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Experimental Verification of Jet Engine Composite Inlet for Bird and Hail Stone Impact Resistance

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Abstract. A simultaneous work between experiments and numerical simulations is necessary to well understand the behavior of a bird or hail during an impact and also the reaction of the impacted material and structure. A simulation methodology is developed and validated to certify the bird-strike resistance of composite air ducts designed for a new generation of jet training aircraft. The physical bird and hail impact tests were performed on real composite part. The results form numerical simulation were compared with test results. Numerical simulation was used also for test preparation and test rig design and optimization for simulation influence of surrounding aircraft structure.

The validated modelling procedure allows for the analysis of numerous bird-strike scenarios, improving the optimisation procedures for aircraft component design, and reducing the cost of development by reducing the need to manufacture test prototypes.

Introduction

Bird and hail strike is a major threat for aircraft structure, as it can lead to serious structural damage. The vulnerable parts of planes or helicopters are windshield, nose, fuselage panels, wing and empennage leading edges, rotor blades, fan blades and engines inlets. Therefore, the international certification regulation requires [1] all forward facing components to prove a certain level of bird strike resistance before they can be employed in an aircraft. A bird or hail impact experiment provides a direct method to examine the impact structure resistance.

The testing program was established to assist in the selection of a composite material and optimised lay-up from the point of view of energy absorption from bird and hail impacts on the air ducts of a new generation of jet training aircraft. The approach for development of a composite air duct for a new generation of jet training aircraft, shown in Figure 1.

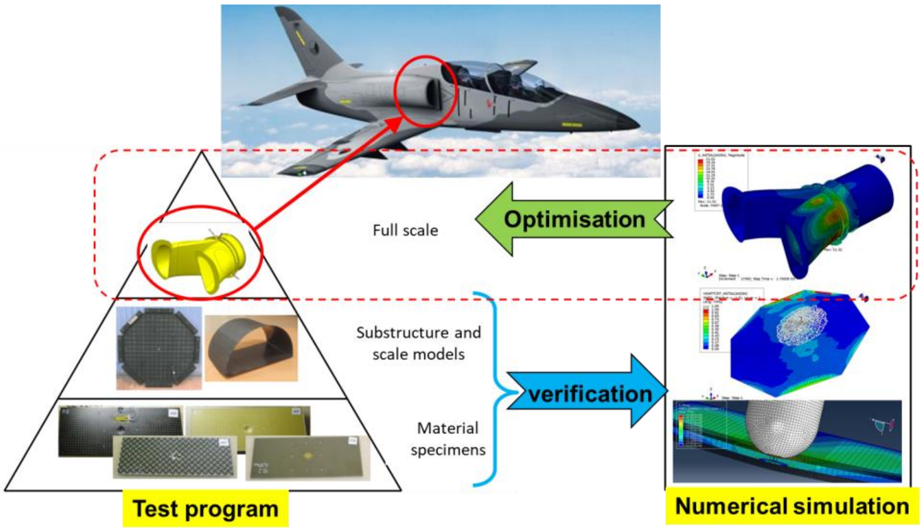

Fig. 1 Building block approach for testing and numerical simulation

The tests and analysis were initiated using low impact energy tests on small test specimens [2] according the procedures given in ASTM D7136M [3] and can be expanded to high-speed impact tests on flat test specimens to verify the manufacture and performance of a complexly shaped part. The flat test specimen used in the high-speed impact resistance verification tests was designed to provide confirmation of the performance of the selected composite material and to assist in the finite element modelling of the global structure. All numerical models were calibrated on the basis of experimental results gathered with an eye toward damage initiation and propagation behaviors. Figure 2 and 3 shows example of bird and hail stone strike experimental and numerical analysis on flat composite test specimens [4].

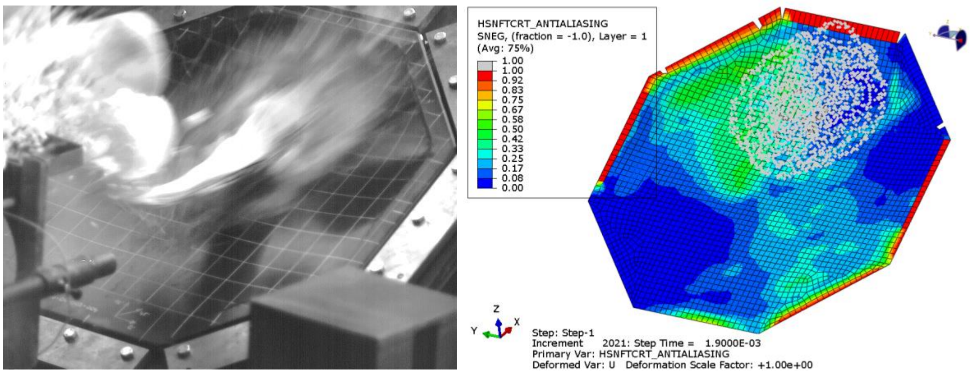

Fig.2 Bird strike test on flat test composite panel (left) and numerical simulation (right) [4]

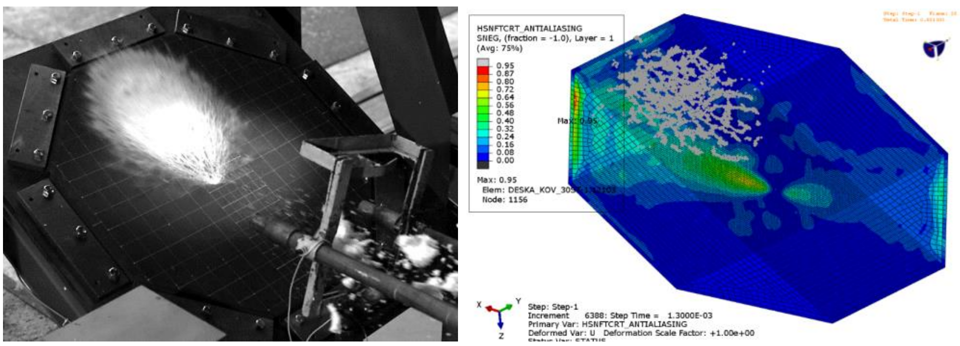

Fig.3 Hail stone impact test on flat test composite panel (left) and numerical simulation (right) [4]

Materials and methods

The physical bird and hail impact tests were performed at the Czech Aerospace Research Centre (VZLÚ) according airworthiness requirements [5] [6]. The required impact velocity was achieved using a properly pressurized air gun-type pressure vessel. The projectiles were accelerated by compressed air through the smooth borehole of the gun barrel up to its required velocity according to the specifications. Figure 4 shows the air gun test facilities.

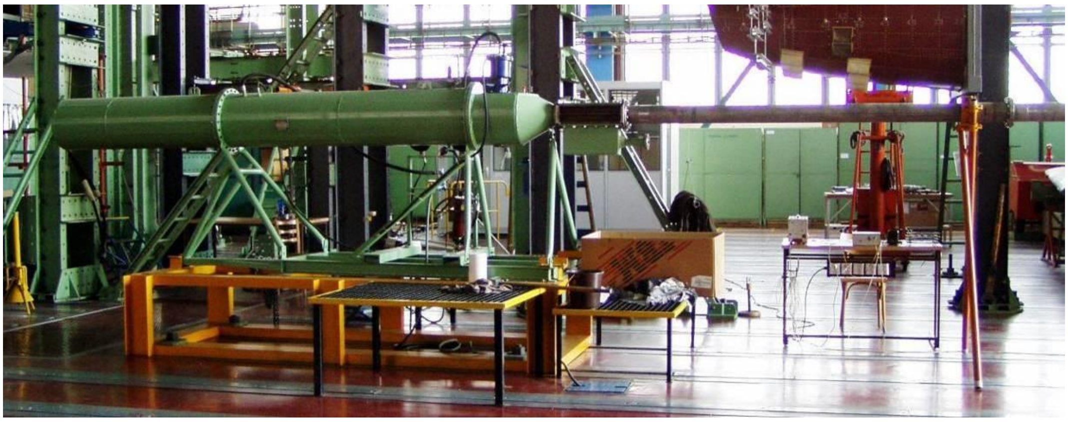

Fig. 4 VZLU air gun used for high speed impact tests

Projectiles

The projectiles used in the impact tests is 1 kg (nominally) bird [5] and for hail simulation, ice ball 25 mm and 50 mm diameter [6] (see figure 5).

Fig.5 Weighting of bird in textile bag (left) for bird strike test and ice balls (25 mm and 50 mm) for hail strike tests

Test specimen and boundary conditions

The full-scale parts of inlet were manufactured in Aero Vodochody Aerospace company using Hexply 8552/AGP193-PW prepregs [7]. The test stand was design and numerical verified from view point of real boundary condition simulation (stiffness of fuselage). Material properties for Hexply 8552/AGP193PW-37 [8] provided in the literature [7] were used for numerical analysis and are given in Table 1.

Tab. 1 Elastic material properties for Hexply 8552/AGP193PW-37 [8]

	E1 [MPa]	E2 [MPa]	Nu12 [1]	Nu13 [1]	Nu23 [1]	G12 [MPa]	G13 [MPa]	G23 [MPa]
Hexply 8552/AGP193-PW	60000	60000	0.046	0.32	0.32	5280	5280	3580

Where E is the Young's modulus, Nu is the Poisson's ratio, and G is the shear modulus.

The test stand was design and manufactured in Aero Vodochody Aerospace company. The design was and optimized from view point of real boundary condition (stiffness of fuselage) by numerical simulation in VZLÚ.

Figure 6 shows test stand and test arrangement for impact tests.

Fig.6 Test stand (left) and arrangement of impact tests (right)

Bird strike test procedure

The required impact speed for test of full scale test specimen was 594 km/h (165 m/s) for bird and 770 km/h (214 m/s) for hail stone [9]. The real speed achieved during the tests was 629 km/h for bird and 789 km/h for hail stone.

Figure 7 shows summary of measurement area for verification of structure behavior after the tests.

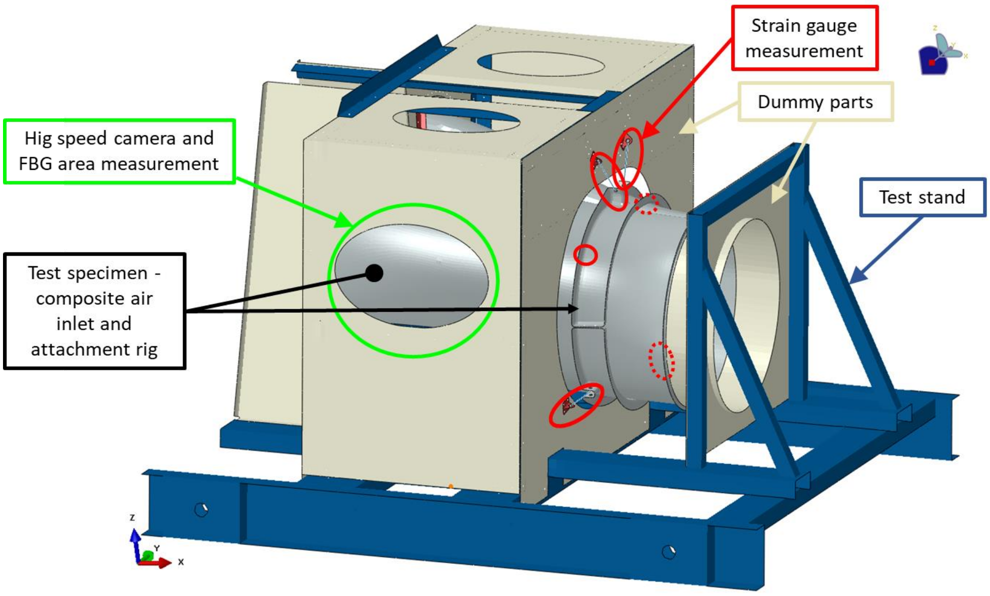

Fig.7 Shema of impact test assembly and measurement

Figure 8 shows example of high speed camera measurement from point of view of displacement in impacted area and analysis of hail stone projectile speed.

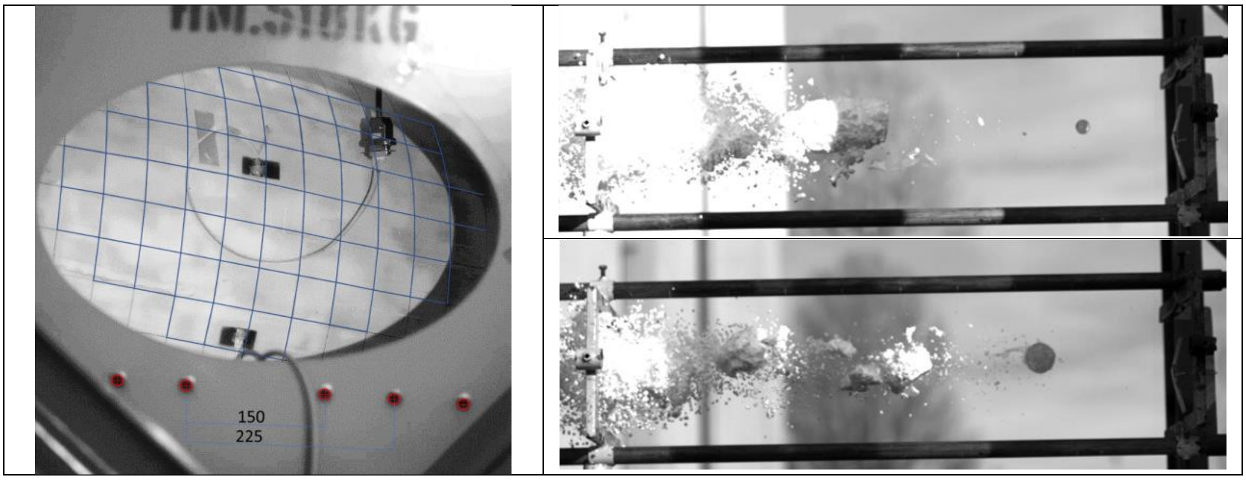

Fig.8 High speed camera pictures for deformation analysis in impacted area (left) and hail stone speed analysis (right upper - 25 mm ice ball; right bottom - 50 mm diameter ice ball)

The measurement by Fiber Bragg Grating (FBG) sensors and strain gauge measurement were performed by Czech technical university (CTU) [10]. Figure 9 shows measurement of strain on composite parts by FBG and attachment rods sensors by strain gauges.

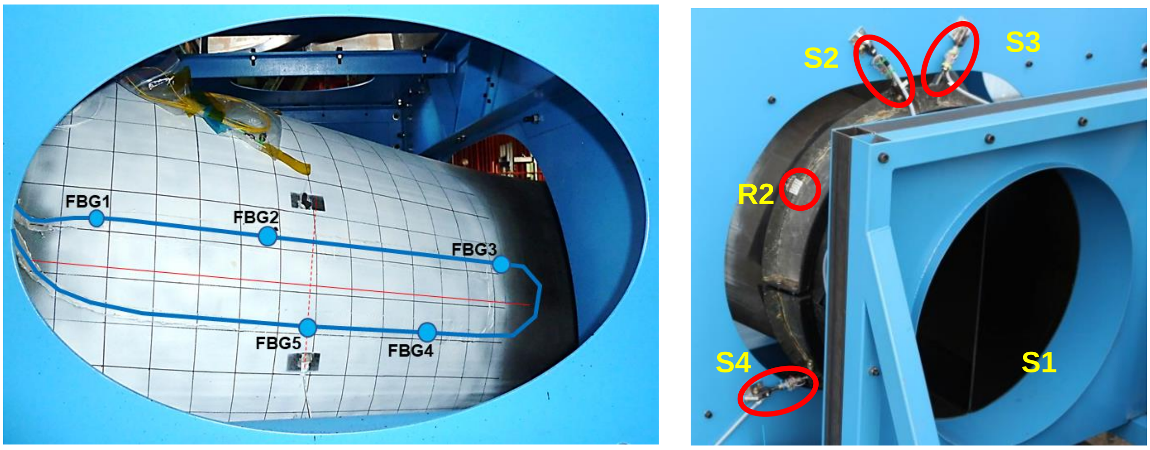

Fig.9 FBG (left) and strain gauge measurement (CTU) [10]

Numerical simulation

The numerical simulation was focused from point of view of high energy impact on birds strike test simulation.

A bird strike is a high-velocity impact in which materials with a huge difference in properties (a bird is a soft impacting material compared to the stiff material of the target aircraft body) come into contact with each other, resulting in nonlinear material behavior, high strain rates, and extremely large deformations. Nonlinear finite element software has the capability to predict the loads and deformations of both the bird projectile and the complex aircraft component being impacted within acceptable levels of accuracy. In high-velocity impacts, the pressure on the bird tissues severely exceeds their limits, causing the bird material to behave like a fluid [3].

Thus, the bird material can be described by the so-called "elastic-plastic hydrodynamic" material model. The hydrodynamic material model is defined in ABAQUS [11] by a tabulated equation of state using Hugoniot curves for water-like homogenized bird materials [12] [13]. The bird nodes were charged with an initial velocity, and a combination of tensile failure and shear failure criteria were used.

The geometry of the projectile (bird) was idealized as a 60-mm-long cylinder with two hemispheric ends having a radius of 60 mm. The bird geometry used in the simulation reflects the general geometry of the bird projectile used in the physical experiments. Figure 10 shows the geometry of the bird model, which was meshed by 10,770, C3D8R 8-node linear brick elements with conversion to particle elements (SPH – Smoothed Particle Hydrodynamics) [11]. The density of the bird material in the model for the defined volume was established to reflect the weight of the birds used in the physical tests.

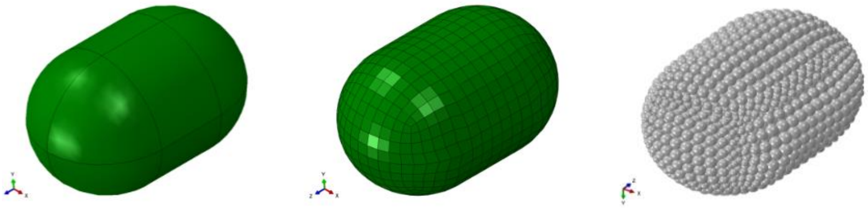

Fig. 10 Geometric model (left), FE mesh (centre), and SPH elements (right), of the idealised bird

To simulate the composite structure, 4-node shell elements (S4R) with a mesh size of 10 mm were used. The test rig was simulated by 4-node shell elements (S4R), truss elements (T3D2) and beam elements (B31).

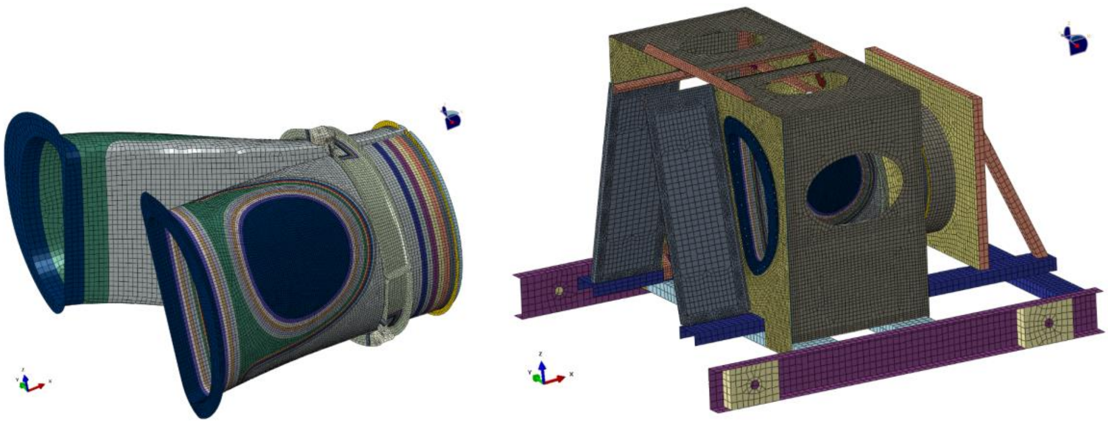

Fig.11 FE model of composite inlet (left) and FE model of test assembly (right)

The FE simulations were performed using the ABAQUS FE software package [11]. An explicit solver with double precision was used for the analysis. The general contact was used for contact analysis. From the point of view of the damage analysis of a composite material, the Hashin's damage material model was used [14].

Figure 11 shows the FE mesh of composite test specimen and full-scale test. Figure 12 shows examples of composite and test rig FE analysis.

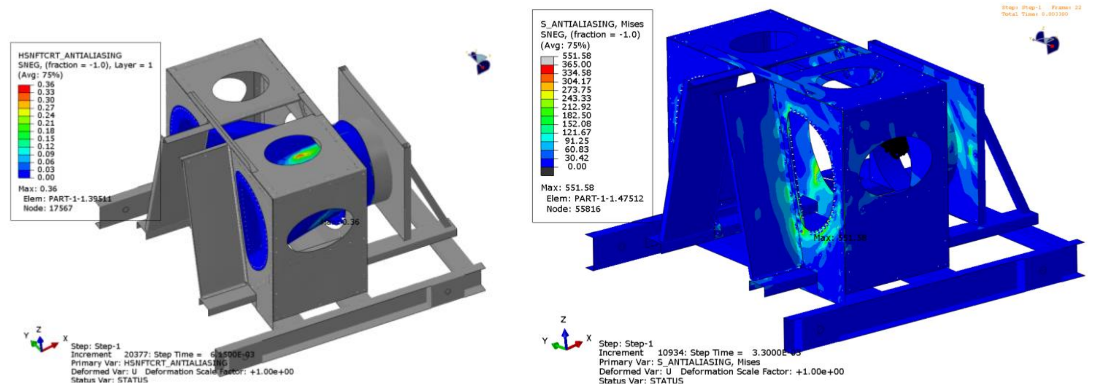

Fig. 12 FE analysis of composite parts (left) and test rig with dummy parts (right)

Results and discussion

Impact test results

The tests were analyzed as follows:

- The displacement in impact area from high-speed camera images.
- The strain from FBG sensors (CTU).
- The forces on rod attachments.
- Non-destructive testing (NDT) before and after impact.

Deformation was analyzed on the basis of the movement of raster lines and scaled on the basis of known dimensions and the camera position. This figure also summarizes the results from the NDT measurements of the demonstrator after testing, to correlate with numerical simulation.

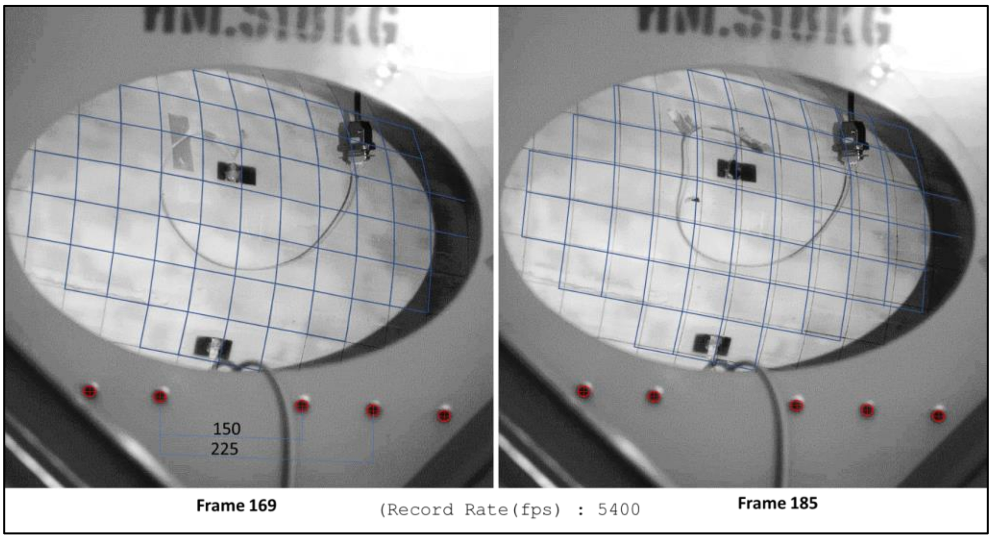

Fig.13 Analysis of high speed camera pictures (grid displacement)

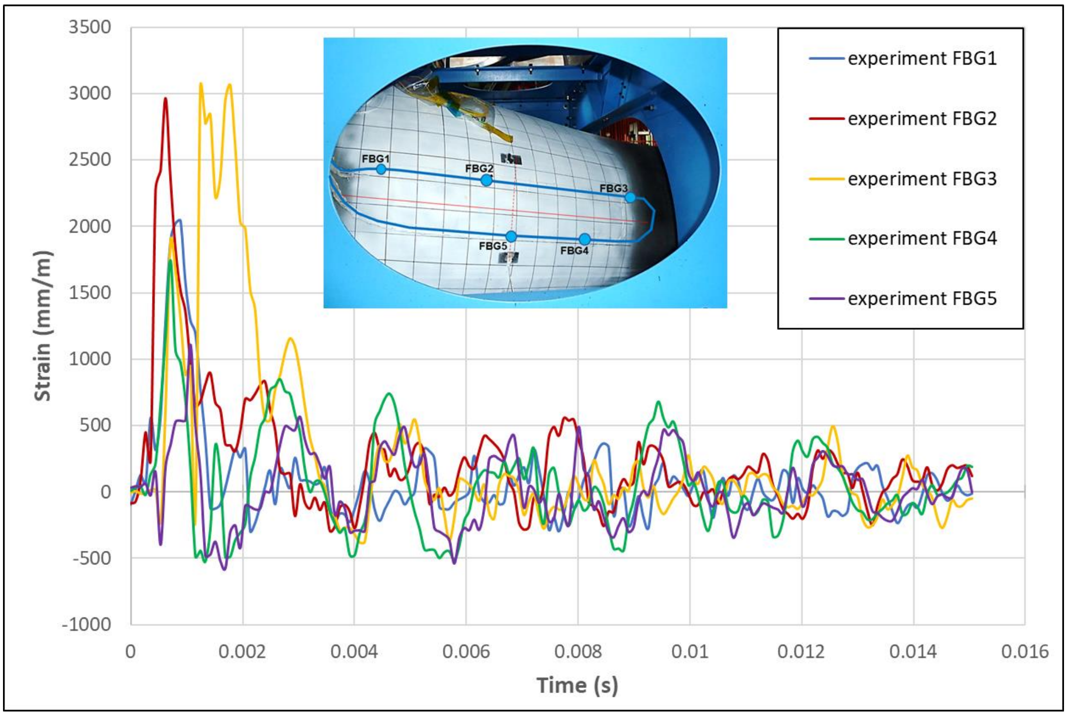

Fig.14 Strain measurement by FBG sensors during impact (CTU) [10]

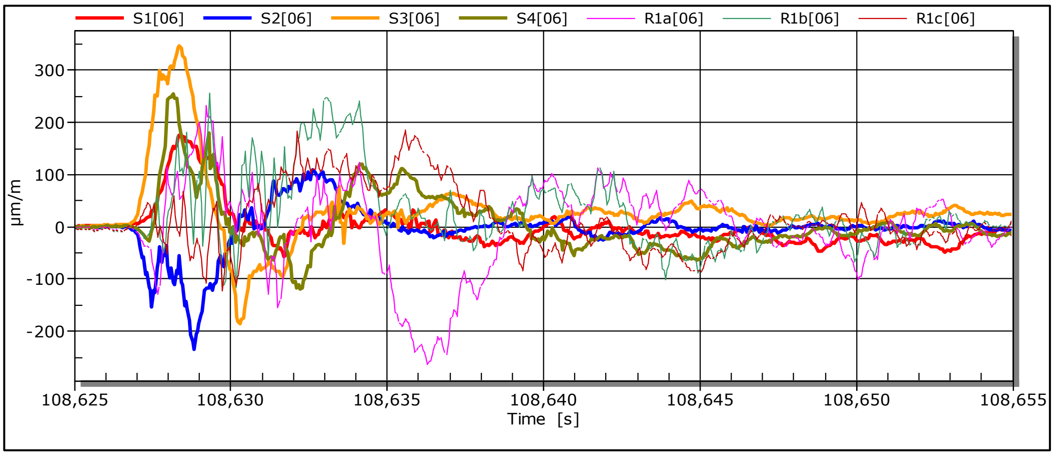

Fig.15 Strain gauge measurement during impact on attachment rods and attachment rig (CTU) (see figure 9) [10]

The whole composite air duct assembly was subjected to detailed non-destructive inspections before and after the impact tests. The NDT activities consisting of visual and ultrasonic inspections were performed by Level 2 qualified NDT staff.

During the inspections, various ultrasound technologies and methods were tested to find the most appropriate inspection procedure (figure 16). Both conventional A-scan inspection using single-element UT probe and B-scan or C-scan inspection using Phased Array technology were performed.

This ultrasonic equipment was used for the activities:

- Flaw detector Omniscan MX2 with UT module OMNI-M-PA16128
- Single-element probe Sonatest PRDT 2550 5MHz
- PA probe 5L64-A2 with contact wedge SA2-0L
- PA probe 2.25L128-I3 with contact wedge SI3-0L
- Manual PA scanner RollerFORM 5MHz

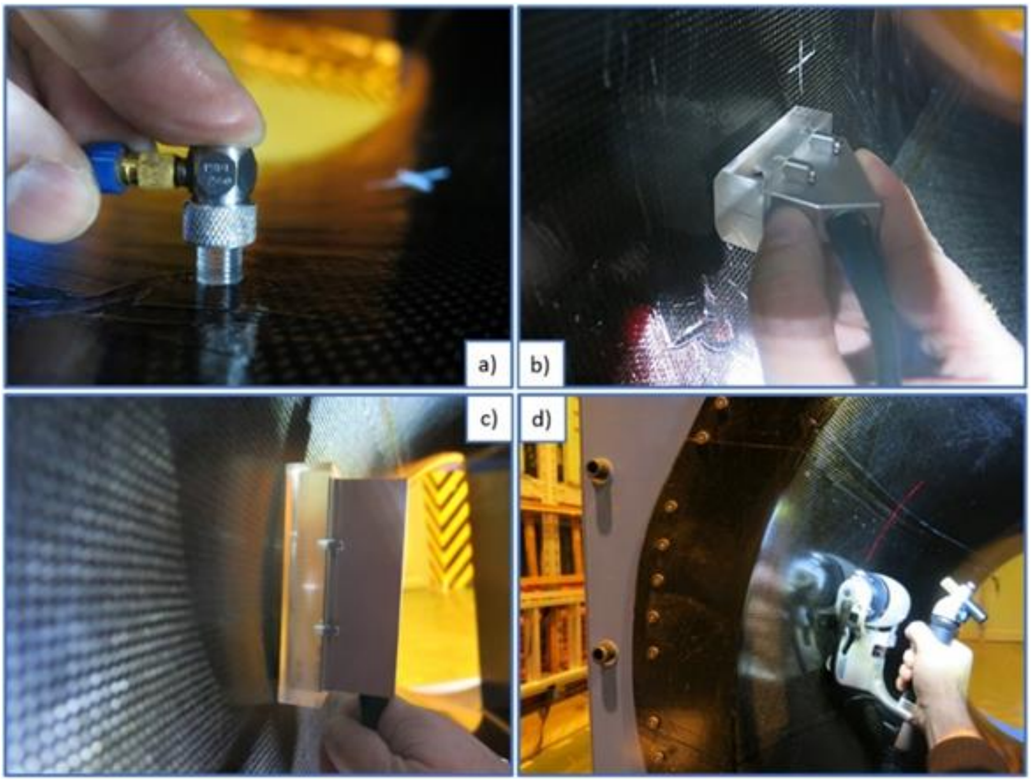

Fig.16 NDT measurement: a) Sonatest PRDT2550 probe; b) PA 5L64 probe; c) PA probe 2.25L128 and d) RolerForm 5 MHz.

Comparison of results

The results from the numerical simulation were compared with the experiment results for bird strike test.

Figure 17 shows the results of the qualitative measurement of the maximum displacement of composite inlet. The measurement was performed for maximal displacement in the measurement are corresponding to the time impact 3 ms.

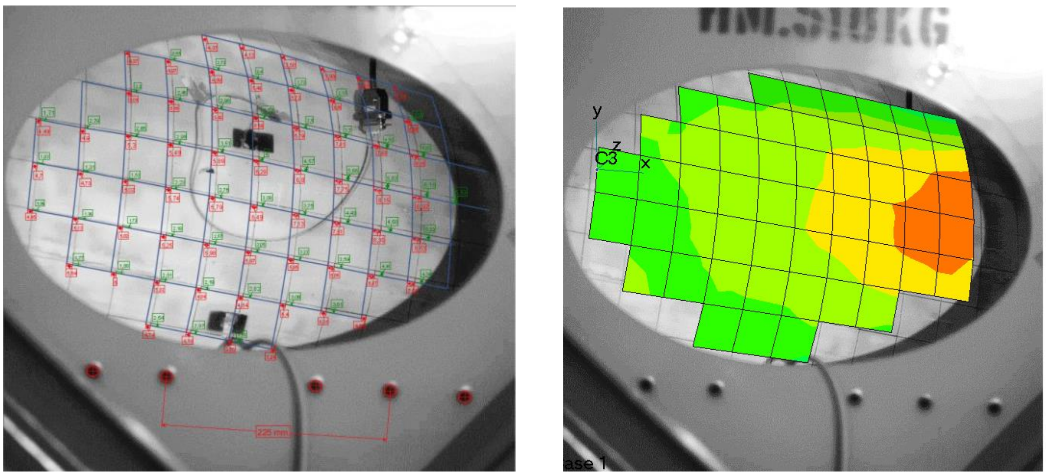

Fig.17 Analysis of displacement on the base of grid movement from high-speed camera pictures

Figure 18 shows comparison of displacement measurement from experiment and result of numerical simulation.

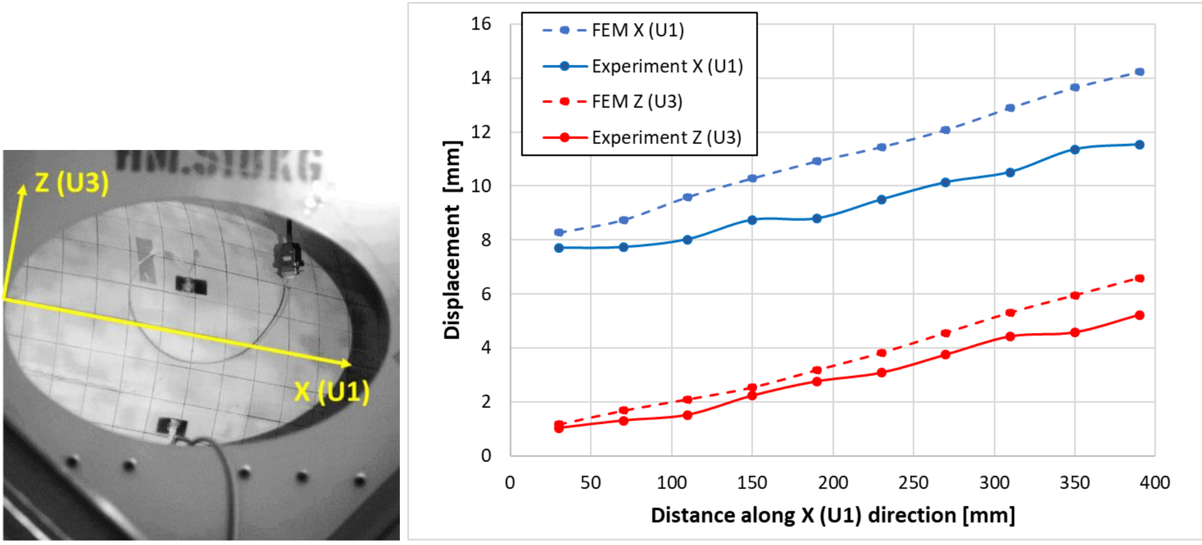

Fig.18 Comparison between qualitative measurement of displacement from high speed camera picture and numerical simulation for time impact 3 ms.

The differences between experiment and simulation is more based resolution of pictures from high speed camera and distortion by perspective.

Figure 19 shows comparison between experiment and numerical simulation on strain gauge measurement on attachment rods.

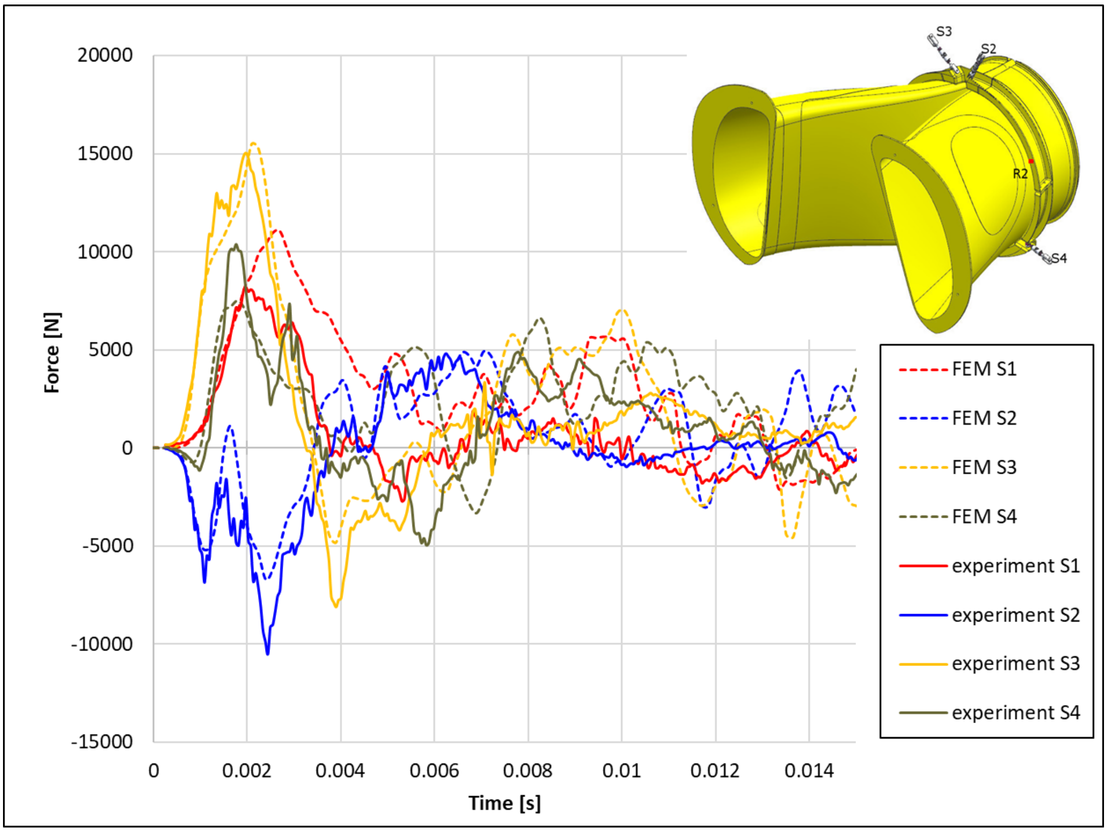

Fig.19 Comparison between experiment measurement of attachment rods load during impact and numerical simulation results. The results were compare for maximal peak of load.

The differences between experiment and simulation form figure 19 is more based on unknown or difficult defined boundary condition e.g. pretension, friction, damping etc.

Figure 20 to 24 shows comparison between results from strain measurement on FBG sensors and numerical simulation. The data used for comparison not filtered.

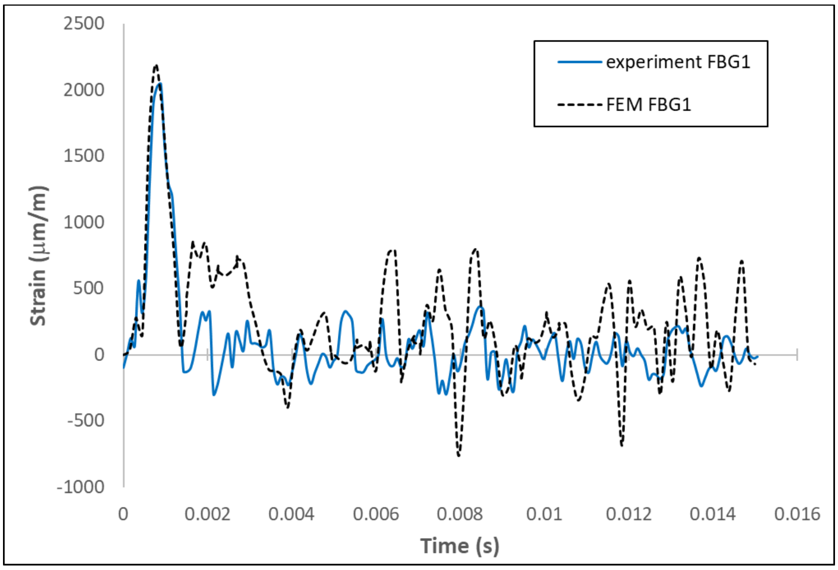

Fig.20 comparison between strain measurement on FBG sensors and numerical simulation for sensors FBG1 (see figure 9)

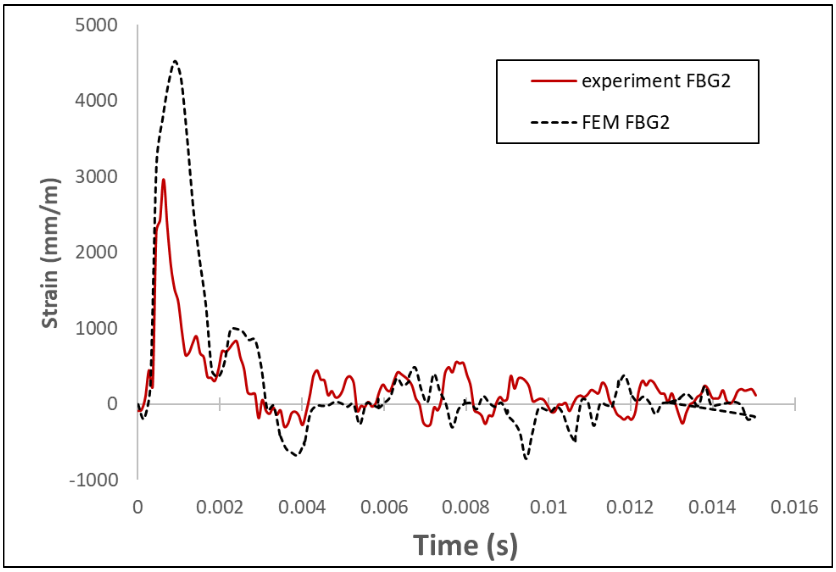

Fig.21 comparison between strain measurement on FBG sensors and numerical simulation for sensors FBG2 (see figure 9)

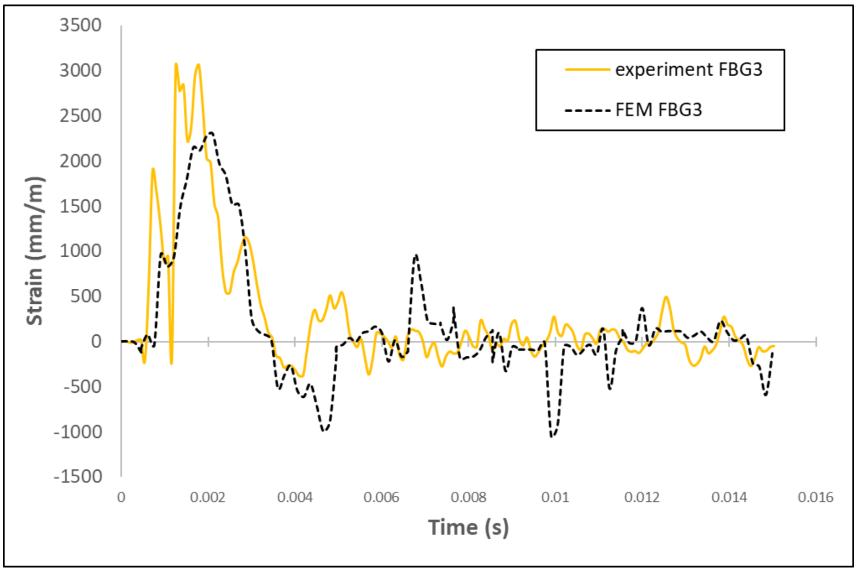

Fig.22 comparison between strain measurement on FBG sensors and numerical simulation for sensors FBG3 (see figure 9)

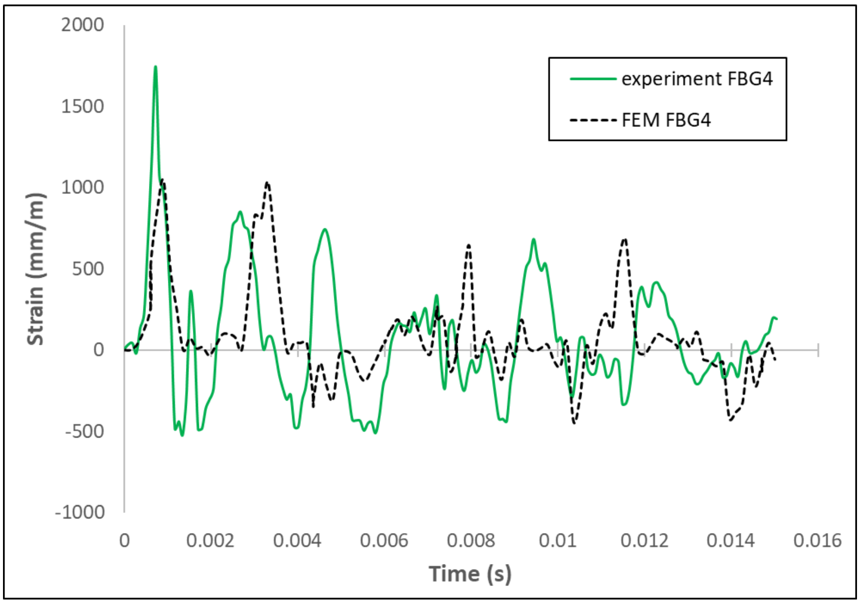

Fig.23 comparison between strain measurement on FBG sensors and numerical simulation for sensors FBG4 (see figure 9)

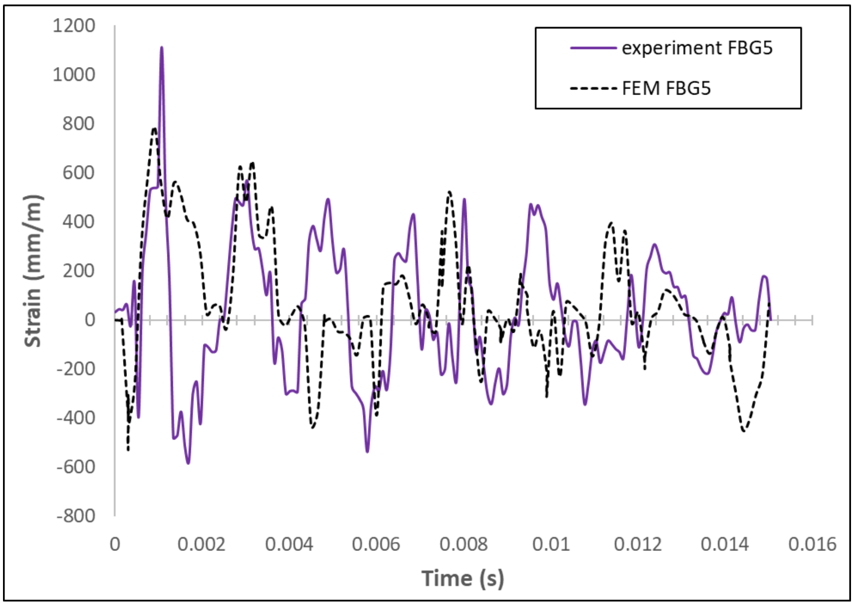

Fig.24 comparison between strain measurement on FBG sensors and numerical simulation for sensors FBG5 (see figure 9)

The results from FBG sensors shows very good correlation with results from numerical simulation especially in sensors near the impact point (sensors (FBG1, FBG2 and FBG5).

The NDT inspection confirm that no damage observed before and after the tests.

Conclusions

The comparison between test and simulation shows good harmony in prediction of structure behavior. The result of tests confirms impact resistance of proposed composite structure design for real service operation according airworthiness requirements.

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