IDENTIFICATION OF MATERIAL PARAMETERS OF UNIDIRECTIONAL COMPOSITE MICROMODEL

Hana Srbová*, Robert Zemčík*, Tomáš Kroupa*, Vladislav Laš*

This work focuses on analysis of longfiber unidirectional carbon-epoxy composite using finite element method on a unit cell. A micromechanical model of the unit cell is created in computational system MSC.Marc using orthotropic elastic fibers and isotropic elastoplastic matrix. The plasticity of the matrix is prescribed in the model by a hardening function. Material parameters of the micromodel are identified using gradient optimization method in OptiSLang system. In the optimization, stress-strain relations obtained from the micromodel are compared with the stress-strain relations from a nonlinear macromodel. The macromodel of the composite material was created in author's previous work. Parameters of the macromodel were identified from experimental tensile tests also using optimization with MSC.Marc and OptiSLang.

Keywords: *unidirectional composite, multiscale analysis, unit cell, finite element method, constitutive relationships, optimization process*

1. Introduction

Composite materials based on carbon fibers and epoxy matrix are used extensively in all fields of industry such as aerospace, sport, automotive and transportation. The knowledge of material characteristics is crucial for the precision of the numerical models used in the designing process. This type of material shows significant nonlinear behavior. Therefore, complex nonlinear material models must be used in order to achieve good agreement with experimental data even for simple tests, such as tensile or shear tests. Modeling of large structures requires the use of macromodels, i.e. homogenized material model. The parameters of the macromodel can be assessed in more ways. By using combination of finite element model with mathematical optimization technique and experimental data or using micromodel of a unit cell, which is periodically repeated volume fraction, with knowledge of mechanical properties of all constituents, fiber and matrix [1]. Micromodel of composite material can be advantageous for deeper analysis of phenomena such as the influence of heterogeneities, for example misaligned fibers and impure matrix, or microdamage mechanisms.

2. Experiment

The experiment was performed on longfiber unidirectional carbon-epoxy composite SE84LV-HSC-4540-400-35 with fiber volume ratio $V_{\mathrm{f}} = 0.55$. This composite is extensively used in aircraft industry. Tensile tests of thin composite strips (Figure 1) cut by water jet from one plate were performed using ZWICK/ROELL Z050 test machine. Results of the experiment were obtained in form of force-displacement diagrams.

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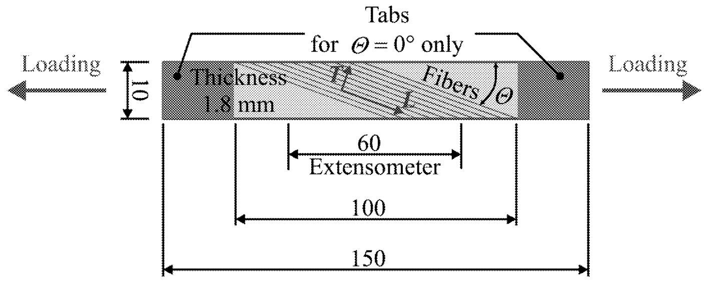


Fig.1: Specimens geometry

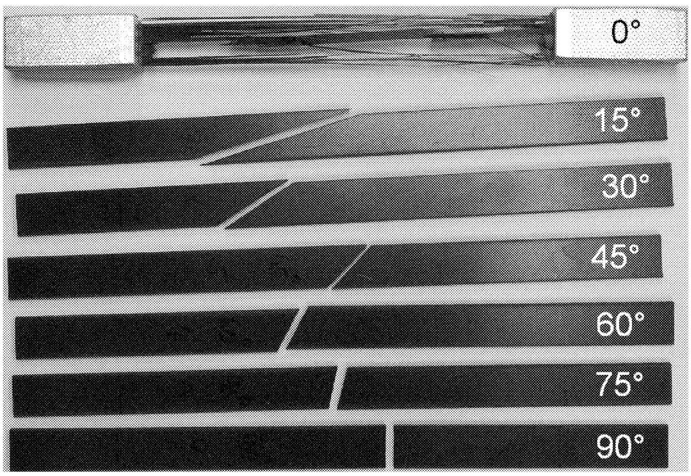


Fig.2: Cracked specimens of UD composite

Loading force direction forms angles 0°, 15°, 30°, 45°, 60°, 75° and 90° with the fiber direction. Specimens loaded in fiber directions from 15° to 90° are damaged by matrix cracking, specimen with fiber direction 0° also by fiber cracking. Therefore, specimens with fiber direction 0° had to be equiped with aluminium tabs. These tabs avoid crushing of the composite due to self-tightening grips of the test machine. The average force to crack 0° specimens reaches 38.4 kN. Cracked specimens are shown in Figure 2 and experimental results are shown in Figure 3. Ten specimens were tested for each fiber direction.

3. Macromodel

Experimental results were used as target curves for the design of the composite macromodel [2] in *MSC.Marc*. The force-displacement diagrams in Figure 3 show non-linear behavior, therefore the constitutive relationship was proposed for directions 1 and 2, the fiber direction and direction perpendicular to fiber, respectively [3]

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} + \begin{bmatrix} S_{111}\,\sigma_1 & 0 & 0 \\ 0 & S_{222}\,\sigma_2 & 0 \\ 0 & 0 & S_{6666}\,\tau_{12}^2 \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} , \qquad (1)$$

where $S_{11} = 1/E_1$, $S_{22} = 1/E_2$, $S_{12} = -\nu_{12}/E_1$ and $S_{66} = 1/G_{12}$ are stress-strain matrix components, E_1 and E_2 are Young's moduli and G_{12} shear modulus, S_{111} represents the adjusting of the misaligned fibers, S_{222} and S_{6666} describe the non-linear matrix behavior. The parameters of relationship (1) were identified in [2]. The resulting values are shown in Table 1.

E_1	[GPa]	108.3
E_2	[GPa]	8.25
G_{12}	[GPa]	5.12
ν_{12}	[–]	0.28
S_{111}	[(GPa)$^{-2}$]	−0.000881
S_{222}	[(GPa)$^{-2}$]	0.761
S_{6666}	[(GPa)$^{-3}$]	561.9

Tab.1: Elasticity parameters of macromodel

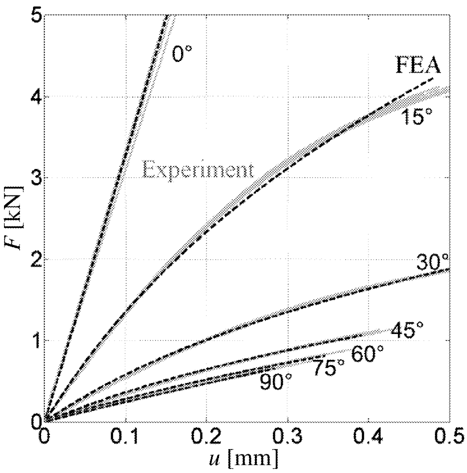


Fig.3: Best fit of force-displacement macromodel diagrams with use of (1)

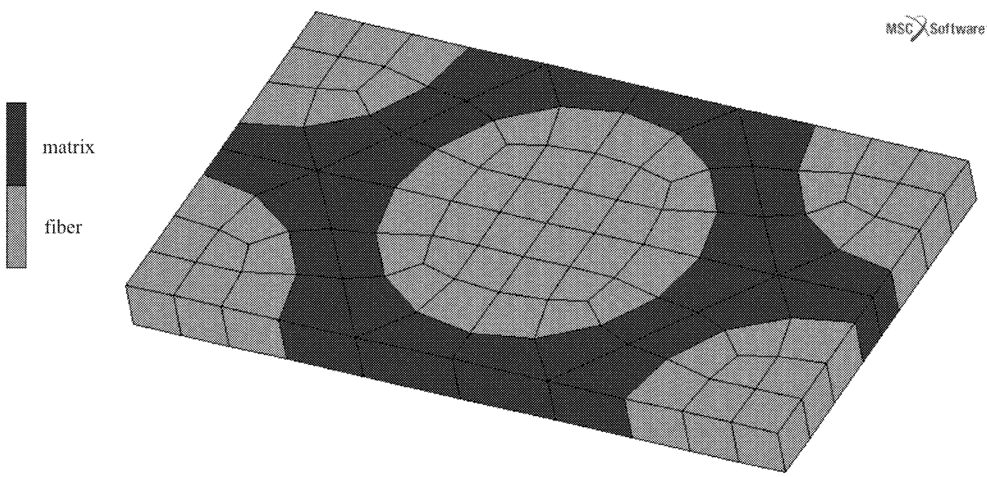


Fig.4: Mesh of a unit cell for fiber volume ratio $V_\mathrm{f} = 0.55$

4. Micromodel

Finite element model (micromodel) of periodically repeated volume (unit cell) of unidirectional composite material was created in finite element system *MSC.Marc* (Fig. 4).

The unit cell must respect the periodic boundary conditions (shown schematically in Fig. 5)

$$\begin{aligned} \Delta u &= u_{\mathrm{B}} - u_{\mathrm{A}} \ , \\ \Delta v &= v_{\mathrm{B}} - v_{\mathrm{A}} \ , \\ \Delta w &= w_{\mathrm{B}} - w_{\mathrm{A}} \ , \end{aligned} \tag{2}$$

where the differences Δu, Δv and Δw must remain constant for all corresponding pairs of nodes (AB) on opposite sides [1].

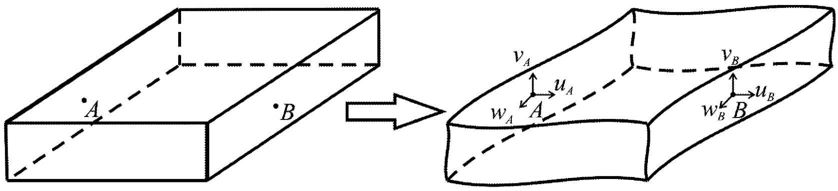


Fig.5: Equivalently deformed opposite boundaries of a non-homogeneous unit cell

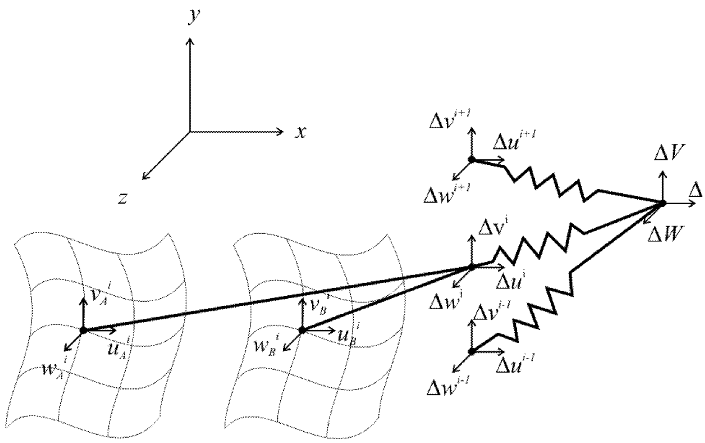


Fig.6: Links and springs ensuring periodical boundary conditions in MSC.Marc [5]

In *MSC.Marc* the periodical boundary conditions have to be implemented using combination of springs and links (in *Fortran* subroutine) [5]. Use of the subroutine requires the unit cell to have corresponding mesh on opposite boundary surfaces. Each pair of nodes is linked to additional auxiliary node, which contains the values of the differences in (2). All auxiliary nodes along one side of the unit cell are connected to a control node by very stiff springs working in accordance with relations

$$\begin{aligned} F_{\mathrm{x}}^{i} &= k_{\mathrm{x}}^{i} \left(\Delta U - \Delta u^{i}\right) \ , \\ F_{\mathrm{y}}^{i} &= k_{\mathrm{y}}^{i} \left(\Delta V - \Delta v^{i}\right) \ , \\ F_{\mathrm{z}}^{i} &= k_{\mathrm{z}}^{i} \left(\Delta W - \Delta w^{i}\right) \ , \end{aligned} \tag{3}$$

where F_x^i, F_y^i, F_z^i are the spring forces, k_x^i, k_y^i, k_z^i is the spring stiffness, ΔU, ΔV, ΔW are values of the differences assigned to a control node and Δu^i, Δv^i, Δw^i are differences assigned to the auxiliary nodes [4]. The stiffness of the spring controls the accuracy of the differences in (2) along one side of the unit cell.

Fiber is orthotropic and its elastic constants as given by manufacturer are shown in Table 2.

E_1^f	[GPa]	230
E_2^f	[GPa]	15
E_3^f	[GPa]	15
G_{12}^f	[GPa]	50
G_{23}^f	[GPa]	50
G_{31}^f	[GPa]	50
ν_{12}^f	[–]	0.3
ν_{23}^f	[–]	0.3
ν_{31}^f	[–]	0.02

Tab.2: Elasticity parameters of fiber

For elastoplastic matrix of the micromodel a work hardening function was proposed in form

$$\sigma = \frac{E^\mathrm{m}\,\varepsilon_\mathrm{p}}{\left(1+\left(\dfrac{E^\mathrm{m}\,\varepsilon_\mathrm{p}}{\sigma_0}\right)^n\right)^{\frac{1}{n}}} \ , \tag{4}$$

where E^m is Young's modulus of matrix, σ_0 is equivalent stress and ε_p is the equivalent plastic deformation.

Perfect bonding between fiber and matrix is assumed, therefore, after applying the load there is no separation between the materials.

Material constants of matrix were identified by gradient optimization method using computational systems *MSC.Marc*, *Matlab* and *OptiSLang*. The optimized functions were the stress-strain relationships for tension in fiber direction 1 and transverse direction 2 and for shear loading in plane 12, i.e.

$$\begin{aligned} \sigma_1 &= \sigma_1(\varepsilon_1) \ , \\ \sigma_2 &= \sigma_2(\varepsilon_2) \ , \\ \tau_{12} &= \tau_{12}(\gamma_{12}) \ . \end{aligned} \tag{5}$$

Therefore, normal and shear loadings were applied on the unit cell.

The resulting relationships of the macromodel and micromodel were enumerated in k points in form of pairs $[\sigma_i, \varepsilon_i^\mathrm{macro}]$ and $[\sigma_i, \varepsilon_i^\mathrm{micro}]$, respectively. The goal was to minimize the sum of parameters Φ for both tensile tests and the shear test, where

$$\Phi = \sum_{i=1}^{k} \left(\frac{\varepsilon_i^\mathrm{macro} - \varepsilon_i^\mathrm{micro}}{\varepsilon_i^\mathrm{macro}}\right)^2 \tag{6}$$

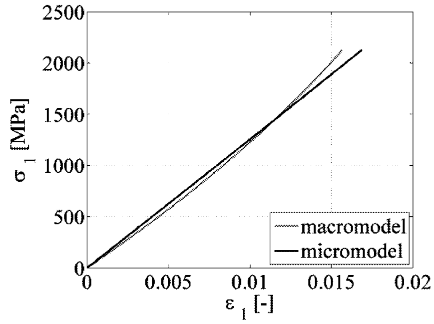
and $\varepsilon_k^\mathrm{macro}$ is the macromodel strain range. Determined material parameters are shown in Table 3.

E^{m}	[GPa]	13.7
σ_0	[MPa]	238.3
ν^{m}	[–]	0.3
n	[–]	0.36

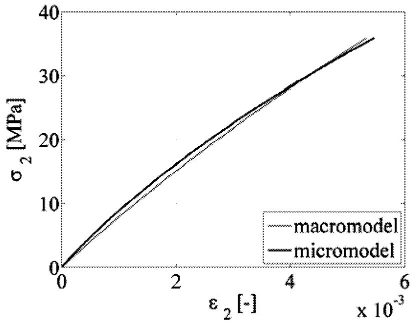
Tab.3: Identified material parameters of matrix

5. Comparison of results

Comparison of results of macro and micromodel for normal and shear loadings is shown in Figure 7 and 8. The effect of fiber misalignment was not modelled in micromodel.



(a) Tension in direction 1



(b) Tension in direction 2

Fig.7: Comparison of stress-strain dependencies in material directions from micro and macromodel for tension in direction 1 (a) and tension in direction 2 (b)

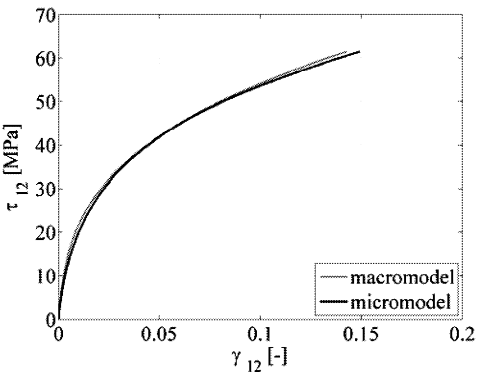


Fig.8: Comparison of stress-strain dependencies of micro and macromodel for shear stress

6. Conclusion

Experimentally obtained results from tensile tests were used to define constants of the constitutive relationship of macromodel of composite. Subsequently the periodical boundary conditions of micromodel were implemented to computational system *MSC.Marc* by a subroutine in *Fortran*. Work hardening function for elastoplastic matrix was proposed and its constants found by optimization process. The stress-strain dependencies show good agreement between macro and micromodel.

In following work, the micromodel will be used for analysis of influence of material heterogeneity, such as fiber misalignment, voids or debonding between fiber and matrix.

Acknowledgement

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