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Numerical Investigation of Open-Hole Damaged Nomex™ Honeycomb Panel Under Three-Point Bending Load

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In the present study, a numerical investigation of three-point bending test of the open-hole damaged sandwich structures with Nomex™ honeycomb core and aluminium alloy skins is carried out. In order to evaluate the degradation of the mechanical properties of these damaged structures, a finite element model is realized and tested using Abaqus/Explicit. To validate the accuracy of the numerical model, the obtained numerical results of the intact panels are calibrated with the experimental results. The load-displacement curves of the damaged structures showed a significant decrease of the peak force and the flexural elastic modulus compared to the intact ones. The study indicated that the degradation level of these mechanical parameters is in a direct relationship with the damage size. In addition, the energy absorption of the damaged panels is calculated and compared to the intact one.

Key words: **finite element analysis, Abaqus, Nomex™ honeycomb, three-point bending test, energy absorption.**

Introduction

THE sandwich composite structures are widely used in aerospace and automotive industry, where engineers endeavour to maximize the efficiency of these structures and to minimize their weight. This type of structure has been shown to be effective in reducing weight and increasing strength and stiffness in a variety of structural forms and applications [1-9]. Honeycombs are manufactured of different engineering materials, including aluminium, steel, aramid paper, glass fibre, carbon fibre, ceramics, etc. Each honeycomb material provides certain properties and has specific benefits. The most commonly used core material in aerospace applications is phenolic resin-impregnated aramid paper, commercially known as Nomex™ [10]. This is mainly due to its flame resistance, good insulating properties, low dielectric properties, large selection of cell sizes, high strength-to-weight ratio, formability, and parts-making experience. Examples of the applications of Nomex™ honeycomb core sandwich in airplane are floors, doors, wing flaps, wing-body fairings, rudders, overhead stowage bins, ceiling or sidewall panels, engine cowls, spoilers, etc [11]. The mechanical behaviour of the Nomex™ honeycomb structures have been widely investigated under the in-plane compressive loading [12-13], out-of-plane compressive loading [14-15] and under three-point bending test [16-18].

A drawback of the use of these structures is that they are usually subjected to different types of damage as ballistic impact, bird strike, dropped tools during aircraft maintenance and tarmac debris kicked-up by the aircraft wheels during take-off or landing [19]. Accordingly, a large number of authors studied the effect of these damages on the structure mechanical properties [12,19-21]. The authors in [12] found that the compressive strength of the open-hole damaged honeycomb may decline about 66% of that of the intact plate due to the stress concentration at the equators of the hole and the local buckling of the honeycomb. In [19], the performance degradation of a damaged 5052 aluminium honeycomb panels under in-plane uniaxial quasi-static compression has been studied. The results suggest that the first maximum compressive load and the mean crushing load of damaged panels decreases as the damage size increases. It has also been deduced that the energy absorption capacity of the damaged panels significantly decreases as the damage size increases and it can be reduced by approximately 50% in some cases. In [20], the numerical study on the role of irregularities (missing cell cluster and variations in the cell arrangements) on the energy absorption under different crushing velocities is carried out. The authors concluded that the energy absorption capacity is more sensitive to the defect in the honeycomb structure with a lower relative density. Park and Kong [21] investigated the compressive strength of the impact damaged sandwich panels and found that the compressive strength is reduced by 5% at impact energy of 2 J and by 19% at impact energy of 3 J.

In this paper, the numerical simulation of three-point bending test of Nomex™ honeycomb open-hole damaged panels with aluminium facesheets are carried out to investigate the degradation of mechanical properties. The

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intact and the open-hole damaged panel (OHDP) are modelled and tested in Abaqus/Explicit. In order to validate the FE model, the intact panel has been tested and the numerical results of the flexural elastic modulus and the peak force have been compared to the experimental ones published in [16]. The load-displacement curves of the intact and the open-hole damaged panels are presented and the corresponding mechanical parameters are compared. In addition, the energy absorption of the damaged panels is calculated and compared to that of the intact one.

Finite element analysis

Numerical model

In order to numerically investigate the behaviour of the open-hole damaged sandwich panels under three-point bending, the finite element model of the intact and the damaged panels has been developed using the finite element code Abaqus/Explicit.

Table 1. Geometrical and mechanical properties of the modelled sandwich panels [16]

Honeycomb core	
Material	Nomex^{TM} (HRH 10-3/16-2)
Core thickness (mm)	19.05
Single wall thickness (mm)	0.108
Double wall thickness (mm)	0.216
Volumic mass of core material (kg/m^3)	710
Elastic modulus (MPa)	1878
Poisson's coefficient	0.4
Tensile yield strength (MPa)	40
Metallic facesheets	
Material	Aluminium alloy Al2024-T3
Top facesheet thickness (mm)	0.25
Bottom facesheet thickness (mm)	0.447
Volumic mass (kg/m^3)	2700
Elastic modulus (MPa)	72400
Poisson's coefficient	0.3
Johnson–Cook plasticity constants	A = 162.5; B = 462.2; n = 0.2846; C=0.0377

The sandwich panel with the dimension of 200×70 mm (Fig.1a) consists of top and bottom aluminium alloy Al2024-T3 facesheets with the thickness of 0.25 mm and 0.447 mm, respectively. The facesheets are separated by a 19.05 mm high Nomex^{TM} honeycomb core HRH 10-3/16-2 with cell size of 4.8 mm, 0.108 mm single wall thickness and 0.216 mm double wall thickness (where aramid-fibre papers are bonded). The geometrical and mechanical parameters of the sandwich panel are summarized in the Table 1.

The damage is represented as an open-hole in the middle of the panel. Three different configurations of the OHDP are modelled in the function of the damage size (r=5 mm, r=7.5 mm, r=10 mm), see Fig.1b.

The FE model has been built using 3D-planar facesheets with the corresponding thickness bonded to the 3D-extrusion honeycomb core with "Tie" constraints. Both the facesheets and the honeycomb core are meshed using the 4-node, quadrilateral shell element, reduced integration with hourglass control (S4R) with element size of 1 mm using five elements through the thickness. However, a refined mesh (0.2 mm) has been applied in the central zone (zone under the puncher) due to the appearance of large deformations in this zone, Fig.2. On the other side, the 4-node three-dimensional bilinear rigid quadrilateral element (R3D4) has been used to mesh the puncher and the supports with the element size of 0.5 mm. The friction between the cylindrical surface of the puncher, supports and the facesheets as well as that of the honeycomb cell walls themselves has not been not taken into account and considered as "frictionless" contact [16]. The mass scaling technic has been adopted to reduce the computational effort while keeping good accuracy of the results.

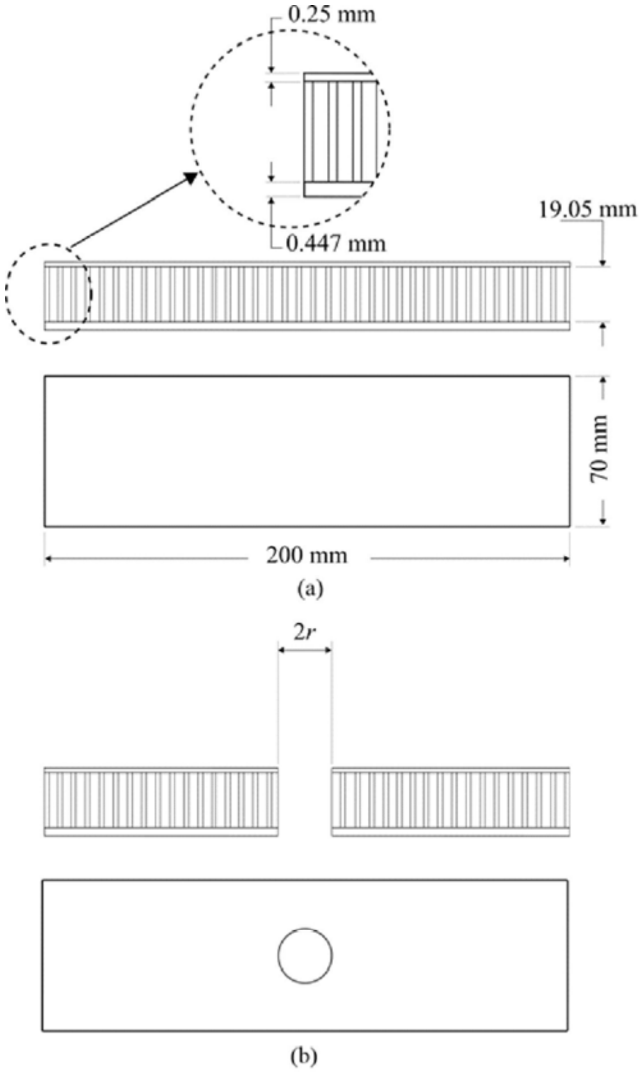

Figure 1. Sandwich panel dimensions: a) intact panel and b) open-hole damaged panel

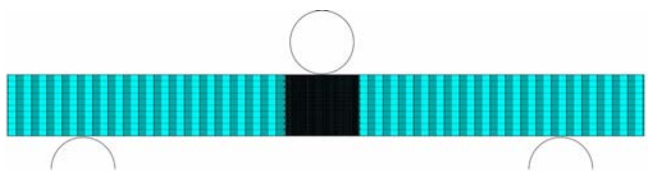

Figure 2. Details of panel mesh with the central refinement zone

In accordance with the data given in [16], Nomex^{TM} honeycomb core has been considered as an elastic perfectly-plastic material and has been modelled with the following properties: Young modulus E=1878 MPa, Poisson's ratio ν=0.4, density ρ=0.71 g/cm^3 and yield strength σ_y=40 MPa. However, the aluminium facesheets have been modelled as an elastic-plastic material and calibrated using the Johnson–Cook model.

Numerical simulation

The numerical simulation of the three-point bending has been controlled by the displacement of the 20 mm diameter puncher, moving toward the panel with constant velocity of V=0.5 mm/s. The panel rests on two fixed semi-cylindrical supports having the same diameter as the puncher. The distance between the centres of the supports has been 150 mm (Fig.3).

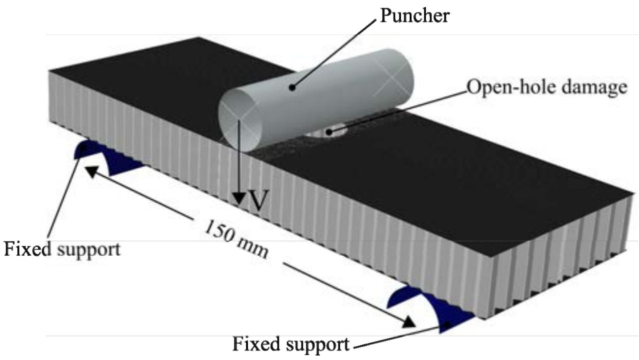

Figure 3. Numerical model of the three-point bending test of the OHDP

The simulations of the three-point bending test have been carried out until the first drop of the load to highlight three essential parameters; the peak force (F_{max}), the flexural elastic modulus (k) and the energy absorption (EA) which represent the area under the load-displacement curve (Fig.4).

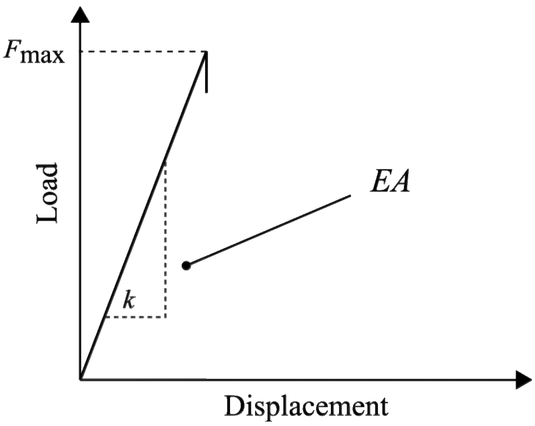

Figure 4. Typical load-displacement curve of a honeycomb sandwich panel under three-point bending

Results and discussion

Numerical model validation

To validate the accuracy of the FE model, the results of the intact panel subjected to a three-point bending have been compared to the average experimental results obtained in the previous work [16]. Both of the average experimental and the FE curves have been represented in Fig.5.

In Fig.5, it is clearly observed that the FE results matched with the experimental ones. Besides, the peak force of the FE and the experimental results are respectively 419.32 N and 426.45 N, which represents the relative error of 1.67%. On the other hand, the flexural elastic modulus of the FE and the experimental results are respectively 473.45 N/mm and 475.72 N/mm, with the relative error of 0.47%. Consequently, it has clearly validated that the FE model is able to accurately reproduce the tests and can be used for further analysis.

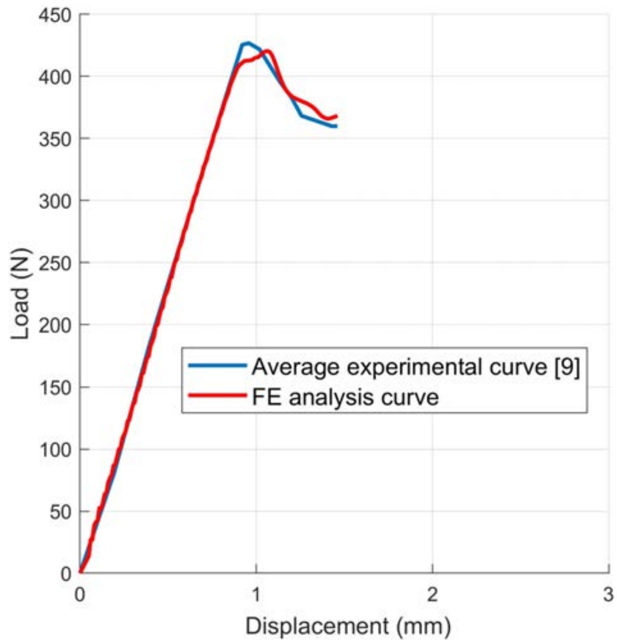

Figure 5. FE and experimental load-displacement responses of the intact panel

Open-hole damaged panel investigation

The load-displacement curves of the intact and the different OHDPs are drawn in Fig.6 and the values of the FE results are summarized in Table 2.

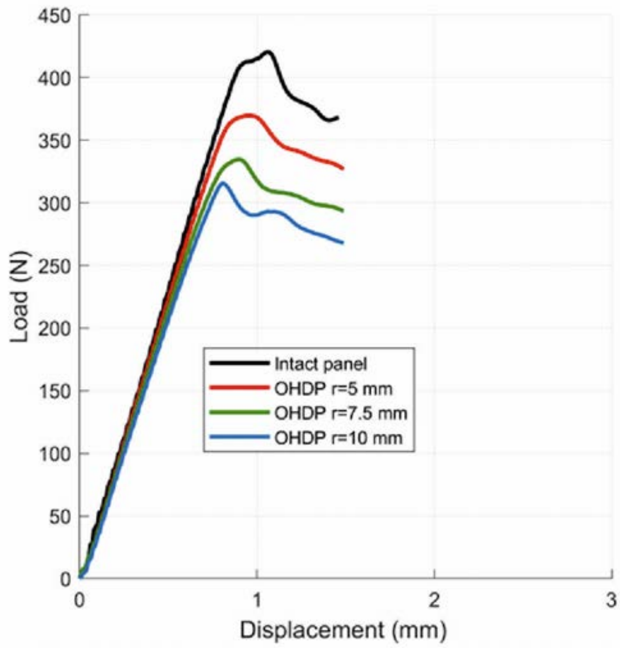

Figure 6. FE load-displacement responses of the intact and the open-hole damaged panels

Table 2. Results of the numerical three-point bending test

Panel configuration	Peak force (F_{max}) (N)	Flexural elastic modulus (k) (N/mm)	Energy absorption (EA) (J)
Intact panel	419.32	473.45	0.40
OHDP r=5 mm	367.63	449.65	0.37
OHDP r=7.5 mm	331.72	440.72	0.35
OHDP r=10 mm	311.07	429.64	0.33

The response of the different panel configurations has the same shape, characterized by a linear elastic region which represents the flexural elastic modulus and a peak force that corresponds to the first drop in the load at which the core under the puncher crushes. From Fig.6, it is noticeable that both above-mentioned parameters decrease significantly when the damage size increases. In addition, the displacement corresponding to the peak force diminishes. To better observe how the parameters change with the damage size, they are illustrated in two different Figures (Fig.7a and Fig.7b).

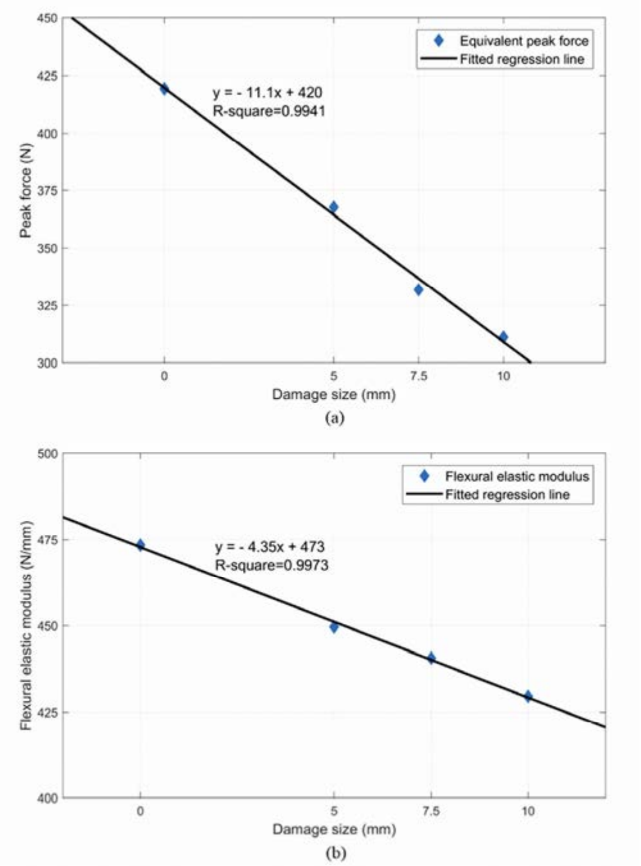

Figure 7. Mechanical parameters versus damage size; a) peak force, b) flexural elastic modulus

The fitted regression lines indicate that both of the flexural elastic modulus and the peak force decrease linearly with increasing the damage size. However, the descent rate of the peak force is higher than that of the flexural elastic modulus.

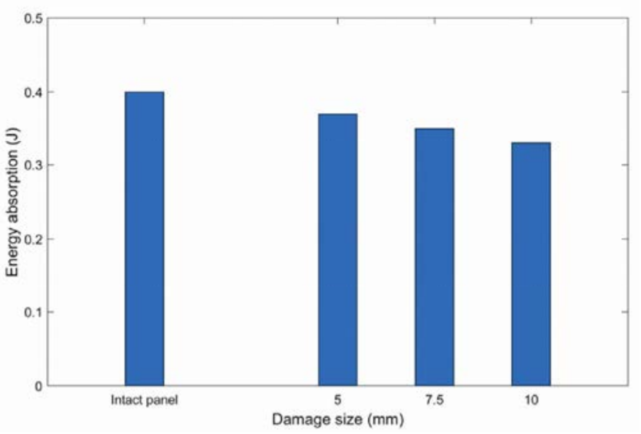

Figure 8. Energy absorbed by the intact and the damaged panels

The decrease of the flexural elastic modulus and the peak force obviously affect the energy absorption capacity of the panel. The bar chart represented in Fig.8 highlights the energy amount that each panel configuration can absorb under three-point bending. It has been found that, compared to the intact panel, the OHDP loss is 7.5%, 12.5%, and 17.5% for the panels with the damage sizes r=5 mm, r=7.5 mm, and r=10 mm, respectively. Furthermore, it is notable that the energy absorption also decreases in a linear way with the damage size.

Conclusions

The present study has numerically investigated the degradation characteristics of the open-hole damaged sandwich panels made of aluminium alloy skins and the Nomex^{TM} honeycomb core. The FE test of the intact panel has been carried out in order to calibrate the model. Very good agreement between the numerical and the experimental results [16] has been concluded. Three different open-hole damaged panels, i.e. three different damage sizes (r=5 mm, r=7.5 mm, r=10 mm) have been tested. The FE analysis of the OHDP under three-point bending has shown a linear decrease of the flexural elastic modulus and the peak force when the damage size increases. It is important to notice that the descent rate of the peak force is significantly higher than that of the flexural elastic modulus. In addition, the energy absorption of the damaged panels has also linearly decreased with increasing the size of the damage.

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References

[1] GIBSON,L.J., ASHBY,M.F.: *Cellular solids: structure and properties*, Cambridge University Press, 1999.

[2] THOMAS,T., TIWARI,G.: *Crushing Behaviour of Honeycomb Structure: A Review*, International journal of crashworthiness, 24 (5) 555-579, 2019.

[3] DJEMAOUNE,Y., KRSTIĆ,B., RASUO,B., RASIĆ,S., RADULOVIĆ,D., DODIĆ,M.: *Numerical investigation of dynamic response of honeycomb sandwich panels filled with circular tubes under low velocity impact in the in-plane direction*, FME Transactions, Vol. 49 (4), pp. 969-976, 2021.

[4] DINULOVIĆ,M., RASUO,B., KRSTIĆ,B.: The analysis of laminate lay-up effect on the flutter speed of composite stabilizers, 30th Congress of the International Council of the Aeronautical Sciences, ICAS 2016, DCC, Daejeon, Korea, 25 - 30 September, 2016.

[5] GARINIS,D., DINULOVIĆ,M., RASUO,B.: *Dynamic analysis of modified composite helicopter blade, FME Transactions*, Vol. 40 (2), pp. 63-68, 2012.

[6] DJEMAOUNE,Y., KRSTIĆ,B.: *Numerical investigation of in-plane crushing of undamaged and damaged honeycomb panels*, 5th International Scientific Conference, COMETa 2020, East Sarajevo, 26-28 November, 2020.

[7] DINULOVIĆ,M., RASUO,B., KRSTIĆ,B., BOJANIĆ,A.: *3D random fiber composites as a repair material for damaged honeycomb cores, FME Transactions*, Vol. 41 (4), pp. 325-332, 2013.

[8] REBHI,L., DINULOVIĆ,M., DUNJIĆ,M., GRBOVIĆ,A., KRSTIĆ,B.: *Calculation of the effective shear modulus of composite sandwich panels*, FME Transactions, Vol. 45 (4), pp. 537-542, 2017.

[9] REBHI,L., DINULOVIC,M., ANDRIC,P., DODIC,M., KRSTIC,B.: *On the effective shear modulus of composite honeycomb sandwich panels*, Scientific Technical Review, Vol. 66 (4), pp. 59-65, 2016.

[10] GIGLIO,M., MANES,A., GILIOLI,A.: *Investigations on sandwich core properties through an experimental–numerical approach*, Compos Part B-Eng, 43 (2) 361–374, 2012.

[11] LIU,L., WANG,H., GUAN,Z.: *Experimental and numerical study on the mechanical response of Nomex honeycomb core under transverse*

loading, Composite Structures, 121, 304-314, 2015.

[12] ZHANG,T., YAN,Y., JIN,C.: *Experimental and numerical investigations of honeycomb sandwich composite panels with open-hole damage and scarf repair subjected to compressive loads*, J. Adhes, 92, 380–401, 2016.

[13] FOO,C.C., CHAI,G.B., SEAH,L.K.: *Mechanical properties of Nomex material and Nomex honeycomb structure*, Composite structures, 80(4), 588-594, 2007.

[14] LIU,L., WANG,H., GUAN,Z.: *Experimental and numerical study on the mechanical response of Nomex honeycomb core under transverse loading*, Composite Structures, 121, 304-314, 2015.

[15] SEEMANN,R., KRAUSE,D.: *Numerical modelling of Nomex honeycomb sandwich cores at meso-scale level*, Composite Structures, 159, 702-718, 2017.

[16] GIGLIO,M., GILIOLI,A., MANES,A.: *Numerical investigation of a three point bending test on sandwich panels with aluminum skins and Nomex™ honeycomb core, Computational Materials Science*, 56, 69-78, 2012.

[17] DJEMAOUNE,Y., KRSTIC,B., RASIC,S., RADULOVIC,D., DODIC,M.: *Numerical investigation into the influence of geometrical and material properties on the bending behaviour of Nomex honeycomb sandwich panels*, 9th International Scientific Conference on Defence Technologies (OTEH), 2020.

[18] XIE,S., FENG,Z., ZHOU,H., WANG,D.: *Three-point bending behavior of Nomex honeycomb sandwich panels: Experiment and simulation*, Mechanics of Advanced Materials and Structures, pp. 1-15, 2020.

[19] DJEMAOUNE,Y., KRSTIC,B., RASIC,S., RADULOVIC,D., DODIC,M.: *Numerical Investigation into In-Plane Crushing of Tube-Reinforced Damaged 5052 Aerospace Grade Aluminum Alloy Honeycomb Panels*, Materials 2021, 14, 4992, 2021.

[20] AJDARI,A., NAYEB-HASHEMI,H., VAZIRI,A.: *Dynamic crushing and energy absorption of regular, irregular and functionally graded cellular structures*, Int. J. Solids Struct, 48, 506–516, 2011.

[21] PARK,H., KONG,C.: *A study on low velocity impact damage evaluation and repair technique of small aircraft composite structure, Composites Part A: Applied Science and Manufacturing*, 42(9), 1179-1188, 2011.

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Numerička analiza ponašanja oštećenog Nomex™ saćastog panela pod dejstvom savijanja u tri tačke

U radu je izvršena numerička analiza ponašanja oštećenog kompozitnog panela sa Nomex™ saćastom ispunom i gornjom i donjom panelnom pločom izrađenom od aluminijumske legure u uslovima savijanja u tri tačke. U cilju određivanja nivoa degradacije mehaničkih karakteristika oštećenog kompozitnog panela, u softverskom paketu Abaqus/Explicit izrađen je kompletan numerički model. Validacija i kalibracija numeričkog modela izvršena je upoređivanjem numeričkih i eksperimentalnih rezultata za slučaj ispitivanja neoštećenih panela na savijanje u tri tačke. Dobijeni numerički rezultati pokazuju značajan nivo degradacije mehaničkih karakteristika oštećenih panela u odnosu na neoštećene, što je u direktnoj korelaciji sa veličinom oštećenja. U radu su takođe određeni i nivoi energije koju oštećeni panele mogu da apsorbuju i te vrednosti su potom upoređene sa ekvivalentnim vrednostima kod neoštećenih kompozitnih panela.

Ključne reči: **metod konačnih elemenata, softverski paket Abaqus, Nomex™ saćasta ispuna, ispitivanje na savijanje u tri tačke, apsorpcija energije.**