous fibers requires the following elastic characteristics of a lamina:

E_{11} – modulus of elasticity of lamina in the direction of fibers (Young);

E_{12} – transverse modulus of elasticity;

G_{12} – shear modulus of elasticity of the lamina;

ν_{12} – Poisson coefficient.

These characteristics are required as input data for finite element analysis of composite specimens. Determination of mechanical properties of material obtained from different layers of fabrics well established fiber orientation. It can only be done by testing. But for laminated composite materials reinforced with unidirectional fibers, approximate estimation of these features can be done using the method of mixtures [3].

Elastic and mechanical characteristics of the material were determined by means of resistive electrical tensometry [3].

Experiments have been conducted in Mechanical Testing Laboratory and Technology, Faculty of Mechanics of the Technical University "*Gheorghe Asachi*" Iasi. Tests were performed on universal testing machine "*WDW-50*".

The results obtained for the modulus of elasticity were compared with the data from charts provided by the manufacturer of fiber glass fabrics. Dependency graphs of modulus of elasticity for different types of fabrics and the fiber content in the composite material are presented in figure 2. Obtained mean values of the modulus of elasticity in result of testing are marked with discontinued lines.

The accuracy of compliance with manufacturing technology and of experiment execution was confirmed to a certain extent by the experiment. Mechanical and elastic values obtained are within the limits provided by the company producing fabrics of glass fibers.

It is evident that the rigidity and longitudinal strength are limited by obtained fibre volume fraction. For hand moulding, the amount of fibers is 30-40%, and using of vacuum assisted resin transfer molding consolidates the material by removing air and the excess of volatile compounds, and allows fiber volume fraction of 50% or more. Using "*prepregs*" which are unidirectional or woven fibers pre-impregnated with epoxy resin partially cured allows increasing fiber volume fraction.

NUMERICAL MODELING

Real tests of specimens were simulated with finite element analysis software ANSYS. This validation of software is necessary to have greater confidence in subsequent simulation results of parts modeled from tested composite materials.

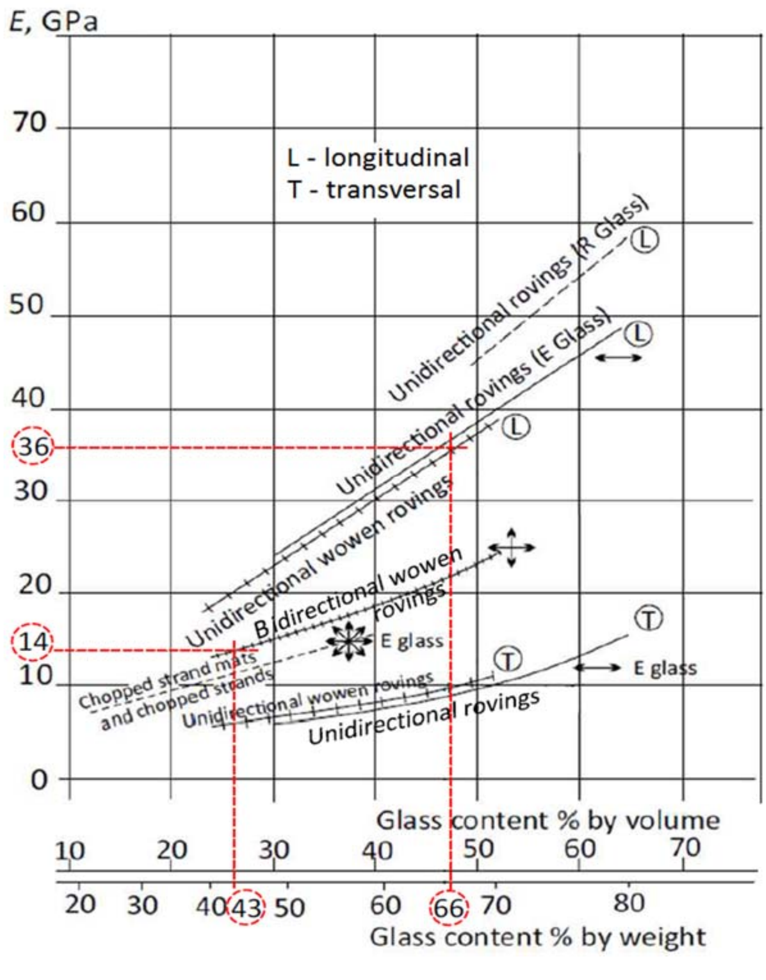


Figure 2. The dependence of elastic modulus on the degree of reinforcement (chart provided by the manufacturer of glass fiber fabrics for the polyester resin with ρ = 1,2 g/cm^3).

In calculation methodology of finite element stiffness matrix the following assumptions relating to material are considered [4]

• each lamina is modeled as continuous medium, linear elastic. Theory does not include cracks, air pockets etc.;

• lamina from composition laminates are orthotropic, parallel and perfectly stuck together;

• fibers are not examined isolated of matrix nor adhesive layer (interface effects are neglected);

• individual layers are bonded ideally to each other. In case of loads application relative slip doesn't appear;

• material behaves linearly ideal elastic, i.e. for each individual layer is applied law of linear elasticity;

• until delamination joints are considered ideal.

All experimentally determined elastic constants were used as input data. Modeling of composite specimens architecture was performed using software ANSYS Composite PrepPost. For specimens meshing four nodes shell finite elements SHELL181 was used. After some preliminary simulations adequate size of finite element was determined for which simulation results converge. In case of tensile test specimen minimal finite element size is 2,5×2,5 mm. For Shear test specimen finite element size is 0,4×0,4 mm.

Meshed specimen and details of nodal displacements and applied load are shown in figure 3, *a*. The distribution of stresses and strain in the specimen is shown in figure 3, b.

Maximum equivalent stress is obtained in the vicinity of fixing mandrel, where is concentrator area. For most specimens material failure occurs especially there figure 3, c. According to the results of the finite element analysis, stresses and strains arising on the rupture region are higher by 10%. In the diagrams constructed by real tests were introduced values of stress and strains from measurement area figure 4.

Deviations observed in the diagram of figure 3 are related to the difference between the modality of attachment of the specimen. During the experiment specimen fixation is on the contour (in the chuck) but in the numerical model fixation of the specimen is on the entire section. Because of that higher tensions arise in the outer layers of the specimen.

The results of finite element analysis of bidirectional fabric specimens are placed in the diagram representing real tests data, figure 5. Due to the fact that during the experiments two transducers

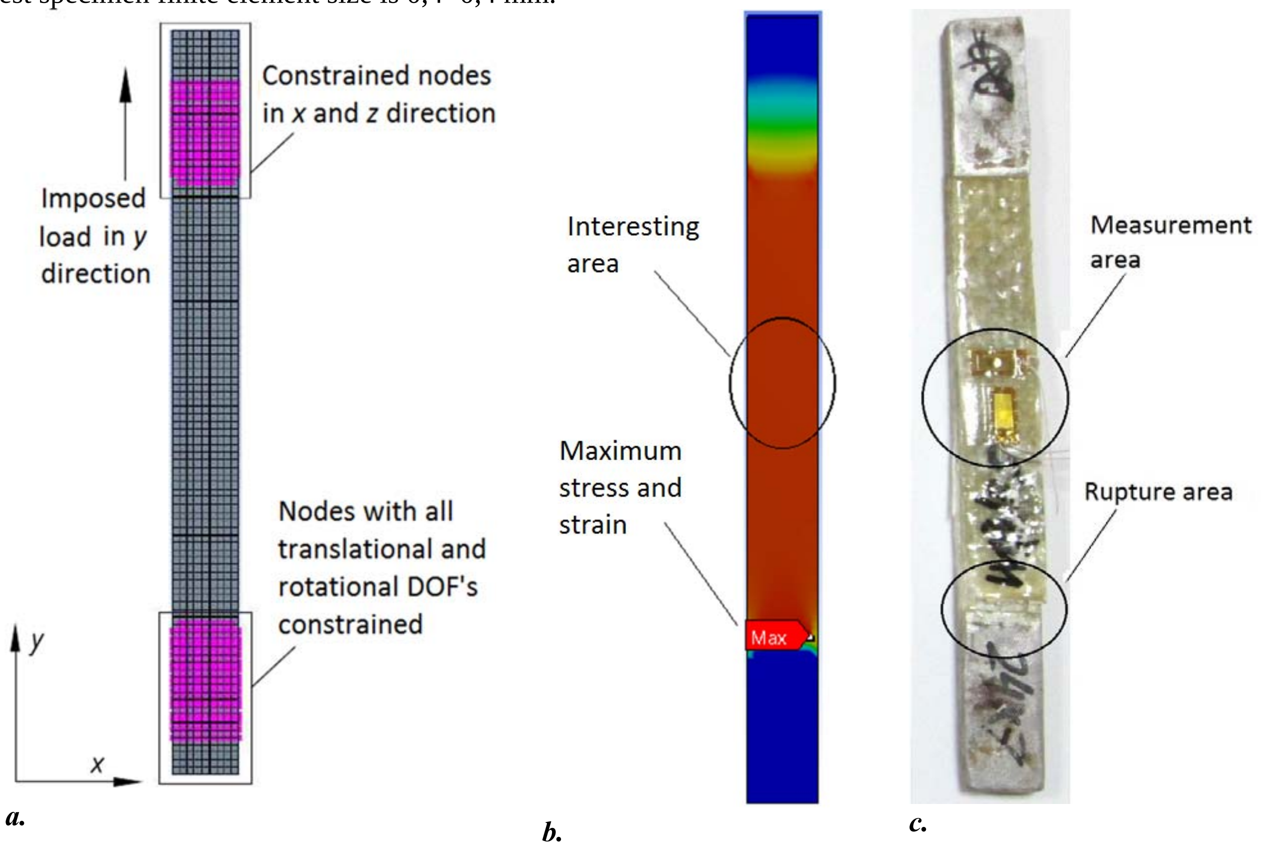
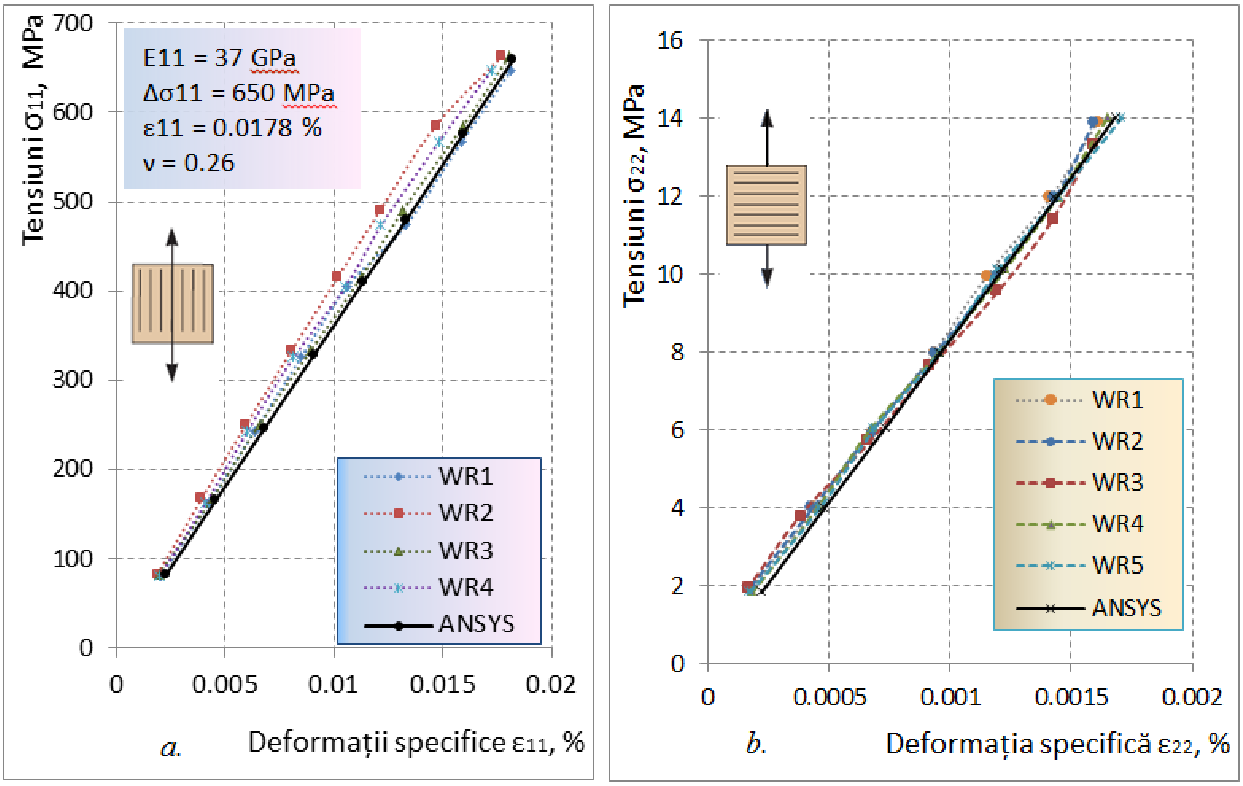


Figure 3. Specimen tensile test simulation:
a – boundary conditions in tensile test; b – stress distribution; c – tensile tested specimen.



a. ***b.***

Figure 4. Response of the unidirectional laminate to axial and transverse tension:
a – longitudinal loaded specimen; b – transverse loaded specimen.

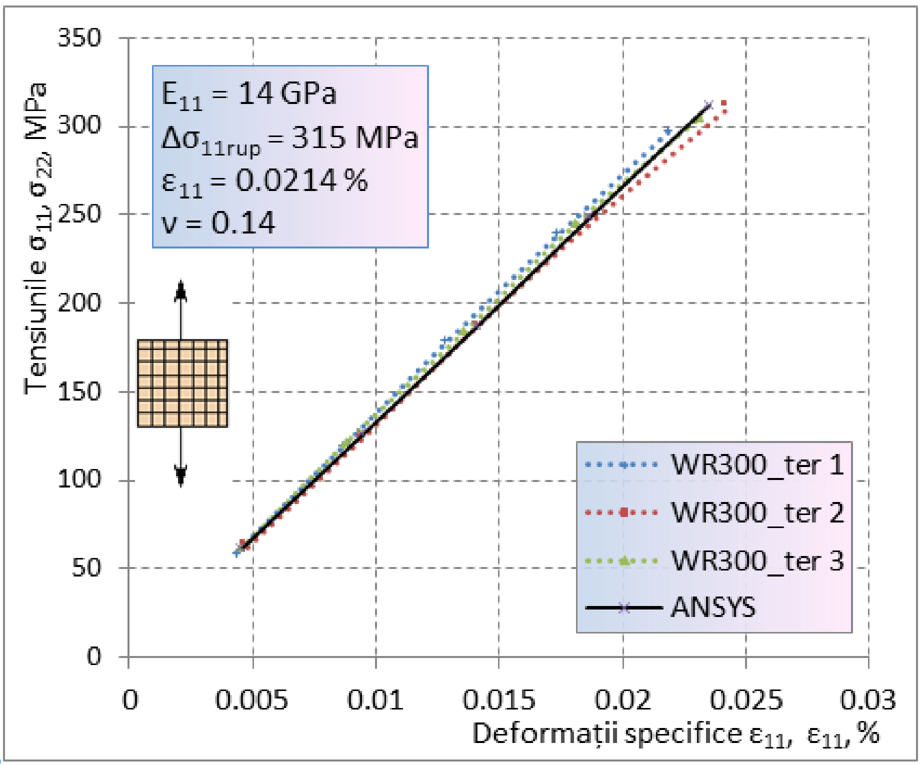


Figure 5. Responses of the bidirectional laminate to axial tension.

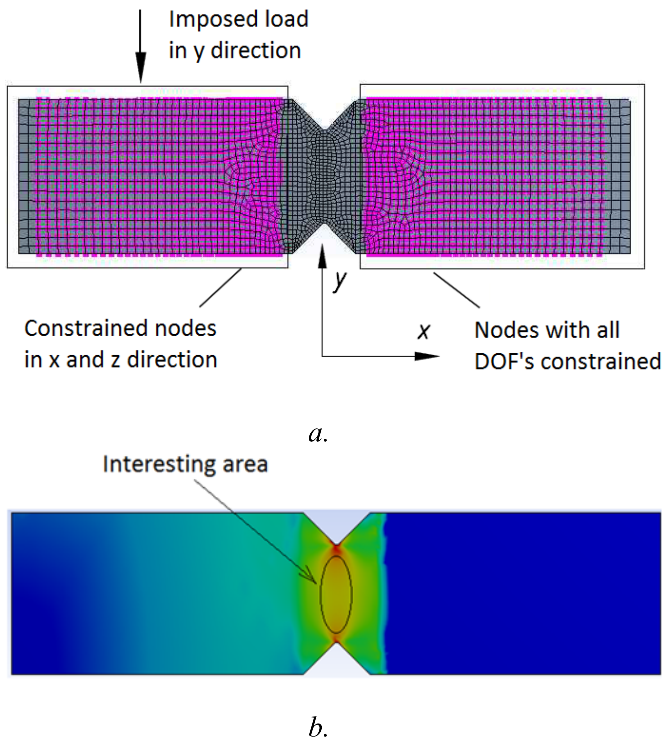


Figure 6. Specimen shear test simulation:
a – boundary conditions; b – stress and strain distribution.

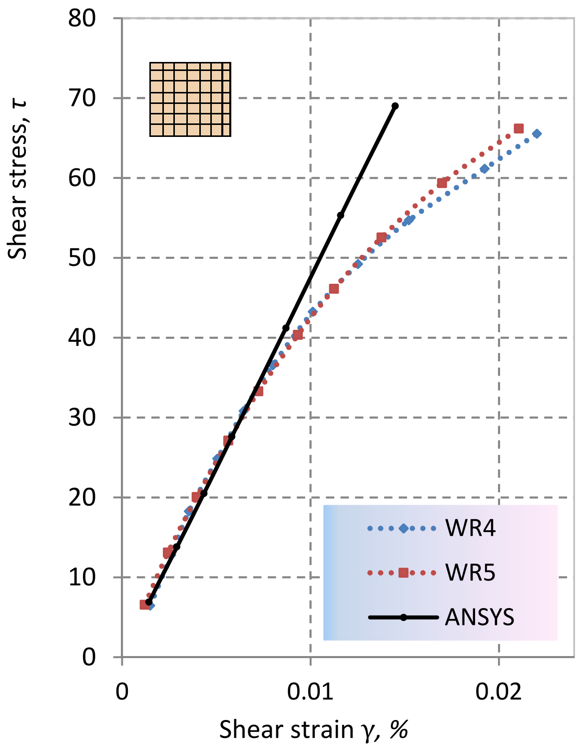


Figure 7. Response of the bidirectional laminate to in-plane shear loading.

were damaged and erroneous data were recorded, in the diagram are displayed results for only three specimens. For bidirectional fabric, as is shown in the diagram, the results correlate excellent.

Details of nodal displacements and shear loading of meshed specimen model is shown in in figure 6 a.

Specimen model boundary conditions have been set taking into account the recommendations in [5]. Stress distribution in the specimen is shown in figure 6 b. Shear stresses and sliding deformations were considered in the measuring transducer area. Comparative chart with the results of finite element analysis superimposed on the test results is shown in figure 7. Given the fact that shear loaded specimen has nonlinear behavior after about 10-12% of the specific deformation (slip) it is normal that curves do not correlate on the entire loading domain.

CONCLUSIONS

For the composite materials reinforced with fabrics were verified cases that influence the correlation of test results with finite element analysis results. First of all, it is important correctness of the determined elastic characteristics of the test material and the errors reducing. Another aspect is related to numerical modeling of the experiment which must be performed as close to the real test. This is achievable only by using special software with modeling capabilities of the composite material and finite element analysis.

Deviations that occur between the numerical model and experiment can be caused by the size of finite elements. In this case were determined finite element dimensions for which simulation results converge.

Setting of the specimen boundary conditions also affects results of the simulation. In this case fixing conditions of the real specimen cannot be respected in the numerical model. This is due to the fact that the real specimen is clamped in chuck on the contour, but the numeric model specimen is fixed on the entire section. For this reason, in the specimens formed from multiple layers stresses and strains are higher in the outer layers. To reduce this measurement error special strain gauges are used that are inserted between layers of fabric at the stage of manufacturing of composite material. Also, it is very important that for simulated specimen, to consider stresses and strains from the same section with the bonded strain gauges.

Based on the obtained results it was created a database of mechanical characteristics of the composite materials for the development of the new concepts in the Centre for Developing of Renewable Energy Conversion Systems. Also, the recommendations of composite material architecture and the blades manufacturing technology were defined, which in the future, will allow serial production of aerodynamic blades for small wind turbines.

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Recommended for publication: 28.09.2016