A Different Approach for Obtaining the Shear Moduli of a Composite Material

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In recent years the composites materials gained a major importance in all fields of engineering, because they offer a successful replacement for classical materials conferring similar elastic-mechanical properties to metal or non-metal alloys presenting several advantages such as reduced mass, chemical resistance etc. Considering this, during the design, dull knowledge of the elastic-mechanical characteristics is of high importance. The present paper aims to create a finite element model able to predict the shear elastic modulus of a double-layered composite material based on the elastic characteristics of its constituents. For this, once the elastic characteristics of the constituents determined, they could be used in the finite element analysis obtaining consequently the shear modulus for the composite material. Also, the shear elastic modulus of the resultant composite was determined experimentally. The results of the finite element model were compared to the experimental values in order to validate the finite element analyses results.

Keywords: composites, fiberglass, shear modulus, FEM

Recent advances in composite material studies present an extensive experimental research in mechanical characterization including labor intensive tensile, bending and vibration tests.

Our previous paper on this subject [1], presented a different approach in material characterization of composite laminated materials, but limited itself to tensile analyses of such materials. The elastic constants of any material is not limited to the Young’s modulus. Considering these, the authors, extended their work towards a full numerical characterization of composite materials, thus presenting in the current paper a finite element model and solution for obtaining the shear modulus of fiber reinforced polymer materials.

A state-of-the-art investigation on current subject was performed. Paper [2] presented a three-point bending numerical simulation with accurate results regarding material characterization. Dian-sen Li et al., presented a parameterized finite element model [3] for a braided composite. Such approach is similar to ours regarding the geometrical pattern of the model.

Failure morphologies obtained from the FEM results were presented in paper [4] alongside the stiffness degradation.

Paper [5] presents a prediction on the elastic properties at a meso scale composite, which is inferior to our micro scale approach.

A detailed approach for boundary conditions was presented in paper [6]. This approach was also used in our previous paper [1].

Experimental part

To deduce the torsional behavior of a non-circular cross-bar, according to Saint Venant following assumptions [7], the authors considered:

a) the bar element is straight, having a constant cross section, without conicity.

b) the load is pure torque and produces only shear stresses;

c) each rod cross section rotates approximately as rigidly, and the rotation of each cross section varies linearly along the longitudinal direction;

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d) the twisting angles as well as the shear deformations must be small, and the deformations must be equal on the ends of the same cross section.

From the hypotheses adopted, it follows:

$$\tau_{max} = \frac{M_t}{W_t} \tag{1}$$

where W_t represents the conventional torsion sectional modulus equal to:

$$W_t = \alpha a^2 b \tag{2}$$

The values of α and β coefficients depending on the ratio b a are found in Table 1.

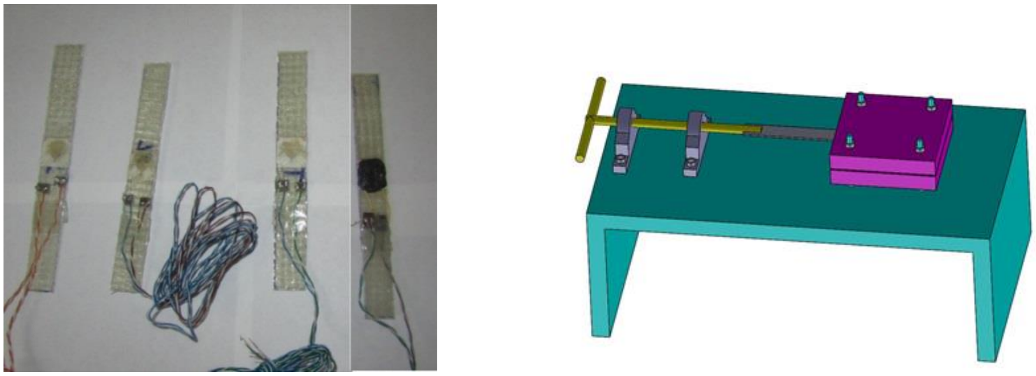
Table 1

THE VALUES OF THE COEFFICIENTS α AND β

b/a	1.0	1.5	2.0	2.5	3.0	4.0	6.0	10	∞
α	0.141	0.196	0.229	0.249	0.263	0.281	0.299	0.313	0.333
β	0.208	0.231	0.246	0.254	0.267	0.282	0.299	0.313	0.333

For the experimental determination of the shear modulus, an experimental device was developed requiring a specimen with a rectangular cross-section. This solution was chosen because the Iosipescu test could not be applied to the tested specimens due to the small specimen thicknesses (between 1 mm and 1.5 mm), the clamping between the Iosipescu devices could not being ensured. Also, a traditional torsion test machine was not used because, generally, it requires circular specimens. Another reason why this experimental device was developed concerns the intensity of the applied torque. The specimens having a very narrow cross-section, the torque applied had to have a very small value, in order not to exceed the elastic strain [7].

To measure the shear deformations produced by the torque, two transducers were attached to the specimen at 45° (fig. 1). The measurements were performed in statically mode, through a Vishay stress-strain bridge. The experimental device is depicted in Figure 1.



a) Two-layer composite specimens for

b) Experimental set-up for obtaining the shear modulus modulus

Fig. 1. Experimental device

Following the experimental determinations, the transverse elasticity moduli on the two main directions were obtained. These were systematized in Tables 2 and 3.

Table 2

EXPERIMENTAL RESULTS FOR LONGITUDINAL DIRECTION

Specimen No.	F [N]	M_t [N·mm]	τ [MPa]	γ[μm/m]	G[MPa]
1.	0.91142	104.8133	15.73773	2659.8	5931.896
2.	0.91492	100.6412	15.11129	2516.4	6003.639
3.	1.0532	115.852	17.3952	2926.8	5913.865
4.	0.91142	104.8133	15.73773	2683.2	5879.123
5.	0.91142	100.2562	15.05348	2516.6	5983.092
Average	**0.940476**	**105.2752**	**15.80709**	**2660.56**	**5942.323**

Table 3
EXPERIMENTAL RESULTS FOR TRANSVERSE DIRECTION

Specimen No.	F [N]	M_t [N·mm]	τ [MPa]	γ [µm/m]	G[MPa]
1.	0.91142	104.8133	15.73773	3144.8	5014.124
2.	0.91486	100.6346	11.9501	2419.2	4985.948
3.	0.91984	101.1824	12.01515	2407.6	5001.14
4.	0.91142	104.8133	15.73773	3129.8	5040.792
5.	0.91978	101.1758	12.01436	2408.6	4999.803
Average	**0.915464**	**102.5239**	**13.49101**	**2702**	**5008.361**

Modelling the torsion phenomena with finite elements requires to obtain the elastic characterization of the constituents. This involves a determination of the Young's modulus and Poisson's ratio. For this, the two components (resin and fiberglass wires) were considered homogeneous and isotropic [8, 9, 10].

As a continuation of the research from [1] for the longitudinal modulus of elasticity of fiberglass wires as well as of the epoxy resin, the experimental results obtained in that research were used (Table 4).

Table 4
YOUNG MODULUS AND DENSITY FOR CONSTITUENTS

Constituent	E[MPa]	σ_t [MPa]	Density [kg/m^3]
Fiberglass yarn	19000	295.74	2448.2
Polyester resin	2964	38.4	1384

In the case of fiberglass wires for the determination of Poisson's coefficient, a device for testing yarns shown in Figure 2 was used for obtaining the elongation of a wire at a certain value of the force. Through the optical microscopy performed on a Leica microscope and ImageJ software the average diameter of a glass fiber wire was determined. 3a. Using the constant volume principle, the transverse contraction was determined. As a result of the measurements, a value of 0.21 for the Poisson’s ratio was obtained for the fiberglass filament.

a) Experimental device for wire tensile testing

b) Wire clamping mode in testing of wire rods

Fig. 2. Experimental device for tensile testing

a) Fibreglass strand optical masurement

b) Woven pattern of fiberglass

Fig. 3. Optical measurements

Results and discussions

The finite element model created for obtaining the shear modulus of the fiberglass composite was based on the geometrical model presented in Figure 4. As it can be seen, the difference between transversal and longitudinal elastic characteristics comes from the different gaps between longitudinal and transversal fiber yarns. On the longitudinal direction (red yarns), a smaller gap of 1.36 mm generates a higher yarn density with 21 strands for every 100 mm of woven fiberglass fabric. On transversal direction (green yarns), the gap of 1.97 mm generates a density of 19 strands for 100 mm.

The geometrical difference between this model and the model presented in paper [1], ensures a proper and correct elastic characterization for the material, with different elasticity moduli for each direction, whereas in paper [1], there was no such a difference.

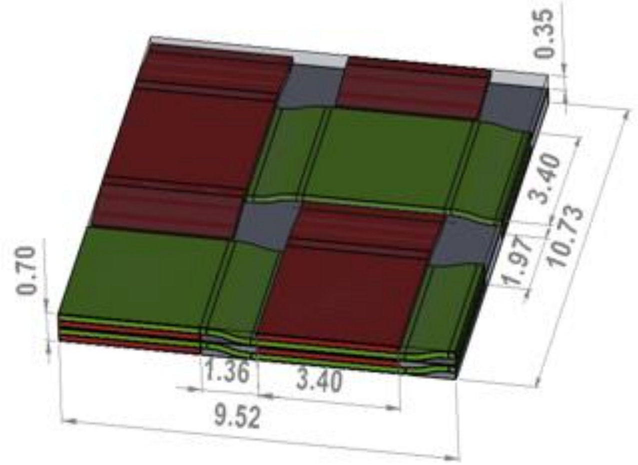


Fig. 4. Geometrical model

In order to create and solve the finite element model, the 3D generated specimen was imported in Ansys Workbench v.19, using the Transient Structural setup. Considering the premises of this analysis, as boundary conditions a fixed support was applied on the z axis, as is shown in Figure 5. Thus, B represents the fixed face of the specimen and A represents the imposed rotation of 0.01 degree per step with a total of 10 steps on the opposite yellow face.

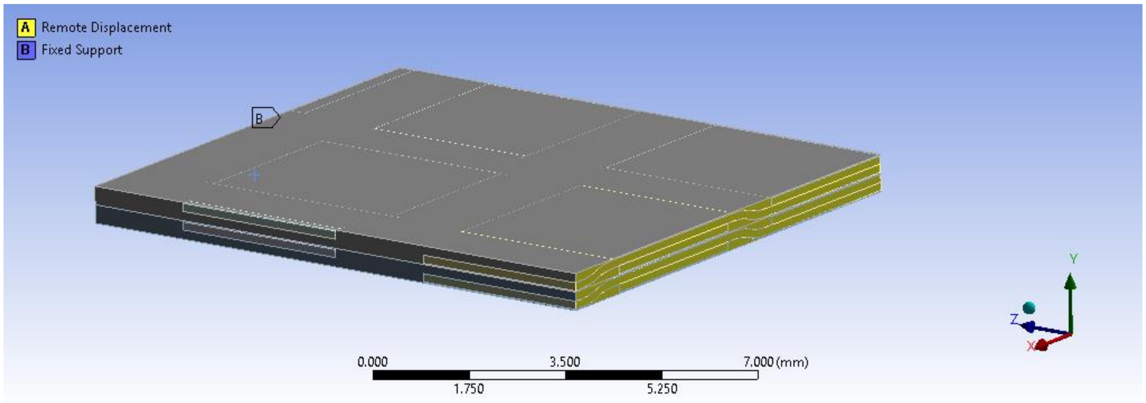


Fig. 5. Boundary conditions

A total number of 100182 nodes and 20336 elements were obtained, as presented in Figure 5. Higher mesh density was achieved in proximity of yarn’s top and bottom (not depicted) side.

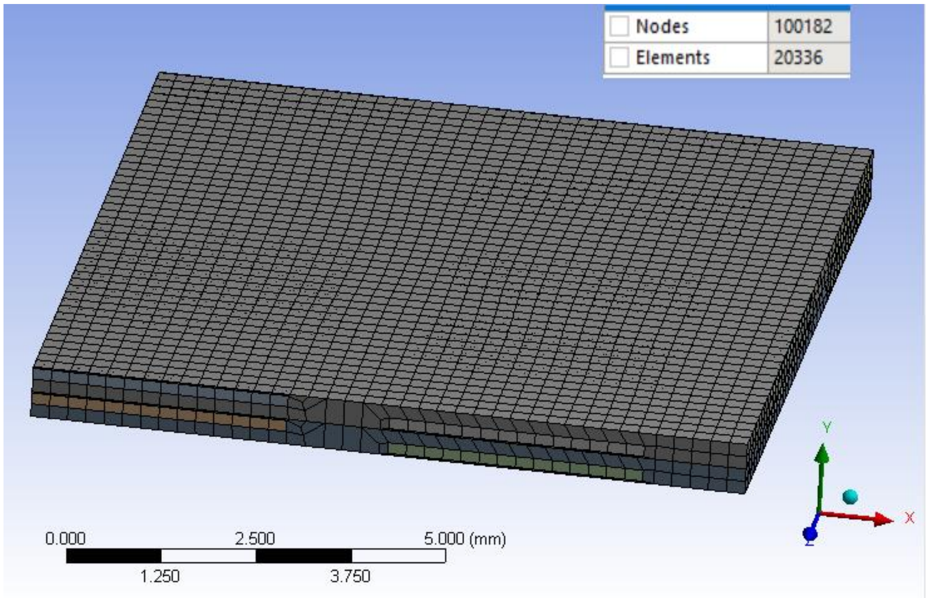


Fig. 6. Mesh details

Considering the transient structural analysis setup, the displacement was applied in ten steps of 0.01 degree, obtaining consequently an evolution of the shear elastic stress and strain. In Figure 7 the shear stress distribution for the longitudinal direction of the material is presented. These results are summarized in Table 5.

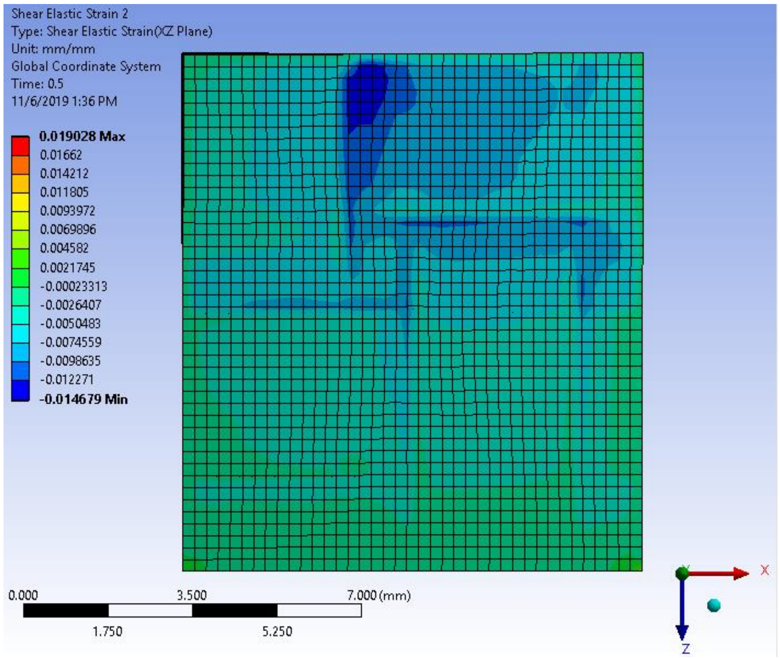


Fig. 7. Shear elastic strain on longitudinal direction

Table 5

FEM RESULTS FOR SHEAR MODULUS ON LONGITUDINAL DIRECTION

Step	τ [MPa]	γ [rad]	G [MPa]
1	4.1001e-002	6.4977e-006	6310.079
2	8.2003e-002	1.2995e-005	6310.35
3	0.123	1.9493e-005	6309.957
4	0.16401	2.5991e-005	6310.261
5	0.20501	3.2488e-005	6310.33
Average	**1.23e-01**	**1.95e-05**	**6310.196**

Same approach was used for obtaining the shear stress distribution in the transverse direction of the material. Results for stress distribution, presented in Figure 8 and in Table 6, are summarized.

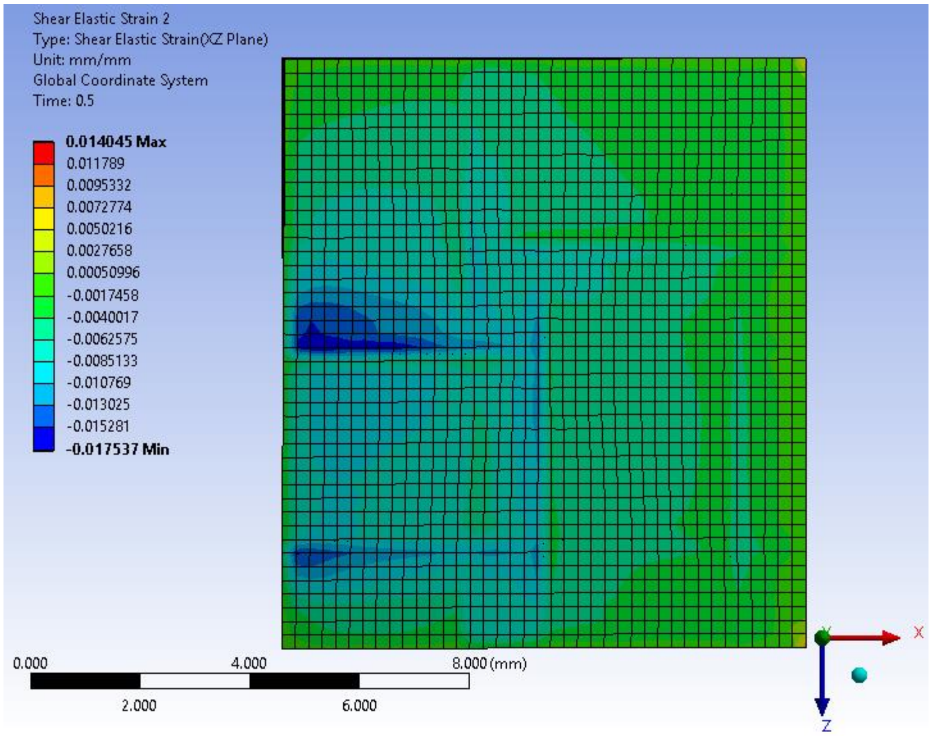


Fig. 8. Shear elastic strain on transversal direction

Table 6
FEM RESULTS FOR SHEAR MODULUS ON TRANSVERSAL DIRECTION

Step	τ [MPa]	γ [rad]	G[MPa]
1	1.3742e-002	2.7219e-006	5048.679
2	2.7484e-002	5.4439e-006	5048.586
3	4.0565e-002	8.1658e-006	4967.670
4	5.4968e-002	1.0888e-005	5048.494
5	6.871e-002	1.361e-005	5048.494
Average	**4.11E-02**	**8.17E-06**	**5032.385**

Conclusions

This paper proposes a finite element model able to predict the transverse elastic characteristics of a double layered composite. The current model is improved in comparison to the one presented in [1], considering the differences in fiber density in the two directions. The differences can be seen in the smallest errors occurred in concordance to those obtained in the experimental part of the previous model, where these have reached values of 15%. The current model has errors less than 1% on both calculated directions, preserving the advantages of being scalable for any number of layers, as well as being able to predict accurately the characteristics of the final composite based on the characteristics of the constituents regardless the used components.

The next step of the research will follow the use of this finite element to predict the improvement of Young's modulus on the two main directions of the material and the Poisson’s ratio. It is also a goal to validate the model using the numerical method of calculation with finite differences as schematized in [11].

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References

1. DRAGHICI, S., PETRESCU, H.-A., HADAR, A., On Obtaining the Young Modulus from Numerical Analysis of Composite Material Constituent, Mat. Plast., **55**, no. 4, 2018, pp. 712-717

2. SUN, B., LIU, R., GU, B., Numerical simulation of three-point bending fatigue of four-step 3-D braided rectangular composite under different stress levels from unit-cell approach, Computational Materials Science, **65**, 2012, pp. 239-246

3. LI, D.S., FANG, D.N., JIANG, N., XUEFENG, Y., Finite element modeling of mechanical properties of 3D five-directional rectangular braided composites, Composites Part B: Engineering, **42(6)**, 2011, pp. 1373-1385

4 WU, L., ZHANG, F., SUN, B., GU, B., Finite element analyses on three-point low-cyclic bending fatigue of 3-D braided composite materials at microstructure level, International Journal of Mechanical Sciences, **84**, 2014, pp. 41-53

5. FAGIANO, C., GENET, M., BARANGER, E., LADEVÈZE, P., Computational geometrical and mechanical modeling of woven ceramic composites at the mesoscale, Composite Structures, **112**, 2014, pp. 146-156

6. JACQUES, S., DE BAERE, I., VAN PAEPEGEM, W., Application of periodic boundary conditions on multiple part finite element meshes for the meso-scale homogenization of textile fabric composites, Composites Science and Technology, **92**, 2014, pp. 41-54

7. DRAGHICI, S., PARAUSANU, I., BACIU, F., PETRESCU, H.A., HADAR, A., PASTRAMA, S.D., A Comparative Experimental-Numerical Analysis on the Vibration Behavior of a Composite Satellite Subset. Mat. Plast., **53**, no. 4, 2016, p. 585-589

8. LI, J., JIAO, Y., SUN, Y., WEI, L., Experimental investigation of cut edge effect on mechanical properties of three-dimensional braided composites, Materials & design, **28(9)**, 2007, pp. 2417-2424

9. KABELKA, J., Prediction of the Thermal Properties of Fiber-Resin Composites (Retroactive Coverage), Elsevier Applied Science Publishers, Ltd., Developments in Reinforced Plastics-III, 1984, pp. 167-202

10. WHITCOMB, J., WOO, K., GUNDAPANENI, S., Macro finite element for analysis of textile composites. Journal of Composite Materials, **28(7)**, 1994, pp. 607-618

11. DUNCA, G., IOVANEL, R.G., BUCUR, D.M., CERVANTES, M.J., On the Use of the Water Hammer Equations with Time Dependent Friction during a Valve Closure, for Discharge Estimation, Journal of Applied Fluid Mechanics, 9(5), 2016, pp. 2427-2434

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