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An Improvement of measurement technique for high speed impact tests analysis

DOUBRAVA Radek[1,a], OBERTHOR Martin[1,b], BĚLSKÝ Petr[1,c] and VÍCH Ondřej[1,d]

[1]VZLÚ (Czech Aerospace Research Centre), Beranových 130, 199 05, Prague – Letňany, Czech Republic

[a]doubrava@vzlu.cz, [b]oberthor@vzlu.cz, [c]belsky@vzlu.cz, [d]ondrej.vich@vzlu.cz

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Abstract. The paper presents improvement methodology and verification of numerical models by quantitative measurement during high speed impact tests. A comparison between the test and simulation results reveals consistency in predictions of damage initialization on composite material and plastic deformation on metal material. The new technique of displacement measurement by optical sensor during impact provided unique value for verification of numerical models was applicate. The results showed the necessity to increase the measurement range of sensors.

Introduction

Foreign object damage (FOD) and especially high-speed impact such as bird or hailstone strikes are an important phenomenon that must be considered when designing aircraft [1]. As a result, it is more important than ever to study and understand the mechanics of high-speed impact.

An increasing number of aircraft manufacturers, aviation companies, and government authorities have been conducting advanced research and development programmes to reduce the annual cost, number of injuries, and fatalities that result from collisions of aircraft with foreign objects e.g. wildlife [2] or hail-stone [3]. To eliminate the harmful effects of bird or hailstone strikes, two main approaches are typically implemented:

1. Bird or hailstone strike prevention strategies that attempt to reduce the probability of a bird or hailstone strike incident e.g. elimination of food sources, keeping grass mowed short, using sonic cannons, recorded predator calls, and other noise generators, using lasers, flying trained falcons, training dogs, using radar equipment etc.
2. Aircraft certification programmes that employ various measures to maintain the integrity of an aircraft against the high loads resulting from high-velocity impacts in accordance with international certification standards.

The second approach will be further developed in this study. International certification regulations require that all forward-facing aircraft components be proved to withstand bird or hailstone strikes to a certain level before they can be used in an aircraft [4,5]. A bird or hailstone impact test provides a direct method for determining bird strike resistance; however, the design of aircraft structures typically involves many iterations, from design to manufacturing to testing and back, requiring that many bird impact tests be conducted. This is not only time consuming but also costly. Furthermore, experimental data from these tests are often narrowly focused, constituting a barrier for their direct use in refining structural design. Owing to these shortcomings, several numerical methods have been developed to simulate bird or hailstone strikes to reduce the number of intermediate tests required and subsequently shorten the duration of the component design phase [6-8].

With regard to high-speed effect in the course of the impact, it is a major problem to obtain data for the analysis of the mechanism of initialization and propagation of damage especially for composite material [9,10].

Impact tests

High-speed tests on simplified structures represented by flat test composite and metal plates (figure 1) have been carried out in order to verify and optimised numerical analyses.

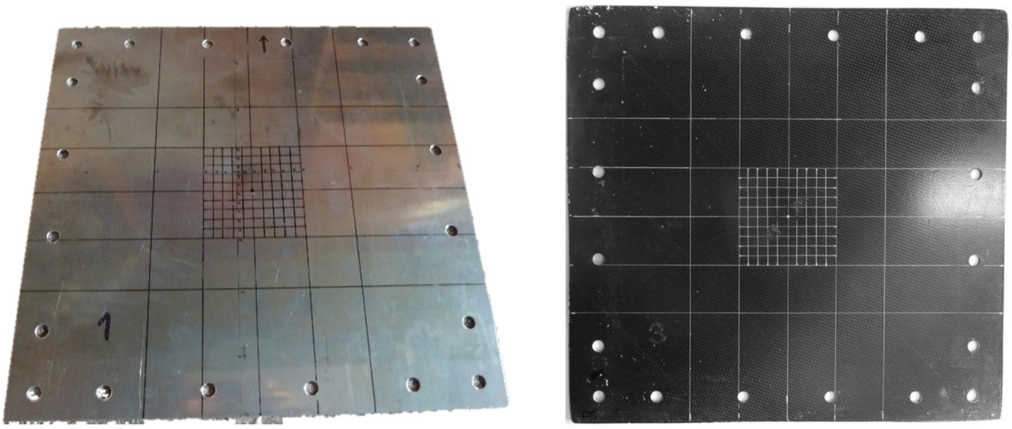


Fig. 1: Metal and composite flat test specimen

The composite flat test panel was manufactured from Hexply 8558/AGP193-PW [11] Carbon Fibre Reinforced Polymer (CFRP) composite laminated shell consisting of 10 layers $(45,0,45,0,45)_s$ impregnated with resin system in the vacuum infusion process. The test specimen was prepared by autoclave curing process.

The metal test panel was manufactured from sheet aluminium alloy 2024-T3 [11] with nominal thickness 2 mm.

The ice ball of 1-inch (2.54 cm) and 2-inch (5.08 cm) diameter [4] were used as hail stone impact projectile (Fig 2).

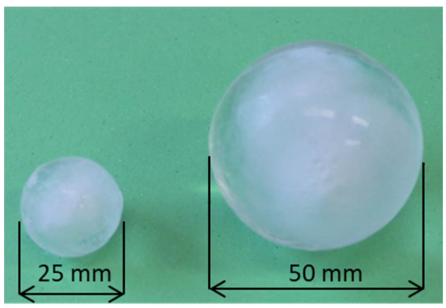


Fig. 2: Hail stone projectiles

The tests were performed in the Strength of Structure Department laboratory of VZLU (Czech Aerospace Research Centre) according to ASTM standard [4]. The air gun of VZLU was used as the test equipment (Fig.3).

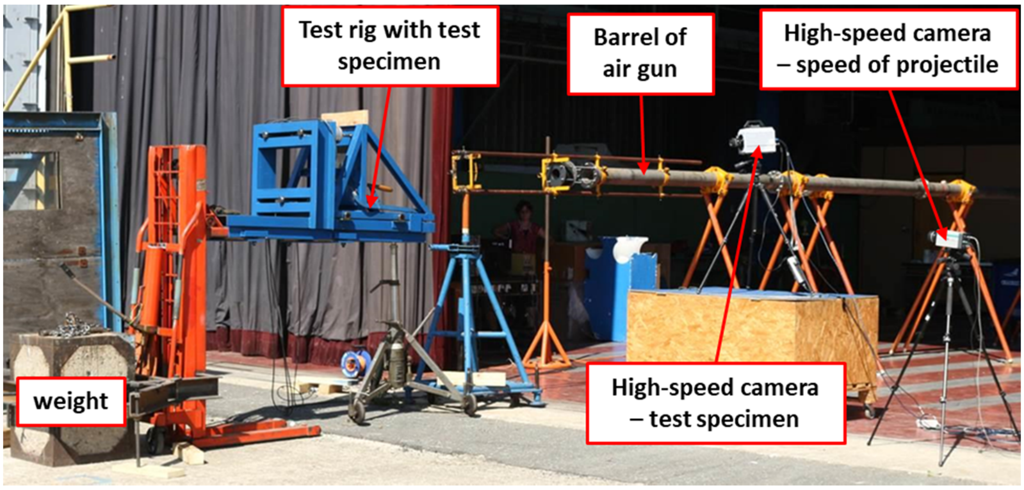


Fig. 3: Test assembly

The standard qualitative technique for high speed impact analysis such as high-speed camera and post-test non-destructive technique (NDT) were used for analysis of test results and verification of numerical model. New technique of displacement measurement by laser triangulation displacement sensor during impact was proposed and used for quantitative analysis and more precision verification of numerical model (Fig. 4).

The test specimen deformation during hail strike was measured using the laser triangulation displacement sensor with controller for analogue signal output. Measuring range of the laser sensor was 20 mm (from 40 to 60 mm off the sensor). Real point of hail impact was then determined by means of high-speed camera record and visual inspection. Measuring rate is adjustable from 1.5 to 49.1 kHz and it was set at value of 20 kHz during the test. Resolution of the sensor is 0.3 μm. Real point of hail impact was then determined by means of high-speed camera record and visual inspection. The video was shot by Photron Fastcam and Dantec NanoSence MkIII high speed cameras. One camera recorded the course of the impact from the front side, second camera was used to measure the hail speed. Velocity measurement by high speed camera was based on measurement of time which is necessary for passing of specific distance.

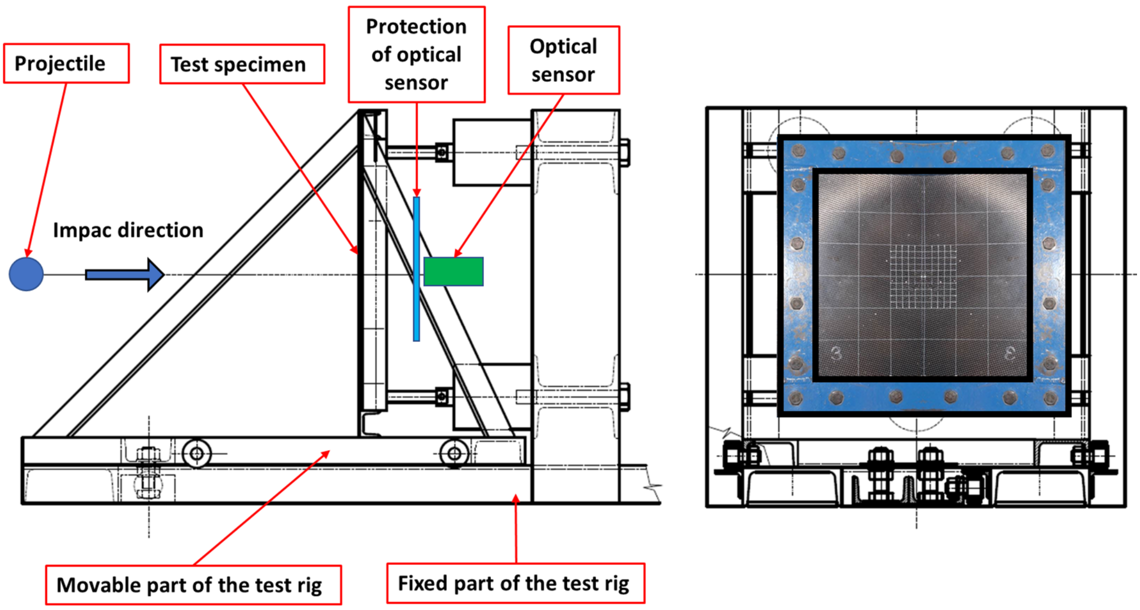


Fig. 4: Test rig with instrumentation for test specimen deformation measurement during impact

NDT of composite panels

Visual and ultrasonic non-destructive inspections of all specimens were performed before and after hail strike tests. For ultrasonic inspections was used Phased Array device (C-Scans) (see Fig.5)

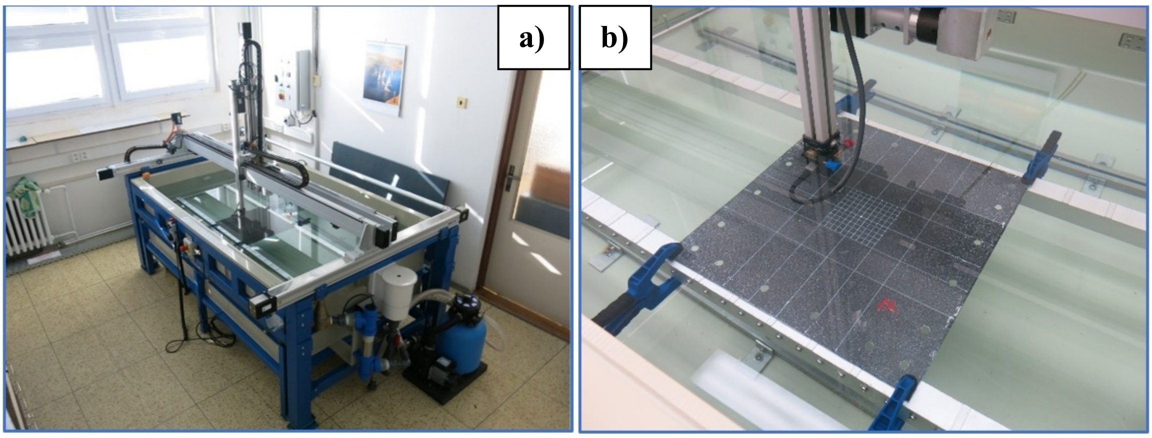


Fig. 5: Ultrasonic test NDI equipment: a) Immersion tank + automated 3-axis scanner system, b) clamping fixture

Amplitude and TOF (Time of Flight) C-scans were generated from measured data during ultrasonic inspections. PEBR (Pulse Echo Back-wall Reflection) and PEFR (Pulse Echo Flaw Reflection) techniques were used for the amplitude C-scans.

For PEBR technique the gate (Gate A) was placed over the back-wall echo and it was synchronized on the interface echo. In case of PEFR technique the start point of the gate (gate B) was behind the interface echo and the end of the gate was before the back-wall echo.

Plastic deformation

Measurement of plastic deformation of the metal test specimens was performed using raster and coordinate recorder after impact test. The plastic deformation was measured in two perpendicular directions in the center of the test specimen (see Fig.6).

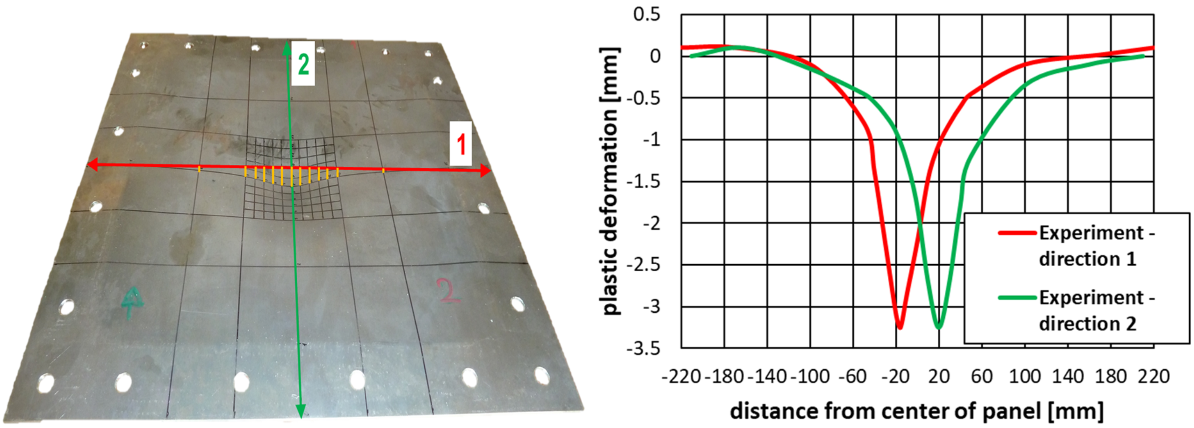


Fig. 6: Measurement of plastic deformation on metal test specimen after impact test

Numerical simulation

The FE simulation was performed using the ABAQUS FE software program [13]. 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., damage, displacement or reaction force.

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. 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 (Fig.7). The method used to adjust hail strike simulations is certified by the Czech Republic Civil Aviation Authority. The geometry of the hail stone model was meshed by 3,936, C3D8R 8 - node linear brick elements with conversion to particle elements (SPH – Smoothed Particle Hydrodynamics) [14]. The shell elements type S4R were used for simulation of the test specimen. The global mesh size of 10 mm was refined to 3 mm at the impact area.

From the viewpoint of the damage analysis of a composite material, the Hashin's damage material model was used [15]. The material properties used in Hashin's model of energy criterion in ABAQUS were adopted from reference [8]. A Johnson-Cook material model [12] was used for the metal test specimen for simulation of elastoplastic and damage behavior.

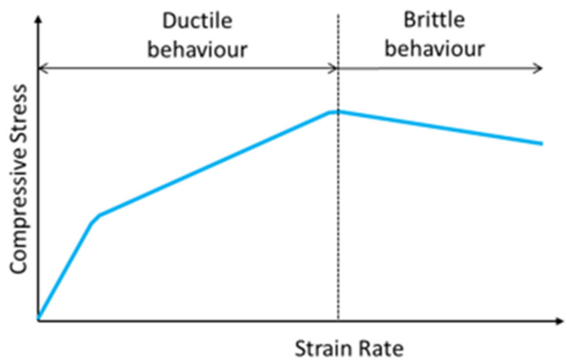


Fig.7: Ice behaviour under stress

Results

The tests results and numerical simulations were compared based on:

- Qualitative measurement – high speed camera pictures, NDT (C-scan)
- Quantitative measurement – displacement during impact and plastic deformation

Analyses of NDT and simulation results

The results from NDT (C-scan) performed after the tests were compared with composite damage criterion from numerical simulation from point of view of size and position of damage. Fig. 8 shows comparison of contour map from C-scan (delamination area) and contour map of Hashin tensile fibre damage initialization criteria. Damage initiation occurs when the index exceeds 1 (red colour in contours maps of FE analysis).

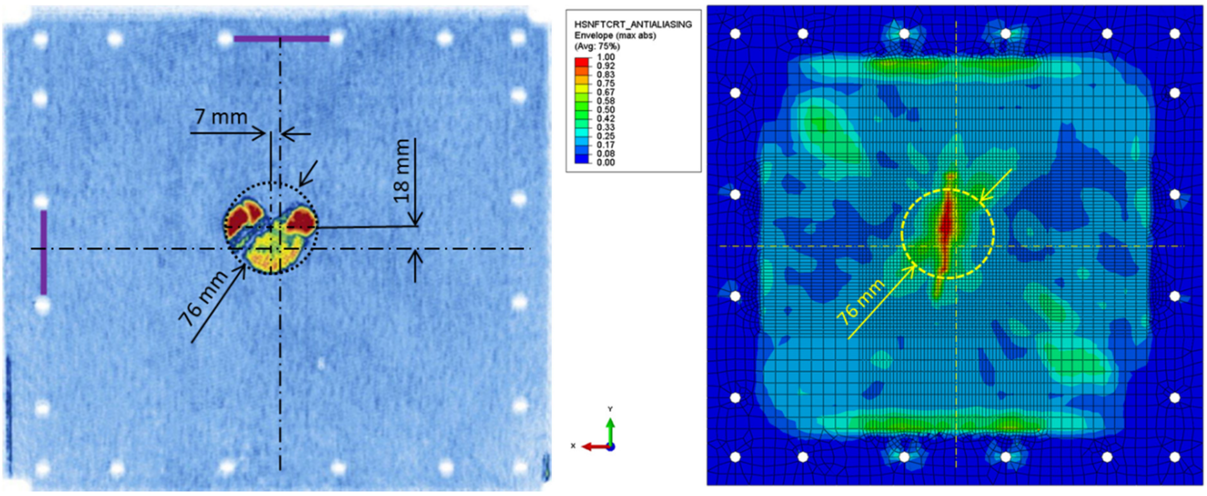


Fig. 8: Comparison between NDT (C-scan) (left) and numerical simulation (tensile fibre damage) (right) for impact test of hail stone 50 mm diameter and speed of impact 362 km/h.

Analyses of high-speed camera pictures with simulation results

The result from high speed camera was analysed from point of view of damage of impactor, analysis of impact point position or uncertainties such as damage of impactor before impact. The second-high speed camera was used for analyses of speed of impactor. The comparison of high-speed camera results with the numerical simulations for the same time of impact (see Fig. 9).

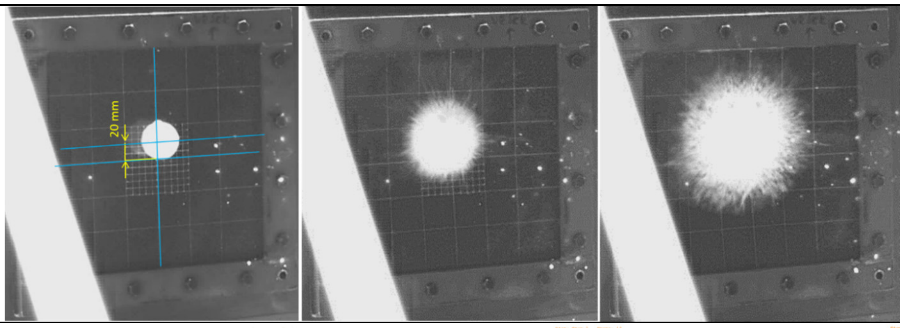
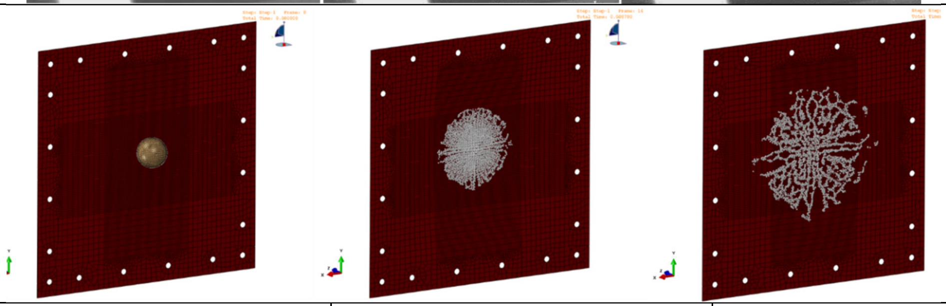
Experiment			
FEM			
Time of impact [ms]	0 ms	0.5 ms	1 ms

Fig. 9: Comparison between experiment and simulation (composite test specimen, impact speed 655 km/h, hail stone 50 mm diameter, solid laminate 10 plies)

Analyses of displacement

The displacement in centre of the test panel during the impact was analysed based on the optical sensor data. From point of view of availability of optical sensor with small range measurement, the measurement was realized only for small energy impact (small speed for hail stone of 50 mm and small diameter of hail stone – 25 mm for high speed). Small energy impact also to ensure no failure of panel and decrease of the sensor damage probability.

Figure 10 show comparison between experiment and numerical simulation. Figure 10 also shows the influence of material damping property. The Railigh damping properties (alpha = 29.4, beta = 2.72 E-7) was used from another project measurement performed in VZLU for analyses of acoustic fatigue [16].

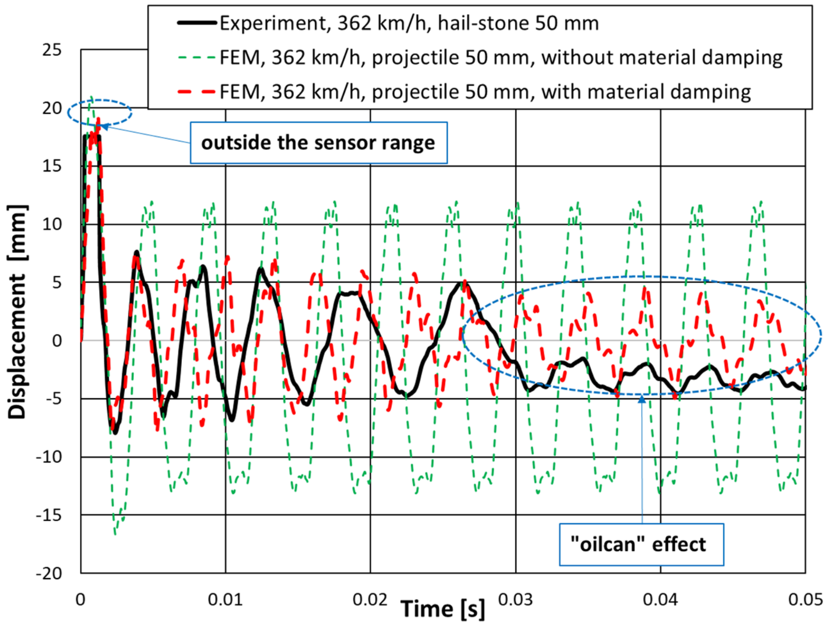


Fig. 10: Result of displacement measurement during impact of hail stone 50 mm diameter on composite panel (10 layers of CFRP) and comparison with simulations

The optical sensor data measured on composite panel shows, that maximal displacement was outside the sensor range (in this case up to 17 mm). The results also show the influence of oilcan effect on the damping and observed negative displacement. The elastic displacement was removed after unmount the test panel from the test rig.

Figure 11 show comparison between experiment and numerical simulation for metal test panel.

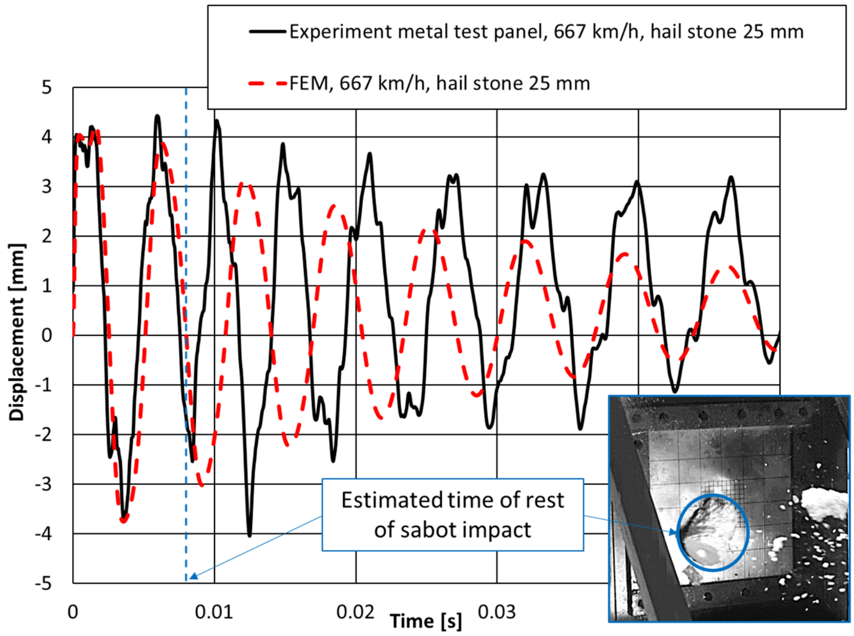


Fig. 11: Result of displacement measurement during impact of hail stone 25mm diameter on metal panel (2024-T3, 2 mm thickness) and comparison with simulation

The result from optical sensor measurement on metal test panel shows the influence of secondary impact of rest of polystyrene sabot on test specimen (Fig. 11). The time of secondary impact was estimated from high speed camera pictures.

Analyses of plastic deformation

Figure 14 shows comparison between experiment and numerical simulation for plastic deformation after impact on metal test specimen. The impact point for numerical simulation was shift on the base of real test results (high speed camera pictures and plastic deformation measurement). The differences between the numerical simulation and the experiment are mainly in the area near to the fixation of the test specimen, wherein reflected the influence of the material spring back due to plastic deformation of test specimen.

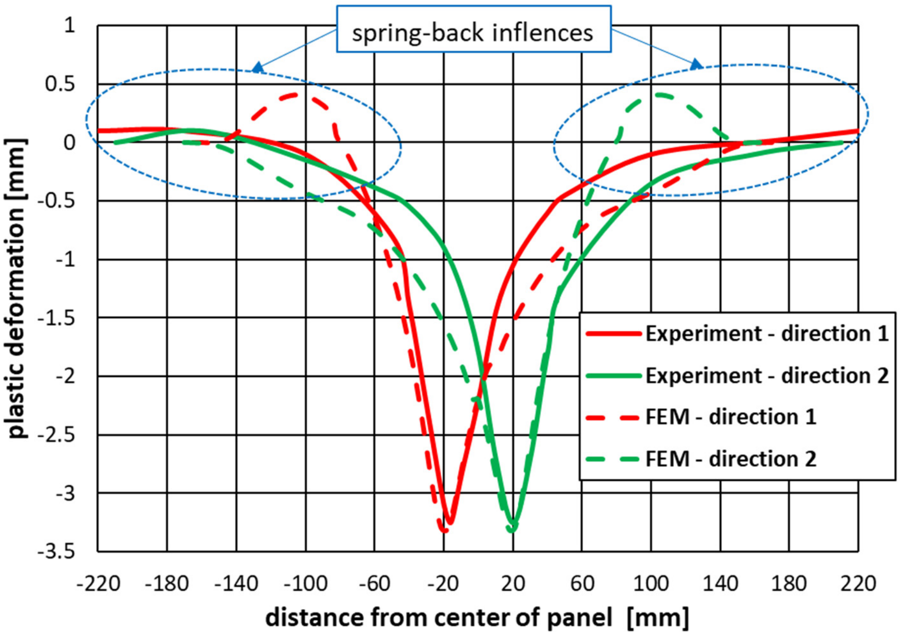


Fig. 14: Comparison between experiment and simulation of plastic deformation after impact on metal test specimen.

Conclusions

A comparison between the test and simulation results reveals consistency in predictions of damage initialization on composite material and plastic deformation on metal material.

The application new technique of displacement measurement by optical sensor during impact provided unique value for verification of numerical models.

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 and metal structures.

At the same time, the results showed the necessity to increase the sensor measurement range for application to the real application related to high-speed impact analyses.

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