Application of bird-strike verified analysis for the design of fast helicopter composite cowling

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Abstract

Purpose – The purpose of this paper is to describe the approach for the design of cowlings for a new fast helicopter from the perspective of airworthiness requirements regarding high-speed impact resistance.

Design/methodology/approach – Validated numerical simulation was applied to flat and simple curved test panels. High-speed camera measurement and non-destructive testing (NDT) results were used for verification of the numerical models. The final design was optimized and verified by validated numerical simulation.

Findings – The comparison between numerical simulation based on static material properties with experimental results of high-speed load shows no significant influence of strain rate effect in composite material.

Research limitations/implications – Owing to the sensitivity of the composite material on technology production, the results are limited by the material used and the production technology.

Practical implications – The application of flat and simple curved test panels for the verification and calibration of numerical models allows the optimized final design of the cowling and reduces the risk of structural non-compliance during verification tests.

Originality/value – Numerical models were verified for simulation of the real composite structure based on high-speed camera results and NDT inspection after impact. The proposed numerical model was simplified for application in a complex design and reduced calculation time.

Keywords Helicopter, Composite, Finite element (FE), Bird strike, Cowling

Paper type Research paper

1. Introduction

Foreign object impacts, such as birds, hail, debris etc., are important phenomena that must be taken into consideration when designing aircraft. The critical parts of planes or helicopters are windshield, nose, fuselage panels, wing and empennage leading edges, rotor blades, fan blades, engines cowlings and inlets (Hedayati and Sadighi, 2015).

International certification regulations require that all forward-facing aircraft components should be proven to withstand bird strikes to a certain level before they can be employed in an aircraft (European Safety Agency, 2012). A bird 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. These empirical verifications, which cause damage to

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expensive prototypes or part of structure (Georgiadis *et al.*, 2008; Guida *et al.*, 2013; Rajesh Poola, 2011) and the biological hazard of using real birds, can be costly and time-consuming. 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 based on CEL (Coupled Eulerian–Lagrangian) (Smojver and Ivancevic, 2010) or SPH (smoothed particle hydrodynamics) (Allaeys *et al.*, 2017; Grimaldi *et al.*, 2013; Cardona *et al.*, 2019) have been developed to simulate bird strikes to reduce the number of intermediate tests required and subsequently shorten the duration of the component design phase. More of these bird models are verified only on isotropic material or impact on the rigid wall (Wilbeck, 1978; Hedayati and Ziaei-Rad, 2013).

The principal objective of the present work is to provide a more universal experimental procedure, applicable, e.g. for a different type of material or technology production, for verification of numerical model for bird strike analysis on the real composite structure. The verified numerical simulation will allow the design to be optimized for the next to satisfy certification on final design respectively expensive prototypes.

The testing program was established to assist in the selection of composite material and optimized lay-up from the point of view of energy absorption from bird and hail impacts on the composite cowlings of the new high-speed helicopter. The tests and analysis were initiated using low impact energy tests on small test specimens according to the procedures given in ASTM D7136M (ASTM D7136M-20, 2020) 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 and simple curved 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 (FE) modelling of the global structure (Doubrava *et al.*, 2019). All numerical models were calibrated based on experimental results gathered with a visual observation toward damage initiation and propagation behaviours. Figure 1 shows the building block diagram for the proposed approach.

2. Materials and methods

The test program aimed to obtain inputs for verification of simulation technique of complex composite airframe design from point of view of high-speed impact resistance. The test

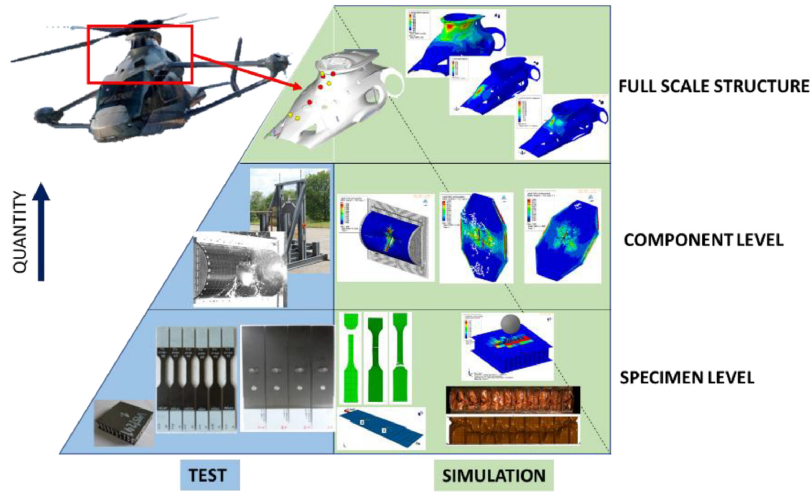


Figure 1.
Building block diagram (BBD) for bird strike resistance analysis of composite cowlings

program was adapted to obtain inputs in terms of application of simplified models for explicit solver analysis (large size of FE elements for a decrease of critical calculation time) and also from point of view of easy production of the test specimen. The simplification of simulation and decrease of calculation time is important for optimization of design, lay-up, fasteners, etc.

The standard and non-standard uniaxial tension and compression tests were used for input material properties onto numerical models on specimen level (see Figure 1). The standard out-of-plane compression performance of the Sandwich was measured according to ASTM C365M standard (ASTM C365/C365M-16, 2016) used to determine flatwise compressive properties of Sandwich cores. The test was performed in the Instron 55R1185 loading machine between two flat platens using a displacement control rate of 1 mm/min (Figure 2).

Non-standard high-speed load uniaxial tests were used to determine material and mechanical joints behaviour at high load rates (see Figure 3). Load rate was 5, 2 and 10 m/s. The main focus was on inputs for simulation of honeycomb Sandwich core and mechanical fasteners of composite parts of the airframe.

The influence of high-speed load and inputs for the FE model of airframe and bird projectile was verified by flat and simple curved test specimens on a component level (see Figure 1). The results from calibration and simulation on specimen and component level were used for simulation and optimization of the real airframe on full-scale level of proposed BBD (Figure 1).

Impact tests for component level were performed at the Czech Aerospace Research Centre (VZLU). The required impact velocity was achieved using a properly pressurized air gun-type pressure vessel. The real bird projectiles (chicken) were used during the experimental verification according to airworthiness requirements (Doubrava *et al.*, 2019). The weight of the bird projectile was 1 kg (European Safety Agency, 2012). The projectiles were accelerated by compressed air through the smooth borehole of a gun barrel up to the required velocity according to specifications. Figure 4 shows the air gun test facilities.

Based on the input data from the specimen level and preliminary design of the structure, test specimens were designed to verify the impact resistance of the structure and numerical models. The experiments aimed to verify both numerical models of the ownership structure

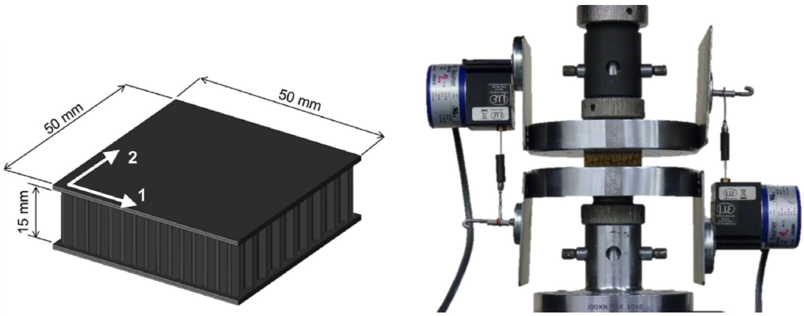


Figure 2.
Out of plane compression test of Sandwich structure

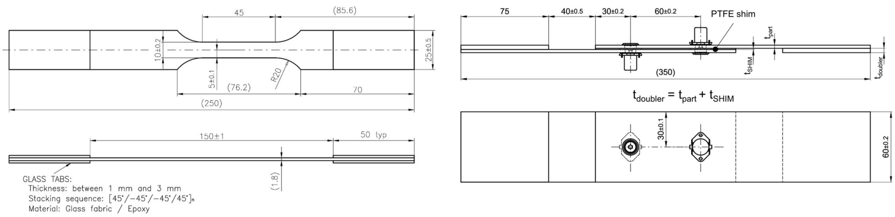


Figure 3.
High-speed load uniaxial tests of composite material and mechanical fasteners of composite parts of the airframe

and the numerical model of the bird projectile. The flat and curved panels were defined in dependency on the preliminary design of the final part, bird mass and impact speed range. The flat test specimens represented monolithic and Sandwich structure design. The simple curved test specimens represented Sandwich structure design. The VZLU test rigs designed from point of view of numerical boundary conditions were used for attachment and instrumentation of the tests (Figure 5).

For the flat test specimen (Figure 6a), it was realized 6 perpendicular impacts and 6 declined impact 45° with a range of impact speed from 375 to 586 km/h. For simple curved test specimens (Figure 6b), it was realized three bird strike tests with a range of impact speed from 326 to 450 km/h. The speed of impact was defined on the result of the previous test from point of view of panel damage or failure. The main criterion was visible damage. The change of projectile speed before impact was about 10%.

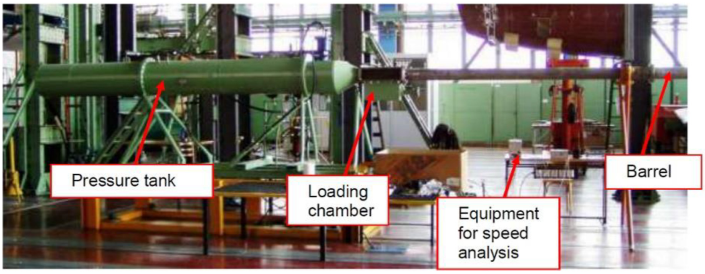


Figure 4.
VZLU air gun for bird strike tests

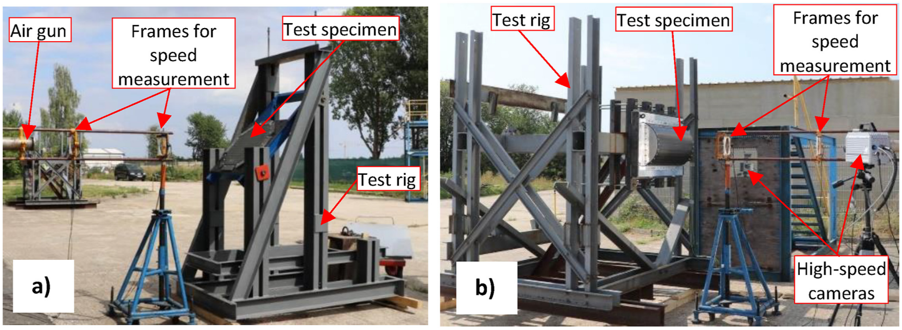


Figure 5.
VZLU test rigs to attached of flat (a) and curved (b) test specimen for bird strike tests

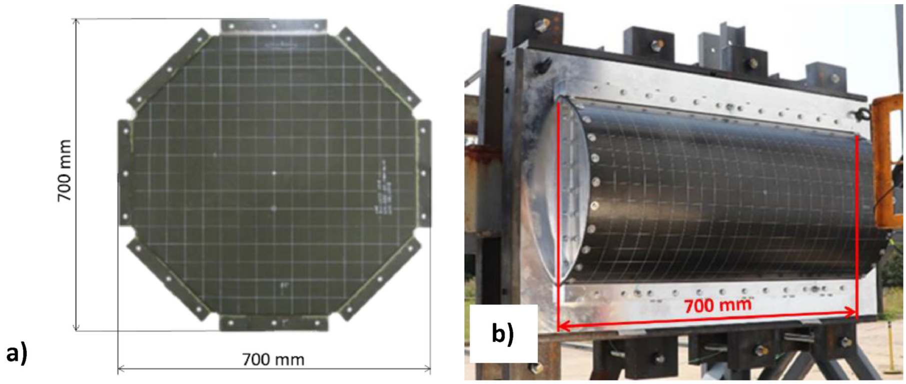


Figure 6.
Flat (a) and curved (b) test specimen

The test results are compared to numerical simulations and the correlation of the models is performed. Altered parameters for material properties calibration on the base of test results were porosity of the projectile, fracture energy of composite material and hardness parameters of crushable foam material model of the Sandwich core. The input parameters for calibration from the test results were maximal displacement during impact, reaction forces and results from non-destructive inspections (NDIs).

Instrumentation of bird strike tests included high-speed camera (Photron FastCam SA-Z type 2100K), measurement of high-speed load cells (KISTLER 9105A) for reaction force measurement and projectile speed measurement based on the principle of time measurement, which the projectile needs for transit of selected distance (high-speed camera Photron Fastcam SA-1).

Visual and ultrasonic NDIs of all specimens were performed before and after bird strike tests. Monolithic panels and skins of flat Sandwich panels were inspected by immersion C-scan Pulse-Echo method.

3. Numerical simulation

The FE simulations were performed using the ABAQUS/Explicit FE software package (ABAQUS 6.14). An explicit solver with double precision was used for the analyses. The general contact of ABAQUS/Explicit was used for contact analysis between all parts of the FE model during impact analysis.

The particle elements with the hydrodynamic material model were used for bird projectile simulation (Abdullah *et al.*, 2021). The hydrodynamic material model is defined in ABAQUS (Grimaldi *et al.*, 2013) by a tabulated equation of state using Hugoniot curves for water-like homogenized bird materials (Cardona *et al.*, 2019). The geometry of the bird model was meshed by 10,770, C3D8R 8-node linear brick elements with conversion to particle elements (Cardona *et al.*, 2019; Abdullah *et al.*, 2021). 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. Two geometry type of projectile (ASTM F330-10, 2010) (sphere and cylinder with spherical ends) was used for analysis (see Figure 7) from point of view of different impact energy distribution.

From the point of view of the damage analysis of composite material, Hashin's damage material model was used (Hashin, 1981; Batra *et al.*, 2012; Sánchez-Sáez and Barbero, 2007; Heimbs, 2011). The expressions for the Hashin tensile fibre failure criteria, after some bi-dimensional simplifications ($\sigma_3 = \tau_{13} = 0$), are shown below in equations (1) and (2). Damage initiation occurs when either of these indices exceeds 1.

$$\left(\frac{\sigma_1}{\sigma_{1u}^t}\right)^2 + \left(\frac{\tau_{12}}{\tau_{12u}}\right)^2 = 1 \qquad (\sigma_1 > 0) \tag{1}$$

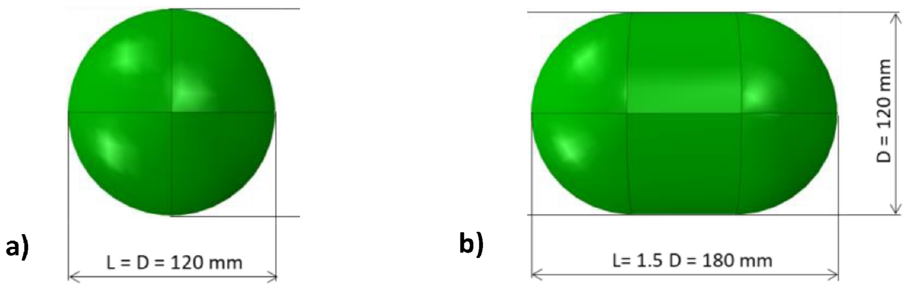


Figure 7.
The geometry of projectiles used for numerical simulation (a – sphere; b – cylinder with spherical ends)

$$\left(\frac{\sigma_2}{\sigma_{2u}^t}\right)^2 + \left(\frac{\tau_{12}}{\tau_{12u}}\right)^2 = 1 \qquad (\sigma_2 > 0) \tag{2}$$

where σ_1 is the stress in direction 1; σ_{t1u} is the ultimate tensile stress in direction 1 (maximum tensile longitudinal strength); σ_2 is the stress in direction 2; σ_{t2u} is the ultimate tensile stress in direction 2 (maximum tensile transversal strength); σ_3 is the stress in direction 3; τ_{13} is the shear stress in plane 1–3; τ_{12} is the shear stress in plane 1–2 and τ_{12u} is the ultimate shear stress in plane 1–2 (maximum shear strength in plane 1–2).

To simulate the composite structure, 4-node shell elements (S4R) with a mesh size of 10 mm were used.

4. Verification of numerical simulation

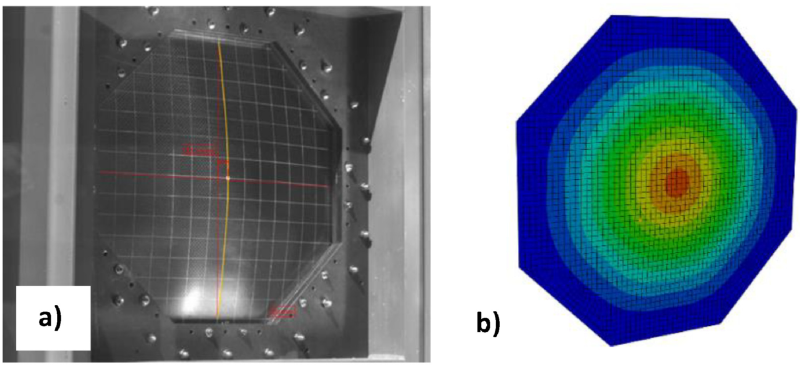
The test results are compared to numerical simulations, and the correlation of the models is performed. Altered parameters for material properties calibration on the base of test results were porosity of the projectile, fracture energy of composite material and hardness parameters of crushable foam material model of the Sandwich core. The input parameters for calibration from the test results were maximal displacement during impact, reaction forces and results from NDIs. The stiffness and strength parameters of the material was not changed.

Figure 8 shows an example of an analysis of maximal displacement during the impact.

Figure 9 shows the comparison between the result of NDI and numerical simulation (red colour shows damaged area). Some differences in the direct comparison of the experiment with numerical simulation stem mainly from the different concentrations of the mass of the real projectile – bird (tissue, bones etc.) during the impact with an ideal numerical model. The differences between simulation and experiment are also caused by the replacement of real physical boundary conditions by substitute mathematical ones in numerical models. Only the real bird projectiles (chicken) were used during the experimental verification.

Curved specimens were inspected manually by the A-scan method. Figure 10 shows the comparison between the test result and numerical simulation from point of view of the damaged Sandwich core.

The results of the tests and numerical simulations were also qualitatively assessed based on the high-speed camera pictures in terms of projectile behaviour and failure of the test specimens (Figure 11).



Note(s): The red line (a) shows an undeformed shape and the yellow line maximal deformed shape

Figure 8. Analysis of maximal displacement from the high-speed camera (a) and the result of numerical simulation (b)

5. Application on real structure

The analyses of full-scale composite cowlings were performed according to CS29.631 airworthiness requirements (Cardona *et al.*, 2019) for a cruise speed of approximately 220 kts and bird mass of 1 kg. The design of composite cowlings and integrated parts of a structure, such as frames, antennas and fasteners, were analysed for 11 bird trajectories and two lengths of the bird projectiles (Figure 12b).

The global FE model (Figure 12a) used the same parameters as used for verification and calibration of FE models of flat and curved panels, such as size and quality of element, properties, etc. The global model was generated from a CATIA CAD model. The FE mesh was generated in HyperMesh software and converted to ABAQUS/Explicit solver. The global model contained nearly 300,000 shells, solid and fastener elements. The fasteners are modelled by spring elements with stiffness calculated by Bruhn methodology (Sánchez-Sáez and Barbero, 2007).

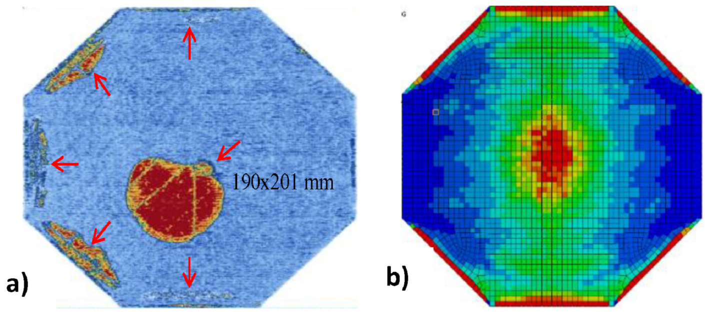


Figure 9. Comparison between NDI (a) result and numerical simulation (b) of the flat test panel

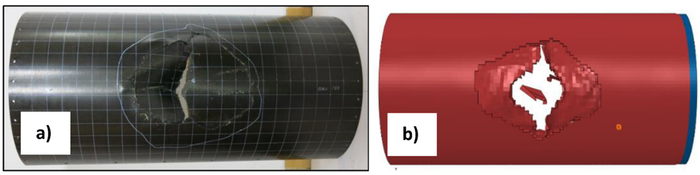


Figure 10. Comparison between NDI result and numerical simulation of the curved test specimen

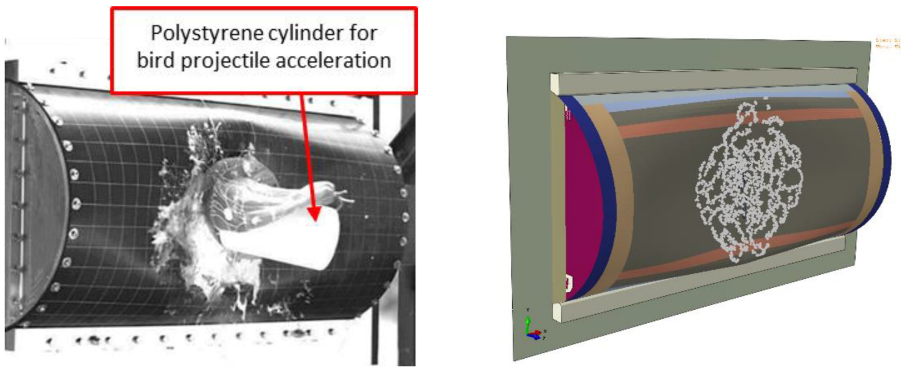


Figure 11. Example of comparison high-speed camera measurement with numerical simulation during impact test on the curved test panel

The analysis parameters for each trajectory were displacement, contact with inner parts mainly in rotor area, composite damage criterion (tensile fibre), Sandwich core damage, a load of fasteners and weight of penetrated parts of the projectile in case of cowling failure.

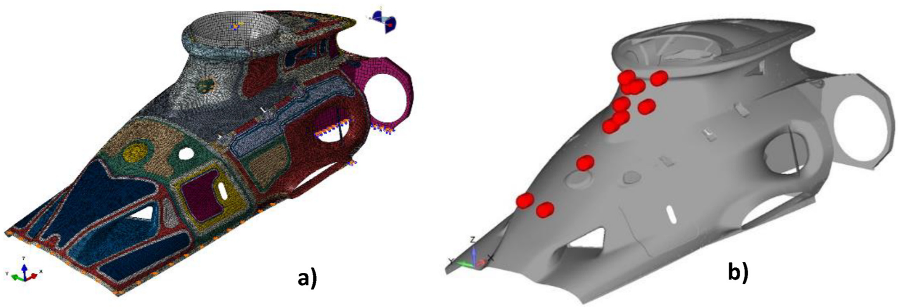
Parameters for evaluation of resistance of the structure to the bird impact from numerical models were as follows:

(1) Maximal displacement – contact with inner structure or rotating parts (Figure 13b).

(2) Composite damage criterion – Hashin tensile fire criterion (Hashin, 1981) (Figure 13c).

(3) Sandwich core damage.

(4) Loading of mechanical joints during the impact – analysing of combined loading of mechanical fasteners by Bruhn methodology (Bruhn, 1973) (Figure 14).



Note(s): The colour in figure (a) shows different section properties

Figure 12. Global FE model of cowlings (a) and trajectory of bird projectile (b)

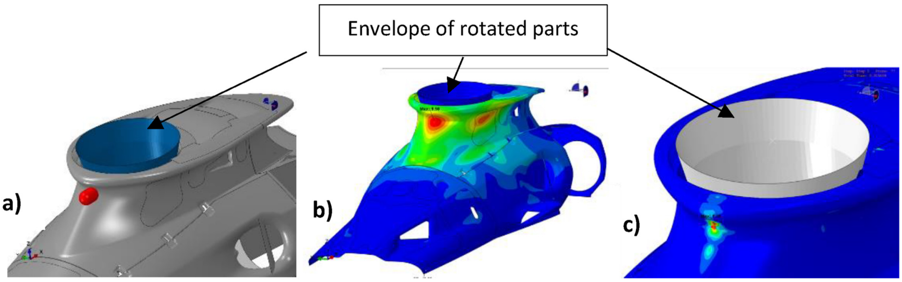


Figure 13. Example of bird strike analysis of impact near the rotated parts ((a) the trajectory of the projectile; (b) contour map of displacement; (c) contour map of composite damage criterion)

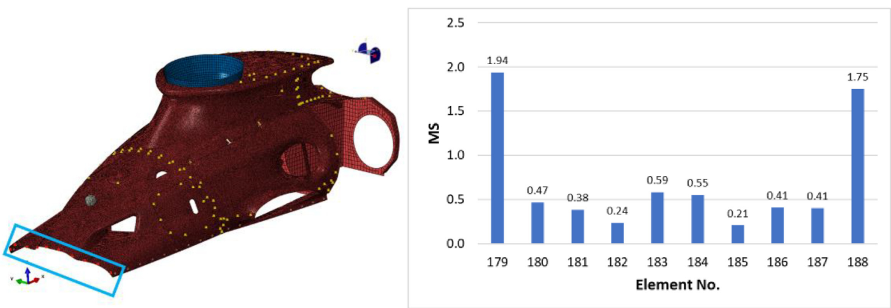


Figure 14. Example of analysis of margin safety (MS) of the mechanical fasteners on the global FE model during the impact

6. Conclusion

The application of validated numerical models on the flat and simply curved test specimen enabled improvements and optimization in the design phase. The experiences obtained in the field of calibration of numerical models for high-speed impacts confirm different behaviour of isotropic and orthotropic material models. The application of verified numerical models in the field of emergency load cases using simple test specimens allows not only the optimization of the design in terms of compliance with airworthiness regulations but also increasing the durability and safety of newly designed composite structures.

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