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THEORETICAL ASSESSMENT, NUMERICAL SIMULATION AND COMPARISON WITH TESTS OF BIRDSTRIKE ON DEFORMABLE STRUCTURES

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Introduction

A typical impact problem encountered during the design of an aeronautical structure can consist either in the birdstrike against external surfaces or in the ingestion of birds into the engine.
A deep interaction exists between the deformation of the structure and the contemporaneous deformation of the colliding bird, heavily influencing the loads time histories, which is continuously modified. For these reason it is necessary to use dedicated FEM codes to deeply investigate the dynamics of the phenomenon in order to perform a global analysis able to take into account the deformation of both the colliding parts.
Notwithstanding, the experimental approach cannot be abandoned; on the contrary, it assumes a fundamental importance to supply reliable terms of comparison for numerical simulations, as well as data for their assessment and verification.
In the following, the results of an experimental-numerical research activity jointly performed at the Aerospace Eng. Dept. of Politecnico di Milano and Aeronautica Macchi on the birdstrike against the external surface of aircraft are reported.

General description

Much of the risks of an impact with a bird during an airplane life can be attributed to the advancement in radar detection techniques as well as the development and increased use of terrain following instrumentation. Flight profiles utilising these technologies place the aircraft in areas of high bird density, below 1500m. For this reason a big impulse to the research in this field has been given.
The birdstrike phenomenon is characterised by:

- loads with high intensity and rapidity: load magnitude of up to 25000 Kg with a duration of approximately one or two milliseconds,
- high strain rates in the material of the bird and the structure impacted,
- large elastic and inelastic strains,
- coupled load/response.

Large nonlinearities are present and the magnitude, duration, temporal and spatial distribution of the load will be dependent on the slope, displacement, and velocity of the loaded structure.
The actual investigation methods are :

- experimental by means of shots on real structures using air cannon,
- numerical by means of finite element codes simulations.

Presently these codes can be divided in two big groups on the base of the spatial description adopted:

- Lagrangian where the entire model of the phenomenon is modelled by means of a Lagrangian point of view (this is the typical point of view of the structural description).
- Eulerian-Lagrangian where part of the model, the bird, is modelled using an Eulerian methods; namely using a grid fixed in the space passed through by the materials. The rest of the model is represented using a Lagrangian point of view.

The Eulerian part of the model is due to the hydrodynamic behaviour of the bird at these velocities and avoid the possibility of a failure of the simulation induced by an excessive mesh distortion. The description of the entire model by means of an Eulerian discretisation is not possible due to the material constitutive laws that need the history of the deformation or the rate of deformation tensors that could not be easily treated with an Eulerian grid. Some codes developed in the first works (like Magna [1], [2]) do not model the bird but apply to the loaded structure a pre-defined pressure time history. But in this case the deep coupling between bird and structure is neglected and the possibility of a second impact after the rebound is not present.

Comparison between different codes

In this part of the work a comparison between different codes and bird models has been conducted. The aim being to find out the different behaviour of different discretisation models working on the same phenomenon. Besides from these first simulations a more reliable model of the bird has been found. As far as numerical codes Msc Dytran and Esi PamCrash have been utilised. Msc Dytran being a Eulerian- Lagrangian code and Pam Crash a Lagrangian code.
With these codes the influence on the results of the constitutive law of bird material as well as the geometry of the bird and the impact angle has been faced. Then a comparison between the two codes has been made and with the experience of these simulations a comparison with experimental impacts on rigid instrumented walls has been conducted.

In a first phase of the work the Lagrangian code has been used simulating impacts on rigid walls. The speed of the bird was 180 m/s and the mass was 1.81 Kg (4 lb), with angles of 90°, 45° and 20°.

Different geometry of the bird has been developed: namely cylindrical and ellipsoid, that are the commonly adopted by precedent works (figg 1,2). In particular the meshes were of 1020 brick for the cylindrical one and 960 for the ellipsoidal one.

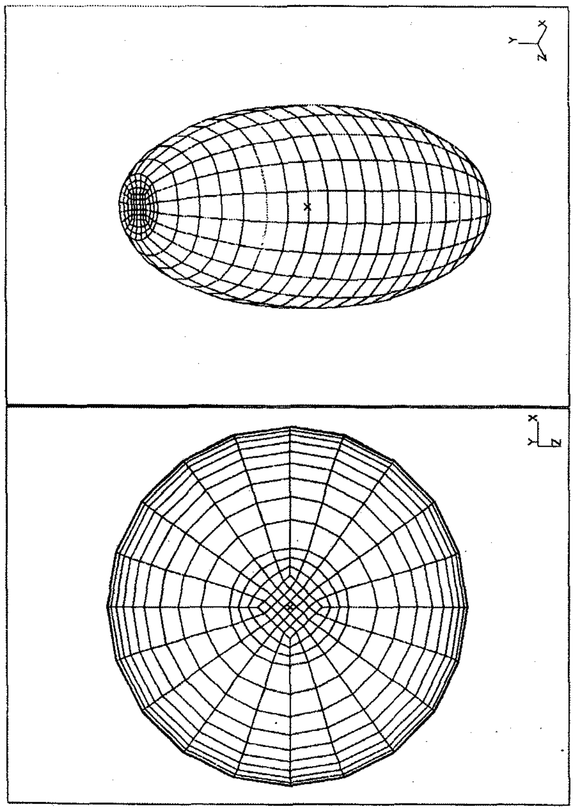


Fig 1: Ellipsoidal model

Then the differences caused by the different constitutive laws of the bird commonly used have been studied. The two materials commonly used are: purely hydrodynamic and hydrodynamic with shear strength and yelding.

A first rough set up of the model has been made by means of a comparison with the existing literature and using an empirical equation (Wisnom) [3] valid for cylindrical bird .

$$F=\frac{2mv^2 sin\vartheta}{l+d\cot\vartheta}$$

where F is the peak force during an impact against a rigid wall with an angle of θ degrees l and d are the dimensions of the cylinder.

The comparison between different simulations has been made on the basis of the Force time histories diagrams,

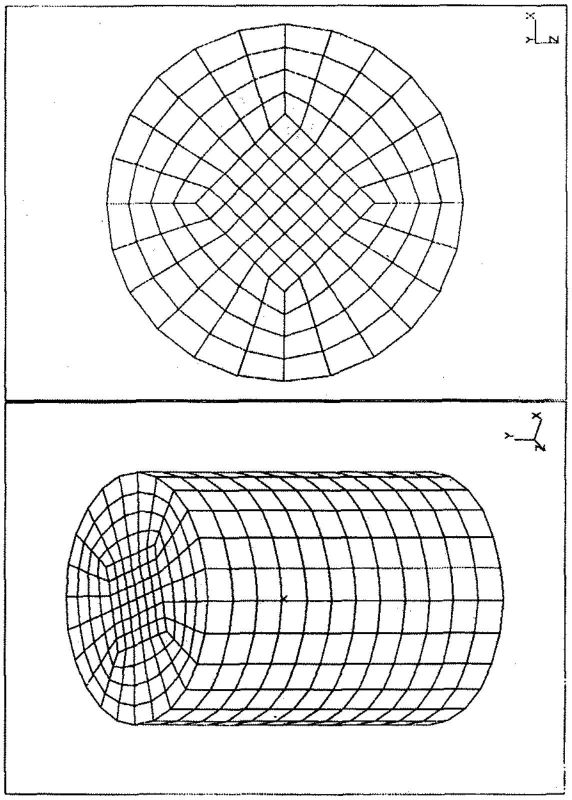


Fig 2: Cylindrical model

where the force is the resultant force normal to the rigid wall, namely with the same impulse in all the simulations the different behaviour of the components has been considered.

A first comparison is between two impacts with the ellipsoid model at 90° but with different materials. Can be seen that the introduction of a little shear strength (that is about 2 Kg/mm^2 of yelding stress) increase the peak value of the force and consequently decrease the duration of the phenomenon (fig 3,4).

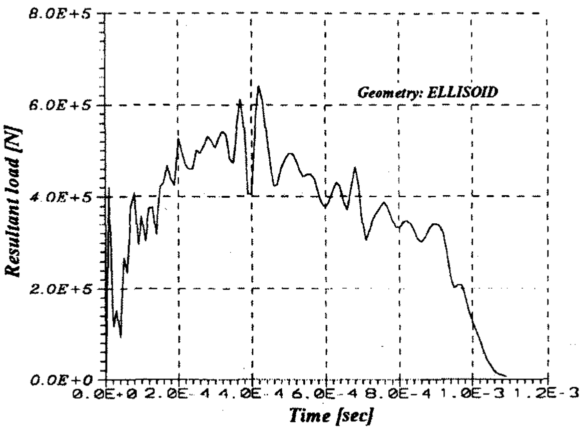


Fig 3: 90° impact. Material with shear strength

The same behaviour but more remarkable can be seen in impacts with an angle of 45° (fig 5,6), where in fact the tangential component of the impact caused a big difference. In general oscillations with amplitude greater than the corresponding ones of the hydrodynamic material can be seen when a shear strength is adopted.

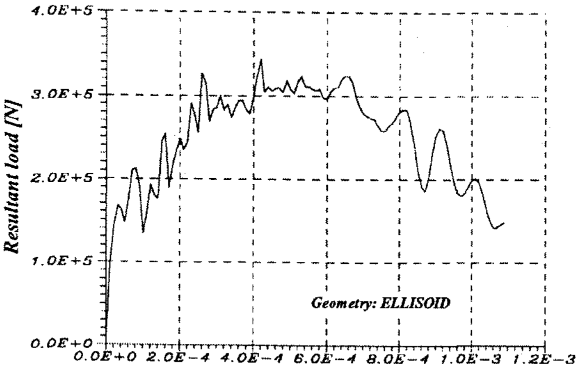


Fig 4: 90° impact. Material without shear strength

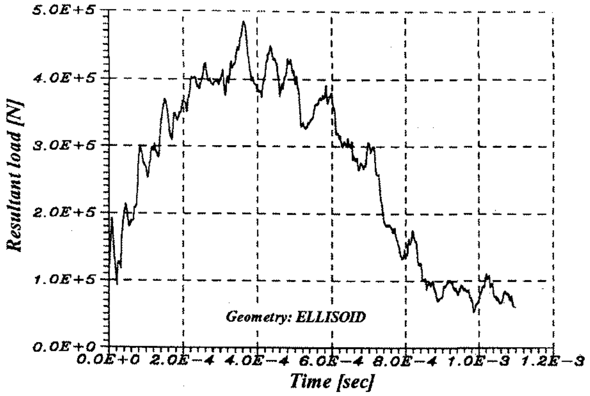


Fig 5:45° impact. Material with shear strength

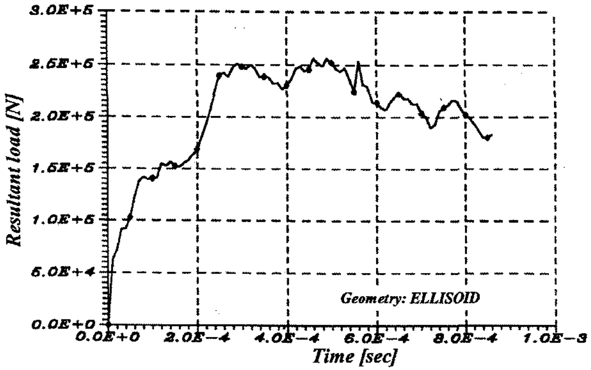


Fig 6: 45° impact. Material without shear strength

Comparing fig 4 and 7, simulations with the same material (the hydrodynamic one) but with different geometry of the bird, we can see a big difference of maximum value and time-history. This is due to the discontinuity of the contact surface during the first phase of the impact in the cylindrical model. This result is also greater than the one predicted with the Wisnom relation. On the contrary a good agreement between the simulations at 45° has been found (figs 6 - 7-a), also with a good agreement with the peak value given by the Wisnom formula.

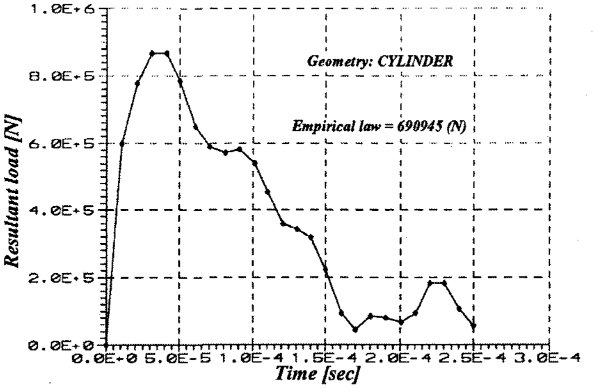


Fig 6: 90° impact: Cylindrical model

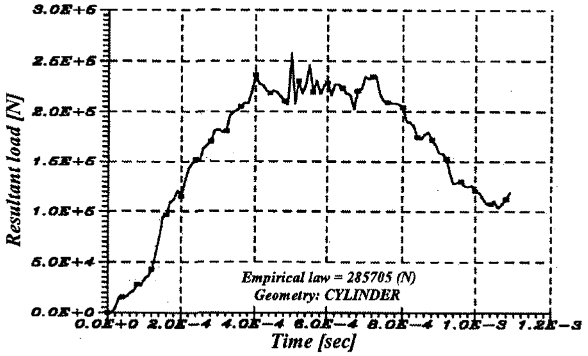


Fig 7-a: 45° impact. Cylindrical model

Some problems have been found from the excessive deformation of the mesh that caused the failure of the simulation due to the presence of zero volume elements.

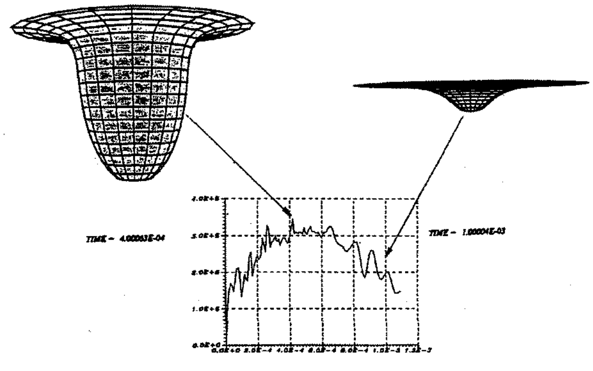


Fig 8: distortion of the model during the simulation

Nevertheless these problems occurred when energy transferring mechanism is completed. In fact we can se that the simulation fails when the deformations are really remarkable (fig 8 is a 90° impact, the most critical for the bird deformations) but the load peak has been largely exceeded. Besides the maximum peak is found when the deformations are still limited and the simulation is surely reliable.

In conclusion we noted differences due to the material mainly in impacts with tangential component of the velocity. The evidence that the cylindrical model is not reliable for 90° impacts and that the shape of the model heavily influences the load time histories has been found. Besides the possibility of an interruption of the simulation, due to excessive mesh distortion, happens only when the main energy transferring mechanism is completed.

The second phase of the study concerned about the same cases previously seen but utilising an Eulerian - Lagrangian code (MSC Dyna). Again impacts against rigid walls surfaces have been simulated using the same conditions showed. In these simulations the mesh dimension depends on the angle of impact instead of the geometry of the bird because the whole space occupied by the bird during the phenomenon must be modelled. In fact 1700 elements have been used for the 90° simulation and 6000 for the 45° impact.

The bird has been modelled again using a cylinder and an ellipsoid. But the material adopted was only the hydrodynamic without shear strength, being the only available in Eulerian - Lagrangian coupled simulations. The constitutive law was the same used in the previous simulations.

The comparison between the Lagrangian and Eulerian-Lagrangian simulations has been made again by means the force resultant time histories. Fig 9-10 refers to 90° and 45° impacts with cylindrical bird. These results are also compared to the Wisnom empirical relation with a good agreement. Should be noted that the Eulerian results are more oscillating.

The same behaviour has been found with the ellipsoid model.

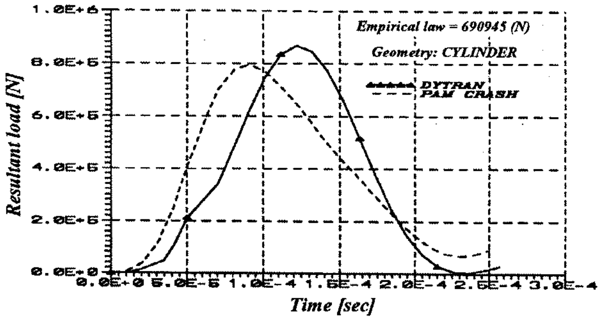


Fig 9: 90° impacts. Comparison between codes

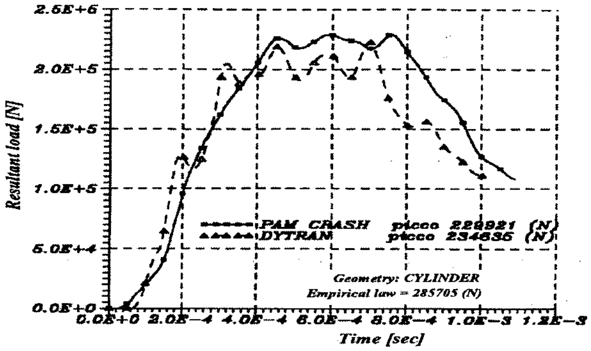


Fig 10:45° impact. Comparison between codes

In conclusion codes completely different, as far as their theoretical formulation, if applied to the same problem, supply similar results, even if with slight differences. Obviously no problems due to the distortion of the mesh were observed in Eulerian code even if more oscillations were present.

Testing

The experimental tests are generally performed by means of a launcher able to accelerate to high velocities dead birds or equivalent gelatinous masses. The launcher, generally consisting in an air-gun, must comply to the following requirements: ability to accelerate bodies of different mass to a pre-determined velocity; ability to launch the mass in a fixed and controlled direction; capability to preserve the integrity of the body during the acceleration. The behaviour of the structure has to be studied in terms of force and pulse, the latter being tightly connected to the force and to its variation during the time. The impact must be considered and impulsive event, because its duration is much shorter than the natural frequencies of the structure.

It is assumed that the body of the bird can be modelled as a fluid and the surface of the structure is perfectly rigid. At the impact, the bird possesses a momentum expressed by:

$$Q = mv$$

where m is the mass and v the relative velocity; when the momentum is completely transferred to the target, its velocity abruptly changes direction, becoming parallel to the surface.

The impact begins when the body comes in contact with the surface and terminates when the trailing edge touches the surface as well. All through the impact, the velocity of the trailing edge remains constant and the duration of the impact is expressed by:

$$T = l/v$$

where l is the length of the body and v its initial velocity. The average impact force can be computed as:

$$F_{ave} = Q/T = mv^2/l$$

These three parameters Q, T, F_{ave} represent the basic quantities describing the impact.

The birdstrike against a rigid surface can be described as a transient fluidodynamic event. It consists of four main phases (shown in fig. 11): initial contact, decrease of the pressure, steady flow along the surface, termination of the contact and vanishing of the pressure.

At the first impact, within the body of the bird a shock wave generates, due to the sudden deceleration of the material (leading edge) which comes in contact with the surface. Owing to this shock wave, a field of very high constant pressures establishes and expands along with the wave itself. The outer surface of the body, being unconstrained, is subjected to a very high stress gradient, which induces tearing of the material, as well as its radial acceleration. So, a pressure release wave starts, moving radially towards the centre of the body. The shock wave is no more flat, because it interacts with the pressure release wave.

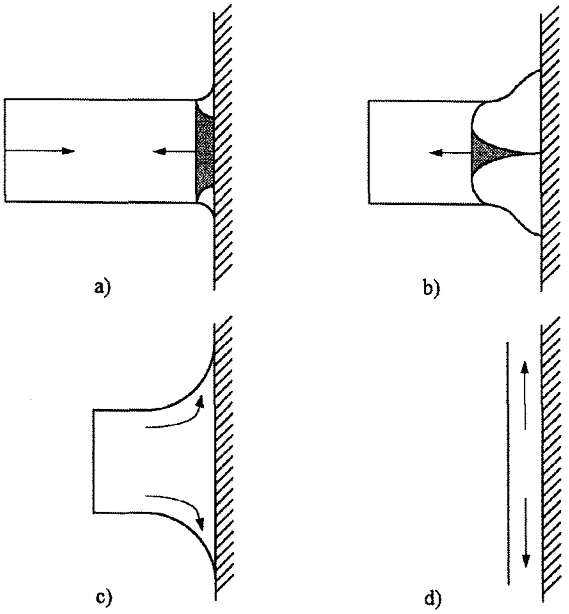

a) b) c) d)

Fig 11: phases of hydrodynamic impact

The maximum pressure value reached during the impact is:

$$P = \rho v v_s$$

where ρ is the material density, v the impact velocity and v_s the velocity of the shock wave. When it reaches the centre of the impact surface, the pressure becomes very low, the initial phase terminates and the pressure decrease begins.

The pressure which establishes at the first impact remains for the time:

$$t_r = rc_r$$

where r is the radius of the body and c_r the wave velocity. The velocity of the pressure release wave is higher than the velocity of the shock wave, because the first moves in a material subjected to a compressive state-of-stress. For this reason, the release wave continues to weaken the shock wave until, in the region lying behind, the pressure tends to vanish.

The decrease of the pressure induces, in the body of the bird, shear stresses much higher than the allowable ones. Owing to repeated reflections of the pressure release wave, the body of the bird assumes the consistency of a fluid and a steady flow establishes, consisting of constant velocities and pressures.

When the trailing edge of the bird approaches the rigid surface, the pressure field interrupts, owing to the presence of a free surface. The steady flow terminates and the pressure decrease, until the trailing edge comes in contact with the surface.

The experimental tests were performed by means of an arrangement made of a steel barrel (125 mm in diameter and 8 m long) connected, through a breech, to a vessel, containing 1,000 l of dried air compressed at a pressure of 20 atm; such an apparatus is capable to launch a bird of 1.8 kg at a velocity of more than 257 m/s.

The value of the pressure is defined according to the mass of the bird and the velocity to be reached.

The projectile consists of a chicken contained into a canvas sack not yet stiffened by the *rigor mortis.* It is placed into the barrel close to the breech and pushed by a polystyrene cylinder having a calibrated diameter able to avoid pressure leakage. The obturator (shown in fig. 12) is made of four cells, separated by mylar sheets at pre-defined failure and progressively pressurised in order to split the pressure gap between the vessel and the barrel. The release mechanism consists of a air-compressed powered pin which perforates the first mylar sheet and induces the failure of the remaining ones: so, the abrupt release of the pressure is obtained.

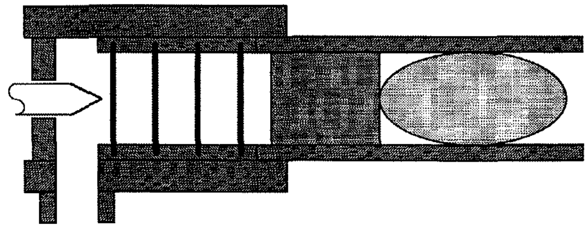


Fig 12

The impact is recorded by means of a 16 mm high-speed camera (10,000 fps), placed in order to have the optical axis perpendicular to the axis of the barrel; a suitable lighting system (100 kW) allows a clear shooting of the impact. The procedure is entirely automated and the impact happens only if the safety conditions are satisfied and when all the test apparati correctly work.

The velocity is measured by means of two couples of photo-cells placed at the edge of the barrel, as well as by a film analyser, connected to a data management system: in fact the velocity of the projectile can be expressed as a function of its position with respect to a reference frame.

The projectile impacts a steel slab 140 mm thick stiffened by a steel frame (fig. 13) and constrained to the rigid structure by means of six load cells; four of then (placed at the angles) measure the forces perpendicular to the surface, while the remaining two, connected to the side closer to the launcher, measure the tangential forces. The load cells (10,000 kg range) consist of steel cylinders, whose deformations are transduced by strain gauges Wheatstone bridges. The signals of the load cells and photo-cells are stored in a data recorder and tranferred to a work station which provides the calibration curves.

Tests are performed for three inclinations of the surface (30°, 60° and 90°) and two impacting conditions (1.8 kg at 139 m/s and 0.9 kg at 257 m/s); each test is repeated three times.

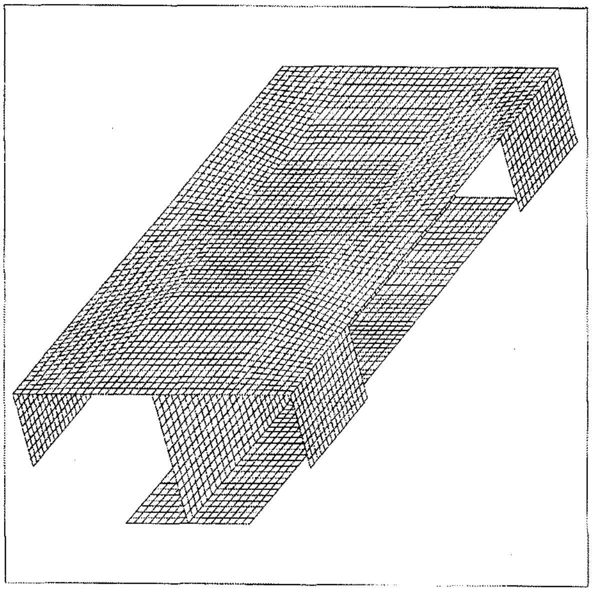


Fig 13

Simulation

The ellipsoidal model of the bird (fig. 1) consists of 960 8-nodes brick elements. It is divided into two parts: one ellipsoidal with a prismatic hole along the major axis; another, prismatic, able to fit the hole, in order to have elements of regular shape close to the axis. An elasto-plastic-hydrodynamic constitutive law was attributed to the material, where the pressure p depends on the non-dimensional parameter μ expressed as:

$$\mu = (\rho/\rho_0) - 1$$

ρ_0 and ρ are the values of initial and actual density.

The general expression of the pressure is:

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3$$

where C_1, C_2 and C_3 are the linear, quadratic and cubic moduli of compressibility: If $\mu < 0$, then $C_2 = 0$. In this simulation only C_1 is $\neq 0$ and equal to $5.22E10^7$ N/mm^2.

Furthermore, the density, shear modulus, yielding stress and tangent plastic modulus have to be defined:

$$\rho = 930 \text{ kg/m}^3$$
$$G = 2.07E6 \text{ N/mm}^2$$
$$\sigma_y = 2E3 \text{ N/mm}^2$$
$$E_t = 6E5 \text{ N/mm}^2$$

The solid ellipsoidal model was covered with 416 contact shell elements made of the same material.

The model of the assembly rigid slab + stiffening frame + load cells constraints consisted of 4928 shell elements of various thickness, made of an isotropic elastic material, defined by the density, Young's modulus and Poisson's coefficient:

$$\rho = 7{,}200 \text{ kg/m}^3$$
$$E = 2.068E5 \text{ N/mm}^2$$
$$\nu = 0.29.$$

The load cells were modelled by means of 2-nodes bar elements, characterised by a non-linear behaviour and defined through the density ρ, linear elasticity k, viscous damping c and mass m:

$$\rho = 7{,}820 \text{ kg/m}^3$$
$$k = 1.7E8 \text{ N/m}$$
$$c = 1E5 \text{ Ns/m}$$
$$m = 20 \text{ kg}.$$

The load cells (bars) were connected to both the shells and the ground through spherical hinges.

A velocity of 136 m/s was imposed to the bird (1.8 kg heavy) few millimetres before the impact against the rigid slab tilted of 30°, having defined *master* the slab surface and *slave* the bird one.

In the following table the main statistics of the simulation are reported:

collision duration	2.4 ms
total phenomenon duration	7.2 ms
CPU time (collision)	60 min
CPU time (total phenomenon)	180 min
time step	0.125 μm
scale factor	0.7
option (hourglassing)	small bend

Tab. 1: Main statistics of the simulation

Correlation

The following figs. 14a-n represent the bird deformation during the collision; figs. 15a-f show the superimposition of the experimental and numerical time histories of the axial forces acting in the load cells.

Initially, a trouble consisting in a 50 Hz sinusoidal noise due to the insufficient insulation between the signal of the load cells and the power supply of the strain gauge bridges was discovered and rapidly overcome, while the curves of the tests already performed were suitably filtered.

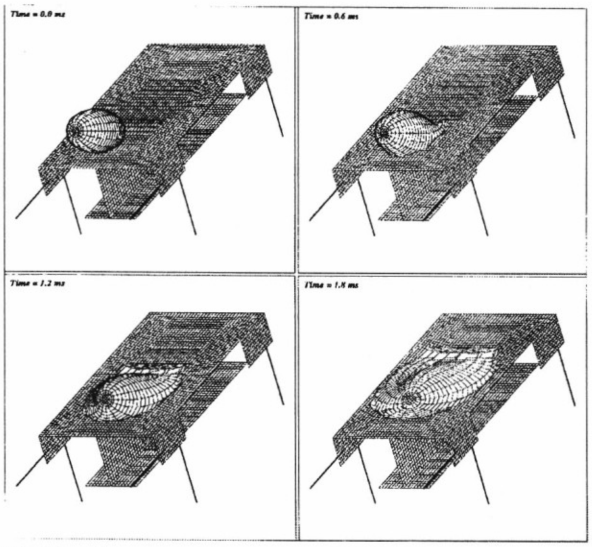


Fig 14 a-d

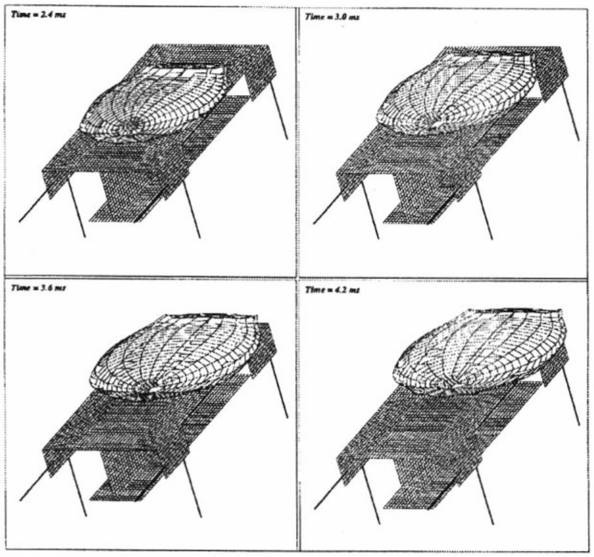


Fig 14 e-h

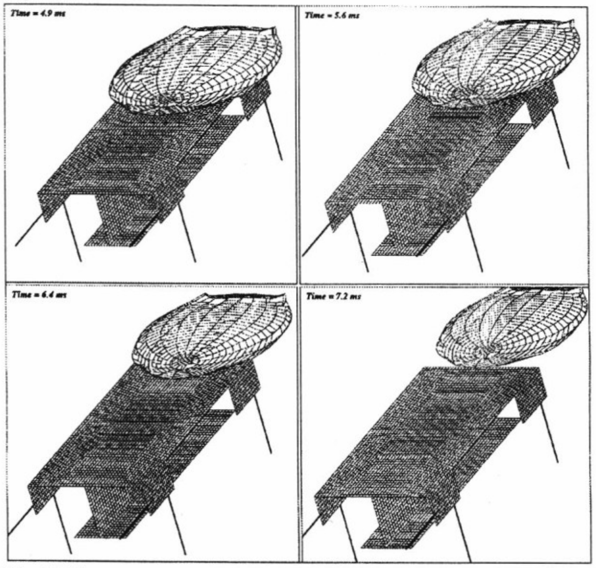


Fig 14 i-n

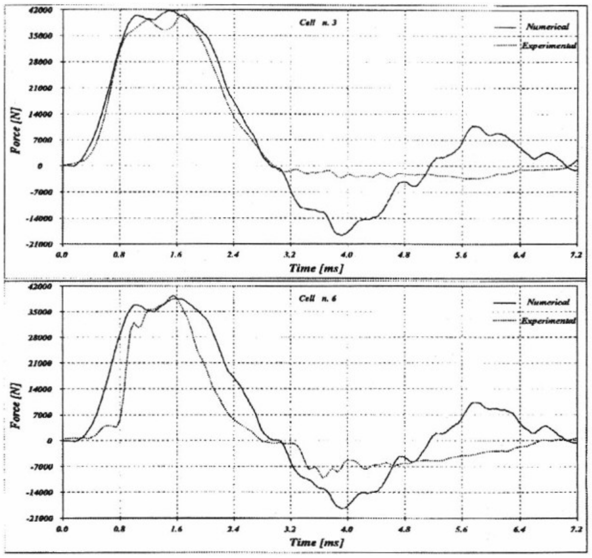


Fig 15 a-b

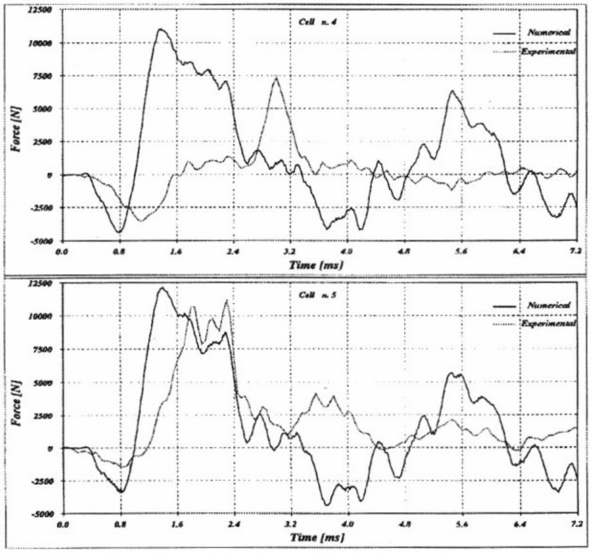


Fig 15 c-d

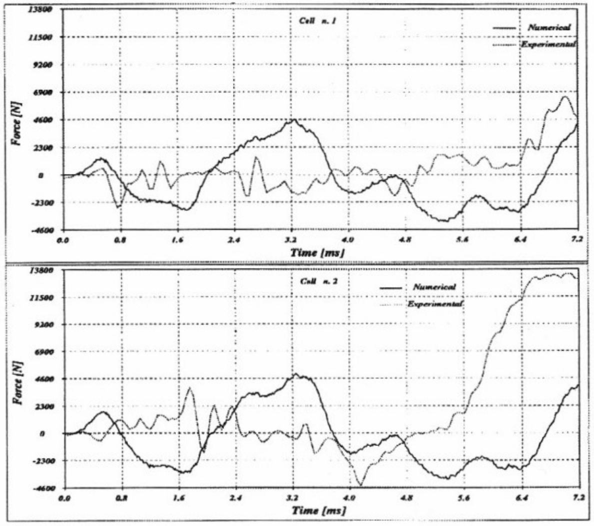


Fig 15 e-f

The load cells Nos. 1,2 measure the tangential forces, while the other cells measure the normal components.
The load cell No.1 shows a slight clearance between the attachments, prevented by a spring with low stiffness and high pre-load. The load cell No.4 presents an anomalous behaviour, consisting in a time delay of the maximum load peak compared to the signal of the load cell No.5.
The comparison of the experimental and numerical curves is quite satisfactory as far as the load cells Nos. 3,5 and 6 (normal forces) are concerned, while the curves belonging to the load cells Nos. 1-2 (tangential forces) do not agree well, owing to the insufficient friction coefficient assumed between the bird and the surface; however, it has to be underlined that this coefficient strongly depends on the surface roughness while the normal forces are function of the bird deformability and pressure distribution, which are parameters much more meaningful and repeatable.
The curves shown in fig. 16 represent the resultant normal forces (given by the addition of the components measured by the load cells Nos. 3-6). The *experimental modified* curve was obtained adding two times the contribution of the load cell No.5 and neglecting the contribution of No.4.

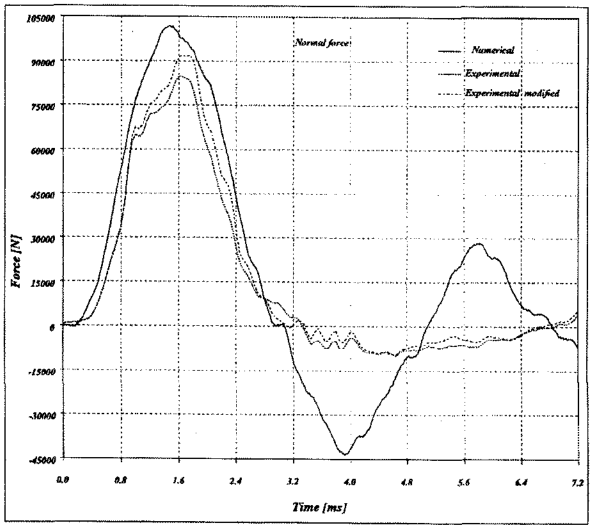


Fig 16

At time t = 2.4 ms, all the normal components of velocity vanish and the bird has transferred to the slab the momentum:

$$Q = mv\sin\vartheta = 123.7\ Ns$$

where θ = 30°; this value of momentum corresponds to the pulse of the normal force, expressed as:

$$I = \int_0^{2.4} F_n(t)dt$$

The following table compares the values of the pulses and the errors, referred to the theoretical value of the momentum:

Pulse	Value [Ns]	Error [%]
Experimental	110.0	- 11
Exp. modified	119.6	- 3
Simulation	144.7	+ 17

Tab. 2: Experimental and numerical results.

On the basis of these reults it appears that the load cell No.4 has not to be considered, because it gives misleading results, possibly due to mounting clearances. In order to assess this effect, the calibration curve has to be checked and the position of celle Nos. 4 and 5 inverted.
The discrepancies existing between the experimental and the numerical results has to be mainly attributed to the dynamic behaviour of the slab and the constraints.

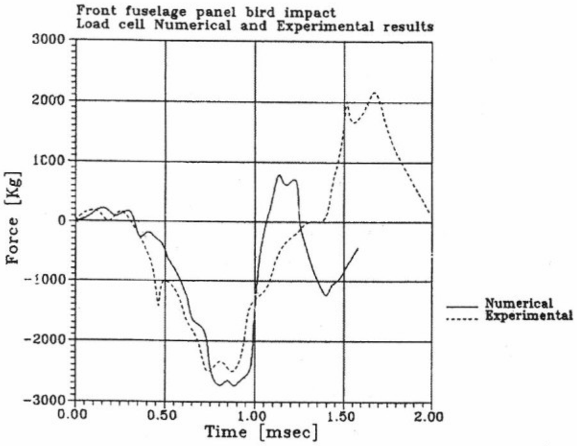
Simulation of an impact on front fuselage panel

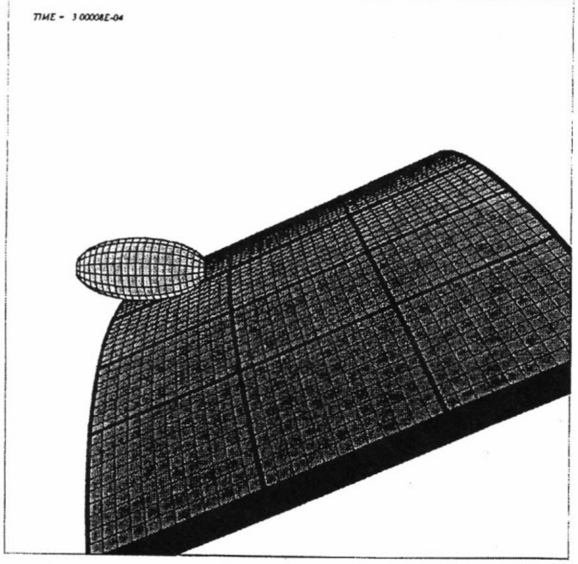
With the experience of the previous study a real impact was faced with the co-operation of Aermacchi s.p.a.. The impact of a bird against a front fuselage aluminium panel belonging to a civil aircraft. The impact was conducted with a speed of 158 m/s with a 4 lb bird and an angle of 25°. The panel was installed on a rigid rig instrumented by means of load cells.
The numerical simulation has been conducted using Pam-Crash code. The model has been developed with:
the bird:
- 960 brick wrapped with 416 shells used to model the contact surface.
- Isotropic- elastic- plastic- hydrodynamic material.

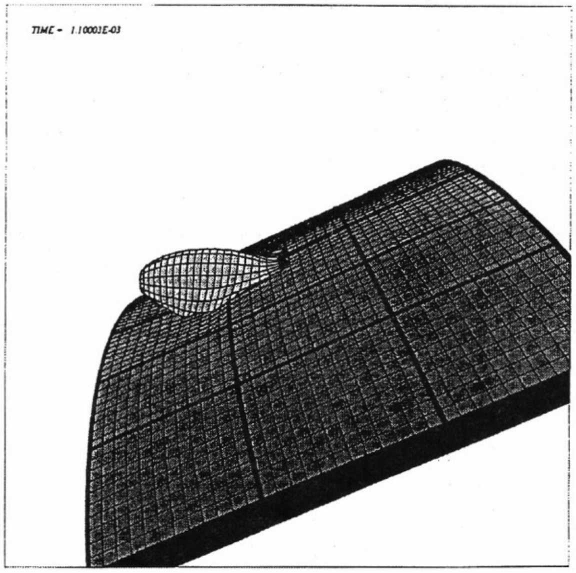
The structure:
- 2456 shells elements, two beams to model the load cells.
- Elastic plastic material for the rig,
- 2660 shells in the skin, 534 beams for the stringers.
- Elastic-plastic with strain rate sensitivity material for the panel.
- the simulation time was 2.5 ms.

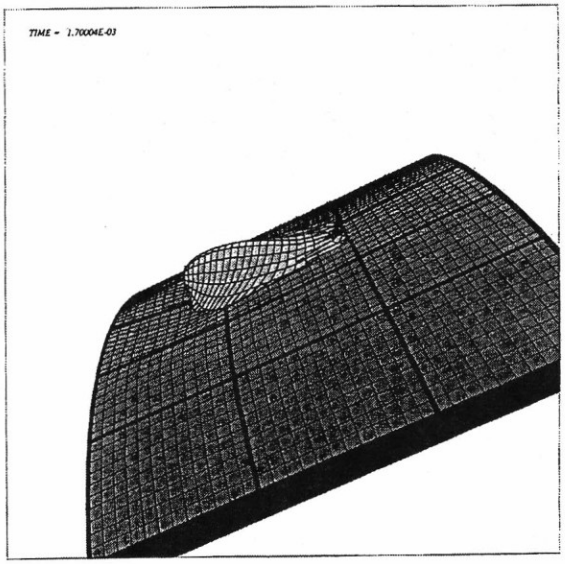
The comparison between the numerical simulation and the experiment has been made on the basis of the load cell time history and the overall structure deformation. We chose the load cells time history because is a global parameter of the behaviour of the panel. Besides this indication is not affected by local conditions that could be predominant if strain gages installed on the surface of the panel were used. The load cells should be also less affected by imperfections in the birdstike during the experiment.

In the comparison we can se two phases: in the first phase there is a good agreement between experiment and simulation both in terms of time history and load peak, in the second phase instead the simulation gives different result, even if the shape of the curve is preserved. But during this second phase the bird is no longer on the panel. Moreover an excessive damping is probably present in the constitutive law of the panel material.
The deformations of the panel and the load time history are reported in the following figures.









Conclusion

The research activity completed up to now allows to draw the following statements:

- the shape of the geometrical model of the impacting bird heavily influences the load time-history;
- codes implementing completely different theoretical formulations supply results quite similar;
- the Lagrangian explicit codes are able to reproduce only partially the evolution of the phenomenon; besides, the failure and separation of the solid elements cannot be obtained;
- the interruption of computing due to excessive mesh distortion only happens when materials characterised by pure hydrodynamic constitutive law are adopted and the main energy transferring mechanism is completed;

- considering the availability of materials models and the flexibility of use, the Lagrangian models seem to be still competitive with Eulerian ones
- the comparison of the results coming from numerical simulations performed with Lagrangian and Eulerian codes and experimental tests carried out on real aluminium alloy and composite front fuselage panels have shown a good agreement both concerning the loads time-histories and the structure deformation.

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