Composite Laminate Deflection during Low-velocity Impact

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Abstract: For the development of a composite structure damage detection system, it is important to create a reliable numerical predictive model of the damaged material. This paper is focused on experimental and numerical analysis of a drop weight impact test and the possibility of its extension by the presence of a laser interferometer for deflection measurment. The subject of the test was 1.58 mm thick composite laminate made of a commercially inaccessible carbon fibre–reinforced epoxy matrix. The impact test was simulated with the help of ABAQUS/Explicit 6.14 solver and compared with the experiment. Results of the laminate deflection were statistically assessed showing 4% difference between the model and the experiment.

Keywords: experiment; impact; deflection; simulation; composite.

1 Introduction

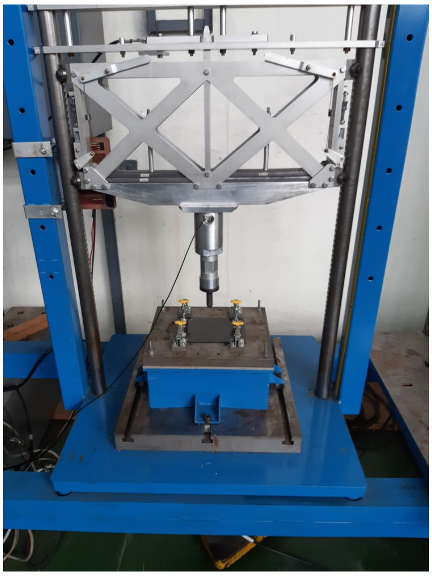
To detect in-service damage of aerospace structures, a structural health monitoring (SHM) system is being developed. It will be able to detect damage produced by structural ageing and impacts during the service life using sensors. Usually, the damage is monitored by periodic inspections, visually or with the utilization of non-destructive inspection (NDI) equipment. The SHM system will enable more frequent inspections using sensors [1, 2], with the final target of a continuous in-flight monitoring, with the potential cost reduction. The SHM system needs a definition of impact damage virtual morphology validated by experimental impact test results.

Collisions between fast-moving objects can lead to their complete, partial or barely visible damage (BVID). Since the change in the properties of the material from which they are made can have a significant relation to the load-cases for which they are designed [3, 4], it is very advantageous to have a computational model that corelates with reality. Due to the fact, that the properties of composite materials are influenced by the production technology, each material is moreover unique. Computational models require large number of parameters that need to be experimentally supported [5–7]. Verification of the response and the rate of damage to the material to impact by a standardized body plays a crucial role here. This work is mainly devoted to the comparison of the simulation with the experiment, which was performed using a drop weight machine, especially the verification of the possibility of its extension by the presence of a laser interferometer.

2 Experiment

Laminate samples were made from components, which properties shows Tab. 1. The composite layup was $[-45/+45/0/90/0/0]_S$ with thickness of 1.58 mm. The experiment was based on ASTM D7136 standard [8]. A total of 5 samples measuring 150 $\times$ 100 mm were cut from the plate using a diamond wheel and milled to the required dimensions. The sample was placed on a rectangular frame with a hole of 125 $\times$ 75 mm and fixed with 4 pressure holders with rubber heads. Using a pad machine impactor (Fig. 1a), the laminate was damaged in the middle of the sample by a spherical steel impactor with a diameter of 12.7 mm with an indicated energy of approximately 10 J. The impactor weight was 5,804 g and the corresponding impact velocity was approximately 1.8 m/s. Design of the impactor ensured that after the recoil, the punch stopped and there was no repeated impact.

The actual pre-impact punch speeds were measured using Hall probes. At the same time, the acceleration was measured using an accelerometer located inside the punch with the recording frequency 20 kHz. The data from the accelerometer were used to calculate the absorbed energy, which was approximately 8 J.



(a) Impact test setup

(b) Laser interferometer optoNCDT ILD 2300-20

Fig. 1: Experiment description.

Tab. 1: Properties of components.

Component	Material	Tensile modulus	Poisson ratio
[-]	[-]	[GPa]	[-]
Matrix	Epoxy	4.30	0.35
Fibre	Carbon	240.00	0.20

To measure the sample deflection under the impactor the laser interferometer was used (Fig. 1b), which works on the principle of optical triangulation. It utilizes a laser beam with a wavelength of 670 nm (max. Power 1 mW) and can be active in two modes. At the first mode the direct reflection of laser beam is used (angle of incidence of the beam is equal to the angle of reflection). In the second mode the diffuse reflection is used (laser impinges on the surface at right angles). The first mentioned mode/method was used in the described experiment. Laser beam angle of incidence was 15° deviated from the perpendicular direction of the surface (the set angle depends on the distance of the sensor from the surface).

The measuring range of the used sensor is 20 mm (40 to 60 mm from the front of the sensor) with a resolution of 0.3 μm. Sample frequency of the detector could be selected from the working range 1.5 to 49.1 kHz. The interferometer was connected to the measuring chain using a C-Box/2A converter, which simultaneously provides power to the sensor, time synchronization and allows setting of its parameters.

3 Model description

The role of the impact in the jig is a model case, where is bending between the support and a local deformation under the impactor, which is difficult to calculate. The task must be formulated very precisely already at the level of elastic parameters. The calculation of material parameters for the simulation was performed by use the values ??for epoxy matrix Hexcel 3501-6 and carbon fibre AS-4 (Tab. 1). Properties of fibres are considered as isotropic here. Elastic properties were calculated by using Halpin-Tsai relations. Strategy of other parameters calculation follows the methodology of Daniel and Ishai [9]. The parameters of efficiency, elasticity, strength, and damage evolution are shown in Tab. 2 and Tab. 3. The experimentally determined values ??were subjected to statistical analysis and compared with the results of simulations performed with the help of the ABAQUS/Explicit 6.14 solver.

In connection with its effective use, elements with a reduced number of integration points were used in the whole model. In case of the test fixture with rubber attachments C3D8R eight-node elements were used.

Tab. 2: Mechanical properties of laminate, Major properties.

Direction	Elasticity	Efficiency parameter	Laminate strength	Laminate damage evolution	Cohesive strength	Cohesive damage evolution
[-]	[GPa]	[1]	[GPa]	[J/m^2]	[GPa]	[J/m^2]
Longitudinal (11)	130.00	10^6	2.970	0.074	-	-
Transverse (22)	12.00	0.68	0.101	0.014	-	-
Transverse (33)	12.00	0.68	-	-	0.101	0.074
Shear (12)	4.99	1.00	0.101	-	-	-
Shear (13)	4.99	1.00	-	-	0.101	0.014
Shear (23)	4.64	1.00	-	-	0.101	0.014

Tab. 3: Mechanical properties of laminate, Poisson ratios.

Direction	Poisson ratio	Efficiency parameter
[-]	[1]	[1]
In-Plane (12)	0.27	10^6
Out-of-Plane (13)	0.27	10^6
Out-of-Plane (23)	0.43	0.31

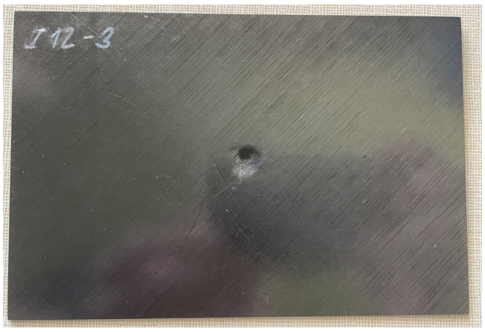
For the instance of the impactor, which we consider to be very rigid and whose elastic deformation is not essential for the result, C3D4 tetrahedral elements were applied. The ply-by-ply method in connection with continuum-shell SC8R elements was used. This modelling technique does not take into account compressive and tensile deformations in the thickness direction of the laminate. For each layer, a minimum number of integration points was considered so that the local bending mode with the influence of transverse shear stresses was properly affected. The number of integration points must always be chosen with respect to the assumed course of the stress components as odd. Delamination of the layers is realized by cohesive contact. The failure of material was considered in the sense of Hashin's formulation.

4 Results

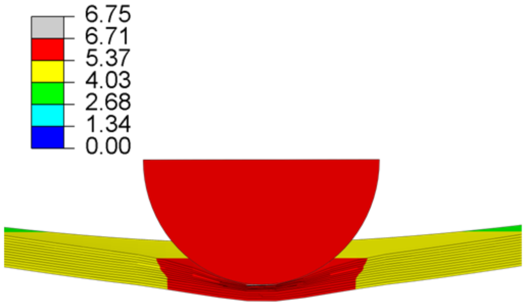
The time while impactor was in contact with the laminate sample was approximately 15 milliseconds. The values of applied energy, which were calculated from speed and maximum bending displacement during the impact test, are pointed in Tab. 4. On the impacted side, a hole could be observed without significant fibre breakage. Approximately 1 minute after the impact, the depth of the pit on the impacted side was measured using an indicator, which was in range from 0.82 to 1.26 mm. The back of the sample was severely damaged. The variety of failures such as fibre breakage, fibre bundle separation and delamination widening in the diagonal direction were observed.

To speed up the calculation, the velocity of the impactor on contact with the sample was increased to 5 m/s compared to the experiment 1.8 m/s. To keep the calculation and experiment energetically equivalent, the weight of the impactor was reduced at the expense of higher velocity. Because it was not an application of classical mass-scaling within an explicit solver, this adjustment did not affect the quality of the result (Fig. 2b). Comparison of experimental results and simulations show Tab. 4 and Fig. 3.

The deflection values obtained by the experimental were on average 4% higher than calculated by the simulation. F-test showed significantly different variances because the simulations were much more consistent. T-test confirmed a statistically significant difference of the means (p-value = 0.04).



(a) Specimen after impact



(b) Deflection under impactor [mm]

Fig. 2: Real and modelled damage.

Tab. 4: Vertical displacement under impactor.

Sample ID [1]	Energy [J]	Experiment [mm]	Simulation [mm]
1	10.42	7.13	6.71
2	10.30	6.90	6.68
3	10.80	6.76	6.79
4	10.22	7.27	6.66
5	10.50	6.89	6.72
Average	10.45	6.99	6.71
Std. dev.	0.22	0.21	0.05

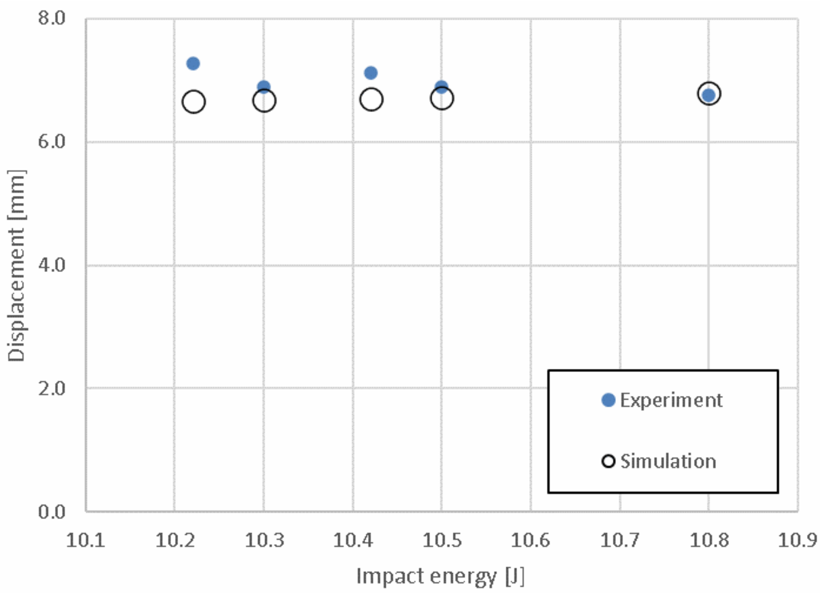


Fig. 3: Vertical displacement (laminate deflection) under impactor.

5 Conclusion

Use of a laser interferometer during the experiments in connection with the verification of simulation results has proven to be very effective. The results, which were subjected to statistical analysis, show a very small deviation of the model and the measurement with a difference 4%. The model can be used to analyse the internal damage of laminates and its effect on the deformation field of the sample at different types of loads.

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