TOWARD A METHODOLOGY FOR THE DESIGN OF BIRD-PROOF INTAKES MADE WITH COMPOSITE MATERIALS

Luigi-M. L. CASTELLETTI* (luigi.castelletti@polimi.it), Marco ANGHILERI*
Department of Aerospace Engineering, Politecnico di Milano, via La Masa 34, 20156 Milano, Italia

Keywords: *Birdstrike, Turbofan Intake, Composite Materials, Nonlinear FEA, SPH Method*

ABSTRACT

Every year, collisions between aircraft and birds cause remarkable losses. Modern aircrafts have to be certified for a proven level of bird impact resistance before being put into operational service. Nevertheless, it is not surprising if the structure of a turbofan-engine intake (basically designed to carry aerodynamic and thermal loads) collapses when colliding with a bird. The collapse of the intake is tolerated, *but the fly-home capability* must *be guaranteed. The research work that eventually led to a methodology to develop bird-proof intakes made in composite materials is here described. It consists of two phases. In a first phase, referring to the experimental data, a bird model, feasible for the analysis of birdstrike and penetration, was developed and the dynamic behaviour of the composite material used in the intake manufacture was characterised. The numerical model of a full-scale birdstrike test was hence validated referring to a post-certification test of an actual intake and used to improve the design of the same intake. In a second phase, a full-scale birdstrike test on the improved structure was carried out using a prototype and the evidences collected are compared with the numerical results. Eventually the close numerical-experimental correlation obtained demonstrates the validity of the proposed methodology and indicates that the same approach is feasible to be extended to similar cases. Indeed, the use of this methodology leads to evident benefits: high-efficiency (low-weight and high-resistance) structures and drastic reductions in design times and costs.*

INTRODUCTION

Since the early beginning of aviation history, birdstrike has been one of the most dangerous threats for aircrafts [1]. Despite the efforts provided to avoid collisions between birds and aircrafts (*active safety*) and to produce bird-proof aircrafts (*passive safety*), every year birdstrike still causes damages for more than eighty millions US-dollars.

A birdstrike is characterised by loads with high intensity and short duration [2]. The materials undergo high strain rates, large deformations and inelastic strains. In addition, a deep interaction exists between the impact loads and the response of the structure. In view of that, full-scale tests are fundamental to develop bird-proof structures. On the other hand, birdstrike tests are extremely expensive and difficult to perform. In order to reduce the number of experimental tests and hence production times and costs, numerical techniques have been developed. In that, since their introduction at the end of the eighties, explicit codes based on Finite Element Method (FEM) have made possible to numerically analyse the event with a satisfactory degree of accuracy and hence to develop high-efficiency bird-proof structures [3].

The structure of an intake is designed to carry aerodynamic and thermal loads and, therefore, it is not surprising that it might collapse when colliding with a bird. The failure of the intake is generally *tolerated*, but the *fly-home capability* has to be guaranteed. For the certification, in particular, a full-scale test is required to demonstrate that the birdstrike does not damage any of those equipments necessary for the correct functioning of the engine, which are usually placed behind the aft bulkhead of the intake (Fig. 1). The intake should either deflect the bird or absorb the most part of the impact energy and stop the bird.

A numerical analysis of a birdstrike onto a turbofan-engine intake is extremely difficult, not only because of the own features of a birdstrike event, but also because of the known problems buried in bird modelling when considering strike and penetration [4]. Furthermore, the external skin-panels of the intake (outer and inner barrels in Fig. 1) are manufactured using composite materials and sandwich technology. As a consequence, the failure of these structures comes abruptly and involving mechanisms difficult to predict [5].

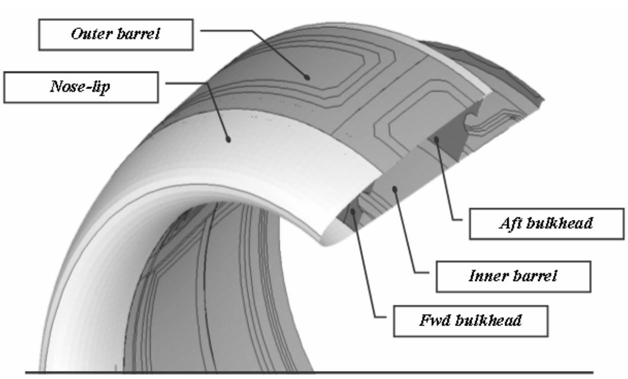


Figure 1. Turbofan intake structural scheme.

In this work, the guidelines for a methodology to develop high efficiency bird-proof intakes made in composite materials are drawn.

The synergy of experimental tests and numerical simulations is the core of the proposed methodology that basically consists of two phases. In a first phase, referring to specific experimental data [6], a bird model feasible for the analysis of birdstrike and penetration is developed and the dynamic behaviour of the composite material used in the intake manufacture is characterised. Hence, a numerical model reproducing a full-scale birdstrike test is validated referring to a post-certification full-scale birdstrike test. In a second phase, the developed intake and bird model is used to improve the design of the intake. A full-scale birdstrike test using a prototype of the new intake structure is carried out and the experimental data collected are compared with the numerical results. The close numerical-experimental correlation obtained demonstrates the validity of the proposed methodology and indicates that the same methodology is feasible to be extended to the design of structures and components with similar characteristics.

Indeed, the use of this methodology leads to evident benefits: high-efficiency structures and drastic reductions in design times and costs.

1 BIRD MODELLING

The numerical model of the bird is central in a birdstrike analysis when using explicit FE codes. On that depend the impact loads.

Customarily, the bird is modelled like a cylindrical water bullet [3]. Since a bird is primarily water and the impact velocities are rather high (order of 150-300 m/s), this model is commonly accepted – though it is not free from criticisms.

Moving from this representation of the bird, a SPH model have been developed and validated referring to experimental tests carried out to collect relevant data to improve existing numerical model of the bird [6]. The tests were carried out using flesh and bone birds (i.e. 4-lb chickens).

1.1 Problem overview

Since late eighties, explicit FE codes have been successfully used to develop high-efficiency bird-proof structures. Nevertheless, the analysis of birdstrike onto compliant structures by means of these codes (based on the Lagrangian approach) is troublesome: in fact, after the early instants of the impact, the distortions in the bird mesh cause a loss in accuracy, a reduction in the time-step and, eventually, a premature (*error*) termination of the simulation. Techniques based on *rezoning* or *restarting* alleviate but not eliminate this limitation.

In that, Eulerian or Arbitrary Lagrangian Eulerian (ALE) approach have shown to be effective and, therefore, some explicit FE codes implement also a Eulerian or an ALE solver. Drawbacks of these solvers (which eventually limit their use) are: the diffusivity, the lack of sharp boundaries and the large computational resources necessary to run the analysis.

Solvers based on Smoothed Particle Hydrodynamics (SPH) method have been recently implemented in the framework of an explicit FE code – proving to be a reliable analysis tool to investigate events characterised by large deformations. In fact, the SPH Method, being (genuinely) meshless, does not suffer the problems of mesh distortion.

In view of the benefits coming from SPH approach [4], a SPH bird model was developed to be part of the methodology to design bird-proof intake here presented.

1.2. Experimental data

The data collected during experimental tests are fundamental in the development of a numerical model.

An intense test programme has been carried out to characterise the numerical model of the bird [6]. Using an air gun, 4 lb-chickens were launched with an initial velocity of 265 kts toward a massive target inclined of 30 deg. The target was instrumented in order to acquire the profile in time of the impact force.

Birdstrike tests are rather difficult to perform and, when made with real birds, the data are not readily extendible. Nevertheless, the considered tests are *repeatable* – as shown by the close agreement among the data obtained and the data acquired *reliable* when compared with the ones of the tests previously carried out [2].

1.3. Numerical model of the bird

The bird was initially modelled as a water projectile with a cylindrical shape (20 *cm* length, 10 *cm* diameter). The SPH particles were uniformly distributed inside the bird body as to form a grid of equally spaced points. The distance among the particles was fixed (also) referring to the characteristic length in the FE models used in birdstrike analyses and represented the necessary compromise between accuracy and CPU time.

The mass of each particle is representative of the initial *influence region* of the particle and, hence, this is a very important parameter for the accuracy and stability of the analysis. The mass was calculated referring to the density of the material and considering the volume of the cubic region of which the particle is the centre of mass.

Constitutive law (the *null* material [7]), and equation of state (the *Gruneisen's* one [7]) were decided after preliminary simulations. No failure criterion was defined.

Impact scenario (i.e. initial velocity and impact angle) and event duration were the ones of the actual experimental tests.

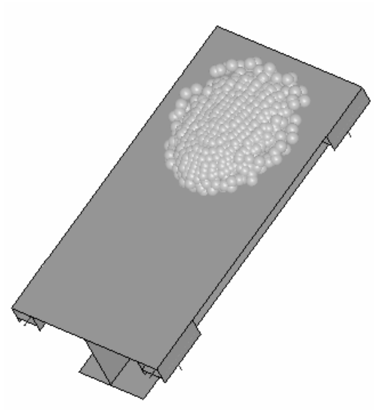


Figure 2. Numerical model of the test carried out for bird characterisation.

1.4 Model optimisation

The initial bird model underwent a optimisation process meant to improve the numerical-experimental correlation by modifying some not completely defined analysis parameters within ranges suggested by commonsense and experimental observations.

After a careful sensitivity analysis, the most relevant parameters related to the geometry and the material of the bird were chosen as optimisation variables.

1.4.1 Framework

In several research fields, the *optimisation* of a numerical model is an established procedure – though it is not always free from criticisms. With regard to the event here considered, an optimisation (intended as improvement of the model) of the bird was deemed recommendable.

Specific functions were written in MATLAB framework to autonomously manage the whole optimisation process. These functions decided the values of the optimisation variables, generated the numerical model, ran the simulation, processed the output and adjusted the values of the optimisation variables. In that, LSTC LS-Dyna worked as a *blind box* that, given an input file, provided the corresponding description of the event.

1.4.2 Objective function

The *objective* of the optimisation process was to find the set of parameters related to bird geometry and material that provides the closest correlation between numerical results and experimental data.

In order to correctly reproduce the mutual interaction between fluid and structure during a birdstrike, it is important to fit not only the maximum and the mean values but also the profile in time of the impact force. For this reason, the object function was defined as the sum of the square of the distance between experimental data and numerical results. This definition of the object function calls for a close correlation between numerical results and experimental data throughout the entire event.

1.4.3 Optimisation scheme

The object function chosen is not particularly *smooth* and, therefore, it was not possible to guarantee that it were defined everywhere in the optimisation domain. It happened that, due to the mutual influence among the optimisation variables, a set of values (admissible when considered separately) caused an error termination of the simulation. When the simulation crashes, it is impossible to give a value to the object function.

Since it was not possible to identify *a priori* unfavourable combinations of admissible parameters, it was implemented a robust zero-th order algorithm based on *Bracketing Method* and developed to be insensitive to *singularity* errors.

More sophisticated optimisation schemes (such as those based on Genetic Algorithm and Response Surface / Radial Basis Function) could have been used. Nonetheless, the efficiency of the optimisation process was not the aim of this research. The scheme used was simple and robust. In addition, the optimisation domain was not wide, the simulations were not particularly time-consuming, and the guess solution (i.e. the solution obtained with the initial set of optimisation variables) was already close enough to an *acceptable* optimum.

1.5. Numerical-experimental correlation

With regard to the SPH bird model previously described, the optimisation process converged in (relatively) few iterations. The numerical-experimental correlation was good when considering the impact forces and the dynamics of the event close to the one in the high- speed movies.

1.6. Discussion

Some further remarks on the obtained results seem appropriate – at this point.

The *rugby-ball* was found to be the optimal shape for the bird. In that, the actual shape of the birds used in the tests had a deep influence. The dimensions of the bird were fixed in the model and therefore the optimal density was higher than the one of the water and the one of a chicken (i.e. the projectiles used in the tests).

The SPH model of the bird provides a qualitatively accurate description of the dynamics of the event: the scattering of the SPH particles is in accord with the experience and definitively similar to the one in the high-speed movie. In that, tension instability had not a negative influence on the accuracy of the solution but, on the contrary, provided *a kind of* convenient failure criterion.

As a matter of fact, the validity of the model worked out relies on the tests used as reference. Nevertheless, when considering numerical-experimental correlation, the relative errors are the same order of the deviation from the mean of the data collected during the tests and, therefore, the developed model is deemed reliable to be used with a certain confidence also in other analyses of birdstrike events.

3. COMPOSITE MATERIAL NUMERICAL MODEL

The external skin panels of the modern turbofan-engine nacelles are manufactured with composite materials that allow efficient design and significant savings in weight of the structures. On the other hand, composite materials are also characterised by a brittle failure mechanism difficult to model when using nonlinear explicit finite element codes.

Investigations on birdstrike onto turbofan-engine intake have demonstrated that an appropriate characterisation of the dynamic behaviour of the composite materials is fundamental for the accurate description of the failure mechanism of the structure.

In view of that, a reliable numerical model for the composite materials used for the external skin panels of the intake was developed and validated referring to specific experimental tests [5].

3.1. Experimental tests

Hopkinson's bar test and *Taylor test* are fundamental to characterise the impact behaviour of a material. In effort to characterise the impact behaviour of the composite material used in the intake manufacturing, two further test typologies were considered: the *vertical crush test*, performed using cylindrical thin-walled cylinders; and the *dynamic tensile test*, performed using specimens similar to the ones used in static tensile tests.

The specimens were made of the same material used for the intake: a Carbon Fibre Reinforced Plastic (CFRP) woven with resin volume fraction of 42%. Two different kinds of stacking sequences were considered: the first one consisting of four $[0/45]_S$ oriented layers and the second one consisting of five [0/45/0/45/0] oriented layers.

3.1.1. Vertical crush test

The specimens used in vertical crush tests were thin-walled cylinders with a nominal diameter of 70 mm and a height of 300 mm.

In the tests a vertical sledge was used. A trolley, constrained to move vertically up and down on the sledge and released via an electro-mechanical system, carried the impacting mass.

The vertical displacement was measured with an incremental encoder. The reaction force of the specimen was evaluated through the vertical acceleration of the trolley – which was measured with a 200 g-accelerometer fixed on the trolley.

Two different impact scenarios were considered: impacting mass 110 kg and impact velocity of 7.5 m/s, and impacting mass of 248 kg and velocity of 5 m/s.

The crash behaviour was consistent and experimental tests were both reliable and repeatable.

3.1.2. Dynamic tensile test

The dynamic tensile tests were carried out using the vertical sledge previously described in combination with a specific test device that converts the impact load in tensile loads [5].

The data acquired and the impact scenarios were the same previously mentioned.

Two different impact scenarios were considered: impacting mass 12.4 kg and impact velocity of 7.5 m/s, and impacting mass of 12.4 kg and velocity of 5 m/s.

The crash behaviour was consistent and experimental tests were both reliable and repeatable.

3.2. Numerical model

In order to develop and validate the numerical model of the composite material, the experimental tests described were reproduced in detail.

The numerical models of the specimens in the two test typologies share the same features. The specimens were modelled using four-node shell elements and Belytschko-Tsay formulation (preferred to more sophisticated ones). A single integration point was defined for each ply throughout the thickness. A sensitivity analysis on the element size was carried out to avoid mesh effects on the numerical results.

Initial and boundary conditions were carefully considered and reproduced the ones of the experimental tests.

3.2.1. Vertical crush test

The cylindrical shells finite element mesh had a characteristic length of 3 mm and consisted of over three thousands shell elements.

A moving rigid wall with the mass and the initial velocity of the impacting mass was used crushed the specimen.

3.2.2. Dynamic tensile test

The specimens used in the dynamic tensile tests were modelled with 1900 four-node shell elements.

A rigid fitting (replica of the actual test facility fitting) was defined.

3.3. Material model

In order to reproduce the dynamic behaviour of the composite material used for the intake, a proven material model specific for laminated composite material structures was adopted – *MAT_158 [7].

Basically, the adopted material model is an elastic-damage material model developed around the idea that damages introduce micro-cracks and cavities into materials and that these defects cause a stiffness degradation with small permanent deformation – unless material undergoes rather high loading and is not close to deterioration. A non-smooth failure surface is assumed and, in order to allow an almost uncoupled failure of an arbitrary composite, all failure criteria are taken to be independent from each other.

The adopted material model also takes into account the strain-rate effects: a viscous tensor, based on an isotropic Maxwell model with up to six terms in the Prony series expansion is superimposed on the rate independent stress tensor.

3.4 Numerical-experimental correlation

With regard to both the tests typologies and both the impact scenarios, the comparison between the *load-shortening* curves experimentally measured and numerically calculated showed a good correlation in terms of loads and absorbed energy as well as in terms of the curve shape and time profile.

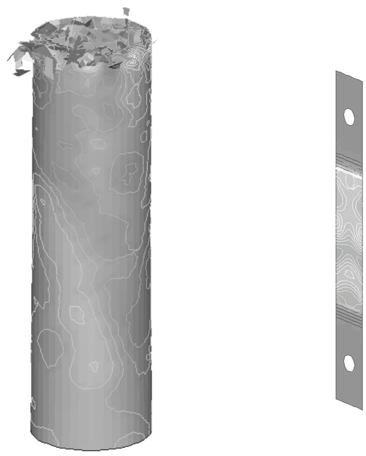


Figure 3. Vertical crush test (LHS) and dynamic tensile test (RHS).

3.5. Remarks

The effectiveness of the adopted material model was eventually recognised: *accurate* in terms of description of the event and *fast* in terms of required CPU-time. An remarkable outcome with implications that go beyond the specific of the event considered.

Indeed, with regard to the methodology here introduced, the material model was eventually established as suitable to investigate the failure mechanism of a turbofan intake.

4. BIRDSTRIKE ONTO A TURBOFAN INTAKE

After having developed the SPH particle model of the bird and after having calibrated the model of the composite material used in the intake manufacture, the reliability of the overall model (intake and bird) as a means to study a bird impact against an intake made with composite materials was investigated.

4.1. Experimental birdstrike test

Full-scale birdstrike tests are extremely expensive and difficult to perform: nevertheless, full-scale tests with prototypes are mandatory in structure design development. In that, after the test with the impact scenario required for the certification of the structure, it is a common practise to carry out also a *further* test usually with an higher impact velocity in order to evaluate the actual resistance level of the structure. The test used here as reference was a *further* test: the bird impacted the intake with a velocity of about 380 kts penetrating inside the airframe through the outer barrel that collapsed after the impact. In Fig. 5-A, the consequences of the impact are shown in detail. The external skin composite panels collapsed under the impact loads and large part of the structure went broken. Nevertheless, most of the bird body was deflected and the part that penetrated through the shattered structure was stopped by the aft bulkhead. The fly-home capability was eventually guaranteed.

4.2. Numerical model

The structure in the *further* test was a 1.60 m-diameter intake which was reproduced in great detail. The SPH particle model of the bird previously described was used.

4.2.1. Intake model

The intake consisted of sixteen parts. Five of these parts were manufactured with composite material, and one, the inner barrel, using the sandwich technology (composite materials skins and Aluminium honeycomb core) to obtain a high flexural-strength/weight ratios and a good noise control. Four parts were made of Titanium alloy Ti-6Al-4V and the remaining of two distinct Aluminium alloys: Al 2219-T62, the nose-lip, and Al 2024-T6, the other parts. The material model calibrated at the first stages of the research work was used for the parts manufactured with composite material. The materials used for the remaining parts were modelled as an elastic material with a piecewise (isotropic) linear plasticity and using for the mechanical properties the typical values. Appropriate Cowper-Symonds coefficients were introduced to model the strain-rate effects.

The FE mesh built on the geometry of the intake, consisted of over sixty thousands four-nodes shell-elements. In order to reproduce the actual constraint that the airframe of the engine imposes to the intake, the inner and outer flanges of the aft part of the intake (in the FE model) were fixed. The riveted fittings were modelled in detailed. Contacts among the parts were carefully modelled.

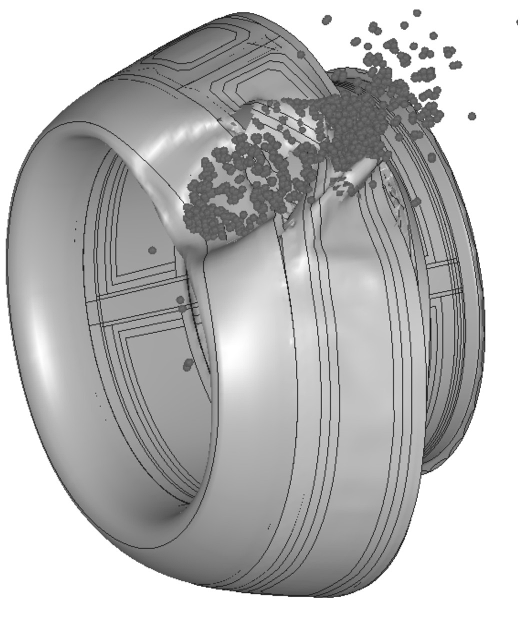


Figure 4. Birdstrike onto a turbofan-engine intake.

4.2.1. Bird model

The SPH bird model developed and validated at the first stage of the research work was used.

The bird/structure interaction was defined through a node-to-surface contact interface –

enforced by mean of *soft* penalty method [7]. A viscous damping was introduced to reduce the spikes due to the SPH/FE coupling.

The impact scenario reproduced in detail the one of the test: boundary conditions were thoroughly imposed.

4.3 Numerical-experimental correlation

The accuracy of the numerical results was evaluated referring to the *after-impact damages* documented in the photographic report and the *dynamics of the events* captured in the high-speed movies.

4.3.1. Post-impact damages

With regard to the post-impact photographic documentation (Fig. 5-A), the numerical simulations gave a rather accurate description of the event and, in particular, of damages reported by the intake in the outer barrel made in composite material (Fig. 5-B).

4.3.2. Impact dynamics

With regard to the dynamics of the events, the results of the simulations and the high-speed movie of the test were close. The SPH bird behaviour was consistent and the description of the bird motion rather accurate – also when the structure collapsed and the bird penetrated into the airframe. The material model adopted give a significant contribution in faithfully reproducing the failure mechanism of the intake even in a such complicated *high velocity impacts* as a birdstrike is.

4.3 Discussion

In view of the results obtained it was demonstrated that the *overall numerical* model (intake and bird) is a reliable tool to analyse the event: both the *behaviour of the bird*, impact and subsequent penetration inside the airframe, and the *failure mechanism* of the structure are close to the ones observed in the experimental test – that also proves a correct representation of the mutual dependency between impact loads and structural response.

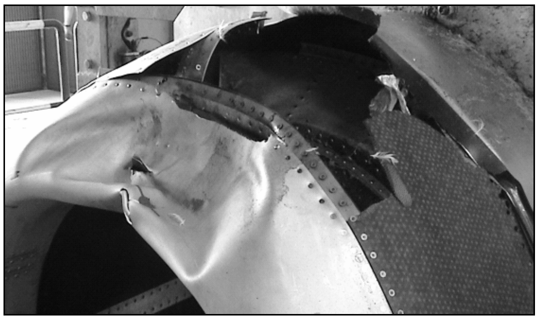
The SPH model is feasible for reproducing in detail the dynamics of the bird and provides an accurate representation of the impact loads.

The composite material model allows to reproduce the failure mechanism of the structure under impact loads – and this result can be readily extendible to other structures in composite material under similar loads.

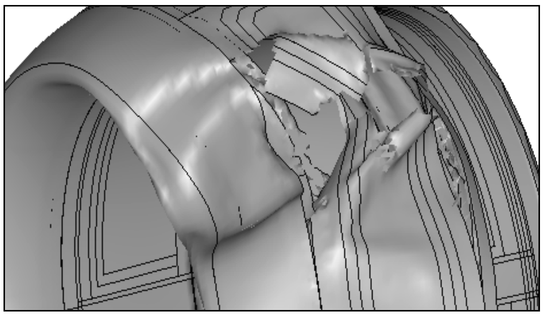
Indeed, the close numerical-experimental correlation not only demonstrated the reliability of the overall model but also indicated the feasibility of the model as a numerical tool to develop high-efficient bird-proof composite material structures.

The importance of the experimental full-scale tests remains as a means to develop and validate the numerical model and to verify the structure. On the other hand, the use of reliable numerical models may significantly reduce times and costs required for structure development and homologation.

Eventually, the overall numerical model here introduced was actually used to modify and improve the design of the intake with regard to birdstrike.



A



B

Figure 5. Consequences of a birdstrike: (A) experimental test and (B) numerical simulation.

5. INTAKE DESIGN DEVELOPMENT

The model previously worked out was eventually used to support the development of the intake design.
The original design, already rather efficient, was further improved in the external skin panels region to reduce the overall weight of the structure and to improve the bird-proof performances. In particular, the redesigning aimed at modifying the failure mechanism of the lower part of the outer barrel near the exhaust and at enhancing the bird deflection mechanism of this part of the intake.

5.1. Numerical model

With respect to the one previously described, the numerical model of the modified intake showed only few differences – most of which in the stack sequence of the composite material skin panels in the lower part of the intake.

The impact scenario was different. The actual homologation test prescriptions were adopted. The bird impacted the intake with a velocity of 360 kts.

The test aimed at verifying that after the birdstrike the fuel line behind the aft bulkhead in the lower part of the intake showed no damages – circumstance fundamental to guarantee the fly-home capability.

5.2. Numerical results

Simulations were carried out to evaluate the bird-proof performances of the modified intake.

In particular, with regard to the *latest* configuration of the intake, it was obtained (Fig. 6-A) that after the impact the nose-lip of the intake undergoes relevant deformation and the outer composite material skin panels collapse. The bird was not entirely deflected: part impacts the aft bulkhead. Most of the initial energy of bird was absorbed by the structure, though. Therefore, the portion of bird that eventually impacted the aft bulkhead was not such to damaged it.

5.3. Numerical-experimental correlation

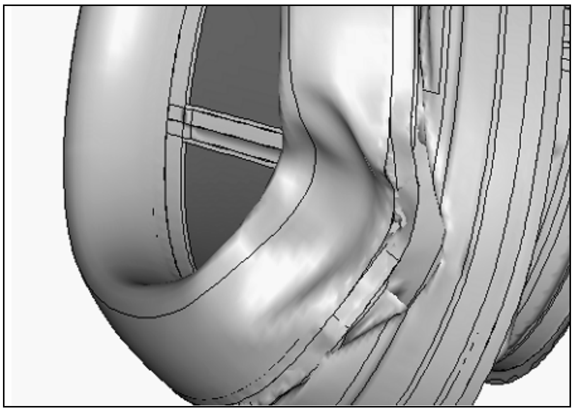
The experimental test carried out for the intake homologation confirmed the results of the simulation with regard to both the after-impact damages and impact dynamics.

5.3.1. After-impact damages

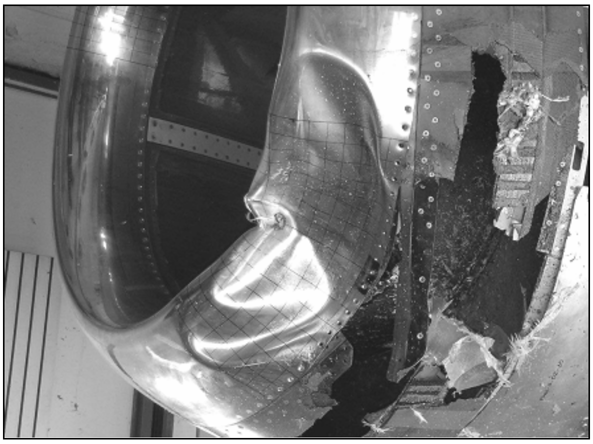
The post-impact damages in the photographic documentation (Fig. 6-B) are similar in dimensions and shape to the one numerically obtained (Fig. 6-A).

5.3.2. Impact dynamics

The impact dynamics observed in the high-speed movies is close to the one obtained in the numerical simulation.



A



B

Figure 6. Comparison between (A) numerical results and (B) post-impact photographical documentation.

5.4. Discussion

The rather close numerical-experimental correlation obtained shows the effectiveness and the accuracy of the overall numerical model developed and, at the same time, demonstrates the reliability of the methodology here introduced as a tool to develop high-efficiency bird-proof intake.

In that, it is has a important part the code used in the simulations. Indeed, LSTC/LS-Dyna 970 [7] is a proven nonlinear explicit finite element code that implements a sound SPH solver. However, as a remark, it should be mention that the methodology here introduced is basically independent from the code used in the simulation and can be readily adapted to the use of other software.

CONCLUSIONS

Birdstrike is a threat for modern aircraft and new design philosophies call for the development of new methodologies to design high efficiency bird-proof structures.

The guidelines of a methodology aimed at developing high-efficiency bird-proof turbofan-engine intakes have been drawn here. The synergy of experimental tests and numerical simulations carried out using explicit FE codes is the core of the proposed methodology that basically consists of two phases. In a first phase, referring to the experimental data, a bird model feasible for the analysis of bird strike and penetration is developed and the dynamic behaviour of the composite material used in the intake manufacture is characterized. The numerical model of a full-scale birdstrike test is hence validated referring to a post-certification test of an intake. In a second phase, the model from the first phase is used to improve the design of the intake and, eventually, a full-scale birdstrike test on the improved structure is carried out. The evidence collected when compared with the numerical results show the reliability of the methodology.

In particular, in the framework of the methodology here introduced, two outcomes with implications that go beyond the event here considered have been achieve. The reliability of the SPH bird model as a tool to investigate the consequences of a bird strike and penetration inside the airframe has been demonstrated. A material model feasible to reproduce the behaviour of a composite structure under impact loads was found and a procedure to calibrate it was established.

The rather close numerical-experimental correlation obtained throughout the research proves the validity of the proposed methodology and indicates the possibility of extending the same methodology to the design of structures and components with similar characteristics.

The benefits coming from the introduction of the proposed methodology are evident: high-efficiency structures and drastic reductions in design times and costs.

REFERENCES

[1] Thorpe J. Fatalities and destroyed civil aircraft due to bird strike, 1912-2002. *International Bird Strike Committee 26th Meeting*. Warsaw, Poland. May 2003.

[2] Taylor H R, Barber J P and Wilbeck J S. Bird impact forces and pressures on rigid and compliant targets. *Technical report, University of Dayton Research Institute, Wright Patterson Air Force Base*. Apr-Dec 1976.

[3] Brockman R A and Held T W. Explicit Finite element method for transparency impact analysis. *Technical report, University of Dayton Research Institute, Wright Patterson Air Force Base*. June 1991.

[4] Anghileri M, Castelletti L-M L and Mazza V. Birdstrike: approaches to the analysis of impacts with penetration. *International Conference on Impact Loading of Lightweight Structures*. Florianopolis, Brazil. May 2005.

[5] Anghileri M, Castelletti L-M L, Invernizzi, F and Mascheroni M. Birdstrike onto the composite intake of a turbofan engine. *5th European LS-Dyna Users Conference*. Birmingham, UK. May 2005.

[6] Sala G, Anghileri M. Theoretical assessment, numerical simulation and comparison with tests of birdstrike on deformable structures. *20th Congress of the International Council of the Aeronautical Sciences, ICAS 96*. pp. 665-674. 1996.

[7] Hallquist J O. LS-DYNA. Theoretical Manual. *Livermore Software Technology Corporation*. 1998