Impact damage analysis of thin composite plates with different layer arrangement

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Abstract

The paper deals with experimental and numerical investigations of the composite plate subjected to low velocity impact. The discussed plates were made of eight-layer Glass Fiber Reinforced Polymer (GFRP) laminate with quasi-isotropic, quasi-orthotropic and angle ply systems and are predefined to conduct the Impact and the Compression After Impact (CAI) tests. The numerical analyses were performed in Ansys® environment. The implicit analyses were conducted with the implementation of the progressive failure algorithm (PFA) and the application of the bilinear traction-separation law. The analyzed problem was solved with implementation of the Hilber-Hughes-Taylor time integration method and with the impact constraints as a element-level time-incrementation procedure. The numerical results have been compared with results obtained experimentally to validate assumed numerical model and introduce necessary modification.

Keywords: debonding, progressive failure analysis, low velocity impact, GFRP, implicit transient analysis

1. Introduction

Fibre-reinforced composite materials are known for their high weight-specific mechanical properties and are therefore used in numerous lightweight engineering applications, in particular in aircraft design [3]. However, a constant concern for such laminates – much more than for similar metallic structures – are impact loads of foreign objects, which can cause internal material damage [2]. This damage can significantly reduce the strength [4], in particular, with the temperature, and it can grow under load and may be difficult to detect [1]. Typical impact scenarios in aircraft design range from a tool dropped on the laminate surface (high mass, low velocity), over runway debris thrown up by the tires or hail (low mass, high velocity) to bird strike during flight (high mass, high velocity) [3]. At present, the phenomenon of the impact with low velocity, in which the material is not perforated, is generally modelled using the decomposition law at the interfaces of the composite layer and with the use of the progressive failure algorithm, where the algorithm can based on the Material Properly Degradation method (MPDG) as well as on the approach Continuum Damage Mechanics (CDM) approach.

2. PFA and bilinear traction-separation law

In a damage mechanics all the failure modes can be represented by the degradation of the material stiffness on the meso-scale (lamina level). Due to heterogeneity of the composite materials, the application of the fracture mechanics is more complex compared to its application to isotropic materials because it is a need to apply not one but several damage parameters d, responsible for the destruction of its individual elements in the failure analysis of composites: d_F - fiber damage variable, d_M - matrix damage variable, d_S - shear damage variable. The Hashin's criterion was implemented to analyze the progressive failure analysis as a damage initiation criterion. It takes into account the following four damage modes: f_{FT} - fiber tension (rupture), f_{FC} - fiber compression (kinking), f_{MT} - matrix tension (cracking), and f_{MC} - matrix compression (crushing). The two-dimensional versions of the failure criterion, in a space of the effective stresses, can be written in following form (1-4):

$$f_{FT} = \left(\frac{\bar{\sigma}_{11}}{T_1}\right)^2 + \left(\frac{\bar{\sigma}_{12}}{S_{12}}\right)^2 \tag{1}$$

$$f_{FC} = -\frac{\bar{\sigma}_{11}}{C_1} \tag{2}$$

$$f_{MT} = \left(\frac{\bar{\sigma}_{22}}{T_2}\right)^2 + \left(\frac{\bar{\sigma}_{12}}{S_{12}}\right)^2 \tag{3}$$

$$f_{MC} = \left(\frac{\bar{\sigma}_{22}}{2S_{12}}\right)^2 + \left(\frac{\bar{\sigma}_{12}}{S_{12}}\right)^2 + \left[\left(\frac{C_2}{2S_{12}}\right)^2 - 1\right]\frac{\bar{\sigma}_{22}}{C_2} \tag{4}$$

In order to achieve the full qualitative and quantitative compliance of the experimental and numerical results, the essential element of the numerical model is the need to take into account the phenomenon of the delamination. In the analyzes of the laminates subjected to impact, the failure on the interface of the layers is induced by the presence of both normal and tangential stresses and leads to the considerations of the mixed-mode debonding. For mixed-mode debonding, both normal and tangential contact stresses contribute to the total fracture energy and debonding is completed before the critical fracture energy values are reached for the components. Therefore, a power law based on energy criterion, used to define the completion of debonding, can be written in following form (5):

$$\left(\frac{G_I}{G_I^c}\right)^2 + \left(\frac{G_{II}}{G_{II}^c}\right)^2 = 1 \tag{5}$$

Additionally, it can be noticed that, defining the bilinear traction-separation law, the cohesive zone model was implemented with the use of augmented lagrangian method and to reduce the burden of experimentation, it was assumed that the

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Table 1: Elastic, fracture and failure properties of GFRP laminate

ρ [kg/m³]	E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12} [-]	G_I [J/m²]	G_{II} [J/m²]	t_n [MPa]	t_t [MPa]
1800	38.5	8.1	2.0	0.27	200	700	10	18
T_1 [MPa]	T_2 [MPa]	C_1 [MPa]	C_2 [MPa]	S_{12} [MPa]	d_{FT} [-]	d_{FC} [-]	d_{MT} [-]	d_{MC} [-]
792	39	679	71	108	0.017	0.014	0.1	0.1

penalty stiffness is the same for all modes. The material model of GFRP laminate is presented in Table 1. E_1 and E_2 are the longitudinal and transverse Young's modulus, respectively, G_{12} is the shear modulus and ν_{12} is the major Poisson's ratio. T_1 and T_2 are the longitudinal and transverse tensile strengths, respectively, C_1 and C_2 are the longitudinal and transverse compressive strengths and S_{12} is the in-plane shear strength.

3. Object of the analysis

The analyzed plates were subjected to low velocity impact. The plates taken into consideration had the following geometrical dimensions: 100 mm wide (dim. a), 150 mm long (dim. b) and the thickness of the laminate amounts to 2 mm (dim. t). The thin-walled plates consisted of eight-layer GFRP laminate. The picture of impact test stand, describing the support and the load conditions and characteristic geometrical dimensions, is presented in Figure 1.

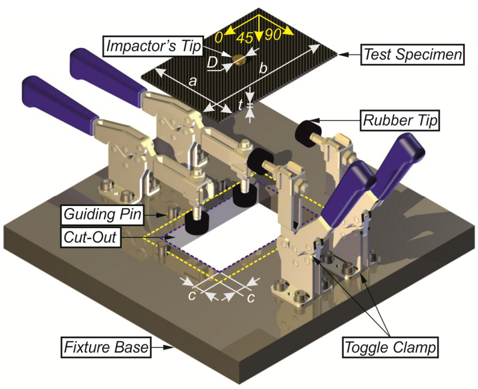

Figure 1: Impact support fixture

The impact tests were carried out with the use of the impactor with the hemispherical shape of the tip. The diameter of the impactor's tip amounted to 0.5 inch.

4. FE model with assumed boundary conditions

The prepared numerical model corresponds to the geometry of each layer of the analyzed laminate (8x0.25mm).

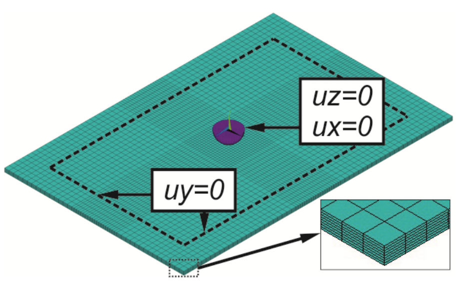

Figure 2: Discrete model of impacted plates

The model was created using three dimensional, eight-node solid structural element and the decomposition zones of the laminate were modelled with the use of four-node, surface-to-surface contact elements and target segments (cf. Figure 2). The load was modelled as a steel, hemispherical impactor impacting in a mid-length and mid-width of the composite plate. The impactor had a mass approximately 3 kg, the velocity of about 2.57 m/s which implied the impact of around 10 J.

5. Conclusions

Within the present study, experimental and numerical investigations of the composite plate subjected to low velocity impact were conducted. The implicit transient analyses were conducted with the implementation of the progressive failure algorithm with the use of material property degradation method (MPDG) and in order to model the decomposition of the laminate the bilinear traction-separation law was assumed between the layers of the composite plate. The Hashin's criterion was implemented as the damage initiation criterion. Based on the performed experimental and numerical studies it has been concluded that the application of the Hashin's criterion lead to a correct prediction of the fiber failure and to the overestimation of the matrix cracking areas. Due to the values of the damage variables, the nature of the occurring damage (mainly the matrix) and the areas of degraded components (small areas of the fiber rapture), the progressive failure method does not determine a significant differences in the courses of the curves of the displacement, the velocity and the impact force in comparison to the analogous curves determined without the use of this method. In relation to conduct a similar impact analyzes, the authors recommend the activation of the impact constraints on the contact element which enforces energy conservation at the contact interface and this algorithm helps to maintain accuracy of the nonlinear transient response over long simulation times.

The determined areas of the matrix damage significantly differ from the experimental results and it will be the subject of the future work of the authors.

References

[1] Chai, G.B. and Manikandan P., Low velocity impact response of fibre-metal laminates – A review, *Comp. Struct.* 107, pp. 363-81, 2014.

[2] Dębski, H. and Ostapiuk, M., Numerical FEM analysis for the part of composite helicopter rotor blade, *J. of Kones* 19(1), pp. 71-77, 2012.

[3] Faivre, V. and Morteau, E., Damage tolerant composite fuselage sizing. Characterisation of accidental damage threat, *FAST* 48, pp. 10-16, 20111.

[4] Khalili, S.M.R., Mittal, R.K. and Panah N.M., Analysis of fiber reinforced composite plates subjected to transverse impact in the presence of initial stresses, *Comp. Struct.* 77, pp. 263-268, 2007