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Soft body impact against aeronautical structures

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Summary. Statistics show that impacts of soft body against aeronautical structure are not so rare events. The damage caused by the impact of hailstones or of birds can sometimes be so heavy to compromise the service life of the vehicle. Companies, research centers and universities are interested in the evaluation of the effects of this kind of events and lots of researching works have been recently developed in this field. In this paper, an overview of the last studies performed at the Laboratory for the Safety in Transports (LaST – Crash Lab.) of Politecnico of Milan are presented throughout experimental tests and numerical finite element models. The validity of the correlation results method to prevent possible heavy consequence caused by these events is shown.

Key words: crashworthiness, soft body impact, explicit finite element code, smoothed particle hydrodynamics

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Introduction

Birdstrike and hail impact are two of the most dangerous events that could happen during the service life of an aircraft.

Every year, despite the ever more widespread use of deterrents to reduce the number of birds in areas near airports, accidents caused by impact of birds are increasing as in Ref. [1]. Although in some cases the crew is able to safely land the airplane, e.g. the accident occurred in 2009 to the US Airways Flight 1549 departed from New York and ditched into the Hudson River near midtown of Manhattan, in other cases the consequences produced by this kind of events can be catastrophic. An example is the HH-60G Pave Hawk accident occurred near Salthouse, England, where four pilots of the RAF lost their lives because of a multiple birdstrike.

The presence of meteorological events such as hailstorms is not a so rare event. Hail structure and geometry can vary from a layered spherical one to a discoidal shape with a diameter from 1 mm to more than 50 mm, depending on the quote and on air temperature.

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The impact of hailstone can have both heavy consequences on structures and barely visible damages that can compromise the fatigue life of the aircraft. An example is the event occurred at the beginning of February 2015 to an A320 that, 45 minutes after the take off from Rio de Janeiro, was forced to land at the same airport because of an hailstorm. See figure 1.

Figure 1. Soft body impact: airplane crash into the Hudson River due to a birdstrike (2009) and hail impact at Rio de Janeiro (2015).

For all these reasons, in the last years the number of research works on soft body impacts is increased. The great variety of bird species underline the non-homogeneity problem in the results because of different bird dimensions, structures and impact conditions, especially the impact angles. To avoid these problems, studies about the development of an artificial bird surrogate were conducted especially by Wilbeck at the end of the sixties [2, 3]. A validated bird substitute can be efficiently used both for structures certification and during the development phases. Recently experimental results were published by Lavoie [4], while the International Bird Strike Research Group presented a research about bird surrogate optimal characteristics [5]. A similar problem occurred in the study of hail impact. Hailstones, impacting against structures, can have different geometry and size due to the temperature, the quote and, more in general, the atmospheric conditions [6]. The need to investigate these events has led researchers to carry out studies on hailstone geometry in order to reproduce them into laboratories in controlled conditions. Some experimental tests have been carried out at the NASA Glenn Research Center by Pereira et al. in order to evaluate the forces generated by a high velocity impact of different types of ice against a rigid target [7]. Kim at al. investigated the impact of hail against different structures, such as rigid plate and carbon/epoxy composite panels [8, 9].

Even if necessary, because of high costs for experimental tests, especially on complex structures, the use of numerical simulations is increasing especially in the last years. Finite element (FE) models allow researchers to perform a greater number of tests under different setup reducing global costs for experimentation. The comparison of different approaches (e.g. Lagrangian, Arbitrary Lagrangian-Eulerian (ALE), Smoothed Particles Hydrodynamic (SPH) or the most recent FE to SPH method) and of different material models [10, 11, 12, 13, 14] allows the definition of increasingly accurate representations of soft body, up to their use for the investigation of further possible impact scenarios.

In this paper, a general overview of the last experimental and numerical research works performed at the Laboratory for the Safety in Transports (LaST-Crash Lab) of the Politecnico of Milan is presented. Experimental tests have been carried out to assess different types of numerical models of birds, bird surrogates and hailstones. A good correlation has been found and the possibility to adopt the proposed general method for the development of future research is demonstrated.

Hydrodynamic theory

A soft body is a body which distributes its force to a target structure during the impact because of its mechanical properties largely inferior to those of the impacted body. Even if it is a solid, at high impact velocity it behaves like a fluid. The best way to describe its behavior in an analytic way is throughout the hydrodynamic theory [15].

The main hypotheses behind this theory are rigid panel, cylindrical projectile made with homogeneous material and a negligible resistance to rupture of the projectile. If we consider the projectile as composed by a system of particles, when it impacts against a target, the particles on the front surface of the projectile have to stop themselves immediately and a shock wave appears. The shock compression is so rapid that the particles far away from the surface behave as if they were under a plane strain state. As the shock propagates up the projectile, the particles at the body edge are subjected to a very high-pressure gradient that caused the creations of release waves. The radial pressure release produces shear stress. If the strength of the material is exceeded, the material of the projectile behaves like a fluid and, after several reflections of the release waves, a condition of steady flow is established. This theory can be summed up into four steps: a shock regime, release regime, steady state regime and termination of impact.

During the shock regime, at the first instant of impact, the flow across the shock can be considered as one-dimensional, adiabatic and irreversible. Starting from the equation of conservation of mass and momentum across the shock wave, the expression of the pressure in the shock region, the Hugoniot pressure, can be written as in (1)

$$P_H = \rho_1 u_s u_p \tag{1}$$

where ρ_1 is the density, u_s is the velocity of the shock propagation and u_p the velocity of the particles. For low impact velocities, the speed of the shock propagation can be approximated with the isentropic wave speed in the material.

During the release phase, radial release waves begin to propagate, in the same region where there is the shock wave, towards the center axis of the projectile. The problem can be considered as two-dimensional and axisymmetric. See figure 2.

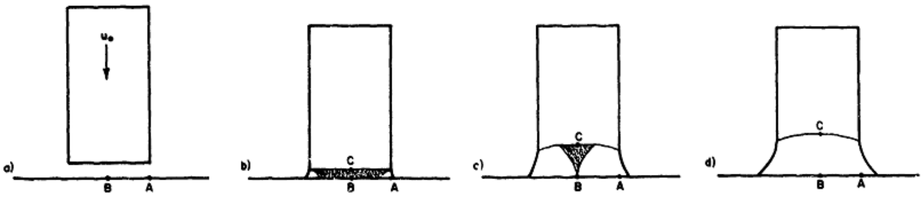


Figure 2. Release waves distribution during a projectile impact [15].

After the impact, the velocities of the shock and release waves are much greater than the initial velocity of the projectile because of high pressure. The curvature of the shock is due to the release process. As the release waves converged in point C, the region in shocked regime disappears. Knowing the time necessary to the release waves to capture the shock wave, obtained from the relation between the speed of the release shock and its displacement, the critical ratio between the length and the diameter of the cylindrical projectile can be defined as in (2).

$$\left(\frac{L}{D}\right)_c = \frac{u_s}{2\sqrt{c_r 2 - (u_s - u_0)^2}} \tag{2}$$

where u_s is the speed of the shock wave, c_r is the sound speed in the shocked region and u_0 is the initial velocity of the projectile.

For a given projectile, if (L/D) is greater than $(L/D)_c$, the shock region will be achieved by the release waves before the impact will reach the back surface of the projectile. See figure 3.

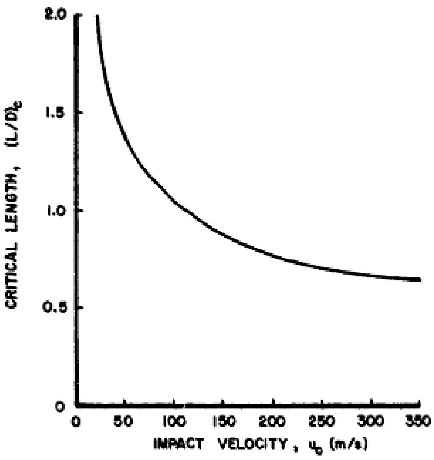


Figure 3. (L/D) critical ratio [15].

In the steady flow regime, the flow properties vary point by point. For low velocity impact, although it's possible to obtain the distribution of pressure starting from the Bernoulli equation, the state equation and the velocity distribution, in literature some analytical expressions for the pressure distribution are available. Two examples are the Bank and Chandrasekhara equation (3) and the Leach and Walker one (4).

$$P = \frac{1}{2}\rho u_0^2 e^{-\xi_1 \left(\frac{r}{a}\right)^2} \tag{3}$$

$$P = \frac{1}{2}\rho u_0^2 \left[1 - 3\left(\frac{r}{\xi_2 a}\right)^2 + 2\left(\frac{r}{\xi_2 a}\right)^3\right] \tag{4}$$

where ξ_1 and ξ_2 are parameters depending on the stagnation pressure and the impact velocity, a is the initial radius of the jet and r is the radial distance from the center of the projectile.

The termination of the impact is the last phase of the projectile dynamic. The total duration of the event can be approximated by the time needed for the projectile to flow through its length.

Experimental tests

The application of the hydrodynamic theory allows to better understand what happened when a soft body impacts onto a structure with a high velocity. Experimental tests and numerical models have been performed both because required by the laws and to evaluate the possibility of a forthcoming application of numerical models for certification purposes of structural components.

Birdstrike

Experimental tests are nowadays the basis for the comprehension of birdstrike events. The Laboratory for the Safety in Transports of the Politecnico of Milan has recently designed and developed a gas gun used for this type of tests. The effect of the impact onto different target structures has been studied.

Birdtrike experimental test setup

As previously said, the major device used for these tests is a gas gun, see figure 4. It has been developed and built at the LaST Lab. exclusively for impact of bird surrogates in ballistic jelly. The main idea is to use a jump in pressure to create the shot. The main components of the gas gun are a pressure tank (max pressure 10 bar), a 180° connecting tube, a shot activation system, a gun barrel (9.2 m long, with an external diameter of 195 mm), and supports.

Figure 4. Birdstrike gas gun.

In front of the gas barrel is located a target structure. The target can vary in shape (from simple plate to complex structure) and in material (from rigid to metal or composite one). See figure 5.

Figure 5. Example of rigid target structure for birdstrike.

The bird surrogate used at the lab is made in a synthetic ballistic jelly, already employed as muscle tissue surrogate, mainly because of repeatability of results. Bird surrogates can be created with different weight, (e.g. 0.65 kg or 1.25 kg), and diameter-to-length ratio (e.g. from 2 to 3). See figure 6. An investigation in this field has been performed to evaluate the effectiveness of the use of this material, comparing results with what is available in literature [16].

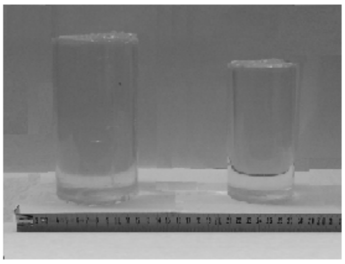


Figure 6. Bird surrogate specimen [16].

To capture the dynamics of the event, a high-speed video camera is used. Some load cells are also used for the evaluation of the load transferred from the bird to the target structure. Results are filtered *a posteriori* using a CFC filter.

Birdstrike experimental results

Experimental tests have been carried out to evaluate the effect of different mass of the specimens on the peak of loads, as the impact velocity changes. To estimate the quality of results, they were compared to data from Barber and Wilbeck. A good correlation among them has been shown [16]. See figure 7.

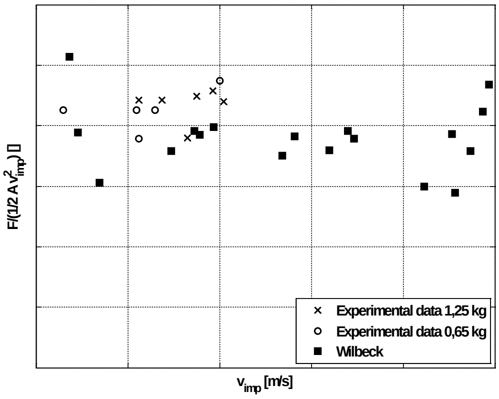


Figure 7. Birdstrike: peak of force for a rigid target [16].

The effect of changing the inclinations of the target structure for different impact velocities has also been considered. From results, it was shown that using an increasing impact angle there is an increase in the peak of force transmitted during the impact. This event is more evident for higher impact velocities. See figure 8.

Figure 8. Birdstrike: impact at 30° - 150 m/s.

Hail impact

The impact of hailstones (even if of small size) against an aircraft can have serious consequences. Even when it doesn’t cause the collapse of the aircraft structures, a hailstone impact is a danger for what is known as invisible damage. For all these reasons an investigation of this kind of event is necessary.

The experimental setup for hail impact tests and numerical simulations used to investigate these events are here presented, jointly with some results that have been obtained in the last years.

Hail impact experimental test setup

For hail impact experimental tests, a smaller gas gun has been developed. See figure 9. The overall structure is similar to the one used for the birdstrike. It consists on a pressure tank (max pressure 10 bar), a shot activation system, a gun barrel (5.8 m long with an external diameter of 70 mm) and supports.

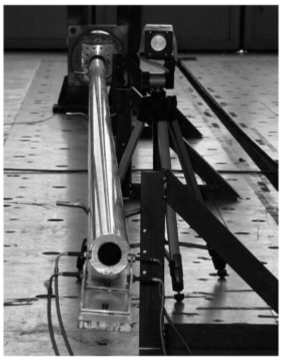


Figure 9. Hail impact gas gun.

In front of the gas barrel there is located a target structure. The target can vary in shape (from simple plate to complex structure) and in material (from rigid to metal or composite one).

The hailstone used for the impact scenario is generally produced using distilled water. As seen for the birdstrike case, different geometries of the specimen have been considered, from a spherical to a prismatic shape but in the last research works, a spherical shape has always been used. See figure 10.

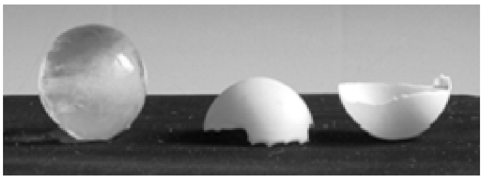


Figure 10. Spherical hail specimen [17].

To capture the event, a high-speed video camera is used to evaluate the dynamics of the event and the impact velocity. Some load cells are instead used for the evaluation of the load transferred from the bird to the target structure during the event. Results are filtered *a posteriori* using a CFC filter.

Hail impact experimental results

As seen for the birdstrike case, an experimental investigation considering different impact velocities has been done. At low velocity impact it’s possible to see the fracture of the hailstone, starting from the impact surface and propagating to the all specimen. As the velocity increases, the hail behaves like a fluid spreading its force onto the target structure, as described in the hydrodynamic theory. See figure 11.

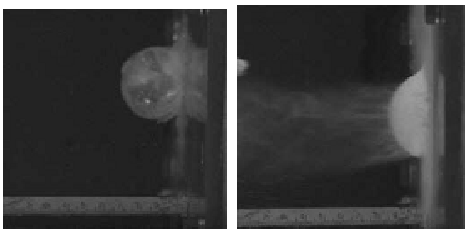


Figure 11. Hail impact: hail impact at 15 m/s (left) and at 205 m/s (right) [17].

Different target structures have also been considered in order to evaluate the effect on different materials, such as thin aluminum panels or composite ones for different impact velocities. See figure 12. From results, it was clear that increasing the impact velocity increases the peak of force, but this growing function follows different power law depending on the material and on the thickness of the plate, higher for rigid structure, lower for deformable one.

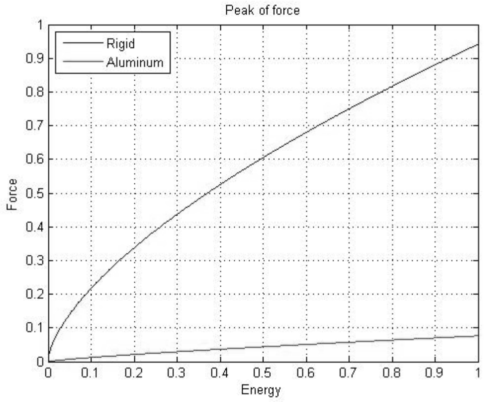


Figure 12. Hail impact: Peak force for different target structures.

This last investigation, jointly with the study and characterization of the target material, is used to set up the bases for the study of real impact events, both experimentally and numerically using explicit non-linear finite element codes, such as Ls-Dyna [18, 19, 20].

Numerical models

The use of numerical models to investigate the soft body impact phenomena is largely increasing and experimental tests are generally used to validate numerical models. Different approaches have been adopted in the last years to investigate these phenomena: from mesh methods, such as Lagrangian one, to meshless methods, like the Smoothed Particle Hydrodynamics.

In the Lagrangian approach, a continuous medium is divided into simple elements. To describe the dynamics of this body, the solution of a system of equation is required. This approach can lose accuracy at very large distortion of elements causing inaccuracy and the increase of the computational cost till the premature termination of the analyses. Smoothed Particle Hydrodynamics (SPH) technique [10-12] was introduced to overcome the limits of the Lagrangian approach. The main difference is the absence of a grid. Therefore, the particles are the computational framework on which the problem is solved using an interpolatory solution of the balance equations. The SPH approach comes with some drawbacks, for example tensile instability and difficult treatment of essential boundary conditions. For all these reasons for many applications the traditional Lagrangian FE approach is still preferred.

At the LaST Lab a huge campaign in this field has been done from the 1990s for different kind of soft body, but mainly focusing on birdstrike and hail impact.

Birdstrike

In the birdstrike simulation field, Anghileri at al. have largely studied and compared different approaches in order to find the best choice that can be adopted in complex simulations. For example in [21] the study of the impact of a cylindrical specimen against a rigid plate has been done considering different mesh methods (Lagrangian, Eulerian and Arbitrary Lagrangian-Eulerian (ALE) ones), discrete method and meshless methods (SPH and Element Free Galerkin (EFG)). See figure 13.

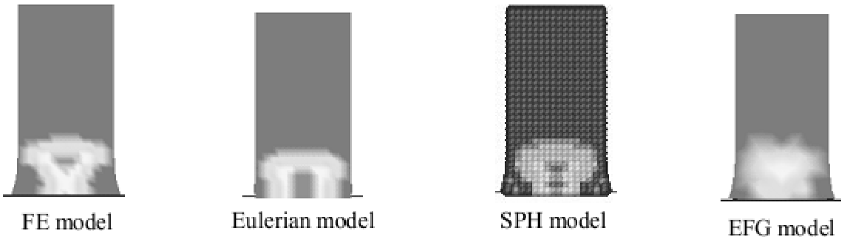


Figure 13. Birdstrike: numerical models using different approaches [21].

A similar approach has been adopted e.g. in [14] and in other researches to describe the impact against a deformable plate. In these cases, different discretizations of the continuum bird model have been considered for the evaluation of the effects of the changing in impact velocities and impact angles. Results demonstrated that for the same discretization, the higher is the impact velocity the higher is the peak of force, as expected [14]. For a constant velocity, the impact against an oblique surface show that the higher is the impact angle, the higher is the peak and average force value. See figure 14.

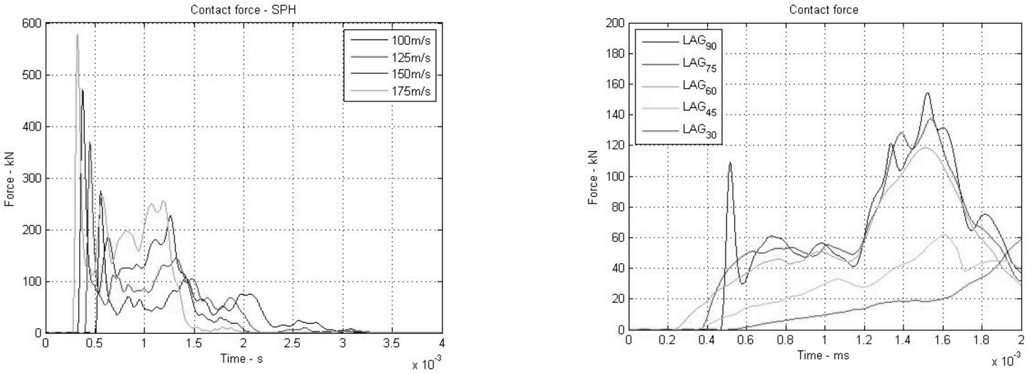


Figure 14. Birdstrike: effect of impact velocity [14] and of impact angle.

In [22] a correlation of the numerical model results with other numerical research works and experimental tests is presented, observing a good agreement. More recently a numerical study has been performed to validate numerical SPH bird models comparing different bird geometries (ellipsoidal and cylindrical) with the hydrodynamic theory and

Wilbeck research [16]. A good agreement has been obtained especially for the Hugoniot and the stagnation pressure. See figure 15.

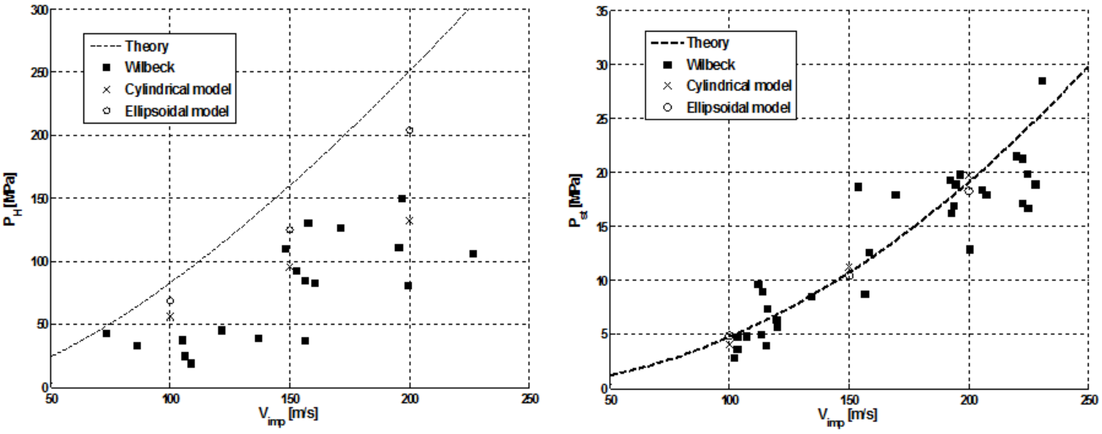


Figure 15. Birdstrike: correlation of SPH model results with the hydrodynamic theory and Wilbeck experimental tests: Hugoniot pressure (sx) and stagnation pressure (dx) as a function of impact velocity [16].

Studies on more complex structure, e.g. structure in rotational motion [23] and engine intake [24], have also been performed. The aim of these works is the study of bird impact event to design new bird-proof structures or to evaluate the effect of these events on real ones. All these studies have been analyzed in accordance with the theory and/or comparing results with real experimental tests. See figure 16.

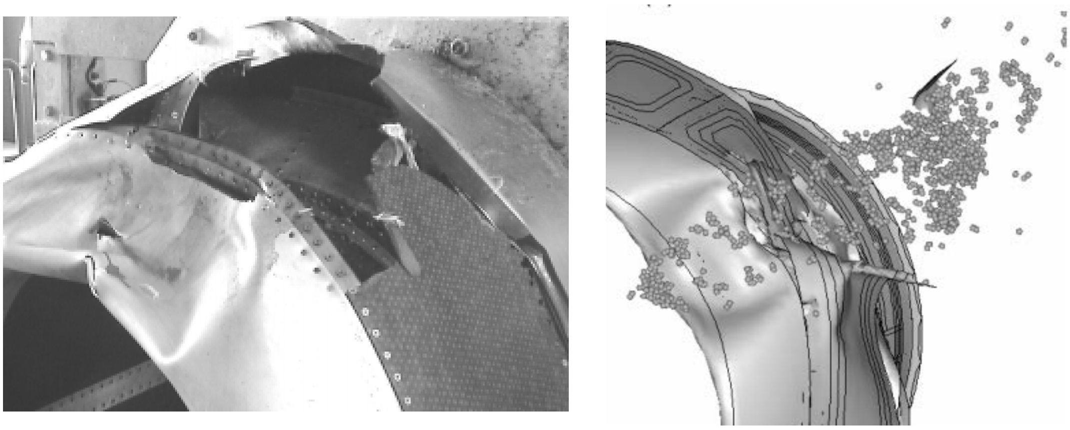


Figure 16. Birdstrike: experimental-numerical correlation of an intake birdstrike [24].

Hail impact

As presented for the birdstrike, also the impact of the hailstone has been numerically investigated using explicit non-linear finite element codes. In the last research work, study on the best way to model a hailstone has been performed considering the discretization of the continuum.

For different approaches, such as Lagrangian and SPH, different element dimensions and/or distributions of the particles have been considered to evaluate similarities in terms of pressure, contact force and plastic deformation of the hail. From results, the best solution is obtained from homogeneous SPH discretization, even if no great differences in some cases have been shown [14]. See figure 17.

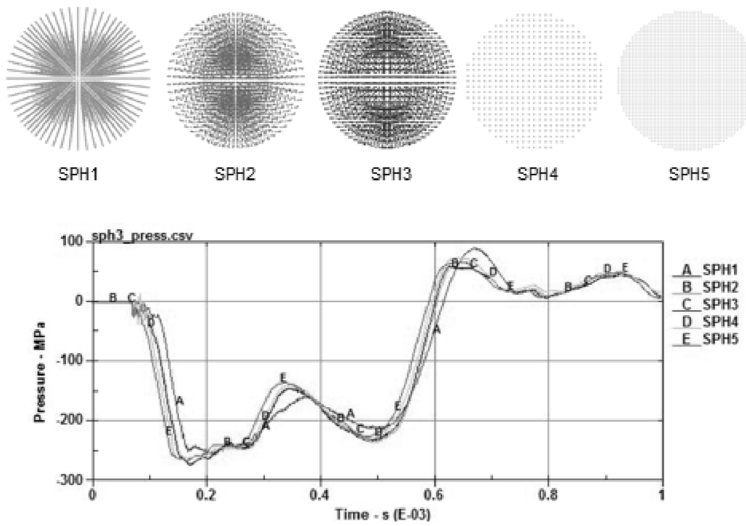
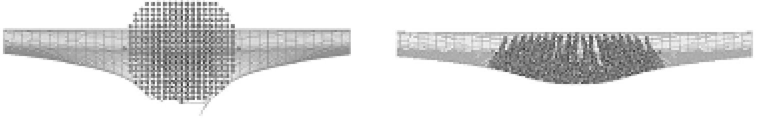
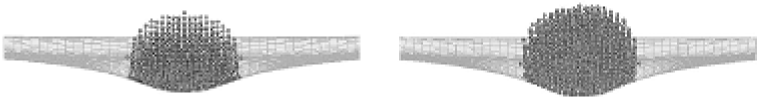


Figure 17. Hail impact: SPH discretization [14].

More than 200 material models are available in Ls-Dyna and some of them are suitable to model soft bodies. In [25] different solutions have been investigated. The isotropic elastic plastic material model was considered but the lack of a specific failure criterion made the model non adequate to represent the behavior of the hailstone like a fluid. The elastic fluid and the elastic piecewise linear plasticity have been considered but presented some problems related respectively to the first instant of impact and the failure mechanism. The elastic plastic hydrodynamic material model instead seems to be a good compromise between the reproductions of the hail behavior before and after the impact. See figure 18.



a - Isotropic elastic plastic *b - Elastic-fluid*



c - Elastic piecewise (isotropic) linear plasticity *d - Elastic plastic hydrodynamic*

Figure 18. Hail impact: Material models [25].

Studies on the effect of the variation of geometry, analysis of different impact velocities and on different target structures have been also performed and the main results were similar to those previously described for birdstrike cases.

Considering the effect of the flight of an aircraft into a hailstorm, in the last years, some case studies have also been performed to investigate multiple hail impact. In [25] for example, after a preliminary single hailstone impact against an intake, ten hailstones impacting the same structure have been modeled. As a result, a good agreement with real cases has been found.

Conclusions and future works

Soft body impact in aeronautical field is not a so rare event and their consequences can sometimes be catastrophic. Airlines have earmarked considerable sums in recent years for the prevention and the study of these events. Experimental tests and numerical model analyses have been performed from the seventies.

In this paper, a simple general review of some of these research works is presented. After a bibliographical review, birdstrike and hail impact have been analyzed under different points of view and comparisons between experimental tests and numerical models are generally performed with the aim of creating a better numerical model that can be used for complex, and more similar to real events, numerical simulations of impact scenario.

Some aspects need more attention. A more accurate study on structure and on hail and bird models are the targets for future research works.

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