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Validation of high-speed impact numerical simulations on flat test panels for real structural analysis

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Abstract. This paper aims to integrate numerical analyses with high-speed impact tests on flat panels for application in real structural design.
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Introduction

Innovative designs of aircraft structures must be validated to meet airworthiness requirements (e.g., [1]). The most commonly used design approach for such structures involves making simulations based on numerical simulations, which require the use of reliable validation techniques, especially when using anisotropic materials, such as fibre-reinforced composite.

Proposed technique

The technique involves validation of FE models based on tests of a simplified structure. The simplification involves the use of flat test panels that ensure:

- Fast automatic meshing with guaranteed element quality
- Application of real boundary conditions according test conditions
- Rapid modification of FE model parameters
- Ease of test specimen production (flat panels)
- Comparability between test results

The following measurement and investigated parameters are used as a standard for high-speed impact:

- High-speed cameras
- NDT before and after impact
- Reaction force measurements

Figure 1 shows a schema of the proposed technique.

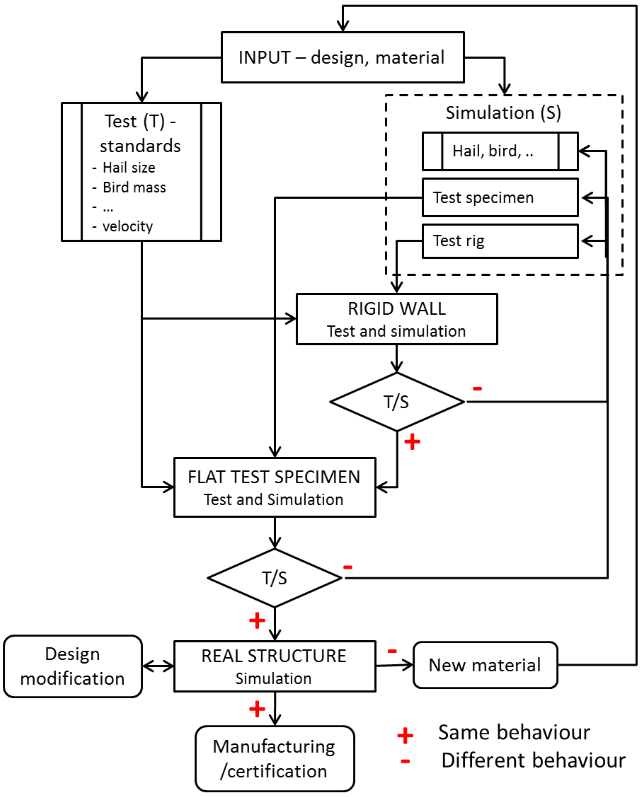

Fig. 1 – Proposed technique for the validation of numerical simulations of high-speed impact

Hail strike tests

The tests were performed in VZLÚ (Aerospace Research and Test Institute) according ASTM standards [2].

Tests were carried out on a flat composite plate that was representative of Krueger flap skin (see figure 2 - left). The dimensions of the test specimen are shown in figure 2 (right).

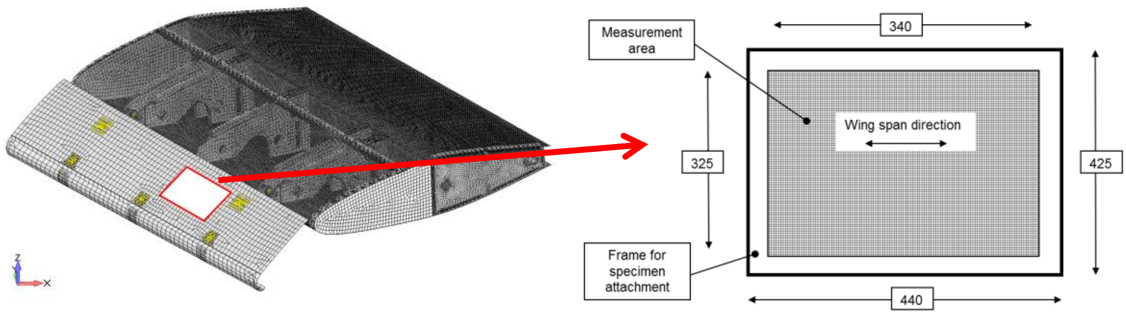

Fig. 2 – Global FE model of the demonstrator with a composite Krueger flap (left) and the proposed flat test specimen for hail strike tests (right)

The flat test specimens were manufactured based on a flap design to transfer the results from the flat test specimen on the real structure through the analysis. The test specimens were manufactured in Polytechnic Warsaw (see figure 3). Two types of composite test specimens were used:

- Skin with 10-layered CFRP composites (test specimen No. 1, 4, and 5)
- Sandwich with two 10-layered CFRP composites and 30 mm thick foam (test specimen No. 2 and 3)

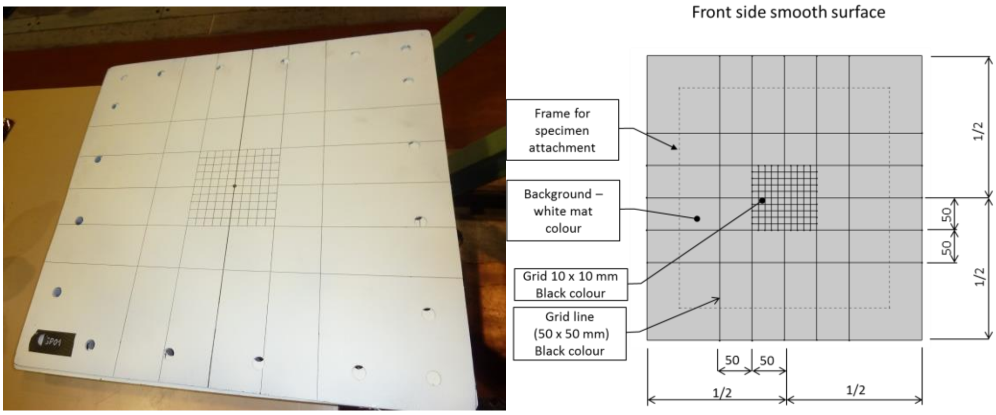

Fig. 3 – Flat test specimen with a raster for high-speed camera analysis

Figure 4 shows the hail strike test arrangement at the VZLU test hall.

Fig. 4 – Hail strike test arrangement at VZLU

Two high-speed video cameras were used to record the hail impact. One camera was positioned in front of the test specimen, and one camera was positioned from behind the test specimen.
An impactor with a 25.4-mm ice ball diameter was used for the hail strike tests (see figure 5).

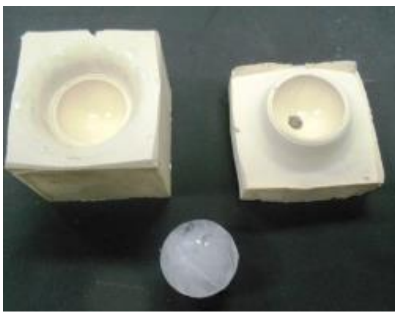

Fig. 5 – Rubber mould and ice ball used for the hail strike tests

The ice ball was accelerated through an air gun with a smooth borehole barrel up to the specified velocity using expanding compressed air (see Figure 6).

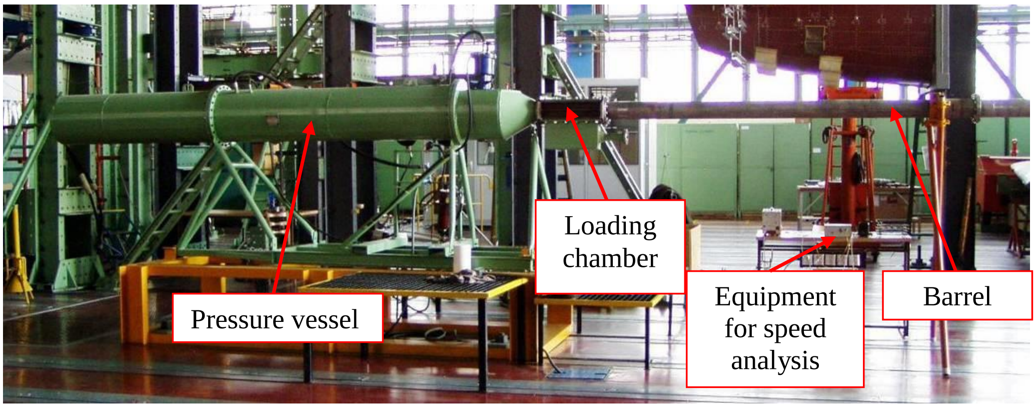

Fig. 6 – Air gun with pressure vessel and loading chamber

A high-speed camera was used to make impact speed measurements.

Test results

The test results were analysed based on:

- High-speed camera pictures
- Plastic deformation and damage patterns
- Reaction forces drawn from load cell measurements

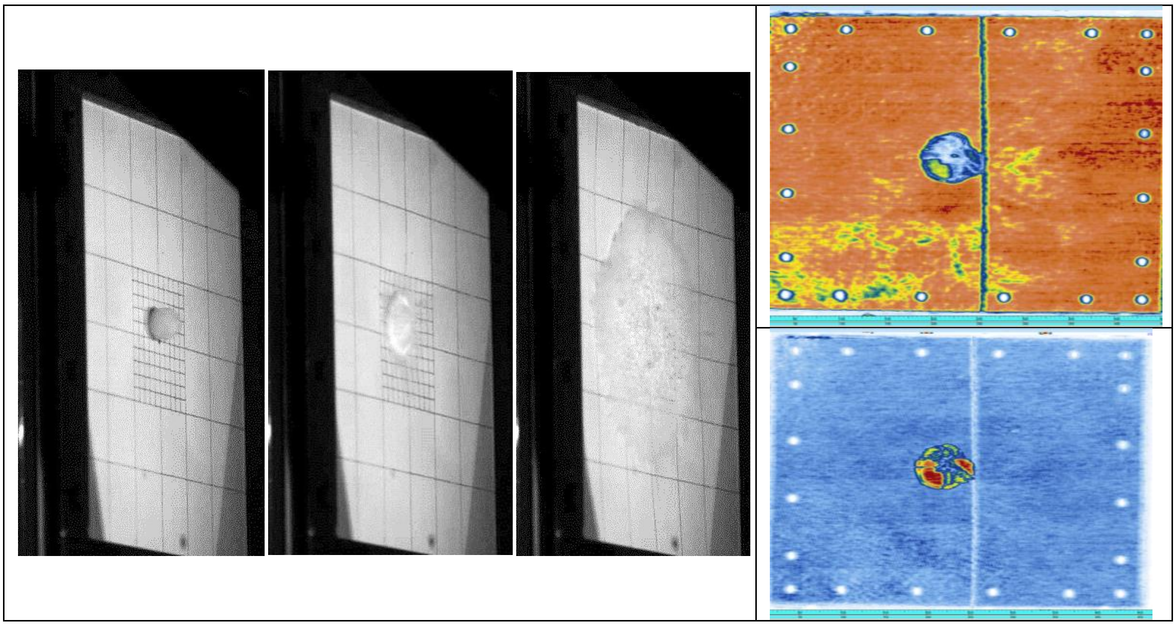

Fig. 7– Analyses of the hail-strike test results (high-speed camera – left, NDT C-scan – right)

Figure 8 shows damage measurements drawn from the C-scan results. The perpendicular hail strike of 640 km/h created an approximately 70-mm dent.

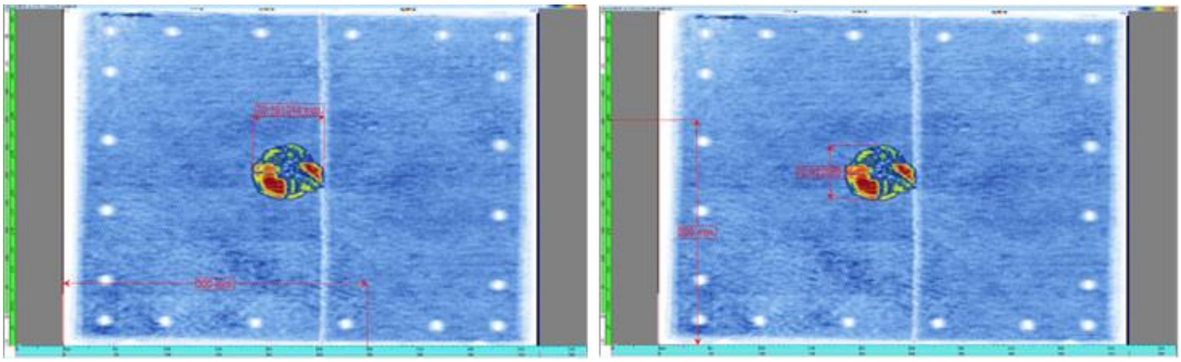

Fig. 8 – Analysis of hail-strike impact damage

Table 1 presents a summary of the test measurement results.

test No.	test specimen	Hail diameter	impact speed	cameras measurement			NDT C-scan		
				front	speed measurement	back	horizintal size	vertical size	average
		mm	km/h	fps			mm		
1	BSP01	25.4	545	8000	3000	500	N	N	N
2	BSPS01		540	10000	3000	500	N	N	N
3	BSPS02		600	10000	3000	500	55.3	52.1	53.7
4	BSP02		525	10000	3000	500	N	N	N
5	BSP03		640	10000	3000	500	70.4	72.3	71.4

Tab.1 – Summary of the hail strike test results (N - without damage)

The reaction force was analysed from load cells measurements during the impact test. Measurements were made on 3 load cells between the moving part of the test rig and frame connected to the ground.

Simulation

The FE simulation was performed using the ABAQUS FE software program. An explicit solver with double precision was used for the analysis. The aim of this analysis was to tune unknown inputs and computational parameters to obtain the same behaviours between the test and simulation, i.e., energy absorption and damage. The same set up was then used for analysis of the entire structure.

In terms of the impactor's (hail) material properties and features, ice is a complex material presenting high degrees of variability. The material density of ice and hail varies and is subject to a range of factors, such as the weather systems through which it was created. Standard ice has a density of 917 kg/m3; while this value slightly increases as temperature declines, it never reaches the density of liquid water.

Ice may exhibit two forms of non-elastic behaviour under stress. Under low-velocity deformation, ice exhibits ductile behaviour and yet as velocity increases, the material become brittle.

The method used to adjust hail strike simulations is certified by the Czech Republic Civil Aviation Authority [3]. Figure 10 shows the geometry and FE model of the impactor.

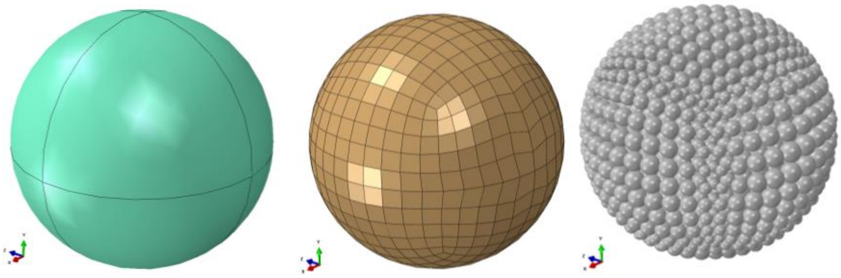

Fig. 10 – Geometry, FE mesh and SPH elements of a ball representing the hail impactor

For the simulation of the composite structure, we used 4-node shell elements (S4R) of different mesh sizes. For the damage analysis of the composite material, Hashin's damage material model was used.

Figure 11 compares the test results (high-speed camera) with the numerical simulation of hail striking a flat composite panel representing a lay-up of a composite flap.

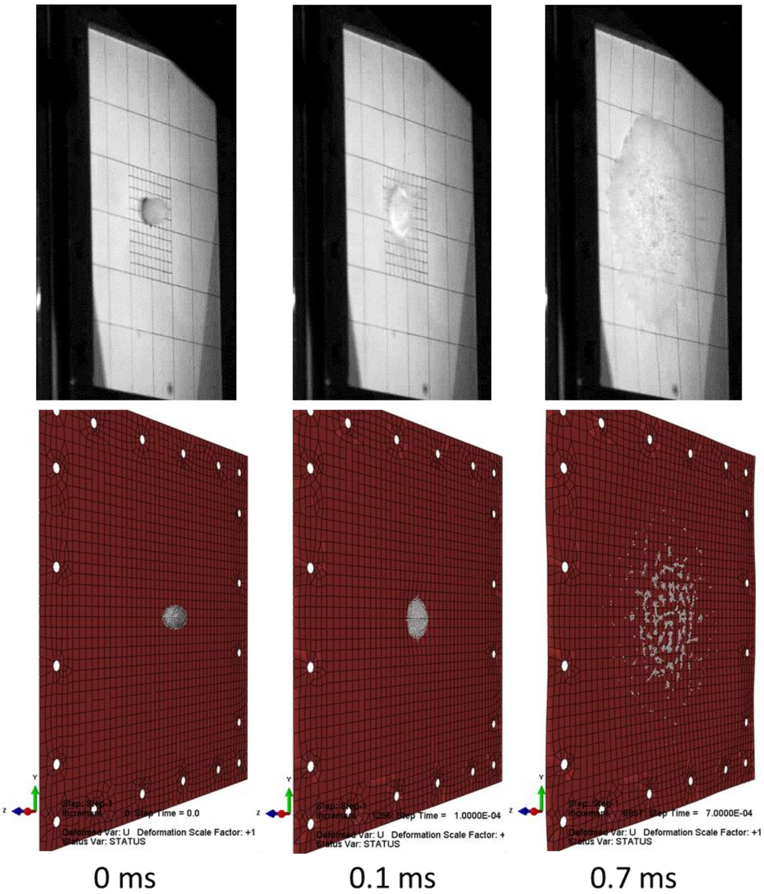

Fig. 11 – Comparison of impactor hail damage between the hail strike test and simulation

Four different impact area FE mesh sizes were used for the influence analysis. Figure 12 shows the results of this analysis.

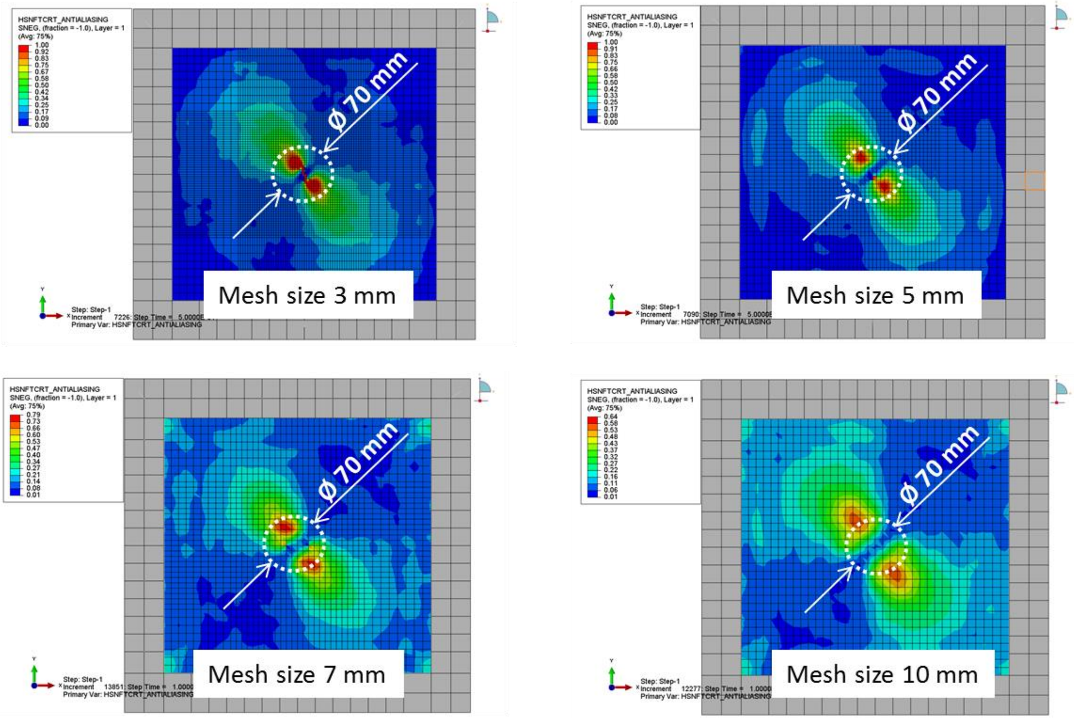

Fig. 12 – Analysis of the FE mesh size effects on damage predictions

Figure 13 compares the test and simulation results in terms of reaction forces during impact.

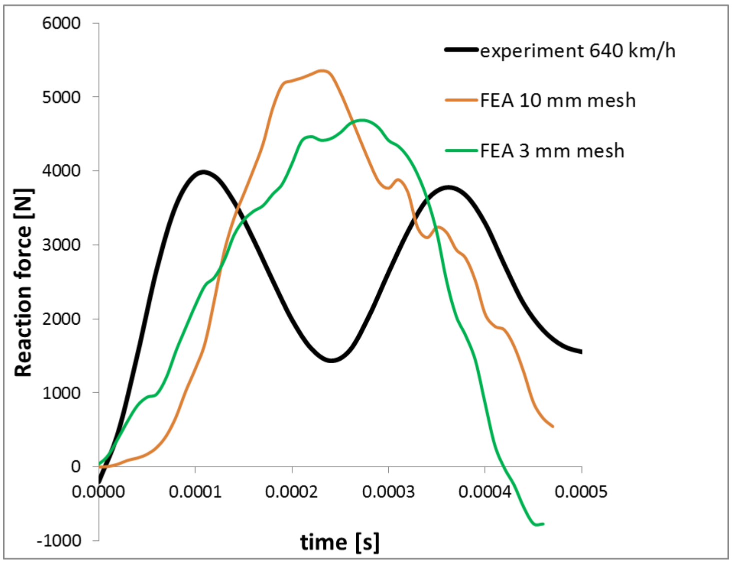

Fig. 13 – Comparison of reaction forces between the test and simulation

The peaks of the test reaction forces (figure 13) are influenced by the load cell scanning frequencies.

The verified simulation of 1” hail strikes (25.4 mm) was used to determine the airworthiness required (e.g., EASA airworthiness CS E 790 [1]) for 2” hail (50.8 mm). Figure 14 compares the above mentioned hail size with the estimation of speed limits for the defined composite material and lay-up for perpendicular impact.

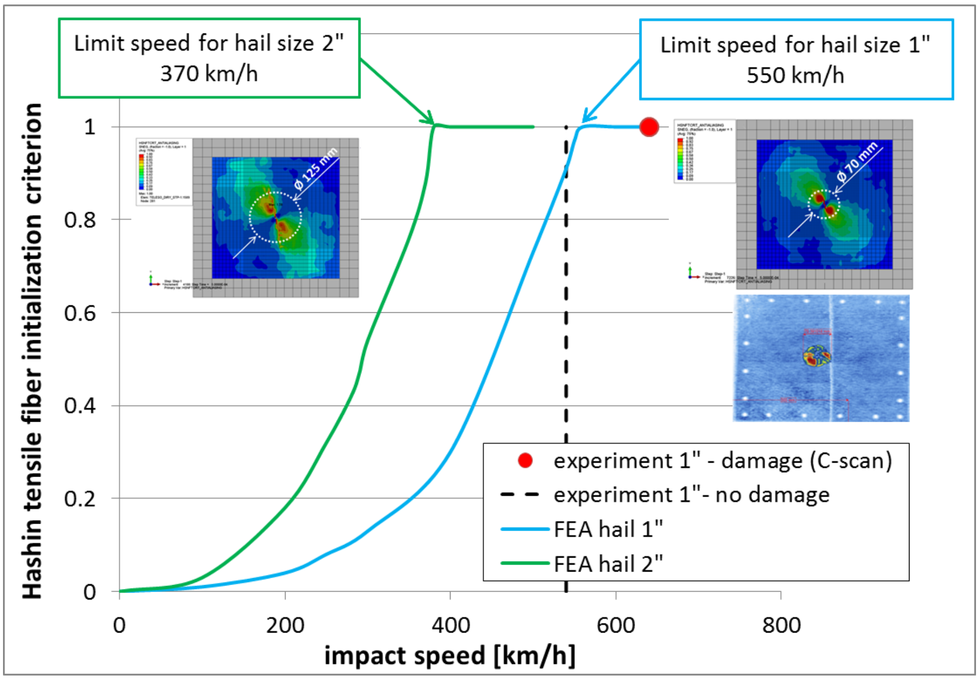

Fig. 14 - Estimation of the impact resistance of 10 layered CFRP composites for the perpendicular impact of 1” and 2” diameter hail.

Conclusions

A comparison between the test and simulation results reveals consistency in predictions of damage initialization and propagation.
These tests provide important information for design and computational analysis. Test and numerical model verification based on different impact speeds also provide important generalizations for the application and optimization of composite structures.

References

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[3] Doubrava, R.: SPH Technique Application for Fast Impact Simulation, report R-5841, VZLU, Prague, 2013