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PROGRESSIVE FAILURE ANALYSIS OF COMPOSITE SANDWICH BEAM IN CASE OF QUASISTATIC LOADING

NAPREDNA ANALIZA POŠKODB SESTAVLJENEGA KOMPOZITNEGA NOSILCA PRI KVAZISTATIČNEM OBREMENJEVANJU

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This paper is focused on a progressive failure analysis of a sandwich composite panel considering a non-linear model of core and skins using explicit analysis. The material properties were determined from tensile and compressive tests of the outer composite skin and the foam core. A user-defined material model was used to describe the non-linear orthotropic elastic behaviour of the composite skin. The material parameters of the outer composite skin were determined using the identification process performed using a combination of optimization method and finite-element simulation. The Low-Density Foam material model was used for the foam core. The obtained material data were validated using a three-point bending test of a sandwich beam.

Keywords: sandwich panel, fiber-glass fabric, foam core, three point bending test, damage, optimization

Članek obravnava napredno analizo poškodb z uporabo eksplicitne analize sestavljene kompozitne plošče z upoštevanjem nelinearnega modela jedra in skorje. Lastnosti materiala so bile določene iz nateznih in tlačnih preizkusov zunanje kompozitne skorje in penaste sredice. Uporabniško določen model materiala je bil uporabljen za opis nelinearnega ortotropnega elastičnega vedenja kompozitne skorje. Materialni parametri zunanje kompozitne skorje so bili določeni z identifikacijskim procesom, izvršenim z uporabo kombinacije metod optimiranja in simulacije s končnimi elementi. Materialni model pene z nizko gostoto je bil uporabljen za jedro iz pene. Dobljeni podatki za material so bili ocenjeni z uporabo tritočkovnega upogibnega preizkusa sestavljenega nosilca.

Ključne besede: sestavljena plošča, tkanina iz steklenih vlaken, jedro iz pene, tritočkovni upogibni preizkus, poškodba, optimizacija

1 INTRODUCTION

The principle of sandwich structures is based on a low-density material (core) placed between two stiffer outer skins. The main purpose of the core is to maintain the distance between the outer skins and to transfer the shear load while the outer skins carry the compressive and tensile load. The outer skins are obviously thinner than the core. This type of structural arrangement has a much larger bending stiffness than a single solid plate made of the same total weight from the same material as a outer skin only. This fact together with other advantages, such as corrosion resistance, product variability and thermal or acoustic insulation, make sandwich structures the preferred alternative to conventional materials in all types of structural applications where the weight must be kept to a minimum value.

2 EXPERIMENTAL SET-UPS AND SPECIMENS

The used sandwich composite panel was manufactured using a vacuum infusion process and its overall thickness was 12.5 mm. The outer composite skins were made from three layers of fibre-glass fabric with the product name Aeroglass (material density ρ = 390 g/m^2) and epoxy resin designated as Epicote HGS LR 285. The thicknesses of the outer composite skins were 1.2 mm. The core of the sandwich panel was a closed-cell, cross-linked polymer foam Airex C70.55. This foam core is characterized by a low resin absorption. The resultant sandwich panel was cured for 6 h at 50 °C.

Tensile and compressive experimental tests were performed using a Zwick/Roell Z050 testing machine on the separated specimens of the laminated composite skin and foam core of the resultant sandwich structure. The foam core was additionally subjected to a three-point bending test too.

Three types of specimens of laminated composite skin were used, the chosen material principal direction (weft) form angle 0° (Type A), 45° (Type C) and 90° (Type B) with the direction of the loading force. The specimens of the laminated outer skin had the dimensions 135 mm × 15 mm and a thickness 1.2 mm. The dimensions of the specimens of the isotropic foam core were 150 mm × 15 mm with a thickness 10 mm. The loading velocity during the tensile tests was 2.0 mm/min in the case of the composite skin and 1.0 mm/min in the case of the foam core. Four specimens for each angle of composite skin and for the foam core were tested.

The three-point bending tests of the foam core were performed on specimens with the same dimensions that were used for the tensile tests. The distance of the supports of the testing device was 100 mm and the diameters of all three supports were 10 mm.

The resulting sandwich beam with the dimensions 330 mm × 50 mm and a total thickness 12.5 mm was subjected to a three-point bending test in order to validate the material data obtained independently for the composite skin and the foam core. The thicknesses of the composite skins were 1.2 mm. The distance of the supports of the testing device was 250 mm and the supports consisted of rotationally joined cylinders with diameters of 30 mm. The loading velocity of the sandwich beam was 20 mm/min. Three specimens were tested in total.

2.1 Material model of the skin

A user-defined material model of the composite skin was implemented in Abaqus software using the VUMAT subroutine written in the Fortran code. The non-linear function describing the stress-strain relationship starting from the deformation ε_{0i} (i = 1, 2) was assumed in the case of the principal material directions 1 and 2 (equations (2) and (4)). The non-linear function with a constant asymptote was considered in the case of the shear in plane 12 [1] (equation (8)). The following equations describe the stress-strain relationship of the laminated outer skin:

$$\sigma_1 = C_{11} \cdot \varepsilon_1 + C_{12} \cdot \varepsilon_2 + C_{13} \cdot \varepsilon_3 \quad \text{for } \varepsilon_1 < \varepsilon_{01} \tag{1}$$

$$\sigma_1 = (C_{11} \cdot (\varepsilon_1 + \frac{A_1}{2} \cdot (\varepsilon_{01}^2 - \varepsilon_1^2) - A_1 \cdot \varepsilon_{01} \cdot (\varepsilon_{01} - \varepsilon_1)) + C_{12} \cdot \varepsilon_2 + C_{13} \cdot \varepsilon_3) \cdot (1-D) \quad \text{for } \varepsilon_1 \geq \varepsilon_{01} \tag{2}$$

$$\sigma_2 = C_{12} \cdot \varepsilon_1 + C_{22} \cdot \varepsilon_2 + C_{23} \cdot \varepsilon_3 \quad \text{for } \varepsilon_2 < \varepsilon_{02} \tag{3}$$

$$\sigma_2 = (C_{12} \cdot \varepsilon_1 + C_{22} \cdot (\varepsilon_2 + \frac{A_1}{2} \cdot (\varepsilon_{02}^2 - \varepsilon_2^2) - A_2 \cdot \varepsilon_{02} \cdot (\varepsilon_{02} - \varepsilon_2)) + C_{23} \cdot \varepsilon_3) \cdot (1-D) \quad \text{for } \varepsilon_2 \geq \varepsilon_{02} \tag{4}$$

$$\sigma_3 = (C_{13} \cdot \varepsilon_1 + C_{23} \cdot \varepsilon_2 + C_{33} \cdot \varepsilon_3) \cdot (1-D) \tag{5}$$

$$\sigma_{23} = (G_{23} \cdot \gamma_{23}) \cdot (1-D) \tag{6}$$

$$\sigma_{13} = (G_{13} \cdot \gamma_{13}) \cdot (1-D) \tag{7}$$

$$\sigma_{12} = \frac{G_{12}^0 \cdot \gamma_{12}}{\left(1 + \left(\frac{G_{12}^0 \cdot |\gamma_{12}|}{\tau_{12}^0}\right)^{n_{12}}\right)^{\left(\frac{1}{n_{12}}\right)}} \cdot (1-D) \tag{8}$$

The constants occurring in equations (1) to (5) are:

$$C_{11} = \frac{E_1 \cdot (1 - \nu_{23} \cdot \nu_{32})}{\Delta} \quad C_{12} = \frac{E_1 \cdot (\nu_{21} + \nu_{23} \cdot \nu_{32})}{\Delta}$$
$$C_{13} = \frac{E_1 \cdot (\nu_{31} - \nu_{32} \cdot \nu_{21})}{\Delta} \quad C_{22} = \frac{E_2 \cdot (1 - \nu_{31} \cdot \nu_{13})}{\Delta} \tag{9}$$
$$C_{23} = \frac{E_2 \cdot (\nu_{32} - \nu_{31} \cdot \nu_{12})}{\Delta} \quad C_{33} = \frac{E_3 \cdot (1 - \nu_{12} \cdot \nu_{21})}{\Delta}$$
$$\Delta = 1 - \nu_{12} \cdot \nu_{21} - \nu_{23} \cdot \nu_{32} - 2 \cdot \nu_{12} \cdot \nu_{23} \cdot \nu_{31}$$

where E_1, E_2 and E_3 are the Young's moduli in the principal directions 1, 2 and 3 and ν_{12}, ν_{23}, ν_{31} are the Poison's ratios in the planes defined by the principal directions 1, 2 and 3. The shear moduli in planes 23 and 13 are designated as G_{23} and G_{13}, respectively. The non-linear behavior in shear in plane 12 (8) is described using the initial shear modulus G_{12}^0, the asymptotic value of the shear stress τ_{12}^0 and the shape parameter n_{12}. The parameters A_1 and A_2 in (2) and (4) describe the straightening of the yarns of the fiber-glass fabric and the loss of stiffness in the directions 1 and 2, respectively. The values of the deformations ε_{01} and ε_{02} indicate the the transitions between the linear and non-linear parts of the stress-strain relationship in the given directions 1 and 2 during the loading.

The maximum stress failure criterion was used to predict failure on the composite skin:

$$F_{1\text{T}} = \frac{\sigma_1}{X_\text{T}} \quad F_{1\text{C}} = \frac{|\sigma_1|}{X_\text{C}} \quad F_{2\text{T}} = \frac{\sigma_2}{Y_\text{T}}$$
$$F_{2\text{C}} = \frac{|\sigma_2|}{Y_\text{C}} \quad F_{12} = \frac{\sigma_{12}}{S_\text{L}} \tag{10}$$

where the subscripts T and C denote the tension and compression, X and Y are the strengths in the principal directions 1 and 2, respectively, and S_L denotes the shear strength.

The values of the degradation variable D are dependent on the kind of occurred failure.[2] The principle of material degradation is shown in **Figure 1** and the degradation parameters are summarized in (11). The degradation parameter after failure initiation was implemented in the case of shear failure ($F_{12} \geq 1.0$ and $\gamma_{12} < \gamma_{12}^F$) from.[3] Due to the non-linear behavior of the composite skin the degradation parameters are assumed in the form:

$$F_{1\text{T}} \geq 1 \Rightarrow D = 1.0 \quad F_{1\text{C}} \geq 1 \Rightarrow D = 0.6$$
$$F_{2\text{T}} \geq 1 \Rightarrow D = 1.0 \quad F_{2\text{C}} \geq 1 \Rightarrow D = 0.6$$
$$F_{12} \geq 1 \text{ and } \gamma_{12} < \gamma_{12}^F \Rightarrow D = 1 - e^{\left(\frac{1}{m_{12}}(F_{12})^{m_{12}}\right)} \tag{11}$$
$$F_{12} \geq 1 \text{ and } \gamma_{12} \geq \gamma_{12}^F \Rightarrow D = 1.0$$

In the case of shear failure the non-negative material constant m_{12} is represented by the integer and γ_{12}^F is the ultimate deformation when the material is fully damaged.

Mathematical optimization was used to identify the material parameters on data from the performed tensile tests of composite skin. The optimization process was

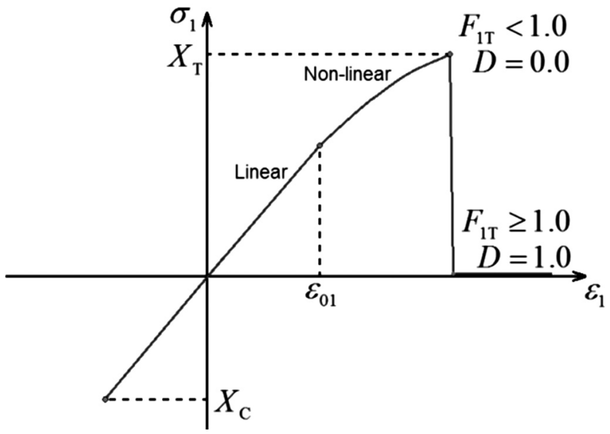

Figure 1: The principle of material degradation in the principal direction 1

Slika 1: Načelo degradacije materiala v glavni smeri 1

handled using Optislang 3.2.0. The material parameters that do not have a significant influence on the results were kept constant during the optimization process. All the material parameters are summarized in **Table 1**.

The parameters E_3, G_{13} and G_{23} were taken from the literature.[4] The strengths of the composite skin were determined directly from the experimental data.

Table 1: Material parameters of the composite skin

Tabela 1: Parametri materiala kompozitne skorje

Optimized values:			Constant values:		
E_1	GPa	16.9	ν_{12}	–	0.337
E_2	GPa	18.5	ν_{23}	–	0.337
G_{12}^0	GPa	4.96	ν_{31}	–	0.28
τ_{12}^0	MPa	39.66	G_{13}	GPa	4.0
n_{12}	–	0.9	G_{23}	GPa	2.75
A_1	–	10.0	E_3	GPa	8.0
A_2	–	14.0	γ_{12}^F	–	0.324
ε_{01}	–	0.0008	ρ_C	kg/m^3	1554
ε_{02}	–	0.005	X_T	MPa	325
m_{12}	–	5	Y_T	MPa	347
			X_C	MPa	65
			Y_C	MPa	67
			S_L	MPa	35

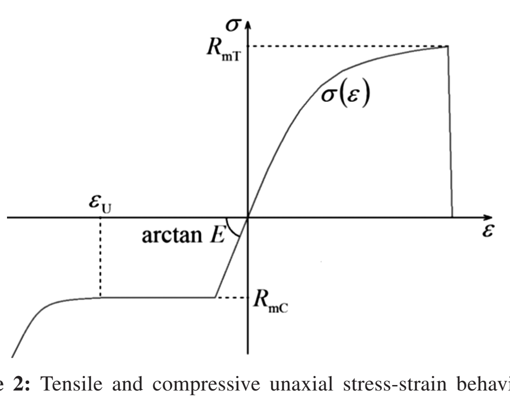

Figure 2: Tensile and compressive unaxial stress-strain behavior of foam core

Slika 2: Vedenje jedra iz pene pri enoosni natezni in tlačni obremenitvi

2.2 Material model of the foam core

The used material model of the foam core was the Low-Density Foam model from the Abaqus software library.[5] This material model is intended for highly compressible elastomeric foams. The material behavior was specified directly via unaxial stress-strain curves for tension and compression (**Figure 2**). In the case of tension the unaxial stress-strain behavior was described via a curve added in the form:

$$\sigma(\varepsilon) = 4.35 \cdot 10^9 \cdot \varepsilon^3 - 8.76 \cdot 10^8 \cdot \varepsilon^2 + \\ +6.09 \cdot 10^7 \cdot \varepsilon - 1.44 \cdot 10^4 \qquad (12)$$

The material is fully damaged after reaching the tensile strength R_{mT}. The compressive behavior of the foam core was described as an ideally elastoplastic material

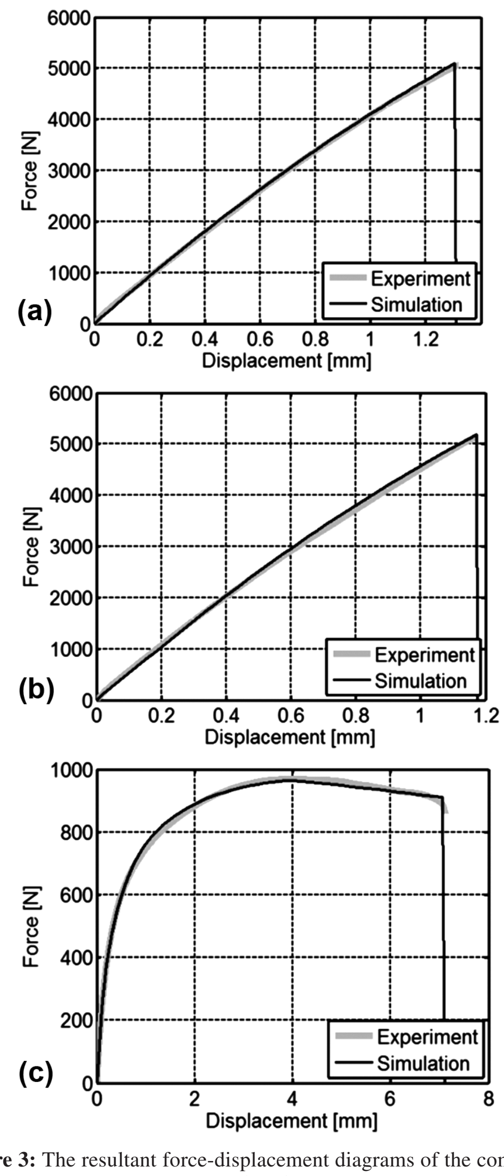

Figure 3: The resultant force-displacement diagrams of the composite skin types A (top), B (center) and C (bottom)

Slika 3: Diagrami sila – raztezek kompozitne skorje A (na vrhu), B (v sredini) in C (spodaj) with the Young's modulus E and the yield limit R_{mC}. The material parameters are summarized in **Table 2**.

Table 2: Material parameters of foam core
Tabela 2: Parametri materiala pene v jedru

E	R_{mC}	R_{mT}	ρ_f	ν	ε_U
MPa	MPa	MPa	kg/m^3	-	-
50	1.2	1.5	60	0.0	0.53

2.3 Numerical simulations and results

The simulations were performed as quasi-static explicit analyses in the FEM software Abaqus 6.11 using finite-strain theory. The numerical models of the outer skin and the foam core were meshed using 8-node solid elements (element type C3D8R).

Figure 3 shows the resulting force-displacement dependencies from averaged experiments and the numerical simulations for specimens of type A, B and C. The resulting force-displacement diagrams of the tensile test and the force-deflection diagram of three-point bending test of the foam core is shown in **Figure 4**.

The numerical model of the sandwich beam was created as a fully contact problem of four bodies – sandwich beam and three supports. The friction between the sandwich beam and supports has been neglected.

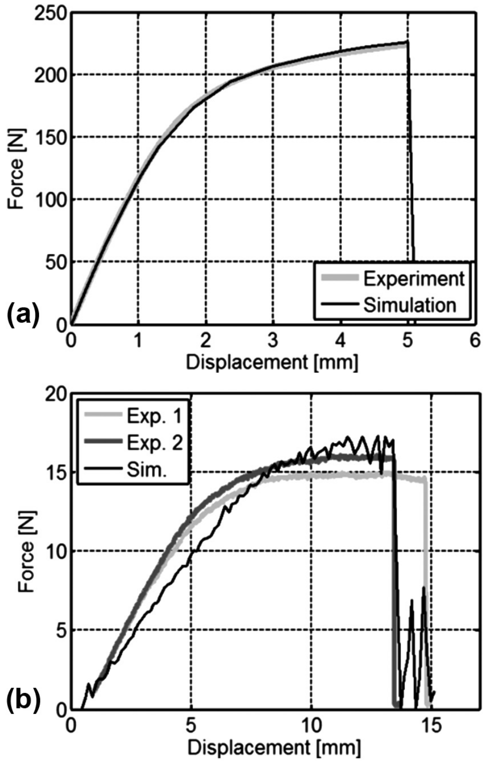

Figure 4: a) The resulting force-displacement diagrams of the tensile test and b) the force-deflection diagram of the three-point bending test of the foam core
Slika 4: a) Diagrami sila – raztezek pri nateznem preizkusu in b) diagram sila – uklon pri tritočkovnem upogibnem preizkusu jedra iz pene

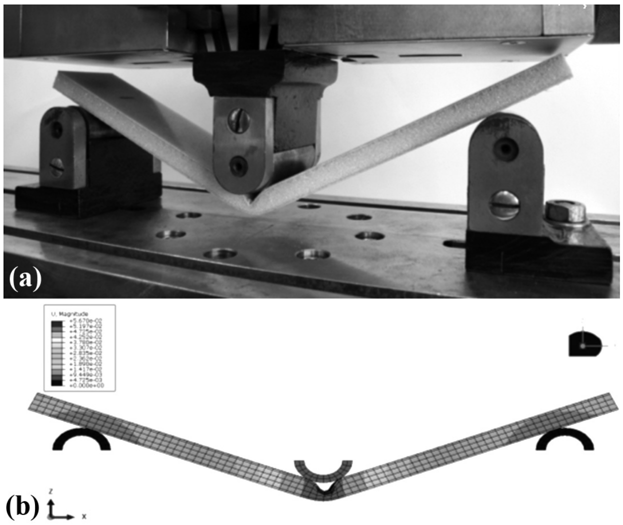

Figure 5: a) The resulting sandwich beam subjected to a three-point bending test and b) the numerical model of loaded sandwich beam
Slika 5: a) Sestavljen nosilec, izpostavljen tritočkovnemu upogibu in b) numerični model obremenjenega sestavljenega nosilca

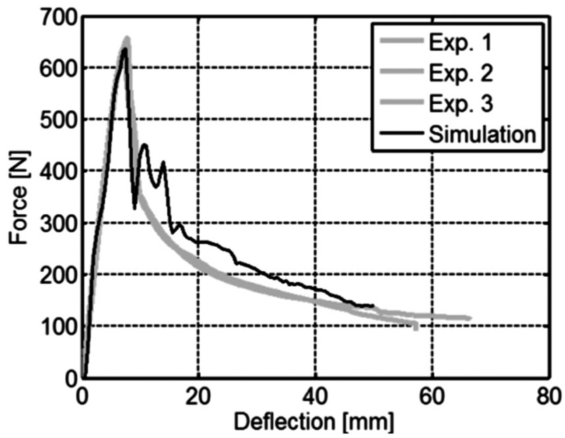

Figure 6: The force-deflection diagram of the three-point bending test of the resulting sandwich beam
Slika 6: Diagram sila – upogib pri tritočkovnem upogibnem preizkusu nosilca

The failure of the upper composite skin occurred in compression in principal direction 2 during loading in place under the center support, both in the case of experiments and the numerical simulation. This situation is shown in **Figure 5**. The comparison of the force-deflection diagrams for the three-point bending tests of the sandwich beam is shown in **Figure 6**.

3 CONCLUSION

The user-defined material model describing the non-linear orthotropic elastic behaviour, considering the progressive failure analysis, was implemented in the FEM system Abaqus. The material parameters of the composite outer skin of the sandwich panel were identified using the mathematical optimization method. In the case of the foam core the Low-Density Foam material model from FEM software library was used. The obtained material parameters of the composite skin and foam core were verified via a three-point bending test of the resulting sandwich beam. The future work will focus on low-velocity impact events involving sandwich plates.

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