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Design criteria for birdstrike damage on windshield

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Abstract. Each aircraft have to be certified for a specified level of impact energy, for assuring the capability of a safe flight and landing after the impact against a bird at cruise speed. The aim of this research work was to define a scientific and methodological approach to the study of the birdstrike phenomenon against several windshield geometries. A series of numerical simulations have been performed using the explicit finite element solver code LS-Dyna, in order to estimate the windshield-surround structure capability to absorb the bird impact energy, safely and efficiently, according to EASA Certification Specifications 25.631 (2011). The research considers the results obtained about a parametric numerical analysis of a simplified, but realistic, square flat windshield model, as reported in the last work (Grimaldi *et al.* 2013), where this model was subjected to the impact of a 1.8 kg bird model at 155 m/s to estimate the sensitivity of the target geometry, the impact angle, and the plate curvature on the impact response of the windshield structure. Then on the basis of these results in this paper the topic is focused about the development of a numerical simulation on a complete aircraft windshield-surround model with an innovative configuration. Both simulations have used a FE-SPH coupled approach for the fluid-structure interaction. The main achievement of this research has been the collection of analysis and results obtained on both simplified realistic and complete model analysis, addressed to approach with gained confidence the birdstrike problem. Guidelines for setting up a certification test, together with a design proposal for a test article are an important result of such simulations.

Keywords: finite element analysis; SPH approach; high velocity impact; birdstrike scenario; glass composite material; windshield component

1. Introduction

When showing compliance with aviation rules, all areas of the aircraft prone to bird strike should be considered, either pressurized or non-pressurized, primary or secondary structure (e.g. windshield, nacelles, winglet, externally antennas and stores, landing gear, canopy and compressor blade). Both Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) list regulations for the aircraft certification process to ensure that each front facing aircraft components be capable of withstanding a birdstrike event, or at least assuring a safe landing of the aircraft, at defined flight speed. Table 1 lists the paragraphs of the Federal Aviation Rules (FAR 2003) and the aircraft component affected:

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Table 1 FAR birdstrike test requirements

Aircraft Component	Bird Weight [lb]	FAR Section
Windshields and Frames	4	25.775 (b), 25.775 (c)
Wing Leading Edges	4	25.571 (e) (l)
Empennage Leading Edges	8	25.631, 25.571 (e) (l)
Engine - Inlet Lip	4	25.571 (e) (l)
Engine - Fan Integrity	4	33.77, 25.571 (e) (l)

For the final certification both FAA and EASA require full-scale tests to demonstrate compliance with these requirements. In order to reduce the number of experimental tests, design engineers perform an intensive numerical analysis addressed to verify the ability of a specific structural component in absorbing such localized impact energy, and to identify the most probable critical location.

Most part of these analyses are carried out with explicit nonlinear finite element (FE) code which allows a good correlation with the real test, at least in its global behaviour, which, indeed, is the objective of the certification tests.

This paper summarizes the activities carried out from the very beginning of a new proposed aircraft windshield, starting from the simulation of a simplified glass panel for investigating separately different design parameters, well defined when dealing with simple geometries. Additionally the analysis of the effect of the surrounding structure has been performed with the objective of limitating at its minimum requirement for an easier and less expensive test setup.

The attention has been mainly focused on the aircraft windshield because of the potential design constraint of widening the pilot window with a larger than usual cockpit window made by two symmetrical single pieces.

The bird strike scenario has been deeply investigated for both aircraft wing leading edge structure using MSC-DYTRAN, (Guida *et al.* 2008, 2009 and 2013) and LS-DYNA software, (Meo *et al.* 2013), and windshield component, (Grimaldi *et al.* 2013). These analyses have showed that the Smoothed Particle Hydrodynamics (SPH) methodology is able to capture the breakup of the bird into debris particles during and after the collision. In particular Guida *et al.* (2011) found that the Lagrangian-SPH combination provided the best results in terms of energy transfer and good prediction of the deceleration of the projectile, compared to the test results.

In the recent years many authors focused their work on this topic, as reported in the review of Heimbs (2011), Georgiadis *et al.* (2008), provided a validated simulation methodology to support the birdstrike certification of the carbon fibre epoxy composite moveable trailing edge of the Boeing 787 Dreamliner. Hanssen *et al.* (2006), investigated bird impact against aluminium foam-based sandwich panel using the Arbitrary Lagrangian-Eulerian (ALE) approach.

The windshield structure plays a key role in studying the birdstrike problem, because of its exposure in front of the airplane. Accordingly, many authors developed studies in order to design bird-proof windshield. Yang *et al.* (2003), elaborated an experimental and FEM windshield subjected to high-speed bird impact. Liu *et al.* (2008), focused on the analysis of an effective numerical method to simulate bird impact aircraft windshield events, using the SPH approach and the explicit finite element program PAM-CRASH. Recently Salehi *et al.* (2010), investigated the effect of the birdstrike on different aircraft windows both numerically and experimentally. They analysed different geometries and materials by using various modelling approach (ALE and SPH).

2. FEM description

The explicit FE commercial code LSTC/LS-Dyna (Hallquist 2006), has been used for modelling the bird strike problem, and in particular the SPH approach was adopted for the presence of highly non-linear phenomena including materials with inelastic strains, high strain rates and large deformations, such occurring during a birdstrike. According to SPH approach, the bird is modelled with a meshless technique, in which the elements are a set of discrete and mutually interacting nodes suitable to model the "consistency" of a bird.

The geometry of the target structure onto the projectile (bird) impacts, refers to a windshield structure of a business jet airplane. As result of the impact, following the International Certification Standards, the windshield must, not only, withstand to the event without bird penetration, but also avoid a complete fragmentation of all transparencies, to ensure acceptable visibility to allow safe flight and landing. This specification could be critical in the case of the windshield made up by only two panels because an impact on a side could cause the failure of the other panel too, or an impact on the canter beam, which divides the two panels, could create a fragmentation of both transparencies at the same time with consequent loss of visibility.

Table 2 shows the main geometrical characteristics of the analysed windshield panel:

Table 2 Geometrical windshield properties

Configuration	Surface [m^2]	Thickness [mm]	Weight [kg]
Double curvature	$A = 1.3$	$t = 20$	$W = 60$

Whereas a schematic plot of the left windshield transparent panel is shown in Fig. 1.

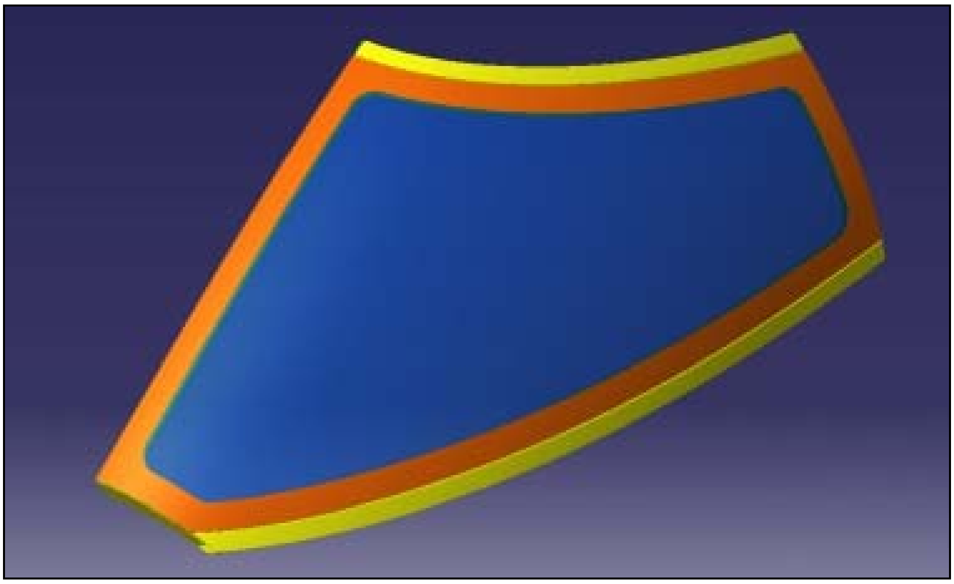


Fig. 1 Configuration of left windshield-surround structure

According to the certification requirements, the weight of the bird is $W = 1.8$ kg, the density is $\rho = 950$ kg/m^3. The geometric model is approximated by a right circular cylinder, Fig. 2, where:

$$D = \sqrt[3]{\frac{2W}{\pi\rho}} = 0.106m \tag{1}$$

having assumed $L = 2D$ and therefore

$$L = 2D = 0.212m \tag{2}$$

In order to comply with fail-safe requirements, a typical windshield is made up by laminated glass. The basic layup of a laminated glass involves two glass panels bonded by polyvinyl-butyral (PVB) interlayer. In the case of an impact, such as the birdstrike, the splinters, caused by the glass failure, remain connected to the PVB-interlayer. Fig. 3 shows the windshield lay-up configuration.

Table 3 shows the glass mechanical properties.

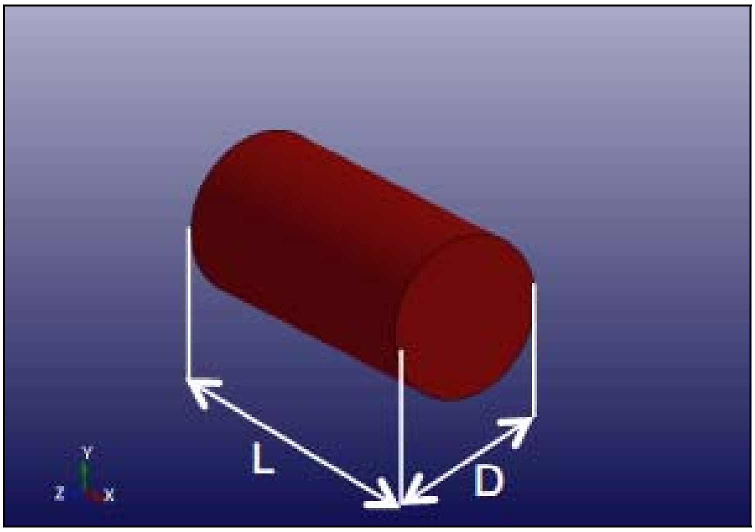


Fig. 2 Cylindrical bird model

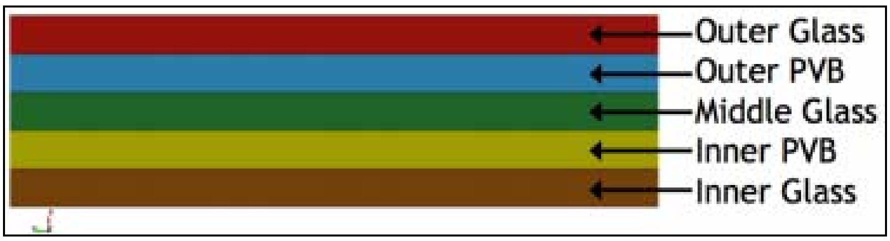


Fig. 3 Windshield lay-up configuration

Table 3 Material properties of the glass

Density [kg/m^3]	Poisson ratio	Young modulus [N/m^2]	Failure strain
$\rho = 2500$	$\nu = 0.22$	$E = 6.895e10$	$\varepsilon_f = 0.35$ %

Table 4 PVB-interlayer properties

Density	ρ = 2500 kg/m^3
Short-time shear modulus	G_0 = 0.33e^9 N/m^2
Long-time shear modulus	G_∞ = 0.33e^9 N/m^2
Bulk modulus	K = 2.0e^6 N/m^2
Decay Coefficient	β = 12.6 s^{-1}
Failure strain	175%

The glass is considered as an elasto-plastic material with a very short plastic portion of a σ-ε curve of a typical brittle material. Such stress-strain curve presents an ultimate tensile stress equal to rupture stress and yield stress because of the brittleness of the material. On the contrary, the plastic material of the PVB (Polyvinyl-butyral), which is interposed between the layers of glass, behaves like a viscoelastic interlayer. This type of material shows good characteristics of strength and transparency, allowing a high deformation before the failure and a good tearing strength. Table 4 shows standard literature characteristics of the PVB material.

Fig. 4 shows a section of the windshield-surround installation. A key role is played by the joint solution used to stick together the layers of the glass laminate, (Timmel *et al.* 2007). The choice of a fixture, rather than the bolts (i.e. mechanical clamp), may significantly affect the performances of the structure in case of both static and dynamic load application. An improved installation is obtained by a continuous clamp of the windshield with the surrounding structure, avoiding bolts and/or joints.

Fig. 5 shows the FE model of the left windshield panel, where each layer of the laminate is modelled with solid elements, both eight-nodes and six-nodes elements, to take into account the curvature of the windshield.

Table 5 reports the thickness of each layer of the glass laminate.

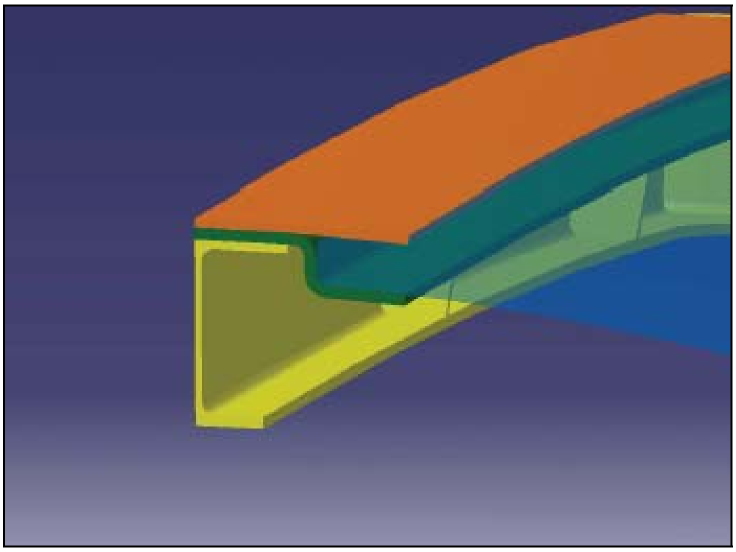


Fig. 4 Windshield-surround installation - geometry

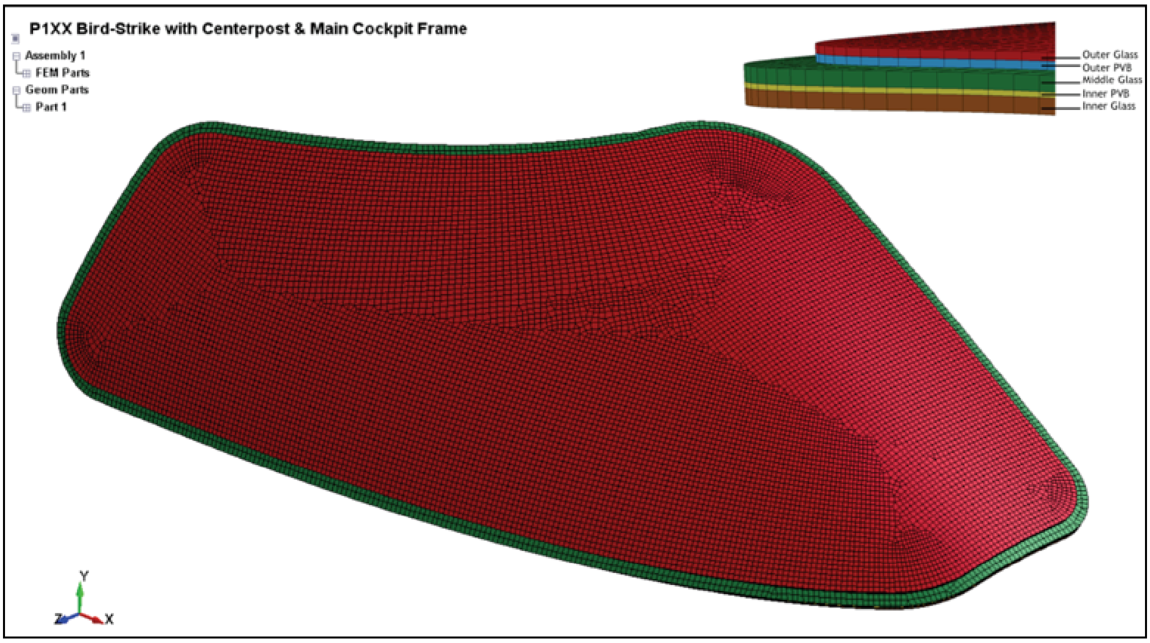


Fig. 5 Full-scale left windshield FE model

Table 5 Thickness distribution of the full-scale laminated model

Outer Glass [mm]	Outer PVB [mm]	Middle Glass [mm]	Inner PVB [mm]	Inner Glass [mm]
3.0	3.0	6.5	2.5	5.0

As mentioned, the SPH approach is used to model the bird, 0. The resulting numerical model employs 28,620 SPH nodes with an average distance between them of 5 mm. The "surrogated" bird has a density of 950 kg/m3 and a porosity of 10%, i.e. it is composed of 90% of water and 10% of air. It impacts the windshield at a speed of 155 m/s, as required by the International Certification Standards.

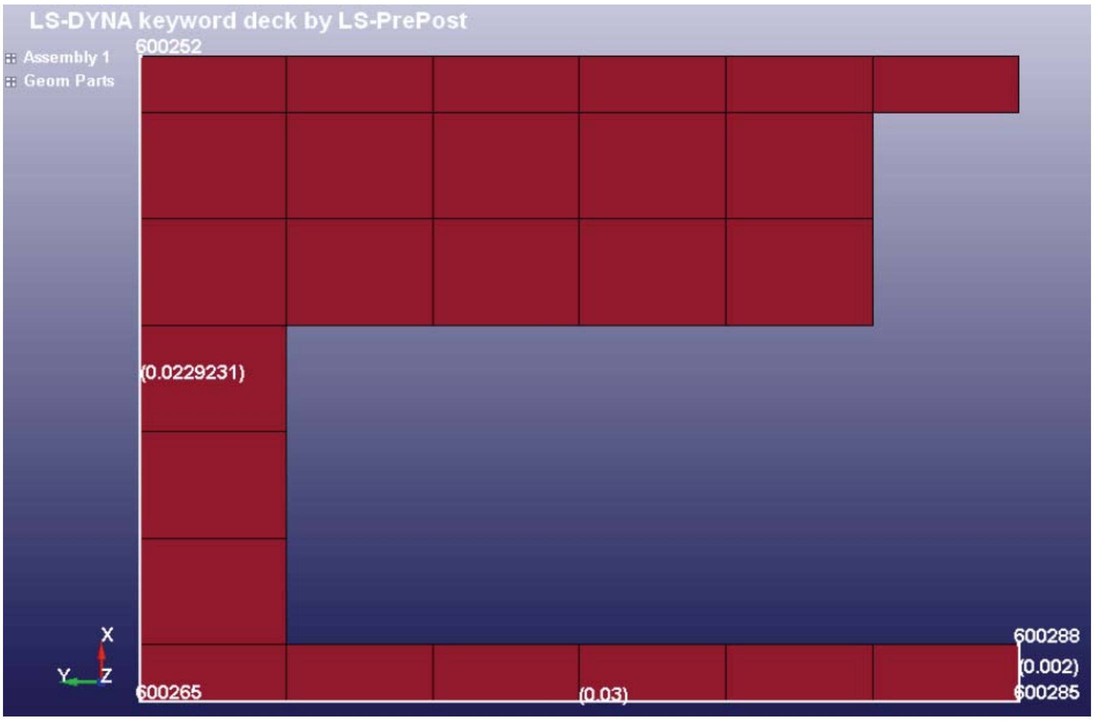
Regardless the modeling method chosen, an idealization of fluid dynamic material has been used for the bird. In particular, a constitutive stress-strain material relationship and a state equation for the pressure-volume relationship have been used:

$$p = C(\varepsilon V) \tag{3}$$

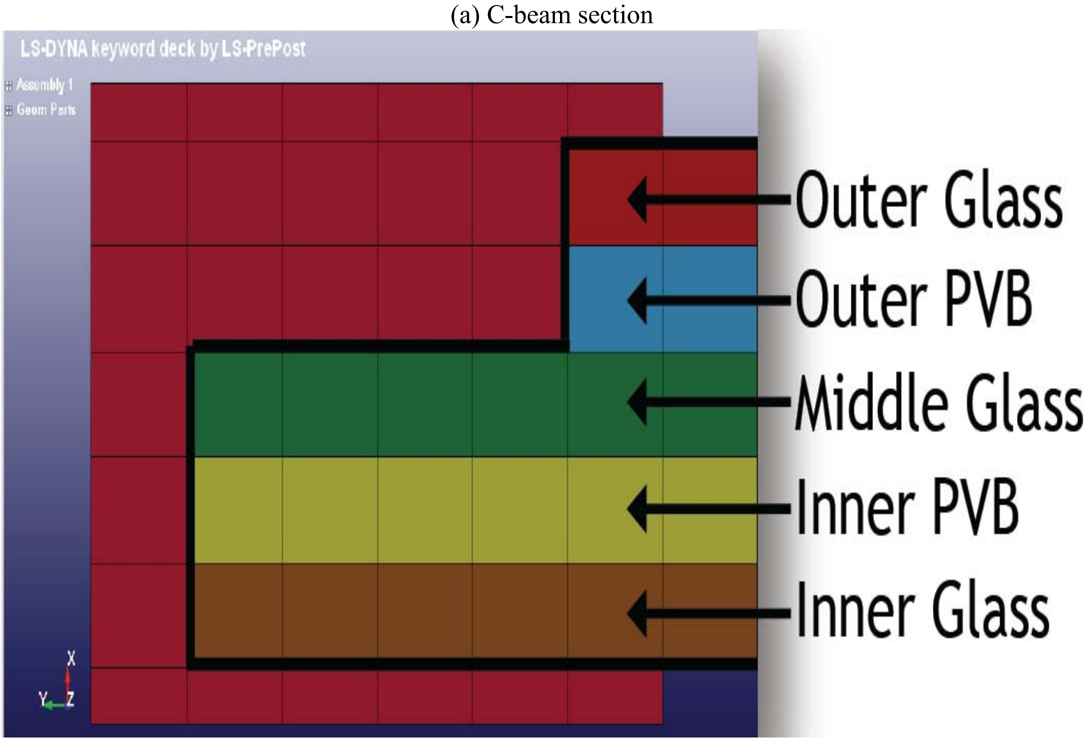
where ε_V is the volumetric strain given by the natural logarithm of the relative volume V. The values of the state equation parameters are listed in the Table 6:

Table 6 Tabulated equation of state

	1	2	3	4	5	6	7	8	9	10
ε_V	0.000	-0.105	-0.118	-0.128	-0.137	-0.154	-0.169	-0.183	-0.195	-0.217
C [Pa]	0.000	$2.37e^8$	$4.25e^8$	$5.86e^8$	$7.27e^8$	$9.72e^8$	$1.18e^9$	$1.37e^9$	$1.54e^9$	$1.84e^9$



(a) C-beam section



(b) Windshield-surround clamp

Fig. 6 Windshield-surround installation – FEM

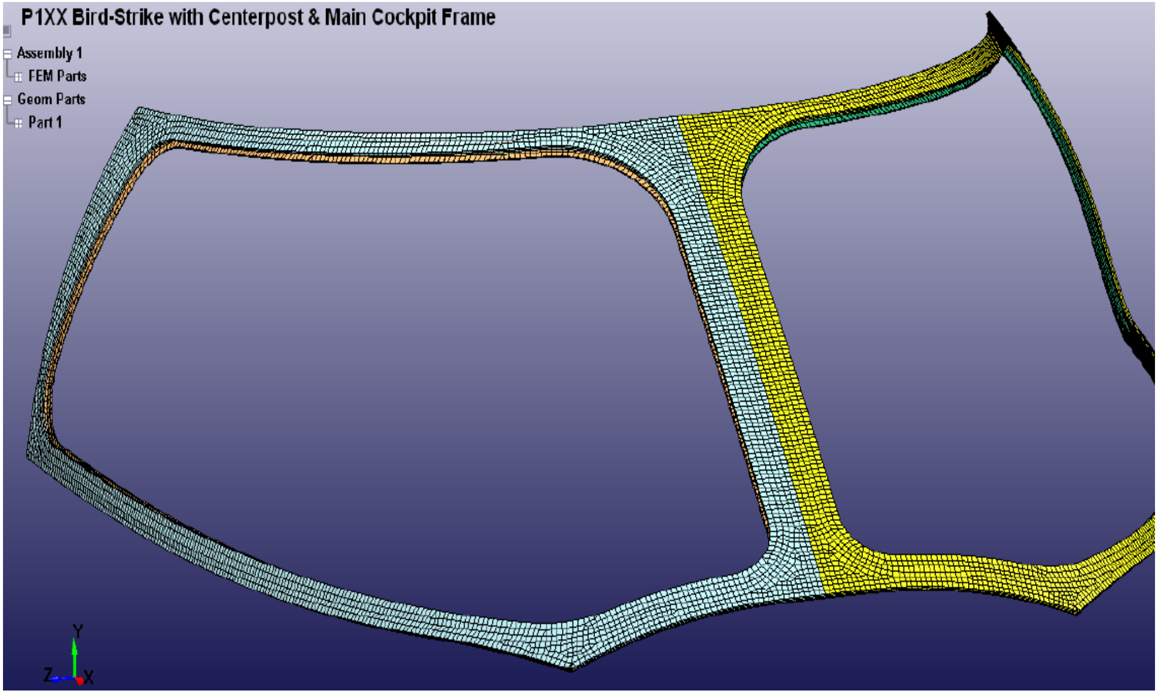


Fig. 7 Complete surround structure

An important part of this analysis is the model of the surround structure and the definition of its interaction with the windshield. Fig. 6(a) shows the FE model of the C-beam cross-section surrounding the square flat plate model, whereas the Fig. 6(b) shows the cross-section of the windshield-surround clamping installation.

Similarly to the laminate layers, the surround structure is modelled by eight-node brick elements. The interaction between surround and windshield has been smeared along its length. Such boundary condition has been modelled by fixing each translational and rotational degree of freedom of the surround contour (clamped condition). Fig. 7 shows the FE model of the complete surround structure.

Fig. 8 shows the proposed main structural components of the cockpit structure. It is made by a main frame, 20 surround frames, a canter beam and a bulkhead. Different modelling approaches have been implemented, taking into account their expected structural behaviour and possible impact response. The main frame has been modelled by 1D beam element, as well as the canter beam which is connected to the main frame, to the surround frames and to the surround structure.
Both the surround frames and the bulkhead have been modelled by fixing the translational degree of freedom along the y- and z-directions, perpendicular to the bird impact direction x.

Furthermore the link between the main frame and the rear part of the surrounding structure has been simulated by the “CONSTRAINED-INTERPOLATION” option offered by the program. It defines the motion of a dependent degree of freedom as result of the interpolation of independent user-defined degrees of freedom, allowing consequently a correct force or moment transfer from the dependent (degree of freedom) dof’s to the independent dof’s of the surrounding structure.

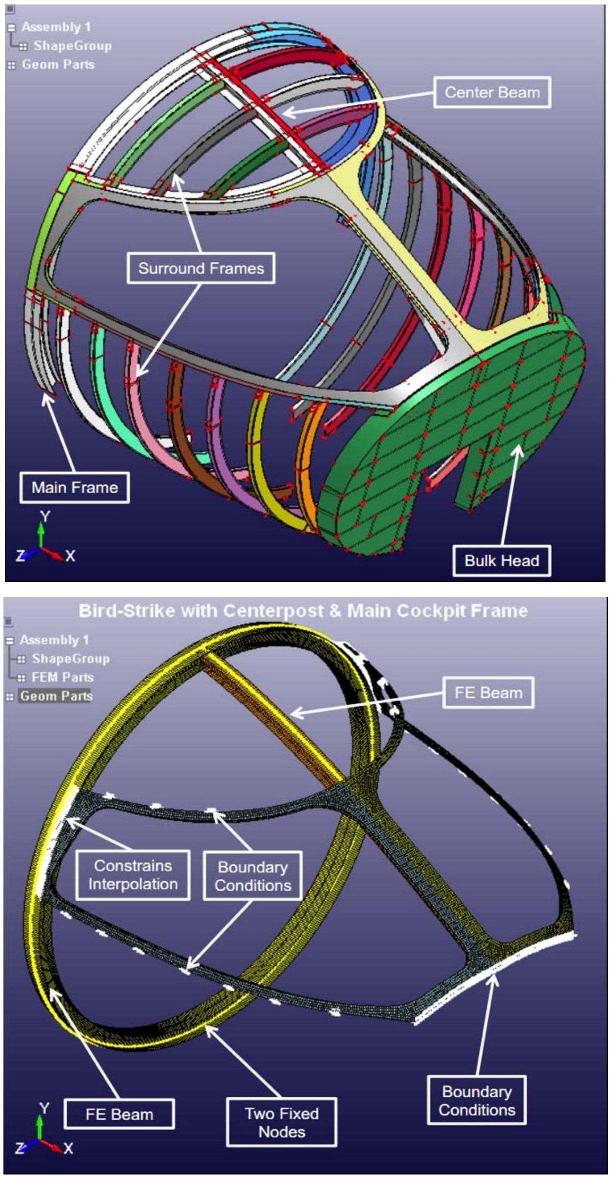


Fig. 8 Geometry and FEM of the cockpit structure

3. Results and discussion

The numerical results of the birdstrike analysis against the full-scale windshield structure are presented in this section.

On the basis of the results obtained on the flat and curved simplified model analysed in the last paper, Grimaldi *et al.* (2013), the results of the parametric analysis allowed to identify about the windshield the best case scenario applying different conditions: three thickness layup configurations varying the impact angle in combination of curvature.

The complete simulation matrix is shown in the Table 7.

The energy transferred to the curved panel during the impact is strongly dependent of the impact angle and in order to design a structure capable to absorb safely the energy of impact involved during the birdstrike, it is preferable to have a windshield structure with an impact angle smaller than 30°, these results are always true for all configurations studied about the windshield curvature and for each layup.

Fig. 9 presents two lateral views of the full-scale windshield model and the simplified one with a radius of curvature equal to 1.273 at an impact angle α =30◦ with a layup of five different layers of same thickness, case 16 of the last Table 7.

Table 7 Numerical simulation matrix

Test n°	Curvature [m]	Impact Angle [deg]	Thickness ratio	Failure
1	$r = \infty$	$\alpha = 90°$	$t_{glass} = t_{pvb}$	YES
2	$r = \infty$	$\alpha = 90°$	$t_{glass} = 2 \text{ x } t_{pvb}$	YES
3	$r = \infty$	$\alpha = 90°$	$t_{glass} = 3 \text{ x } t_{pvb}$	YES
4	$r = \infty$	$\alpha = 60°$	$t_{glass} = t_{pvb}$	YES
5	$r = \infty$	$\alpha = 60°$	$t_{glass} = 2 \text{ x } t_{pvb}$	YES
6	$r = \infty$	$\alpha = 60°$	$t_{glass} = 3 \text{ x } t_{pvb}$	YES
7	$r = \infty$	$\alpha = 30°$	$t_{glass} = t_{pvb}$	NO
8	$r = \infty$	$\alpha = 30°$	$t_{glass} = 2 \text{ x } t_{pvb}$	NO
9	$r = \infty$	$\alpha = 30°$	$t_{glass} = 3 \text{ x } t_{pvb}$	NO
10	$r = 1.273$	$\alpha = 90°$	$t_{glass} = t_{pvb}$	YES
11	$r = 1.273$	$\alpha = 90°$	$t_{glass} = 2 \text{ x } t_{pvb}$	YES
12	$r = 1.273$	$\alpha = 90°$	$t_{glass} = 3 \text{ x } t_{pvb}$	YES
13	$r = 1.273$	$\alpha = 60°$	$t_{glass} = t_{pvb}$	YES
14	$r = 1.273$	$\alpha = 60°$	$t_{glass} = 2 \text{ x } t_{pvb}$	YES
15	$r = 1.273$	$\alpha = 60°$	$t_{glass} = 3 \text{ x } t_{pvb}$	YES
16	$r = 1.273$	$\alpha = 30°$	$t_{glass} = t_{pvb}$	NO
17	$r = 1.273$	$\alpha = 30°$	$t_{glass} = 2 \text{ x } t_{pvb}$	NO
18	$r = 1.273$	$\alpha = 30°$	$t_{glass} = 3 \text{ x } t_{pvb}$	NO
19	$r = 0.636$	$\alpha = 90°$	$t_{glass} = t_{pvb}$	YES
20	$r = 0.636$	$\alpha = 90°$	$t_{glass} = 2 \text{ x } t_{pvb}$	YES
21	$r = 0.636$	$\alpha = 90°$	$t_{glass} = 3 \text{ x } t_{pvb}$	YES
22	$r = 0.636$	$\alpha = 60°$	$t_{glass} = t_{pvb}$	YES
23	$r = 0.636$	$\alpha = 60°$	$t_{glass} = 2 \text{ x } t_{pvb}$	YES
24	$r = 0.636$	$\alpha = 60°$	$t_{glass} = 3 \text{ x } t_{pvb}$	YES
25	$r = 0.636$	$\alpha = 30°$	$t_{glass} = t_{pvb}$	NO
26	$r = 0.636$	$\alpha = 30°$	$t_{glass} = 2 \text{ x } t_{pvb}$	NO
27	$r = 0.636$	$\alpha = 30°$	$t_{glass} = 3 \text{ x } t_{pvb}$	NO

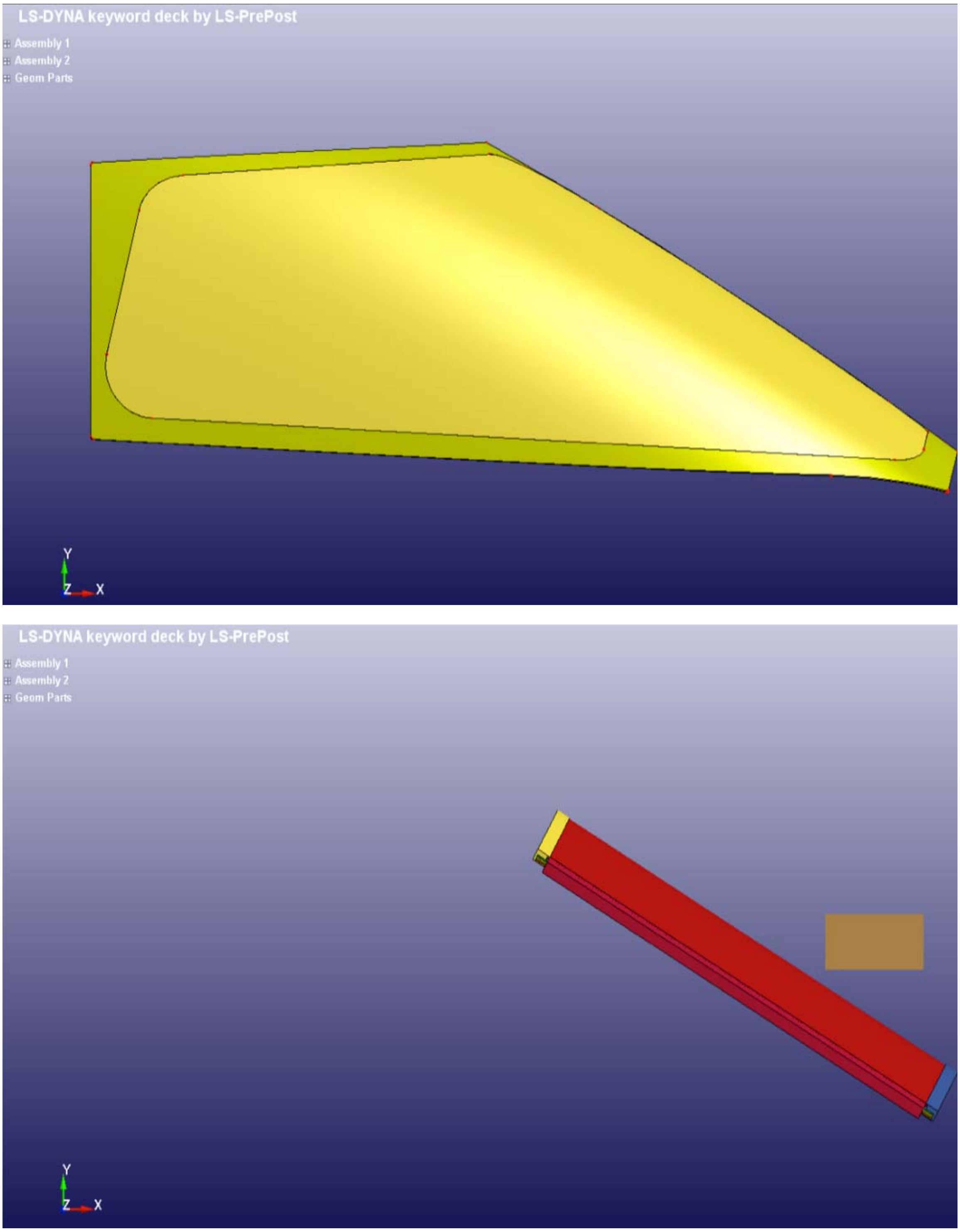


Fig. 9 Full-scale and simplified windshield models

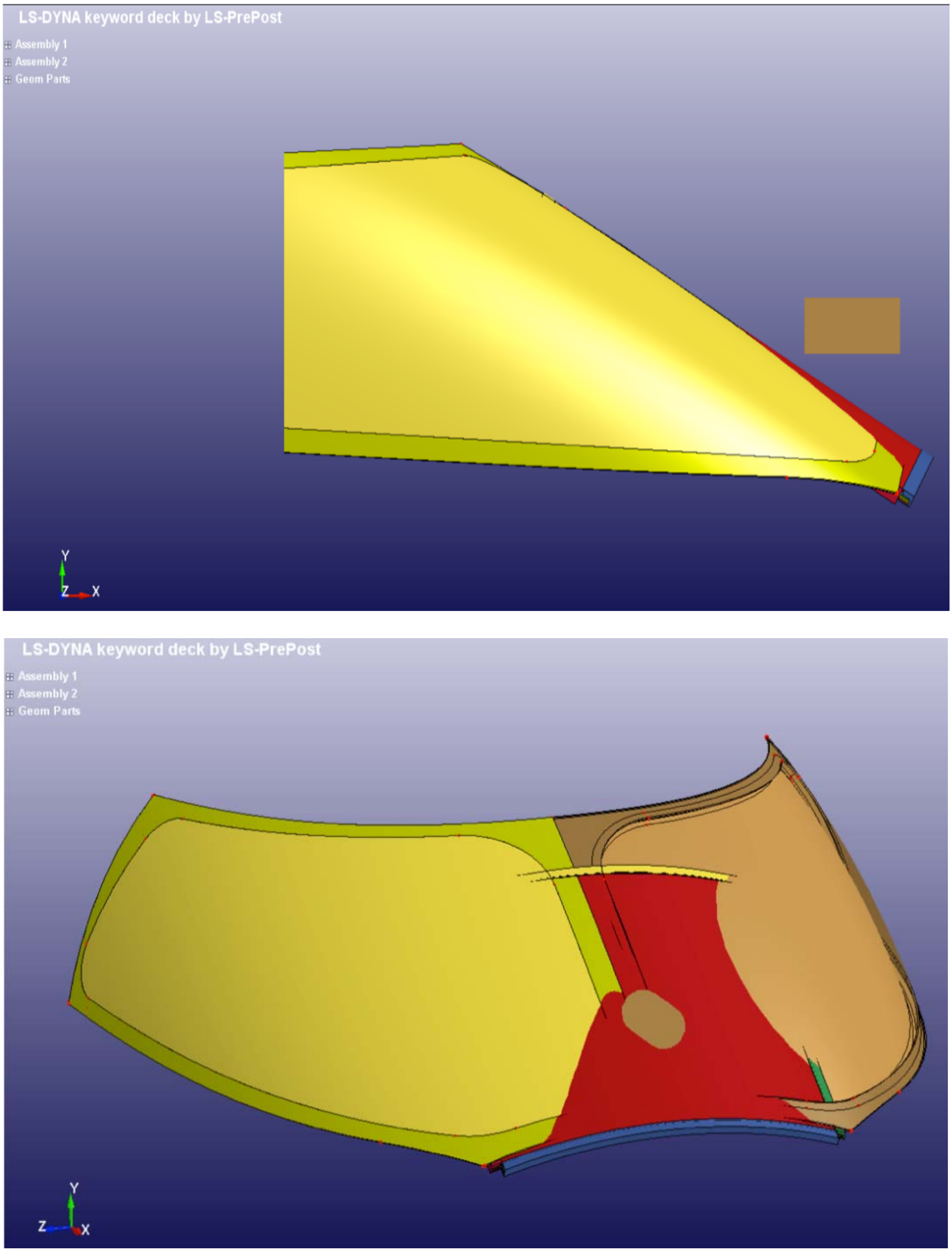
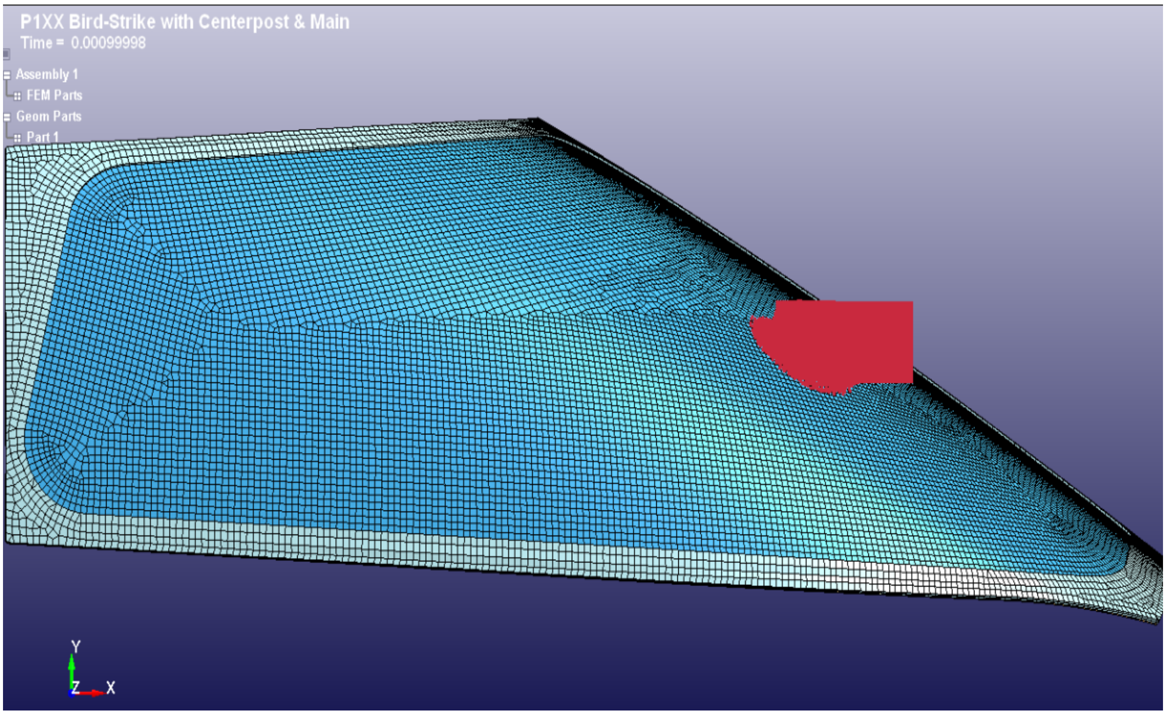
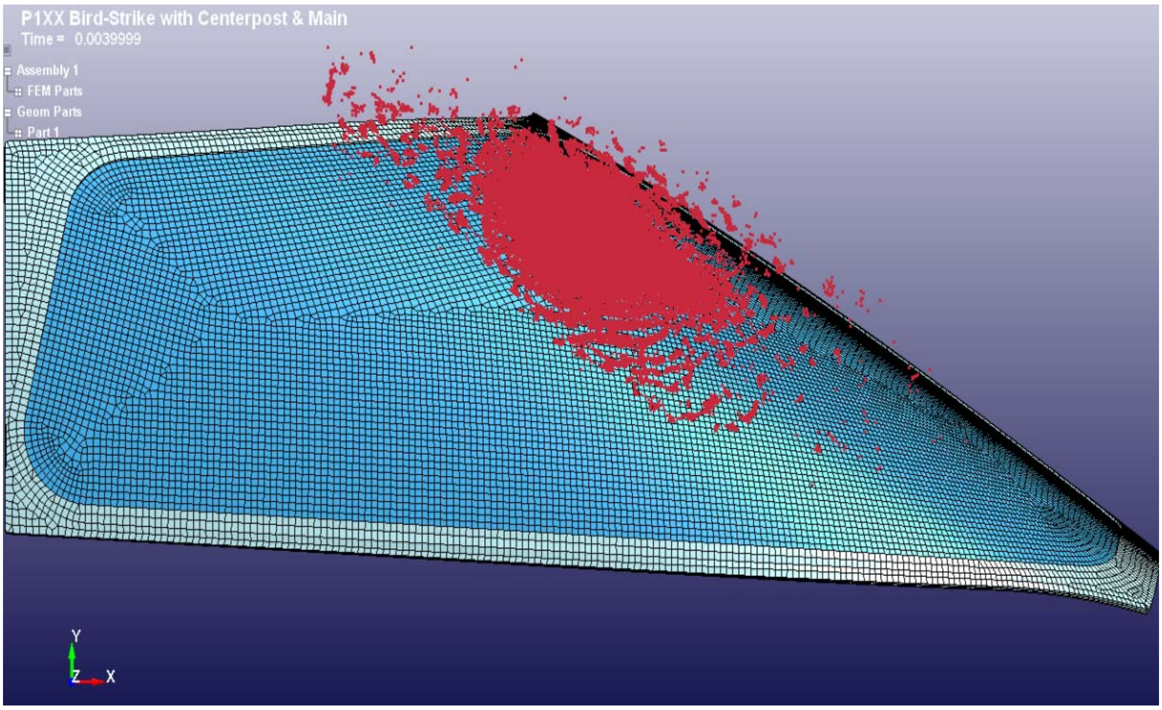


Fig. 10 Overlap of the complete and simplified windshield models



$t = 0.001$ sec



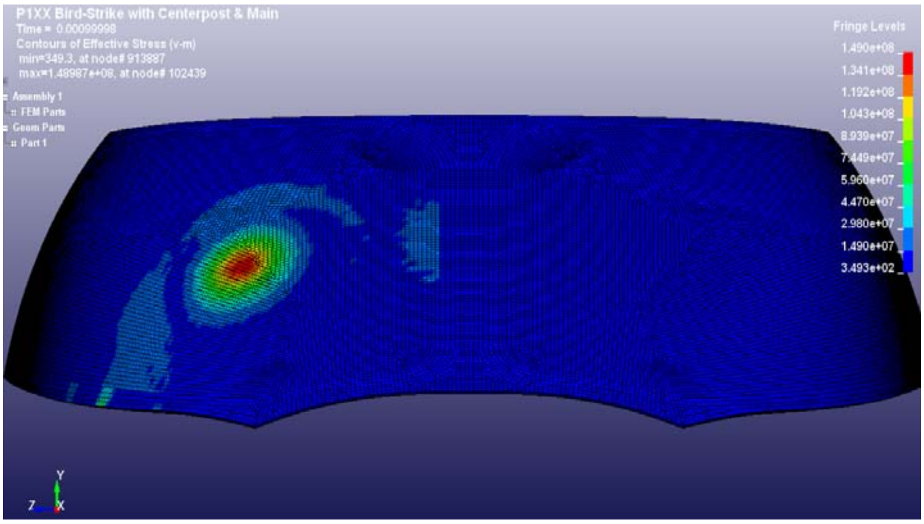
$t = 0.004$ sec

Fig. 11 Bird impact scenario for the complete model

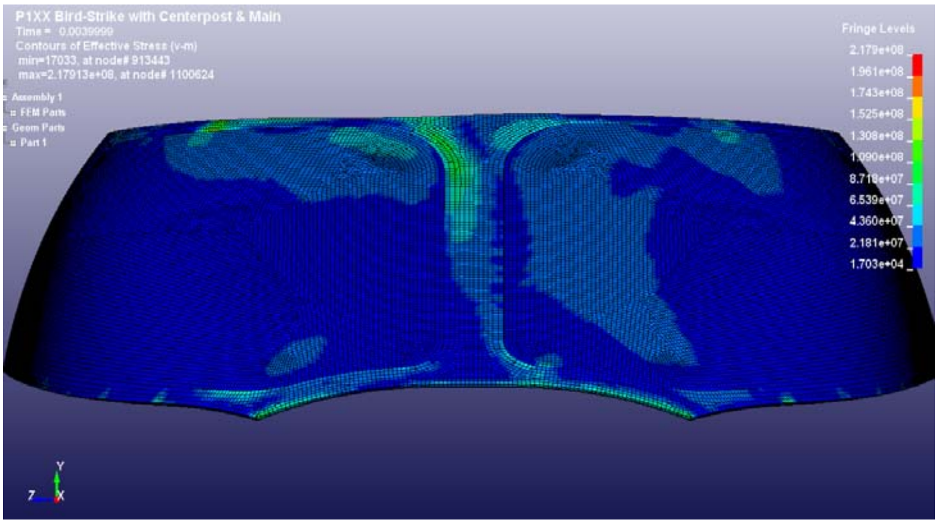
The overlap of the both models, reported in Fig. 10, shows that the simplified model simulates rather well the real model, at least in the impacted area.

Furthermore, recalling that for the complete model the averaged thickness of the glass ply is twice as much as the interlayer one, it comes out that the simplified model, employing geometrical parameters which are consistent with those of the complete model, yields results satisfactorily correlated with those of the complete model simulation.

Fig. 11 shows two plots of the birdstrike against the full windshield model, at t = 0.001 sec and t = 0.004 sec, respectively. The deformation of the bird during the impact and its squashing into the windshield is well simulated.



t = 0.001 sec



t = 0.004 sec

Fig. 12 Von Mises stress on the complete windshield model

Furthermore in Fig. 12 the contour plots of the corresponding von Mises stresses of the windshield are reported. As expected, the impacted area of the windshield reaches its maximum stress value during the first 1.5 milliseconds, remaining below the threshold of the glass failure.

Fig. 13 presents the displacement time-history of the impacted area of the right windshield panel. It reaches a maximum value of 3.7 mm after 1.2 milliseconds starting to the instant of the impact. Then the panel tends to return to its initial configuration, reaching a final value of 2.6mm at the end of the simulation, (5 msec).

Fig. 14 and Fig. 15 show the time-histories of the internal energy for each layers of the right and left panel of the windshield, respectively, in the case of the bird impact on the right panel only. It is interesting to highlight that only a small amount of energy is transferred from a panel to the other, allowing the conclusion of absence of any failure for the not-impacted panel.

Additionally the energy peak is reached at a delayed time in the unimpacted panel, justifying the conclusion of a "spreading out" of the energy from a very localized area toward a larger surface, moreover reducing any incipient failure, 0.

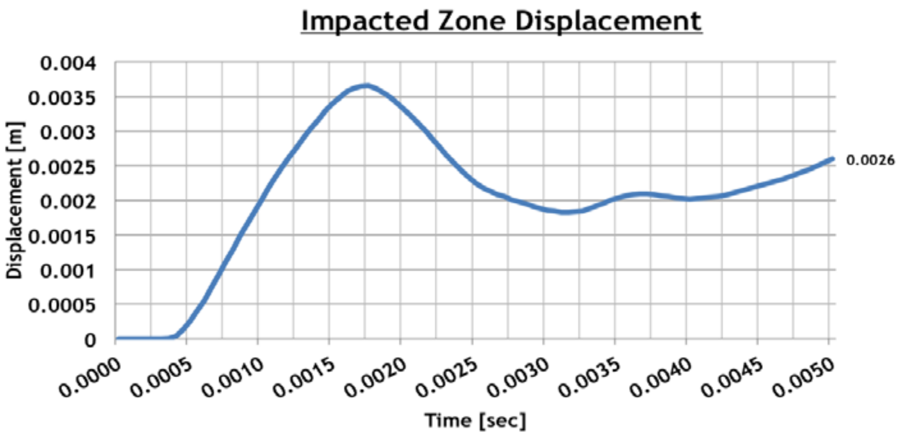


Fig. 13 Displacement of the impacted zone of the right panel

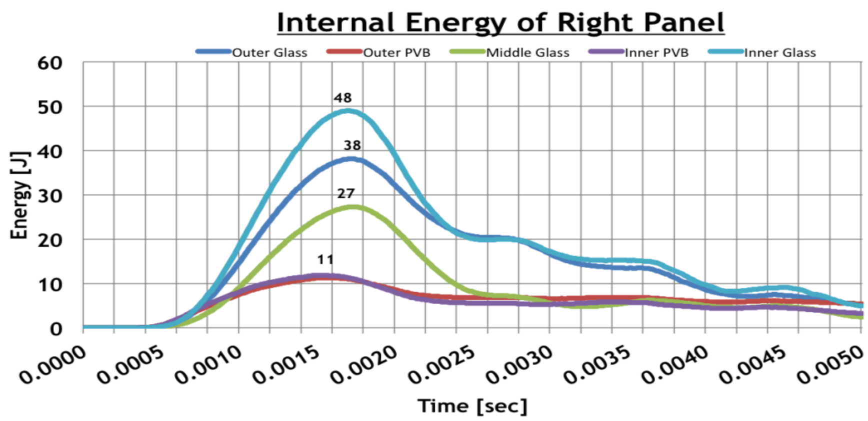


Fig. 14 Internal energy for each layer of right panel

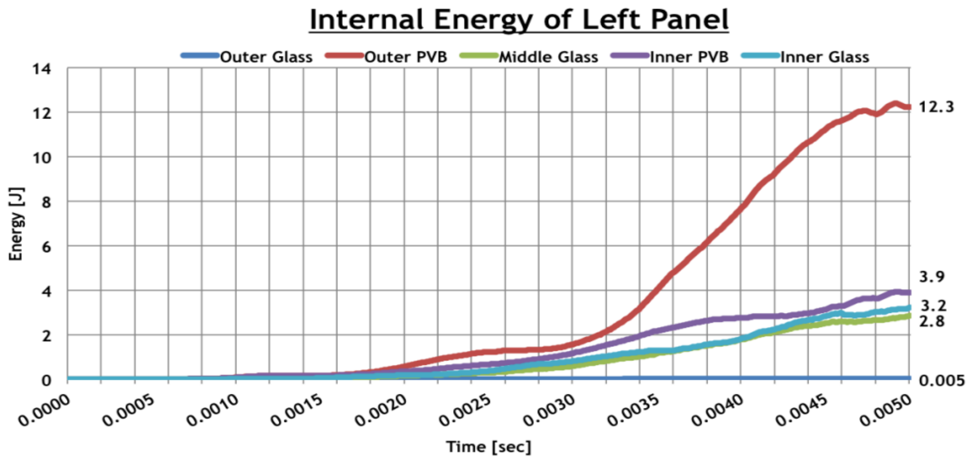


Fig. 15 Internal energy for each layer of left panel

In order to identify the most critical impact condition, based on a model, which realistically correlates the structural behaviour, a considerable number of simulations have been carried out, impacting different areas on the windshield. One of the most interesting cases is shown in Fig. 16

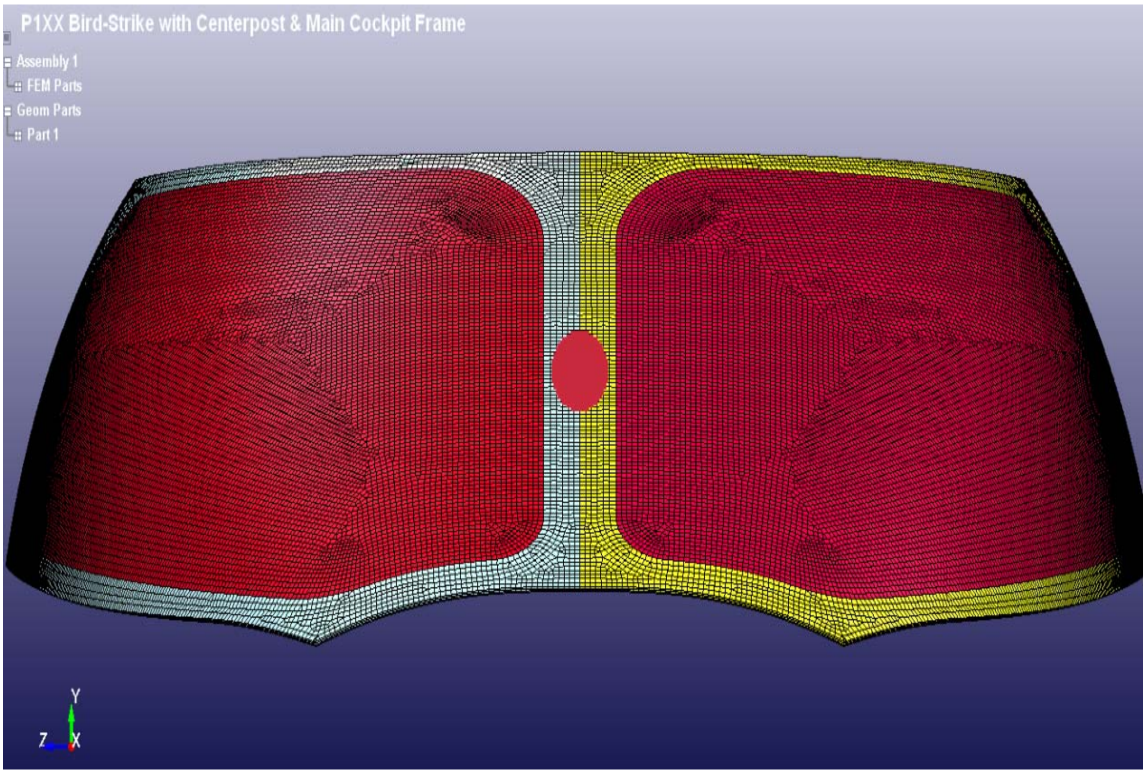


Fig. 16 Birdstrike against the center beam of the surround structure

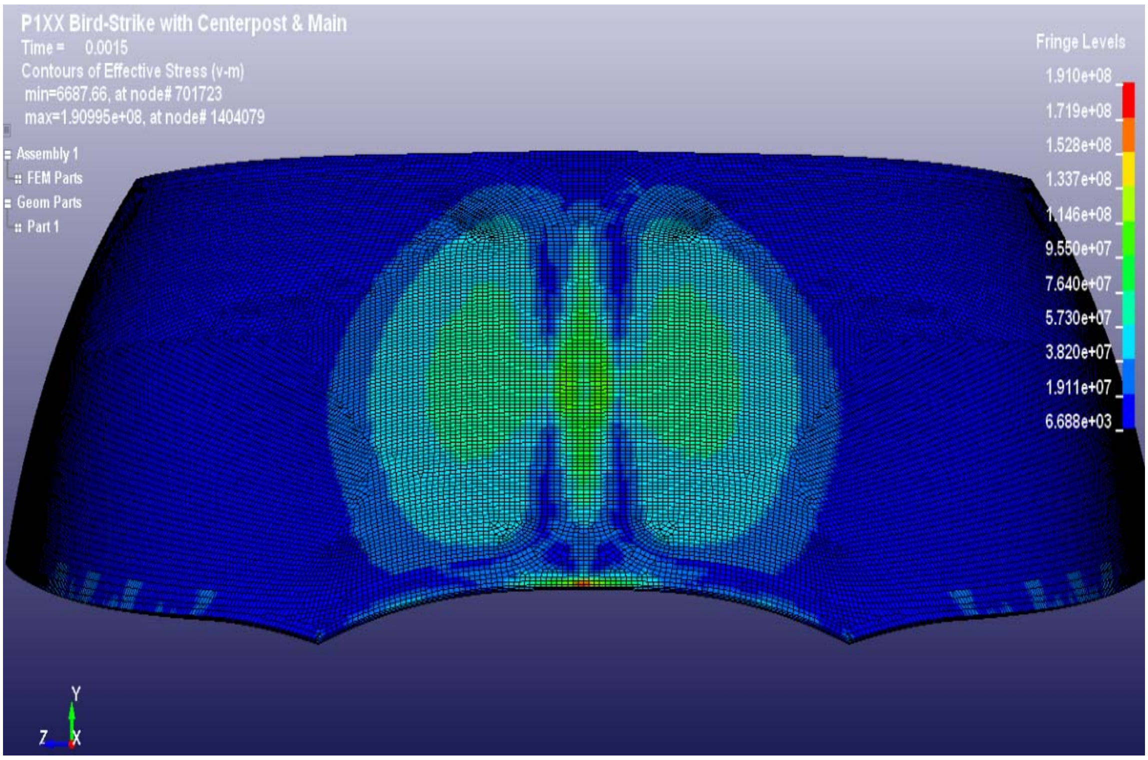


Fig. 17 Von Mises stress plot for birdstrike vs the center beam

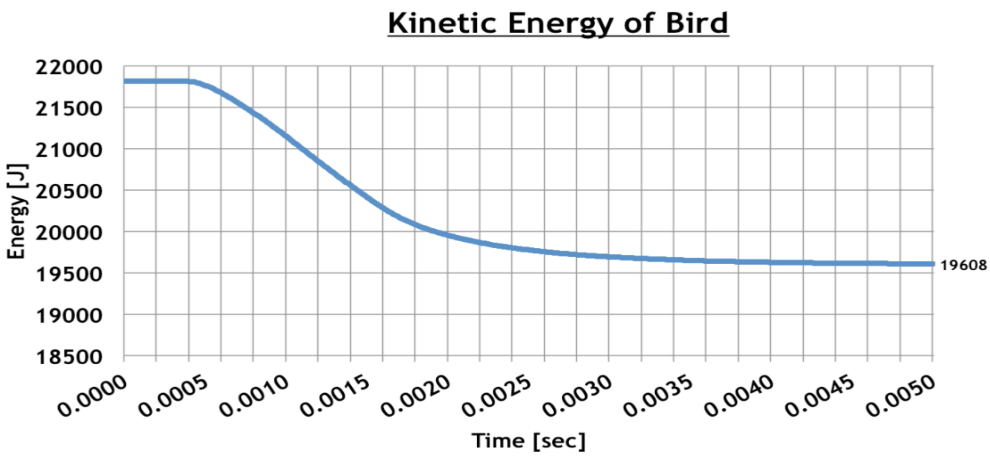


Fig. 18 Kinetic energy of the bird

where the bird hits the center beam of the surround, which divides the two panels of the windshield. It could appear to be the most critical, because, at least intuitively, it might cause a simultaneous failure of both panels, with a propagation of the cracks in both directions with a consequent loss of visibility for both panels.

The numerical simulation provided the interesting (and perhaps unexpected) result of no failure in both panels. At the end of the analysis the stress levels reached values well below those obtained in the previous case, Fig. 17, justified by the active participation of the central beam to the absorption of the impact energy.

The last time-history, shown in Fig. 18, recalls another key aspect of the birdstrike windshield interaction. It, in fact shows that the kinetic energy of the bird at the end of the simulation remains a big percentage of that before the impact. In this specific case, only 9% of the impact energy of the bird is transferred to the windshield, and most part is dissipated in other forms of energy, such as heat, elastic, sliding energy and so on. This is mainly consequence of the impact angle of the bird, and the double curvature of the windshield, which result desirable design parameters able to avoid penetration of the bird, and fragmentation of the glass.

4. Conclusions

The goal of this work has been the development of a methodological numerical approach to the study of the birdstrike problem for the design, verification, and optimization of a bird-proof windshield of an airplane. The SPH approach has been confirmed to be the most suitable and feasible methodology to simulate the dynamics of a high-speed bird impact (Monaghan 1992).

Both bird SPH and target FE model have been prepared by the LS-PrePost pre-processor software, while each numerical simulation has been performed by using LSTC/LS-Dyna explicit solver.

The results obtained by the numerical simulation of a complete aircraft windshield, including its surrounding structure, have verified its capability to withstand the impact force transferred by the bird during the impact, by the virtue of its material properties and geometrical characteristics (small impact angle and double curvature), allowing the bird to slide along the windshield and to continue its path reducing the transfer of its kinetic energy to the structure.

One important conclusion of this work has been the collection of results and experiences able to define a “rule of thumb” for the design of an airplane windshield structure compliant with the requirements of the airworthiness rules.

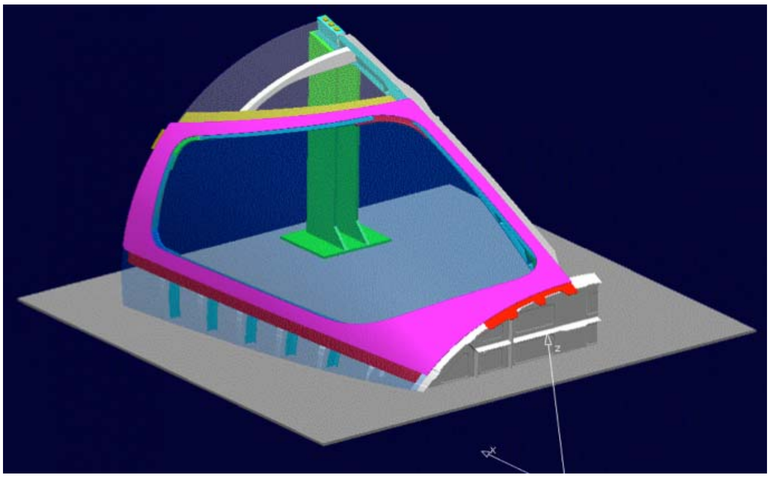


Fig. 19 Birdstrike test article proposal

Additionally it has permitted to trace the guidelines for designing a birdstrike test article proposal, Fig. 19, minimizing the reproduction of the full front structure of the aircraft.

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