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IDENTIFICATION OF THE MATERIAL PARAMETERS OF A UNIDIRECTIONAL FIBER COMPOSITE USING A MICROMODEL

IDENTIFIKACIJA PARAMETROV MATERIALA ENOSMERNEGA KOMPOZITA Z UPORABO MIKROMODELA

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The paper is focused on the identification of material parameters of the substituents of an unidirectional carbon-epoxy long-fiber-reinforced composite. Simple tensile tests using thin coupons with various fiber orientations were performed and force-displacement diagrams were obtained. A model of a unit cell is created in MSC.Marc. Fibers are considered to form a non-linear, elastic, transversely isotropic material and the matrix is considered to be an elasto-plastic isotropic material. The unit cell is loaded by a uniaxial stress up to the same level of loadings as the experimental samples. The sum of the squared differences of displacements between the numerically and experimentally obtained force-displacement diagrams is minimized within an identification process. The parameters of the linear relation between the Young's modulus of fibers and strain in the fiber-axis direction, and three shape coefficients of the matrix work-hardening function are searched. The identification process is performed using the MSC.Marc, OptiSlang optimization software and Matlab.

Keywords: unidirectional fiber composite, non-linear behavior, optimization, identification, matrix work-hardening function, representative volume element, unit cell, micromodel

Cilj dela je bila identifikacija parametrov materiala za nadomestek pri enosmernem ogljik-epoksi dolgovlaknatem ojačenem kompozitu. Enostavni raztržni preizkusi z uporabo odrezkov z različno orientacijo vlaken so bili izvršeni in dobljeni so bili diagrami sila – pomik. Model z enotno celico je bil ustvarjen v MSC.Marc. Vlakna so bila upoštevana kot nelinearen elastičen, prečno izotropen material, matica pa je bila upoštevana kot elastoplastičen izotropen material. Vsota kvadratov razlik v pomiku med numerično in eksperimetalano doseženimi diagrami sila – deformacija je bila minimalizirana z identifikacijskim procesom. Iskani so bili parametri linearne odvisnosti med Young modulom vlaken in deformacijo v smeri osi vlaken ter trije oblikovni koeficienti za deformacijsko utrditev matice. Proces identifikacije je bil izvršen z uporabo MSC.Marc, OptiSlang-softvera za optimizacijo in Matlaba.

Ključne besede: enosmerni vlaknati kompozit, nelinearno vedenje, optimizacija, identifikacija, funkcija deformacijske utrditve matice, reprezentačni element volumna, celica enote, mikromodel

1 INTRODUCTION

Composite materials are widely used in all fields of industry such as aerospace, sport, automotive and transportation. Frequently used composites are based on a carbon-fibers and epoxy matrix for its high specific strength and stiffness. The knowledge of the material characteristics is crucial for the accuracy of the numerical models used in a designing process. The above type of composite shows a significant non-linear behavior. Therefore, complex non-linear material models must be used in order to achieve a good agreement with the experimental data even for the simple tensile tests. The modeling of large structures requires the use of macromodels, i.e., homogenized material models. The parameters of a macromodel can be assessed either by using a combination of a finite-element model with the mathematical optimization technique and experimental data or by using a micromodel of a unit-cell element, which is a periodically repeated volume fraction, with the knowledge of mechanical properties of all the constituents. A micromodel of the composite material can be advantageous for deeper analyses of the phenomena such as the influence of heterogeneities or microdamage mechanisms, etc.

2 EXPERIMENT

Tensile tests of the thin coupons made of unidirectional long-fiber carbon-epoxy composite SE84LV-HSC-450-400-35 were performed on the testing machine ZWICK/ROELL Z050. The coupons were cut by a water jet from one large plate.

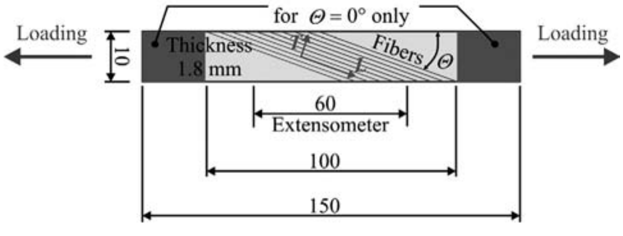

Figure 1: Geometry of composite coupons (mm) [1]
Slika 1: Geometrija odrezkov kompozita (mm) [1]

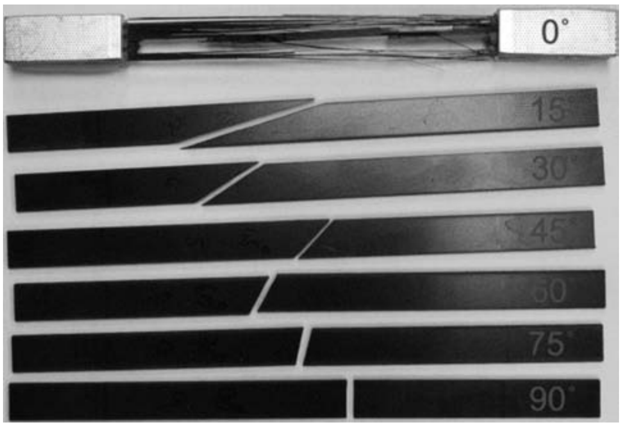

Figure 2: Cracked specimens with aluminum tabs[1]
Slika 2: Razpokani vzorci z aluminijevo podlago[1]

The fiber direction forms the angles of 0°, 15°, 30°, 45°, 60°, 75° and 90° with the direction of the loading force (**Figure 1**). There were 10 specimens tested for each angle. Cracked specimens[1] are shown in **Figure 2**. The specimens loaded along the fiber direction are fractured due to a fiber failure. All the specimens loaded at a different angle are fractured due to a matrix failure.

The resulting force-displacement diagrams are shown in **Figure 3**.

2.1 Micromodel

A finite-element model (micromodel) of a periodically repeated volume (unitcell, **Figure 4**) of the unidirectional composite material was created in the finite-element system MSC.Marc[2]. A perfect honeycomb distribution of the fibers and a fiber-volume ratio of 55% were assumed (**Table 1**).

Table 1: Geometry ratios of a unit cell
Tabela 1: Geometričma razmerja enotne celice

Fiber radius	r
Short side length	1.28 r
Long side length	2.22 r

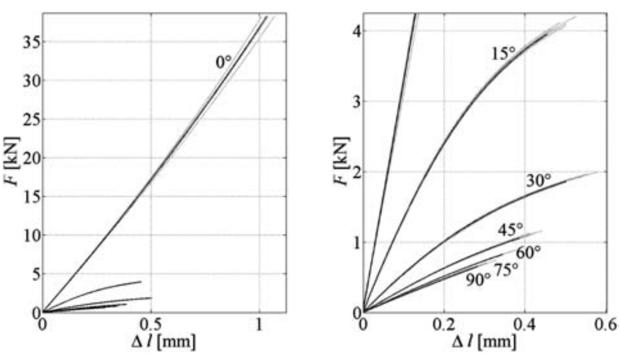

Figure 3: Measured force-displacement diagrams (grey) for each fiber angle and the corresponding averaged values (black)
Slika 3: Izmerjeni diagrami sila – pomik (sivo) za vsak kot vlakna in ustrezne povprečne vrednosti (črno)

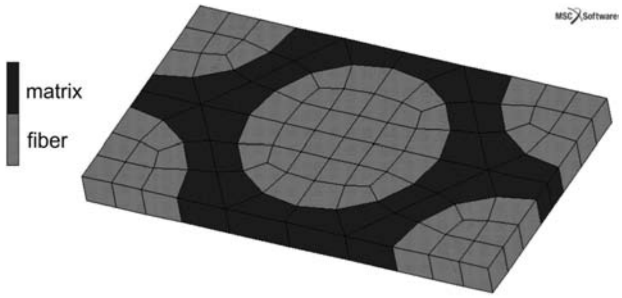

Figure 4: Three-dimensional mesh of a unit cell
Slika 4: Tridimemzionalna mreža enotne celice

Assuming the uniaxial stress across the whole specimen, the behavior of the material can be simulated by loading the unit cell with the normal stress σ corresponding to the external force F:

$$\sigma = \frac{F}{A} \tag{1}$$

where A is a cross-section of the specimen.

The global coordinate system (xyz) is given with the force direction (x) and the direction perpendicular to the composite surface (z). The local coordinate system (123) is defined with the unit-cell edges, where the axis directions correspond to the fiber direction (1) and the directions perpendicular to it (**Figure 5**).

The loading force is transformed to the local coordinate system using the transformation:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} \cos^2\varphi & \sin^2\varphi & 2\sin\varphi\cos\varphi \\ \sin^2\varphi & \cos^2\varphi & -2\sin\varphi\cos\varphi \\ -\sin\varphi\cos\varphi & \sin\varphi\cos\varphi & \cos^2\varphi \end{bmatrix} \begin{bmatrix} \sigma_1 \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

where φ is the angle of rotation between the local and the global coordinate systems[3].

The results from the finite-element analysis (strains) are transformed back to the global coordinate system using the transformation[4]:

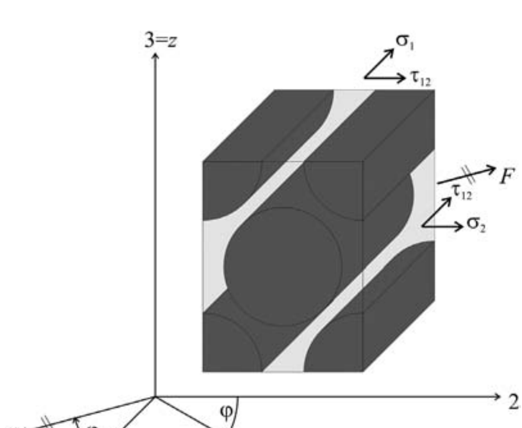

Figure 5: Rotated coordinate systems
Slika 5: Rotirani koordinatni sistem

$$\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{bmatrix}=\begin{bmatrix}\cos^2\varphi & \sin^2\varphi & -\sin\varphi\cos\varphi\\ \sin^2\varphi & \cos^2\varphi & \sin\varphi\cos\varphi\\ 2\sin\varphi\cos\varphi & -2\sin\varphi\cos\varphi & \cos^2\varphi-\sin^2\varphi\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix} \quad (3)$$

The unit cell must also respect the periodical boundary conditions (shown schematically in **Figure 6**):

$$\begin{aligned}\Delta u&=u_B-u_A\\ \Delta v&=v_B-v_A\\ \Delta w&=w_B-w_A\end{aligned} \quad (4)$$

where Δu, Δv and Δw are the translation differences of a pair of opposing nodes in directions 1, 2 and 3, respectively. These differences must remain constant for all the pairs of the corresponding nodes on the opposite sides[3].

In MSC.Marc, the periodical boundary conditions were implemented using a combination of links defined in the Fortran subroutine and springs.

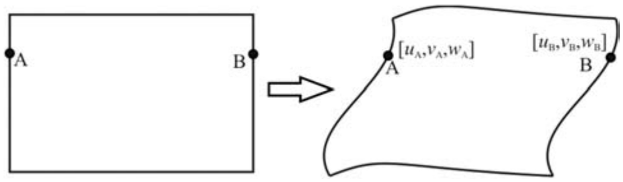

Figure 6: Equivalently deformed opposite boundaries of a heterogeneous unit cell
Slika 6: Ekvivalentno deformirane nasprotne meje heterogene enotne celice

Table 3: Identified material parameters
Tabela 3: Identificirani parametri materiala

g	(–)	23.23
E^0_{11}	(GPa)	189.93
E^m	(GPa)	7.17
σ_0	(kPa)	88.15
n	(–)	1.56
$\Delta\varphi$	(°)	– 0.36

2.2 Material models

The experimental results from the tensile tests show a non-linear behavior of the composite even when loaded in the fiber direction (**Figure 1**). In order to capture this phenomenon a non-Hookean material model was considered for the fibers. The dependence of the longitudinal Young's modulus of fibers on strain is:

$$E_{11}(\varepsilon_{11})=E^0_{11}(1+g\varepsilon_{11}) \quad (5)$$

where g is the coefficient describing the measure of non-linearity and E^0_{11} is the initial Young's modulus of fibers in the longitudinal direction[5].

The fiber is modeled as a transversely isotropic material[6,7]. The standard material constants given by the manufacturer are in **Table 2**.

Table 2: Material parameters of the fiber given by the manufacturer
Tabela 2: Parametri materiala vlaken, dobljeni od proizvajalca

E^0_{11}	(GPa)	230.00
$E_{22} = E_{33}$	(GPa)	15.00
$G_{12} = G_{23} = G_{31}$	(GPa)	50.00
$\nu_{12} = \nu$	(–)	0.30
ν_{31}	(–)	0.02
V_f	(–)	0.55

The work-hardening function which respects a non-linear behavior of the matrix was proposed in the following form:

$$\sigma=\frac{E^m\varepsilon_p}{\left[1+\left(\dfrac{E^m\varepsilon_p}{\sigma_0}\right)^n\right]^{\frac{1}{n}}} \quad (6)$$

where ε_p is an equivalent plastic deformation[1]. The matrix material was modeled to be isotropic having a Poisson's ratio of $\nu^m = 0.3$ (given by the manufacturer).

2.3 Identification process

The average curve for the experimentally obtained force-displacement diagrams was calculated for each angle of the fiber direction. These averaged diagrams are considered as target curves for the further analysis.

Hereafter, the unit cell was loaded with the stress components corresponding with the uniaxial loading of the samples (2). The unit cell is loaded up to the range corresponding to the maximum value of the loading force in the target curve. The displacement dependence on the axial force is obtained by transforming the unit-cell strains back to the global coordinate system (3).

The numerically obtained force-displacement diagrams are subsequently compared with the target force-displacement curves.

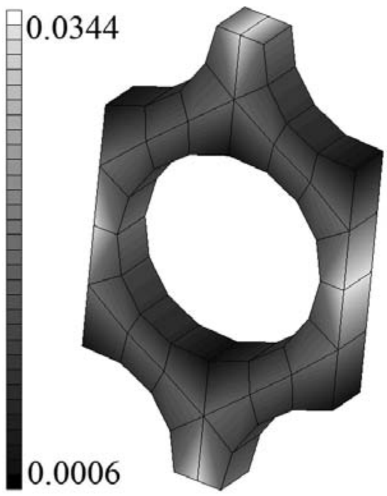

Figure 7: Equivalent plastic-strain contours in the matrix for φ = 30° at the maximum load
Slika 7: Ekvivlenten kontur plastične deformacije matice za φ = 30° pri največji obremenitvi

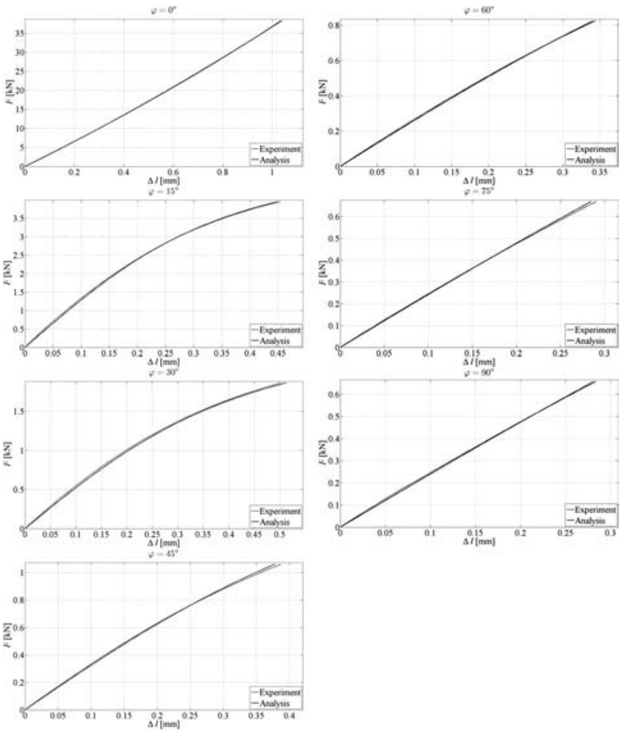

Figure 8: Comparison of the experimental and numerical force-displacement diagrams for all the angles φ

Slika 8: Primerjava eksperimentalnih in numeričnih diagramov sila – pomik za vse kote φ

An optimization process was performed using Matlab, the optimization system OptiSlang and MSC.Marc. The goal was to find the best combination of all material coefficients by minimizing the sum of the squared differences of the numerical and experimental displacements Δl calculated as:

$$e=\sum_{\varphi} e_{\varphi} =\sum_{\varphi}\sum_{i=1}^{N}\left[\frac{(\Delta l_i^{\mathrm{EXP}}-\Delta l_i^{\mathrm{FEA}})^2}{\Delta l_N^{\mathrm{EXP}}}\right] \tag{7}$$

Besides the material parameters from relations (5) and (6) an inaccuracy of the cutting of the samples was taken into account. This inaccuracy $\Delta\varphi$ was attributed to the angle φ (**Figure 5**).

The identified material parameters are summarized in **Table 3**, an example of the plastic strain in the matrix is shown in **Figure 7**, and the resulting force-displacement diagrams are compared in **Figure 8**.

3 CONCLUSION

The tensile tests of the unidirectional fiber-reinforced carbon-epoxy composite coupons were performed for different angles of the fibers. A micromodel of the composite material was created. Parameters of the non-linear material models of both constituents (matrix and fibers) were identified in the optimization process. The parameters were identified by minimizing the error between numerically and experimentally obtained force-displacement diagrams. Moreover, a manufacturing inaccuracy during the specimen cutting was taken into account in the optimization.

Future research will be aimed at the effects of the material imperfections, such as fiber undulation or inclusions in the matrix, and the modeling of the material-failure processes.

Acknowledgement

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