FE STUDY OF WINDSHIELD SUBJECTED TO HIGH SPEED BIRD IMPACT

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Abstract

External aircraft components of an aircraft such as windshield, leading edges engine structures are susceptible to collisions with birds. Aircraft windshields and engine components are especially vulnerable to damage. Airworthiness standards require that these critical components should be capable of withstanding bird strikes at critical flight speed to a certain degree. In particular, windshields should comply with the very stringent airworthiness regulation (CS25 and FAR25), [1] and [10], which states that windshield must guarantee sufficient visibility for safe continuation of the flight and landing after a bird impact.
The paper presents the numerical results of an ongoing joint research program developed between academic partners and Piaggio Aero Industries to design a bird-impact resistant laminated glass structure used for a typical aeronautical windshield. Sensitivity studies were carried out to assess the influence of geometrical parameters such as panel dimensions, the thickness, the curvature, as well as impact parameters, bird size and velocity, impact angle, boundary conditions. A detailed nonlinear transient finite element analysis was carried out using an explicit FE code, continuing a research approach on these topics, [3-5], these results allowed to provide possible guidelines for future windshield design.

1 Introduction

For commercial aircrafts bird strike poses one of the most dangerous threats to a safe flight, because of high energy levels as a consequence of capability to operate at a speed greater than 250knots. The aircrafts have to be certified for a proven level of impact resistance, in this way an aircraft has to assure the capability of a safe fight and landing after the impact against a bird at cruise speed. The present study concerns the analysis of the effects induced by the airframe on the currently installed on a typical Piaggio Aero Industries business aircraft windshield with the purpose to clarify if the possibility to fit the glass to the airframe could induce some positive effects on the windshield behaviour during a bird strike.

Actually, the windshield designed retained by Piaggio Aero Industries is composed of two parts symmetrically disposed and separated by the centerpost. This windshield is a hoop-loaded design consisting of a fiberglass edge attachment system that is bonded to the inboard and outboard glass, by the titanium bolts, for load transfer of the airframe. This installation is sensitive to the crack propagation, the fracture pattern is typically originated in correspondence of hole of the bolt under the pressurization loads and aerodynamic ones [Fig. 1].

Fig. 1. Crack Of Windshield

The actual aircraft windshield installation presents several titanium bolts positioned along the edge glass to fix the windshield on the surround. The investigation of the effects induced by geometric shape and surround-windshield surface coupling brings to produce an alternative solution for future CS/FAR 25 aircraft application to fit the windshield on the airframe, no more by titanium bolts but constraining the glass and surround with the rubber, adopting a "plug solution". Reducing the bolts number it could be possible to reduce the failure about crack propagation along the glass, [12].

This design improves the structural behaviour of the glass and allows an easier manufacturing of the window itself. The finite element analysis allows to confirm the validity of the approach because the damage due to the impact against a 4 pound bird results to be satisfied according the regulations, and the results provided guidance in the design, development and testing of the future glass composite windshield structures.

The use of advanced computer simulation to reproduce the bird strike on new structural components can be a powerful tool for the development of new components and for minimizing the number of tests to be performed. Furthermore it allows to analyze bird impacts at locations and in conditions not considered in the experimental tests and to evaluate the impact response for different structural and material parameters before the actual fabrication of the prototypes, thus reducing time and cost incurred in empirical testing. To perform a bird strike test, it is necessary to make up the test article, in the case of a strike on the windshield it is necessary to assembly the windshield with the surround and the part of the cockpit. The windshield cost may reach up to some tenths of thousand of US dollars, and similarly the test with a pressure gun. The budget about this test is very onerous and it stands to reason the solver can aid in the design. Current generation of nonlinear explicit finite element programs can greatly help designers and structural analysts for a more realistic and optimized design and verification of aircraft components to bird strike conditions, [5].

2 Finite element analysis

Scope of this work is to illustrate the preliminary structural design of the windshield retained by Piaggio AeroIndustries on a typical business jet aircraft. A FE model has been generated by MSC/PATRAN code importing the windshield geometry [Fig. 2]. Windshield is composed of two transparencies LH and RH having double curvature and each windshield area is 1m^2. In order to comply fail-safe requirements two layers of HerculiteII and one layer of interlayer material type PVB have been considered.

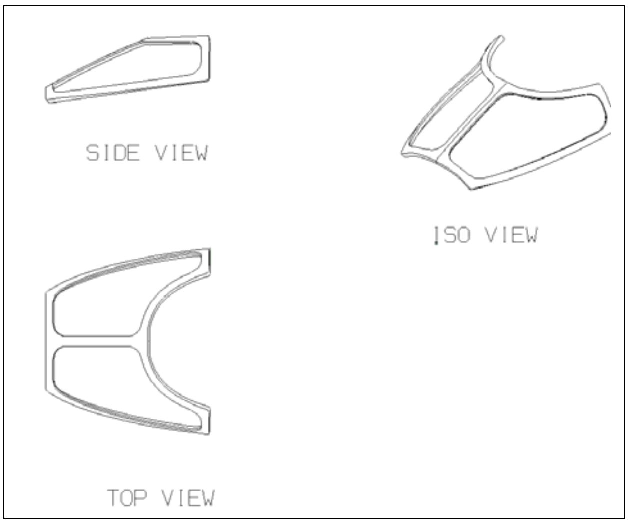


Fig. 2. Windshield Geometry About Jet Aircraft

2.1 Finite element model

The lay up of the laminated glass presents two layers of glass divided by one layer of plastic material, [Fig. 3]. The laminated glass is modelled as a solid with three-dimensional CHEXA elements, while the outer plies of glass were modelled as plates using bi dimensional CQUAD elements, with nodes matching with the solid external nodes, [11]-[13].

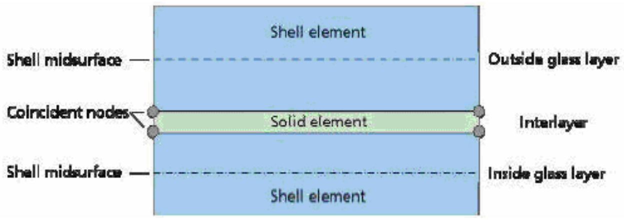


Fig. 3. Glass Laminated Layup

FE model consists of 54,296 finite elements, which 27,148 are CQUAD elements and 27,148 are CHEXA elements for the interlayer. The mesh is very crowded, which allows a very careful analysis although it entails an increase in the computational time. The bird is modelled as a cylindrical shape body consisting of 8,000 CHEXA elements, the bird weight is 1.8kg and the density is 482.5Kg/m^3, the dimensions of bird are 106mm about the diameter and with a cylinder height equal to 212mm.

2.2 Material

The bird is characterized by a specific material card, which defines in the nonlinear finite element the behaviour of linear fluid material, defining the density, and pressure.

Density [*Kg/m^3*]	482.5
Pressure *[N/m^2]*	2.2 10^9

Tab. 1. Bird Properties

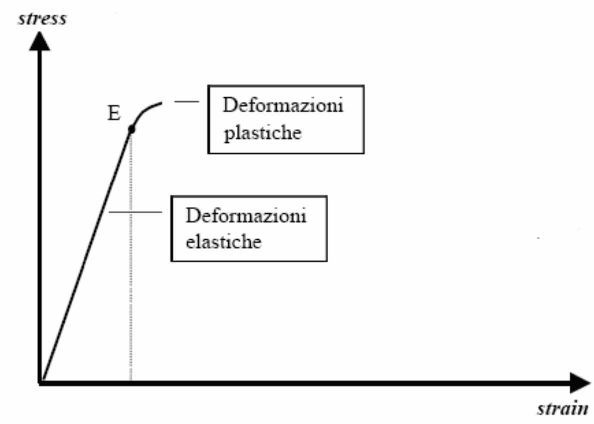
With laminated glass, glass becomes a safe product. Indeed, during a shock, if glass breaks, the interlayer retains the glass fragments thus avoiding the projection of fragments and the risk of laceration, [9]. Moreover it confers on the glazing a residual rigidity guaranteeing the stability of its processing and ensures the retention of the striker, [8] and [14]. The laminated glass is composed of alternate layers of glass and plastic material, such as PVB Polyvinilbutirral, which are materials with very different characteristics and so they respond in a different way to the load applied to the sample, [11].

The glass is an amorphous, transparent and isotropic material, with characteristics of high brittleness if subjected to both dynamic and static loads [7]. The Tab. 2 shows the characteristics:

Density ρ *[Kg/m^3]*	2,400
Young Modulus *E[N/m^2]*	8.14 10^{10}
Poisson ratio υ	0.22
Yield stress σ_y *[N/m^2]*	2.4 10^8

Tab. 2. Glass Properties

In order to model the glass we considered it to be an elastic-plastic material with an infinitely small plastic part of the σ-ε curve so that we could treat it like brittle material. Tab. 3 shows the stress strain curve, the failure stress is identified in the plastic stress because the material presented as a brittle material.



Tab. 3 – Stress Strain Curve About The Glass Material

The elastic-plastic behaviour of the material is taken into account and it is possible to define an isotropic hardening using von Mises yield criterion with a plasticity algorithm which includes the strain rate using the Cowper-Symonds law. In the crash phenomenon we consider the effect of velocity of load application and the strain-rate effect. When the strain-rate runs up, some materials show an increase in strength and their behaviour is defined by Cowper-Symonds law:

$$\frac{\sigma_d}{\sigma_y} = \left(1 + \frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{p}} \qquad (1)$$

where σ_d represents the dynamic stress, while σ_y the yield stress.

The plastic material is the PVB (Polyvinilbutirral) and it is interposed between two layers of glass and has typical characteristics of a viscoelastic interlayer. This type of material shows good characteristics of strength and transparency, besides allowing a high deformations before the failure and a good tearing strength. Tab. 4 shows standard literature characteristics of the PVB material:

Density ρ *[Kg/m³]*	1,100
Bulk modulus *K[N/m²]*	$2\ 10^{10}$
Short time shear modulus G_0 *[N/m²]*	$3.3\ 10^8$
Long time shear modulus G_∞ *[N/m²]*	$6.9\ 10^5$
Decay factor β	12.6
Failure strain ε_f	1.57

Tab. 4. Interlayer Properties

The interlayer gives a special impact strength to the glass, which can absorb a part of the impact energy thanks to its deformation. Furthermore it avoids the fragmentation of glass by its adhesive property, which could be very dangerous for the occupants of the aircraft. The interlayer is modelled as a linear viscoelastic material, and we can write the relation of shear modulus in terms of time:

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t} \qquad (2)$$

The plot of this function is shown in Fig. 4:

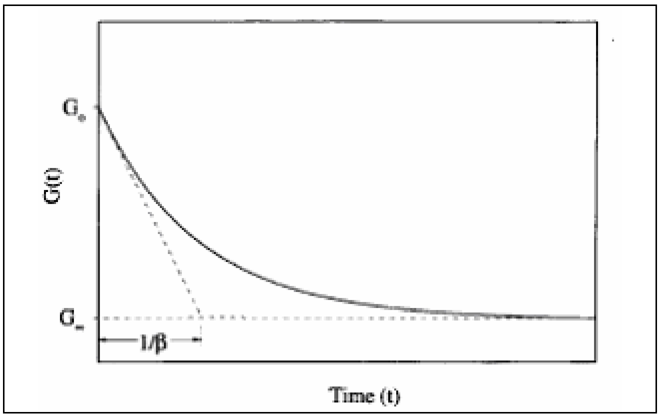


Fig. 4. Function Of The Shear Modulus In The Time

Therefore, the volumetric behaviour of PVB is assumed to be linear, that is:

$$p = -K\varepsilon_{kk} \qquad (3)$$

where K is the bulk modulus and ε_{kk} the relative deformation. The Young modulus of the interlayer [E_p] and the Poisson coefficient [υ_p] are defined by equation (4) and (5):

$$E_p = \frac{9KG_0}{3K + G_0} \qquad (4)$$

$$\nu_p = \frac{3K - 2G_0}{6K + 2G_0} \qquad (5)$$

Known K and G_0 it is possible to obtain the properties of the material. About the PVB used for the windshield installation, the short time shear modulus $G_0 \approx 1GPa$, and long time shear modulus $G_\infty \approx 1MPa$. Since the impact duration is in the range of milliseconds, the stress relaxation modulus G(t) of PVB changes very little during impact. In this short time, PVB behaves like a solid glassy material with $G(t)=G_0$.

2.3 Load condition

In order to study the bird-strike problem we used the lagrangian approach and defined a study bird velocity of 154m/sec. For the Lagrangian bird technique the bird is modeled using Lagrangian brick finite elements with the properties of a fluid. The bird elements are given with an initial pressure causing the bird to impact the structural finite element model, with master-slave contact interfaces defined to apply the bird element loads to the structure. Bearing in mind we defined the bird as a mass able to release a pressure equal to 2,200MPa during an impact. The pressure value is estimated according to an empirical formula, [6]. The lagrangian formulation is used mostly to describe solid materials. However, a Lagrangian description of this problem may result in loss of bird mass due to the fluid behavior of the bird which causes large distortions in the bird. Considering the bird as a fluid element is the cause of failure due to large distortions and consequently these distortions are the cause of the large variations about volumetric strain (which measures the ratio of change of body's volume) in some elements of the modeled bird. This loss of mass may reduce the real loads applied into the impact. In an explicit finite element analysis, the time step is determined by the smallest element dimension, and a severe mesh distortion may cause a decrease in time step up to an unacceptably low value for the continuation of the calculations. These excessive distortions cause failure due to volumetric strain in some elements of the modeled bird. The lagrangian approach offers a lot of advantages related to the eulerian technique as for example the computational time is lowest than the eulerian approach.

2.4 Boundary condition

It is clear that it was difficult to model the boundary conditions of the windshield in a simple way, but on the first approximations we chose to model only the windshield without the surround and the cockpit structure. Furthermore the boundary conditions are defined fixing every translational and rotational degree of freedom, of the windshield contour, simulating the real consistence of the rubber around contour of windshield. The presence of bolts would be produced by the modeling of windshield springs stiffness set to high values in order to simulate rigid contacts between titanium bolts and aluminum spacer. These aspects are avoided because the stress concentrations in the holes are reduced at minimum, thanks to use of a plug approach, such as a rubber material which completely constrained the windshield in the surround, in this way the bolts are absent and the stress peak, too. Indeed about the contact modeling we chose to consider a contact between master and slave surfaces, where the surface of the bird was the master while windshield one was the slave. In this case we took into account that the nodes of slave surface cannot penetrate in the master surface too.

3 Results

The impact of the composite windshield was simulated for velocity to 154/s and a bird mass of 4lb. Actually the study windshield design retained by Piaggio Aero Industries presents a glass with two layers of HerculiteII and one layer of interlayer material type PVB. We studied a first model of transparency fitted at the surround with titanium bolts and this configuration didn't satisfy the strike and the penetration was present on whole transparency. More critical zones were in correspondence of fittings, because there were the stress concentration propagates by the hole. Furthermore the model was improved, indeed the bolts are replaced with the rubber along the edges of the windshield. The total impact energy was absorbed, the penetration was not present and the failure zone only regarded the zone impacted by the strike. We performed a great deal of simulations on the FE windshield model, which carried out a set of results about the stress distribution of every layer of the laminated glass, the possibility of failure of some elements. We fixed an endtime of 4ms for our simulations, and about it, in the Fig. 5 we can see the FE model at the end of simulation, and in particular the high deformation of the bird defined as a linear fluid.

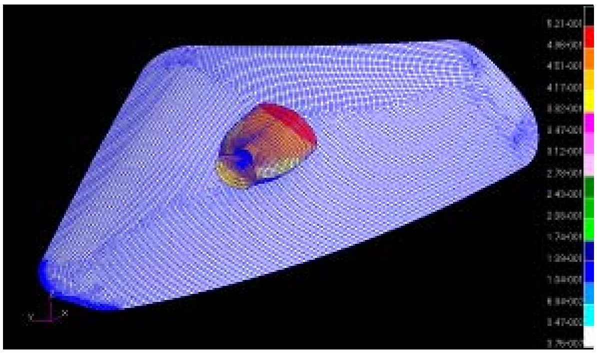


Fig. 5. Impact Bird Against Windshield

The impact angle is quite far from 90 degree. The windshield position offers an angle related to the waterline of the aircraft, which is favorable in this numerical test. The impact produces a sliding between two surfaces, producing a large reduction of the contact force related to impact characterized by a normal strike. In Fig. 5 we can see the behavior of the bird, as soon as the bird hits the target, and after this first contact the bird rotates upward causing a sliding on the windshield surface.
In Fig. 6 is shown the stress distribution of the outer glass layer of the windshield, this is the part of windshield impacting with the striker.

The fringe indicates the highest value of stress concentrated in the point of impact.

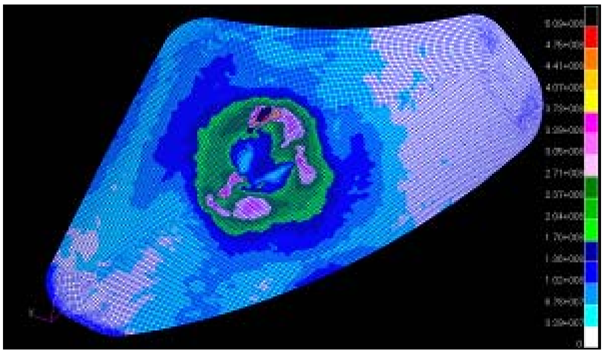


Fig. 6. Stress Map On The Outer ply

We can also see a participation of the most part of the structure to the absorbing of the impact energy. This is possible thanks to interposition of the plastic interlayer which seems to transfer part of the energy consequent upon the impact to the periphery of the structure. The deformed shape is shown in Fig. 7, in this figure the failed elements have not written in the output file. And it shows the stress plot on the configuration. The failure occurs when the equivalent plastic strain exceeds the 3.5%. Then it shows the Von Mises stress on the bidimensional element and by examining it, it is possible to distinguish the initiation of damage in the buckled region highlighted by the fact that the maximum stress on the inboard ply were larger than the allowable stress. This showed us that the outer ply was not able to withstand the birdstrike.

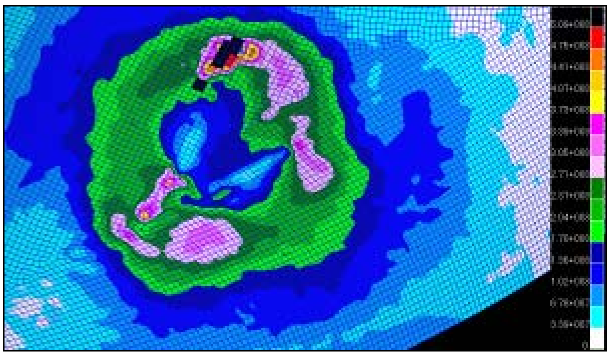


Fig. 7. Zoom About The Impacted Windshield

In Fig. 8 is represented the final stress distribution of the plastic interlayer of windshield.

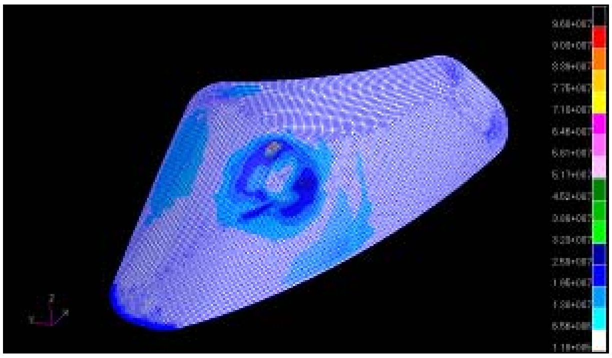


Fig. 8. Stress Map On The Interlayer

It is interesting to note a symmetric distribution of the stress around impact point and a participation of others two peripheral zones of the layer. Unlike previous case, thanks to the significant plasticity of the interlayer we don't note any elements failure.

In Fig. 9 is represented the final stress distribution of the inner glass of the windshield.

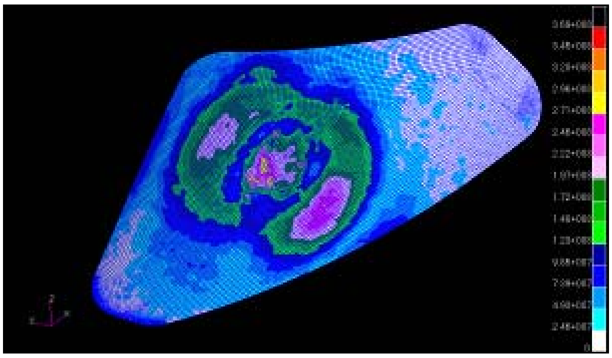


Fig. 9. Stress Map about The Inner Layer

The stress distribution is clearly similar to outer glass one (shown in Fig. 6), but with a significant difference: in this case there is not any elements failure, as we can see better in the Fig. 10.

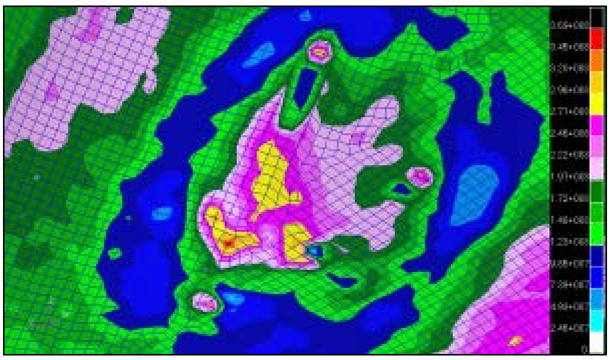


Fig. 10.Zoom About The Impacted Inner Layer

Conclusions

1. Glass materials are very brittle and require little energy to create the first failure in the material. The possibility to create a composite material as an union of the viscoelastic material, as PVB, to the glass material aids the possibility to create a safety product because if glass breaks, the interlayer retains the glass fragments thus avoiding the propagation and laceration.
2. Geometric shape of the windshield due to double curvature of the surface and very considerable impact angle are favorable to reduce the affects of the strike. The contact forces, recorded during an impact of this type, reduce the damaged zone after impact.
3. The tensile strength of PVB increases with an increasing strain rate and this is probably due to a strain rate dependent behavior of the glass, [11].
4. Reducing the number of bolts we reduced the stress concentration in the constrained point, in other word, the stress in the constrained hole are origin of crash propagation and then the failure. The possibility to change the lining with the bolts permit to realize an uniform distribution along the windshield contour reducing the stress concentration. This technique is largely diffuse in the automotive field even if the air speed are significantly different by car speed but a plug solution can be a new concept to idealize a fixed point between the surround and the glass cockpit.

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