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IDENTIFICATION AND VERIFICATION OF THE COMPOSITE MATERIAL PARAMETERS FOR THE LADEVÈZE DAMAGE MODEL

IDENTIFIKACIJA IN VERIFIKACIJA PARAMETROV KOMPOZITNEGA MATERIALA ZA MODEL LADEVÈZE

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In this investigation we examine the properties of a layered composite material and verify the Ladevèze material model implemented in PAM-CRASH software. The complex material model incorporates plasticity, failure and damage mechanisms and is suitable for dynamic phenomena, such as crash tests. The experimental tests were performed on appropriate laminated specimens made from unidirectional, pre-impregnated, composite fiber (prepregs) – coupons with axially oriented fibers, coupons with fibers at 45°, and ±45° cross-ply laminates. The tests included simple tensile tests to fracture and cyclic tensile tests. Numerical models were created for the finite-element analysis using shell elements. A mathematical optimization was then used to minimize the error between the experimental and numerical results in terms of load-displacement curves for all the tested configurations by varying the material characteristics.

Keywords: composite, identification, carbon, fiber, epoxy, plasticity, experiment, finite-element analysis

Identifikacija lastnosti plastastega kompozitnega materiala in verifikacja modela Ladeveze za material s PAM-CRASH-sofverom. Kompleksen model materiala vključuje plastičnost, prelom in mehanizem poškodbe ter je primeren za dinamične fenomene kot preizkus trka. Preizkusi so bili izvršeni na primernih laminatnih vzorcih, izdelanih iz enosmernih predimpregniranih kompozitnih vlaken (prepreg) – kuponov z osno orientiranimi vlakni, kuponov z vlakni pod kotom 45° in križnimi laminati ±45°. Preizkusi so obsegali enostavne raztržne in ciklične natezne preizkuse. Pripravljeni so bili numerični modeli za analizo po metodi končnih elementov z uporabo lupinastih elementov. Matematična optimizacija je bila nato uporabljena za zmanjšanje napak med eksperimentalnimi in numeričnimi rezultati s krivuljami obremenitev – pomik za vse preizkušene konfiguracije s spremembami karakteristik materiala.

Ključne besede: kompozit, identifikacija, ogljikova vlakna, epoksi, plastičnost, preizkusi, končna elementna analiza

1 INTRODUCTION

Composite materials are modern materials with advantageous strength- and stiffness-to-mass ratios compared to classical materials, such as steel or aluminum [1,2]. Namely, the carbon-fiber-reinforced plastic composites consisting of continuous carbon fibers and a matrix can have similar or better strength than steel structures and they can have similar or less weight than aluminum structures. As their properties are highly oriented (generally anisotropic), the greatest strength is achieved in the direction of the fibers. This can be utilized especially in the case of the design of components with excessive loading in a specific direction.

Composite materials are increasingly used in the aerospace and automotive industries for the reason mentioned above. Numerical simulations help to design the desired components or complex structures, including the possibility to optimize the fiber orientations or lay-ups. Nevertheless, it is important to know the correct material parameters and to use the appropriate material model. This material data must be obtained from experimental measurements. An integral part of any material model is the failure/damage prediction possibility. Many material models have been proposed so far, but none of them is perfect or universal [6]. The basic failure criteria, such as the maximum stress, maximum strain and others, are not interactive criteria. This means that there is no relation between the stress components in different directions. In this respect, the so-called interactive criteria, such as Tsai-Wu [1], are more suitable for crash simulations. On the other hand, the disadvantage is that we cannot distinguish between the matrix and fiber failure, which is important in an impact simulation. The most recent failure criteria (the so-called direct mode criteria), such as Puck [8] or LaRC [3], use the advantages of both types [9].

The Ladevèze material model [5] in the PAM-CRASH software [7] is implemented only for a multi-layered, thin shell element and transient analysis (i.e., the explicit code). It includes the following modes of failure of a composite material: debonding, micro-cracking, delamination, and fiber breaking. The Ladevèze damage model also includes inelastic material deformations caused by the matrix-dominated loading. The plasticity of the matrix cannot be neglected in general and the effect is best seen, for example, in the case of cyclic loading.

2 MATERIAL AND DAMAGE MODELS

The constitutive relationship for materials with a linear response is usually written in the form of the extended Hooke's law [1]. The constitutive relationship of the Ladevèze material model can be written with similar formulae, except that elastic constants are herein modified by additional damage parameters or functions [4,5]. The crucial relations are summarized in **Table 1**. The superscript 0 denotes the initial values (damage free) of the material constants. The quantities d_{11}, d_{22} and d_{22} represent the fiber damage in tension, matrix damage, and fiber-matrix debonding damage, respectively. The effect of d_{12} is shown in the relation of the actual (G_{12}) and initial ($G^0{}_{12}$) values of the shear moduli. The shear damage function Y_{12} is derived from the strain energy E_{d} for an anisotropic material, where Y_{C} and Y_0 are the critical shear damage limit and the initial shear damage threshold, respectively. The parameter Y_{R} represents the shear failure.

Another important improvement to the composite material model is obtained by the inclusion of the matrix plasticity behavior. This is incorporated by changing the yield stress during the cyclic loading. The yield stress is given by $R(\varepsilon^P)$, which is a function of the initial yield stress R_0, the plastic deformation ε^P and the hardening coefficients β, m. This represents a power-law approximation of the experimental curve.

The fiber tensile damage (longitudinal damage) is characterized by the initial ($\varepsilon^i{}_{11}$) and ultimate ($\varepsilon^u{}_{11}$) fiber tensile damage strains.

3 EXPERIMENT AND SIMULATIONS

In this study, laminated composite coupons made of HexPly 913C prepregs with Tenax HTS 5631 carbon fibers are tested (see **Figures 1–3**). The material characteristics needed for the numerical models are obtained from the experimental data. The detailed description of the measurement can be found in [7]. It consists of three types of tests:

- simple tensile test on $[0]_8$ laminates,
- simple tensile test with load/unload cycles on $[\pm 45]_{2S}$ laminates,
- simple tensile test on $[45]_8$ laminates.

Figure 1: Fractured $[0]_8$ specimen
Slika 1: Prelomljen vzorec $[0]_s$

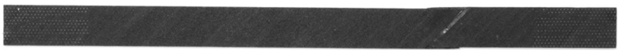

Figure 2: Fractured $[\pm 45]_{2S}$ specimen. The position and orientation of the cracks is emphasized
Slika 2: Prelomljen vzorec $[\pm 45]_{2S}$. Poudarjena sta položaj in orientacija razpok

Figure 3: Fractured $[45]_8$ specimen
Slika 3: Prelomljen vzorec $[45]_8$

Simple [0] tensile test

The tensile test was conducted on UD composite coupons with the $[0]_8$ fiber composition (see **Figure 1**). The coupons were loaded by displacement (speed 1 mm/min) until rupture. The force–displacement curve was measured, see **Figure 4**.

The initial Young's modulus $E^0{}_{11}$, the initial fiber failure value $\varepsilon^i{}_{11}$ and the critical fiber failure value $\varepsilon^u{}_{11}$ were assessed from the data obtained using Hooke's law.

The averaged experimental results were used directly in the material model within the corresponding numerical simulation. The results of the simulation are in a good

Tabela 1: Relacije modela Ladevèze za lupinaste elemente[4,5]
Table 1: Ladevèze model relations for shell elements [4,5]

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \\ \varepsilon_{23} \\ \varepsilon_{13} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_{11}^0(1-d_{11})} & \frac{-\nu_{12}^0}{E_{11}^0(1-d_{11})} & 0 & 0 & 0 \\ \frac{-\nu_{12}^0}{E_{11}^0(1-d_{11})} & \frac{1}{E_{22}^0(1-d_{22})} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{G_{12}^0(1-d_{12})} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}^0(1-d_{12})} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{12}^0(1-d_{12})} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{13} \end{bmatrix}$$

$$G_{12} = G_{12}^0(1-d_{12}), \qquad d_{12} = 1 - \frac{G_{12}}{G_{12}^0}$$

$$E_d = \frac{1}{2}\left[\frac{\sigma_{11}^2}{E_{11}^0} - \frac{2\nu_{12}^0}{E_{11}^0}\sigma_{11}\sigma_{22} + \frac{\langle\sigma_{22}\rangle_+^2}{E_{22}^0(1-d_{22})} + \frac{\langle\sigma_{22}\rangle_-^2}{E_{22}^0} + \frac{\sigma_{12}^2}{G_{12}^0(1-d_{12})}\right]$$

$$Z_d = \frac{\partial E_d}{\partial d_{12}} = \frac{1}{2}\frac{\sigma_{12}^2}{G_{12}^0(1-d_{12})^2}, \; Y_{12} = \sqrt{Z_d}$$

$$Y_{12} = Y_C d_{12} + Y_0$$

$$Y_R = \sup(Y_{12})$$

$$R(\varepsilon_P) = R_0 + \beta(\varepsilon^P)^m$$

$$\varepsilon_{11}^i \le \varepsilon_{11} < \varepsilon_{11}^u$$

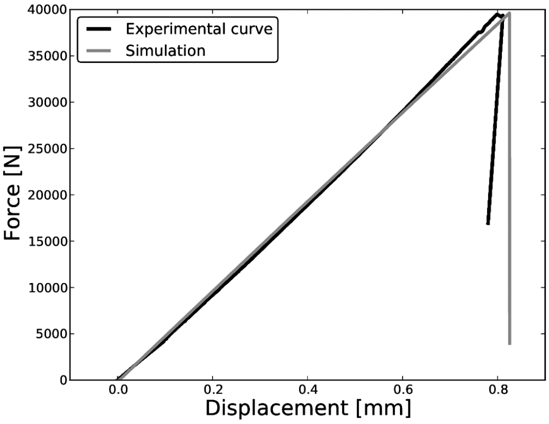

Figure 4: Load–displacement curves from the $[0]_8$ test
Slika 4: Krivulji obremenitev – pomik za preizkus $[0]_8$

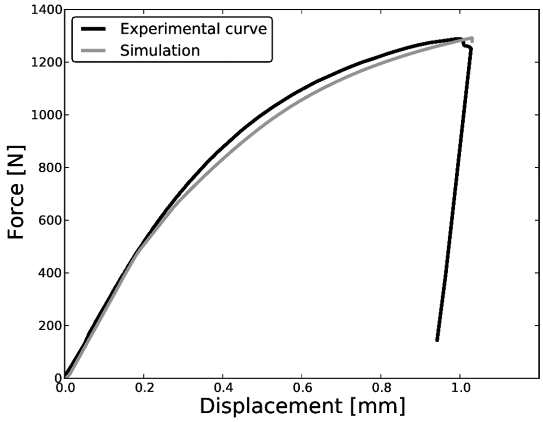

Figure 5: Load–displacement curves from the $[45]_8$ test
Slika 5: Krivulji obremenitev – pomik za preizkus $[45]_8$

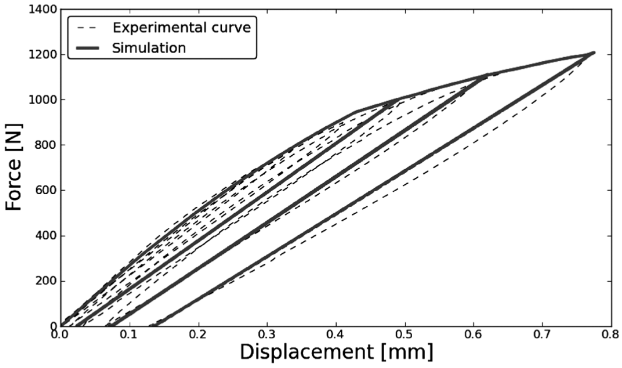

Figure 6: Load–displacement curves from $[\pm 45]_{2S}$ test
Slika 6: Krivulji obremenitev – pomik za preizkus $[\pm 45]_{2S}$

agreement with the experimental data (see **Figure 4**). The constants ε^i_{11} and ε^u_{11} have similar values as the whole cross-section ruptured at the same time.

Cyclic $[\pm 45]_{2S}$ tension test

The composite coupons (**Figure 2**) were loaded by a cyclic loading – 6 cycles (load/unload) with increasing load amplitude (700 N, 800 N, 900 N, 1000 N, 1100 N and 1200 N) and the force–displacement curves were obtained. The nonlinear behavior and the plasticity of the composite material can be clearly seen from the results. This phenomenon is given by the plastic behavior of the matrix or fiber-matrix interface. The stress and strain vectors in the principal material directions (the fiber direction and the transverse fiber direction) must be calculated from the experimental data using the relations for the stress/strain transformation for each lamina. Consequently, it is possible to calculate the actual shear modulus G_{12}.

Tabela 2: Identificirane karakteristike materiala
Table 2: Identified material characteristics

Parameter	Symbol	Value
Elastic properties		
Young's modulus in fiber direction	E^0_{11}	125.295 [GPa]
Young's modulus in transverse direction	E^0_{22}	7.446 [GPa]
Shear modulus in plane 12	G^0_{12}	3.720 [GPa]
Shear modulus in plane 23	G^0_{23}	3.720 [GPa]
Poisson's ratio	ν^0_{12}	0.3126 [-]
Failure properties		
Initial fiber failure	ε^i_{11}	0.01366 [-]
Critical fiber failure	ε^u_{11}	0.013661 [-]
Shear failure	Y_R	0.036 $[\text{GPa}]^{1/2}$
Damage properties		
Critical shear damage	Y_C	0.0655 $[\text{GPa}]^{1/2}$
Initial shear damage	Y_0	0.0040 $[\text{GPa}]^{1/2}$
Plastic properties		
Yield stress	R_0	0.049 [GPa]
Hardening parameter β	β	0.85 [GPa]
Hardening parameter α	α	0.24 [-]

The material parameters responsible for the nonlinear response of the numerical model were optimized using the PAM-OPT tool to minimize the error between the simulated and experimental data. Relatively good agreement between the experimental and the simulated curves was obtained; however, the maximum force in this case was not correctly predicted.

Simple $[45]_8$ tension test

For the validation of the shear failure parameter Y_R a simple tension test on the $[45]_8$ laminate was performed (**Figure 3**). This parameter will ensure that the material fails when the load exceeds a certain limit **Figure 5**.

Recalculation of the cyclic test with the new shear failure parameter in the material model led to a significant improvement of the correlation with the experimental data. The comparison of the resulting curves is shown in **Figure 6**. The resulting values of all the parameters of the Ladevèze model used are summarized in **Table 2**.

4 CONCLUSION

The combination of three types of experimental measurements and numerical simulations in the finite-element code PAM-CRASH was performed. A mathematical optimization was used to obtain the parameters of the used Ladevèze material model that incorporates plasticity, damage and failure. The resulting comparison of the numerical and experimental data in terms of load–displacement curves shows a very good agreement.

In future work, a similar investigation will be performed on textile composites. The applicability of the Ladevèze model will thus be tested on a material with even more complex behavior.

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5 REFERENCES

[1] Berthelot, J. M. (1999). Composite materials, Springer, New York

[2] Daniel I. M., Ishai O.: Engineering mechanics of composite materials, Oxford University Press, Inc. (1994)

[3] Dávila, C. G., Camanho, P. P. (2003). Failure Criteria for FRP Laminates in Plane Stress, NASA/TM-2003-212663 report, NASA

[4] Greve L., Pickett A. K.: Modelling damage and failure in carbon/epoxy non-crimp fabric composites including effects of fabric pre-shear, Composites Part A: Applied Science and Manufacturing, 37 (**2006**), 11, 1983–2001

[5] Ladevèze P., Le Dantec E.: Damage Modelling of the elementary ply for laminated composites, Compos. Sci. Technol., 43 (**1992**) 3, 257–2671

[6] Laš V., Zemčík R.: Progressive damage of unidirectional composite panels, Journal of Composite Materials, 42 (**2008**) 1, 25–44

[7] PAM-CRASH 2007. Solver Notes Manual. ESI-Group, Paris

[8] Puck, A., Schurmann, H., Failure analysis of FRP laminates by means of physically based phenomenological models. Composites Science and Technology, 58 (**1998**), 1045–1067

[9] Soden, P. D., Kaddour, A. S., Hinton, M. J., Recommendations for Designers and Researchers Resulting from the World-wide Failure Exercise, Composites Science and Technology, 64 (**2004**), 589–604