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LINEAR TWO-SCALE MODEL FOR DETERMINING THE MECHANICAL PROPERTIES OF A TEXTILE COMPOSITE MATERIAL

LINEARNI DVOSTOPENJSKI MODEL ZA DOLOČITEV MEHANSKIH LASTNOSTI TEKSTILNEGA KOMPOZITA

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The engineering mechanical constants for a description of mechanical macro-scale models of carbon and aramid textile composite materials are calculated using finite-element analyses. Two sub-scale models of representative volumes are used. The micro-scale model represents a periodically repeated volume consisting of fibers and a matrix within each interweaved yarn. The meso-scale model represents a unit cell of four interweaved yarns, which is repeated within the whole composite with the properties obtained from a micro-scale model and matrix. The finite-element models are built with the commercial packages Siemens NX 7.5 and MSC.Marc 2008r1 using subroutines.

Keywords: composite, textile, linear, carbon, aramid, epoxy, tensile, finite-element analysis

Z uporabo metode končnih elementov so izračunane inženirske konstante za opis mehanskega makrodimenzionalnega ogljik-aramidnega modela kompozita. Uporabljena sta dva poddimenzionalna modela za manjše ustrezne prostornine. Mikrodimenzionalni model je periodično ponavljanje prostornine, ki se ponavlja za ves kompozit za matico in vpleteno vlakno. Mezodimenzionalni model je spletna celica iz štirih vpletenih vlaken in se ponavlja v vsem kompozitu z lastnostmi mikromodela in matice. Modeli končnih elementov so vgrajeni v paketa Siemens NX 7.5 in MSC.Marc 2008r1 z uporabo podrutin.

Ključne besede: kompozit, tekstil, linearen, ogljik, aramid, epoksi, natezne lastnosti, končni elementi

1 INTRODUCTION

A knowledge of the precise values of the mechanical properties of materials is crucial for the capability of models to predict the behavior of analyzed structures. This is also the case for the modeling of composite materials. Several material properties of the composites can be calculated directly from experimental results (Young's moduli from tensile tests, etc.). The presented paper is aimed at a determination of the elasticity constants of textile composites using sub-scale models to determine the properties that cannot be measured and calculated directly from the experiment (shear modulus, etc.). The models were used for the prediction of the elasticity constants of two materials with a simple plain weave. This type of material was chosen because of the possibility to measure directly the Young's moduli in the principal material directions using tensile tests. Nevertheless, the shear modulus was fitted on the linear part of the measured curves using a gradient-optimization algorithm and the Poisson's ratios of the whole textile composites were identified using a digital image correlation[1]. The material data of the constituents were given by the manufacturer and the dimensions of the periodically repeated volume (unit-cell element – UCE) of the textiles were measured using a digital camera.

2 EXPERIMENT

The effective material parameters were determined using simple tensile tests performed on a Zwick/Roell Z050 test machine on thin strips with the dimensions given in **Table 1**.

Table 1: Dimensions of the strips
Tabela 1: Dimenzije traka

		Carbon	Aramid
Length	mm	100.00	100.00
Width	mm	10.00	10.00
Thickness	mm	0.30	0.35

Three types of specimens were used for each material. One of two principal directions of the textile fabric form the angles 0°, 45° and 90° with the direction of the loading force. Once the force-displacement diagrams (**Figures 1 and 2**) were measured, the Young's moduli in directions 1 and 2 and the shear modulus were fitted on the linear parts of the curves using a combination of a plane-stress finite-element (FE) model and the gradient-optimization algorithm implemented in OptiSLang software (the methodology is described in[2,3]). A digital image correlation[1] was used for the calculation

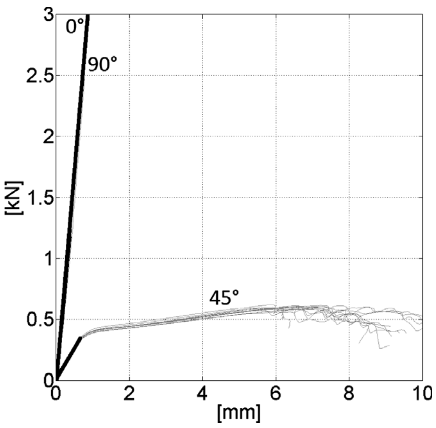

Figure 1: Force-displacement diagram (gray) for Carbon/Epoxy, with fitted parts (black)
Slika 1: Odvisnost sila – premik (sivo) za ogljik/epoksi s približki (črno)

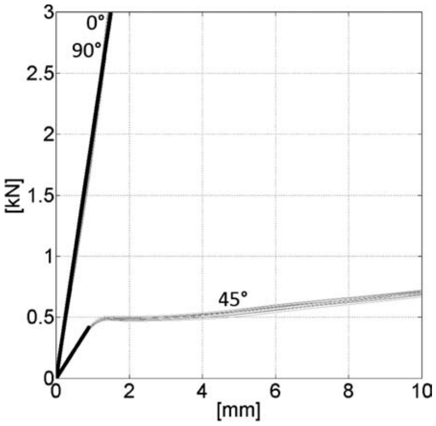

Figure 2: Force-displacement diagrams (gray) for Aramid/Epoxy, with fitted parts (black)
Slika 2: Odvisnost sila – premik (sivo) za aramid/epoksi s približki (črno)

of the Poisson's ratios. The elasticity parameters of the textiles are shown in **Table 2**.

Table 2: Elasticity parameters of textile composites
Tabela 2: Parametri elastičnosti za tekstilne kompozite

		Carbon/Epoxy	Aramid/Epoxy
E_1	GPa	31.05	15.85
E_2	GPa	29.73	15.66
G_{12}	GPa	1.83	1.24
ν_{12}	–	0.19	0.31

3 UNIT-CELL ELEMENTS

Axes orientations in UCE (**Figure 4**) are shown in **Figure 3**. Dimensionless geometry of UCE of yarns is shown in **Table 3**. The ideal distribution of fibers in the yarns, the perfect saturation of the yarns by the matrix and the volume fiber fractions V_f = 0.6 and V_f = 0.7 are considered in the calculations.

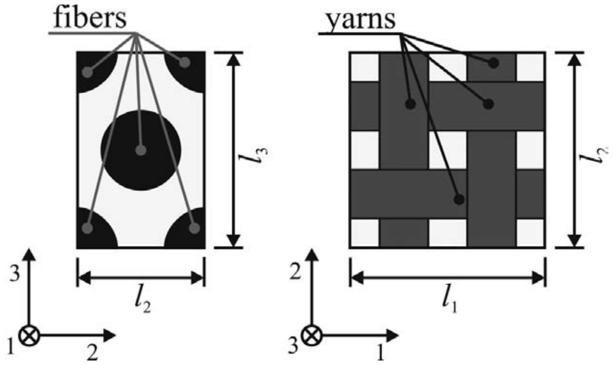

Figure 3: Material axes: yarn (left), textile (right)
Slika 3: Osi materiala: vlakno (levo), tekstil (desno)

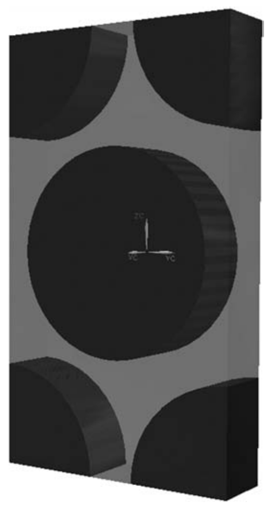

Figure 4: UCE geometry of yarn with V_f = 0.6 (fibers – black, matrix – gray)
Slika 4: UCE-geometrija vlakna z V_f = 0.6 (vlakna – črno, matica – sivo)

Table 3: Dimensions of the unit cell of the yarn
Tabela 3: Dimenzije spletne celice

l_1	[-]	1
l_2	[-]	4
l_3	[-]	$4 \cdot \sqrt{3}$

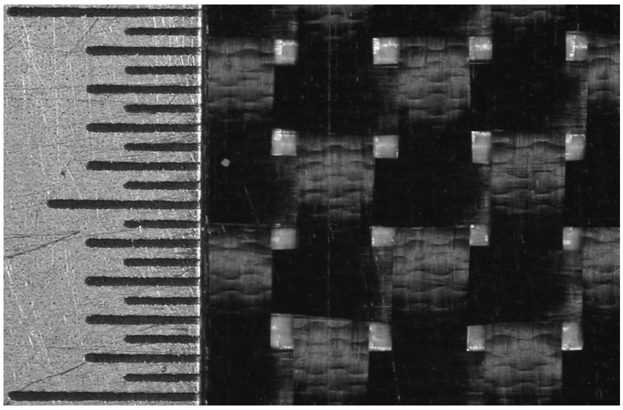

Figure 5: Photograph of Carbon/Epoxy specimen
Slika 5: Posnetek vzorca ogljik/epoksi

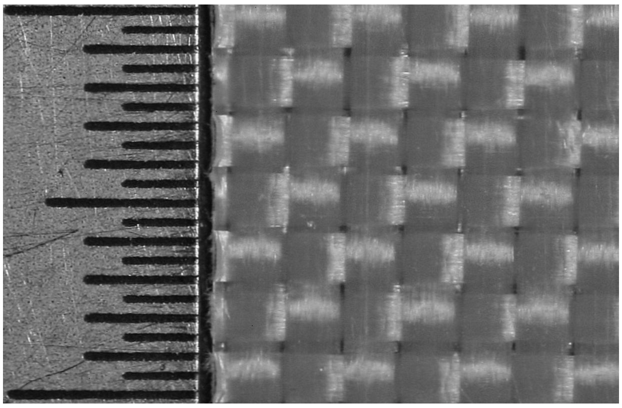

Figure 6: Photograph of Aramid/Epoxy specimen
Slika 6: Posnetek vzorca aramid/epoksi

The dimensions of the UCE of both materials, which were measured using detailed photographs provided by a Canon EOS 400D digital camera (**Figures 5 and 6**) are shown in **Table 4**.

Table 4: Dimensions of textile unit cells
Tabela 4: Dimenzije spletne celice tekstila

		Carbon/Epoxy	Aramid/Epoxy
l_1	mm	5.00	3.00
l_2	mm	5.00	3.00
l_3	mm	0.30	0.35

4 BOUNDARY CONDITIONS

In the FE model of the UCE (**Figure 7**) it is necessary to invoke pure tensile conditions or pure shear conditions to determine the elasticity parameters. Furthermore, the UCE has to be fixed in space to eliminate rigid body modes. Finally, the periodic boundary conditions have to be satisfied. The effect of the periodic boundary condition on the UCE with two periodically tied faces is sketched in **Figure 8**.

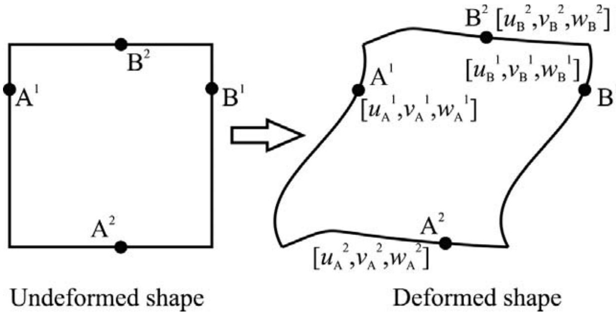

Figure 8: Scheme of the effect of the periodic boundary conditions
Slika 8: Shema učinka periodičnosti mejnih pogojev

Each corresponding pair of nodes on opposite faces of the FE model must fulfill the conditions [4–6]

$$u_B^i - u_A^i = d_u^i,\ v_B^i - v_A^i = d_v^i \quad w_B^i - w_A^i = d_w^i \text{ for } i=1...N \tag{P}$$

where i is the index of the corresponding constrained faces; N is the total number of the periodically constrained faces; u, v and w are the displacements in the 1, 2 and 3 direction; and d_u^i, d_v^i, d_w^i are displacements of the appropriate retained nodes in which the loading is applied (**Figure 9**). The UCE of the yarns is periodically tied in all three directions and the UCE of the textiles is tied in direction 1 and 2 (**Figure 9**).

For the determination of the Young's modulus E_1 and the Poisson's ratio ν_{12} of the textile composite the model is loaded with $\sigma_1 \neq 0$ and the other loadings are equal to zero. Normal strains in direction 1 and 2 are calculated as

$$\varepsilon_1 = \frac{d_1^1}{l_1},\ \varepsilon_2 = \frac{d_2^2}{l_2} \tag{e12}$$

and the Young's modulus and Poisson's ratio are

$$E_1 = \frac{\sigma_1}{\varepsilon_1}, \nu_{12} = \frac{\varepsilon_2}{\varepsilon_1} \tag{E1ν12}$$

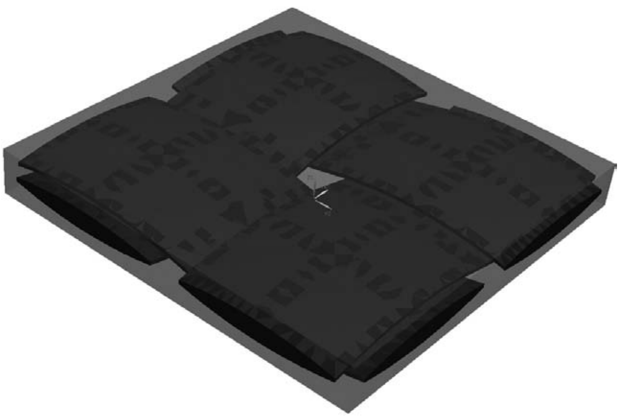

Figure 7: UCE geometry of Carbon/Epoxy textile composite (yarns – black, matrix – gray)
Slika 7: UCE-geometrija kompozita ogljik/epoksi (trakovi – črno, matica – sivo)

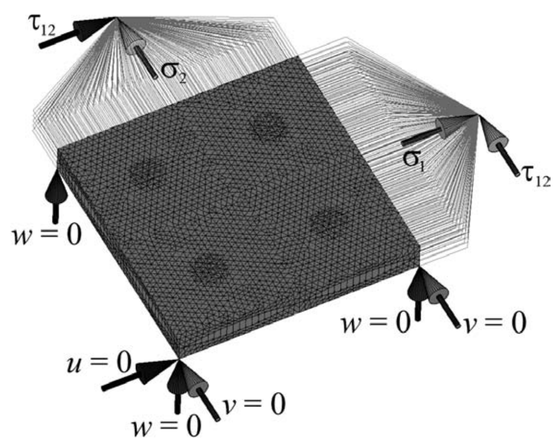

Figure 9: Boundary conditions and links used for periodic boundary conditions for UCE of Aramid/Epoxy textile
Slika 9: Mejni pogoji in povezave, uporabljene za periodične mejne pogoje za UCE aramid/epoksi tekstil

For the determination of the shear modulus G_{12} the model is loaded by $\tau_{12} \neq 0$. The other loadings are equal to zero. The shear strain in plane 12 is calculated as

$$\gamma_{12} = \frac{d_2^1}{l_1} + \frac{d_1^2}{l_2} \tag{g12}$$

and the shear modulus is

$$G_{12} = \frac{\tau_{12}}{\gamma_{12}} \tag{G12}$$

The same scheme is used for the determination of the elasticity constants in the other directions or planes.

5 INPUT PARAMETERS

Carbon (Toray T600) and Aramid (Twaron K1055) fibers are transversely isotropic materials. Their elasticity parameters are given in **Table 5**.

Table 5: Elasticity parameters for fibers
Tabela 5: Parametri elastičnosti za vlakna

		Carbon	Aramid
E_1	GPa	230.00	104.00
E_2	GPa	7.05	5.40
E_3	GPa	7.05	5.40
ν_{12}	–	0.30	0.40
ν_{23}	–	0.30	0.40
ν_{31}	–	0.02	0.02
G_{12}	GPa	50.00	12.00
G_{23}	GPa	50.00	12.00
G_{31}	GPa	50.00	12.00

The matrix is manufactured from epoxy resin (MGS® L 285) and hardener (MGS® 285). It is considered to be a linear isotropic material (**Table 6**).

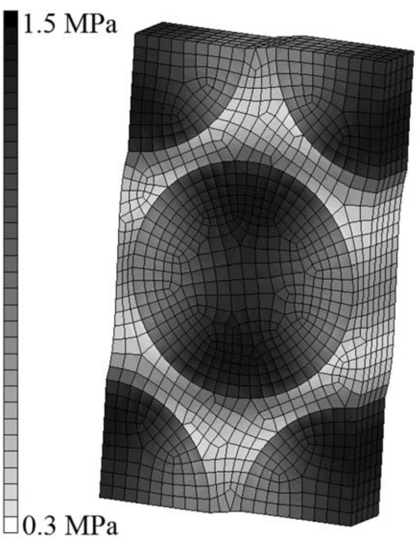

Figure 10: Deformed FE model of the UCE of yarn under shear loading in plane 23 (shown values of shear stress τ_{23})
Slika 10: Deformiran FE-model za UCE-spleta pri strižni obremenitvi v ravnini 23 (prikazane vrednosti strižne napetosti τ_{23})

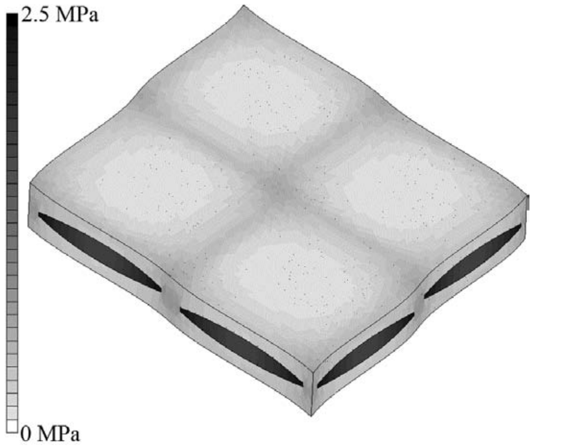

Figure 11: Deformed FE model of the UCE of the textile under shear loading in plane 12 (shown values of shear stress τ_{12})
Slika 11: Deformiran FE-model UCE za tekstil pri strižni obremenitvi v ravnini 12 (prikazane vrednosti strižne napetosti τ_{12})

Table 6: Elasticity parameters for the matrix
Tabela 6: Parametri elastičnosti za matico

		Epoxy
E	GPa	3.00
ν	–	0.30

6 RESULTS

The effect of the periodic boundary conditions is shown in **Figures 10** and **11**. Opposite faces of the UCE are deformed in the same shape. The elastic properties of the yarns are shown in **Table 7**. The results are shown for both fiber volume fractions (V_f). Similarly, the results for the textiles are shown for both V_f (**Table 8**).

Table 7: Calculated elasticity parameters of the yarns
Tabela 7: Izračunani parametri elastičnosti za spleta

		Carbon/Epoxy		Aramid/Epoxy	
V_f	–	0.60	0.70	0.60	0.70
E_1	GPa	138.87	161.54	63.46	73.55
E_2	GPa	7.05	8.33	4.36	4.60
E_3	GPa	7.05	8.33	4.36	4.60
ν_{12}	–	0.30	0.30	0.36	0.37
ν_{23}	–	0.36	0.34	0.40	0.40
ν_{31}	–	0.02	0.02	0.02	0.02
G_{12}	GPa	4.26	5.90	3.42	4.34
G_{23}	GPa	3.88	5.45	3.15	4.01
G_{31}	GPa	4.26	5.90	3.42	4.34

Table 8: Calculated elasticity parameters for textiles
Tabela 8: Izračunani parametri elastičnosti za tekstil

		Carbon/Epoxy		Aramid/Epoxy	
V_f	–	0.60	0.70	0.60	0.70
E_1	GPa	27.75	31.89	14.08	15.72
E_2	GPa	27.75	31.89	14.08	15.72
G_{12}	GPa	2.60	3.30	2.21	2.60
ν_{12}	–	0.33	0.33	0.28	0.29

7 CONCLUSION

Multi-scale models for the prediction of the elasticity constants of textile composites with a simple plain weave were developed and presented. Good agreement of the Young's moduli was achieved between the calculated and experimental values. However, the shear moduli are slightly over-predicted. The calculated Poisson's ratios were calculated with acceptable accuracy only for the Aramid/Epoxy textile. Future research will be aimed at the non-linear, plastic and damage behavior of the matrix, the damage behavior of the fibers and an investigation of the imperfections and the unit-cell element dimensions of the textiles.

Acknowledgement

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8 REFERENCES

[1] R. Kottner, R. Zemčík, V. Laš, Mechanical characteristics of rubber segment – shear test. In: Experimental Stress Analysis 2007

[2] T. Kroupa, R. Zemčík, J. Klepáček, Temperature dependence of parameters of non-linear stress-strain relations for carbon epoxy composites, Mater. Tehnol., 43 (**2009**) 2, 69–72

[3] T. Kroupa, R. Zemčík, V. Laš, Improved non-linear stress-strain relation for carbon-epoxy composites and identification of material parameters, JCM, 45 (**2011**) 9, 1045–1057

[4] P. P. Camanho, C. G. Dávila, S. T. Pinho, J. J. C. Remmers, Mechanical response of Composites, ECCOMAS, Springer 2008

[5] B. Hassani, E. Hinton, Homogenization and structural topology optimization, Springer 1999

[6] R. Zemčík, K. Kunc, T. Kroupa, R. Kottner, P. Janda, Micromodel for failure analysis of textile composites, In: YSESM, Trieste, Italy, 2010, 48–51