MULTIPLE BIRDSTRIKE ANALYSIS A SURVEY OF FEASIBLE TECHNIQUES

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Abstract

Statistics show that, despite the efforts provided to avoid collisions between aircraft and birds, birdstrike still represents a threat for flight safety. Therefore, aircraft components, before being allowed into operational use, have to be certificated for a proven level of bird impact resistance. Characteristic features of the birdstrike such as the coupling between impact loads and structure response gave a significant impulse to the development of numerical techniques that could replace the costly experimental tests. In particular, the explicit codes based on the Finite Element Method have shown to be a valid tool to develop high efficiency bird-proof structures. Nevertheless, when simulating such an event, these codes suffer the huge distortions of the mesh and, therefore, events such as a multiple bird impact are still out of the reach of these codes. In the years, alternative approaches to the problem have been proposed. In particular, different models of the bird such as those related with the Eulerian/Arbitrary Lagrangian Eulerian approach or with the Smoothed Hydrodynamic Method have been proposed. In this work, the impact of two birds against the inlet of a modern large-size aircraft has been considered. Using LSTC LS-Dyna, four different bird models have been investigated: Lagrangian Finite Element, Arbitrary Lagrangian Eulerian, Smoothed Particle Hydrodynamic, and nodal masses model. The obtained results were compared one with the others and eventually advantages and disadvantages of the different models have been highlighted and discussed.

Keywords

Multiple birdstrike, Explicit Finite Element codes, Arbitrary Lagrangian Eulerian approach, Smoothed Particle Hydrodynamic Method

Acronyms

FEM	*Finite Element Method*
ALE	*Arbitrary Lagrangian Eulerian*
SPH	*Smoothed Particle Hydrodynamic*
DEM	*Discrete Element Method*
CFRP	*Carbon Fibre Reinforced Plastic*
EOS	*Equation of State*

Introduction

Collisions between birds and aircrafts have been reported since the very beginning of aviation history (Ref 1) though, at that time, collisions had not tragic consequences.

In last twelve years, all over the world, are died over one hundred and fifty-five persons. For the same period, the cost of damages caused directly and indirectly by bird impacts was over four hundreds and eighty millions of US dollars (Ref 1, 2). Indeed, the feature that makes the bird-strike an actual *menace* for flight safety is the high frequency with which it occurs. Differently from what common people use to think, bird-strike is not a rare event. In the United Stated, between 1990 and 2003 (Ref 1), have been recorded every year six thousands strikes against civil aircraft and about three thousands and five hundreds against military aircraft. As only one impact on five is actually recorded, these numbers are only a partly estimation of the real problem.

Furthermore, it is important to recognise as false myth that bird-strike is a problem of the past.

The aircraft structure up to mid-seventies was not designed to carry impact loads and this made the bird impact menace even more serious. Nowadays, the bird-strike is one of the most severe design constraints, which transversally interests all the aircraft parts. The leading edges of wings and control surfaces, engines, nose cones, and transparencies are the parts of an aircraft most at risk with regard to bird impact. The civil and military design requirements call for constraints to be adhered to as a function of part location and contribution to overall airframe body strength. Nevertheless, a completely bird-proof aircraft does not exist. Indeed, it would be too heavy to fly.

In the years, several methods for the *active prevention* of bird impacts, which involved *Engineering*, *Ornithology* and *Environmental Sciences* have been developed. These methods have contributed to drastically reduce the bird-strike occurrence though, despite the successes obtained, they have not completely eliminated the problem. Therefore, it is important that the aircraft structures are able to guarantee a certain level of functionality even after a birdstrike in all those cases in which it is unavoidable.

The first approach to the design of bird-proof structure was experimental, but performing birdstrike tests has so many drawbacks that it was suddenly clear the need for numerical techniques which allow designing light bird-proof structure. Indeed, the typical features of the bird impact such as the coupling between impact loads and structure response gave a significant impulse to the development of specific numerical techniques (such those described in Ref 4, 5), which stand as milestones in the history *of Finite Element Method* (FEM).

Explicit codes based on FEM are currently extensively used as a valid tool to design bird-proof lightweight structures. Since their first appearance, these codes have been shown to be a feasible alternative to the costly experimental tests (Ref 4, 5). Nevertheless, when simulating long-lasting birdstrike events, FE models suffer the huge distortions in the mesh of the bird (Ref 6-8), which cause a remarkable loss in accuracy, an increase in required CPU-time and, sometimes, a premature termination of the simulation. Hence, a FE model of the bird makes it possible to analyse *only* the early phases of the event and therefore this model is appropriate to develop and verify the structural design, though the analysis of events such as a multiple birdstrike (i.e. the simultaneous impact of two or more birds) remains out of reach.

Indeed, as the number of reported multiple birdstrike is likely to grow, new studies on the subject seem mandatory.

The number of birds of a flocking species likely to impact an aircraft in a multiple bird-strike is of profound interest to realise bird-proof structure (Ref 9). In the absence of effective *control techniques*, it is evident that the probability of striking a bird of a certain species rises as the number of individuals of that species increases. Furthermore, if the species is a flock-forming species the risk of a *multiple impact* becomes particularly serious.

The number of birds of flock species around airports and therefore the probability of an aircraft encountering a flock in operation is rising. Tolerating this threat requires a considerable degree of engineering effort. Mathematical models developed on purpose (Ref 9) show that a structure certified to fail safely after a single bird impact is likely to be struck by more than one bird on nearly a quarter of encounters with a flock.

Full-scale multiple impact tests are extremely expensive and required specific facilities.

Therefore, customarily, the consequences of multiple impacts are evaluated using explicit FE codes. In particular, coupled Eulerian/Lagrangian approach is somewhat common in multiple bird impact simulation (Ref 8). Unfortunately, coupled analyses required *adequate* computational resources. In fact, being necessary to discretise a somewhat wide region in the space, it is necessary to define a remarkable number of Eulerian solid elements – which, eventually, represent a compromise between model dimensions and results accuracy.

In this scenario, the use of *meshless* and *gridless* approaches, which do not suffer mesh distortions and do not require remarkable computational resources, could be definitively rewarding (Ref 8). Notwithstanding this, applications of these approaches are still somewhat rare in literature.

In this work, considering the simultaneous impact of two birds against the intake of a modern large-size turbofan, four different models of bird have been investigated:

(a) the customary Lagrangian FE model,
(b) the Arbitrary Lagrangian Eulerian (ALE) model,
(c) the Smoothed Particles Hydrodynamics (SPH) model, and
(d) the nodal masses model (Ref 7).

Though the FE model of the inlet is developed in a preliminary design phase, it shows the whole typical features of this component.

The different numerical models of the bird had been already validated referring to experimental tests performed on purpose (Ref 8).

For all the simulations, it was used one of the most known and proven commercially-available FE code: LSTC LS-Dyna 960 (Ref 10, 11), which provided a common framework for implementing the different models.

The results obtained were compared one with the others and then advantages and disadvantages of the different models have been highlighted and, eventually, discussed.

Numerical model

Using the FE model of an intake developed in a preliminary design phase, the simultaneous impact of two birds was investigated.

The intake has the whole typical features of this component: composite material structures and sandwich technology (Ref 8, 12).

The birds impact the intake in two different regions and with two different velocities (75 *m/s* and 95 *m/s*). The impact regions and the velocities of the birds were chosen to amplify the typical problems due to the distortions in the FE mesh.

FE model of the intake

The original FE model of the inlet was constructed on the geometry of the intake.

The mesh consisted of 23062 four-nodes shell elements. The model consisted of fourteen different parts though it was not particularly detailed (in the model are not present exhausts, door-panels or apertures) being developed in a preliminary phase of the intake design. However, the model had the customary features of a modern inlet. The external skin panels were made with *composite materials* and (typical) *sandwich technology* was used to manufacture the inner barrel.

On the other hand, as a reasonable simplification at this stage, the riveted joints were not modelled.

When defining the mechanical properties, the dynamic characteristics of the materials were

considered for both metallic and composite materials.
In particular, the numerical model of the composite material was validated by means of experimental vertical crash tests performed using cylindrical specimens (Ref 12). Two different sets of staking sequences were considered. The tested specimens have the same nominal dimensions and were made of the same material: a *Carbon Fibre Reinforced Plastic* (CFRP) woven with resin volume fraction of 42%.
The original FE model of the intake was slightly modified after the first simulations in order to have a finer mesh in the impact regions (Fig 1).

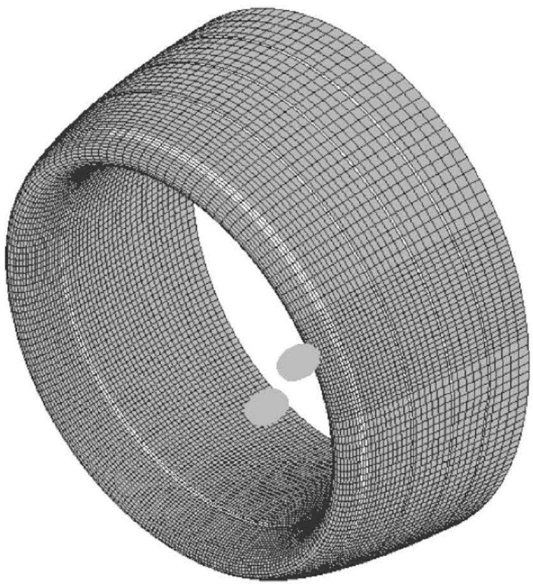


Figure 1. Numerical model of the intake.

separately validated referring to the data collected during specific characterisation tests.
For what about the *shape* of the bird, it was recalled that in some testing situations, such as a straight impact against a compliant structure, it is important the length of the bird. On the other hand, in other different situations, such as the test of slicing effect of rotating aerofoil, the diameter is the most critical parameter (Ref 13).
Historically, a number of different shapes (Fig 2) that allow the most appropriate values of mass, density, diameter and length have been suggested. In particular, considering a *straight* impact, it was demonstrated that the ellipsoidal shape provides an impact load distribution and a time profile, which are the closest to the experimental data.

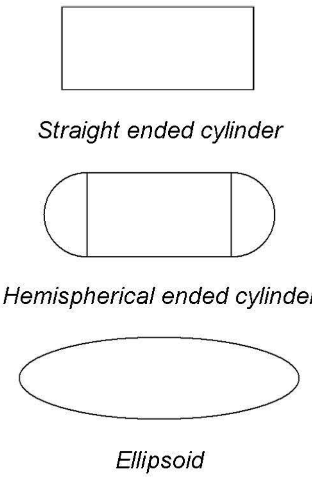


Figure 2. Three typical bird shapes (Ref 13).

Numerical models of the bird

As previously mentioned, four different bird models have been investigated: Lagrangian FE, ALE, SPH, and nodal masses model.
When analysing a birdstrike, the numerical model of the bird is central: not only the *mechanical property* but also the *geometry* are fundamental for a close numerical-experimental correlation. For that reason, the different bird models have been

For what about the *mechanical properties* of the bird, the starting point was the water (Ref 5). In particular, the bird was modelled using a fluid-like material devoid of deviatoric stress, with the density and viscosity of the water (*MAT_NULL in Ref 10, 11) and featured with the Grüneisen's Equation of State (*EOS_GRUNEINSEN in Ref 10, 11) for water.

FE model. The Lagrangian FE approach is customary for the Continuum Mechanic and widely used for the analysis of impact events. This approach is extremely efficient when considering nonlinear problems though it has its weak point in the excessive mesh distortions, which are usual in events featuring soft-bodies or fluid-like materials. In fact, adopting the Lagrangian approach, the FE mesh is constructed on the material. Hence, when the material undergoes large distortions, also the mesh undergoes the same large distortions, which are likely to cause an unacceptable loss in accuracy, a considerable increase in required CPU time (due to the fall of time-step value), and sometimes, a premature analysis termination.
Nevertheless, the use of Lagrangian FE model is somewhat customary for birdstrike analysis (as in Ref 5) thought the bird is usually modelled as a cylinder. This shape is preferred to the ellipsoidal one because it allows building a regular hexahedral solid mesh.
Regardless, a somewhat regular FE mesh was built on an ellipsoidal geometry proceeding iteratively (Fig 3). In particular, the FE model eventually consisted of 1749 solid elements the sizes of which ranged from a minimum of 4.6 *mm* to a maximum of 15.2 *mm*.

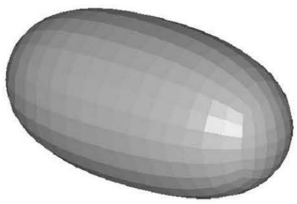


Figure 3. FE mesh of an ellipsoidal bird.

When compared with the experimental evidence (Ref 8), this model gave, *qualitatively*, a commonsense description of the event and, *quantitatively*, a good numerical-experimental correlation with regard to the impact forces.
No failure criterion was defined for the bird. When defined, in fact, the numerical-experimental correlation gets worse.
The interaction between the bird and the intake was defined using the high efficiency *Distributed Parameter Contact Algorithm* of LSTC LS-Dyna (Ref 10, 11).

ALE model. The ALE approach is not common in Continuum Mechanic and the applications mainly concerned the motion of fluid-like materials, explosions or forging. Following a pure Eulerian approach, the material flows through a mesh fixed in the space and, consequently, this approach is well suited to model large deformation of the material. The ALE approach differs in that the Eulerian mesh can move arbitrarily and, consequently, the ALE approach has an advantage when the motion of the material covers a wide region of the space. The Eulerian approach, in these cases, is not recommended because the number of the elements in the Eulerian mesh would have to be so large to maintain a reasonable accuracy in the calculation that the CPU-time required for the analysis would be unacceptable.
The ALE model of the bird was obtained from the ellipsoidal FE model previously described simply by adding a *void* surrounding region to avoid overflow of the material during the impact.
The interaction between the bird and the intake was defined via *Coupling Algorithm*. In particular, a four-point grid at the interface was chosen to improve the accuracy (Ref 10, 11).

SPH model. The Smoothed Particle Hydrodynamics Method was initially introduced to analyse astrophysical and cosmological phenomenon. Subsequently, the method was also extended to the analysis of problems somewhat different from the original one. In particular, in recent years (since mid-nineties), the SPH Method has shown to be a feasible alternative to the FE Method in the study of the continuum dynamic under large distortions.

The main difference between SPH and FE Method is in the discretisation of the continuum. The FE mesh is replaced with a set of particles endowed with a mass, which interact one with each other without direct connectivity. Indeed, the particles are the basis of an interpolator scheme based on the kernel function that is the core of the method.

One of the weaknesses of the SPH Method is the lack of sharp boundaries which makes imposing the boundary conditions troublesome and that, eventually, affects also the definition of fluid-structure interaction. Another weakness of the SPH Method is the so-called *tension instability* that is a numerical collapse of the continuum under tension. However, considering the motion of fluids, tension instability is not so evident as a problem – even if it is present.

The SPH model of the bird, here, was obtained filling the ellipsoidal geometry with particles equally spaced. The distance among the particles was a compromise between accuracy and required CPU-time. Eventually, the model consisted of 1445 particles.

The mechanical properties of the bird were the same of the previously described models.

The interaction between the bird and the intake was defined using the *Nodes to Surface Contact Algorithm*. Also, the *soft* option was activated to compensate the differences in mass and stiffness of the parts in contact (Ref 10, 11).

Nodal masses model. The nodal masses discretisation is unconventional modelling technique that recalls the Discrete Element Method (DEM). This technique, initially used to overcome the customary limitations of the FE model of the bird in presence of large mesh distortions, allowed achieving remarkable results especially when considering normal bird impacts (Ref 7, 8), which eventually encouraged its development. Indeed, the nodal masses bird model allows modelling the bird impact in a simple and effective manner.

The number of nodal masses, 1445, was the same of the SPH particles and the same was the definition of the interaction between the bird and the intake.

The difference between nodal masses and SPH particles model was the interaction among the zero-dimensional elements, which is completely absent when considering the nodal masses model. Indeed, the main drawback of the nodal masses model is the lack of internal interaction that eventually leads to the lack of dissipation mechanisms and hence to an unrealistic bird behaviour. Explicitly defining internal *stiffness* and *damping* by means of discrete elements is troublesome and not exactly recommendable for an explicit FE analysis. Indeed, the use of the viscous damping provided by the Contact Algorithm to damp high-frequency noise has been shown to be appropriate to compensate the lack of internal dissipation mechanisms and therefore adopted as part of the nodal masses model of the bird (Ref 8). In this way, the Contact Algorithm provides to the bird model not only an artificial stiffness but also an artificial damping.

With regard to the experimental data (Ref 8), it was observed that not only the numerical-experimental correlation, but also the description of the impact improved. Furthermore, the viscous damping indirectly increases the stability of the numerical model because it avoids unrealistic stress singularities due to the discreteness of the nodal masses model.

The value of the viscous damping was fixed at 20% of the critical one.

Results obtained

The results obtained were compared considering the description of the event (i.e. graphical output of the simulation), and the required CPU-time.

Description of the event (Fig 4)

The FE mesh of the bird (Fig 4a), also due to the lack of a failure criterion, underwent huge deformations during the analysis. These deformations, caused a drastic drop in the time-step and, eventually, a premature termination of the simulation, t = 1.4 *ms*. Therefore, it was possible to analyse only in the early stages of the impact of the second bird.

In addition, the ALE model (Fig 4b) suffered the severe conditions of the impact considered. In fact, though the ALE approach is indifferent to the distortion of the bird, the *motion* (translations and rotations) and the *expansion* of the Eulerian mesh, which were required to follow the bird, were such to rise doubts about the accuracy of the results (as highlighted in Fig 4b, the first bird disappeared during the simulation). Nevertheless, the analysis reaches a normal termination.

The SPH model of the bird (Fig 4c) allowed studying in detail and with a certain level of confidence the impact of both the birds. Furthermore, this model gave the representation of the event the closest to the experience collected during the experimental tests (Ref 8).

The simulations performed using the nodal masses model (Fig 4d) reach a normal termination though the behaviour of the bird seemed somewhat unrealistic thought not particularly different from that of the SPH model in the scatter of the bird. Indeed, the damages on the structure were less severe.

As there are not experimental evidences for the multiple impact considered, a direct comparison with the actual damages caused by the impact is not possible. Nevertheless, it is worth noticing that the FE (before the analysis ended) and the SPH models of the bird produced similar damages on the structure. On the contrary, also due to the fine grid defined at the interface, the ALE model produced more severe damages. Indeed, with regard to the damages caused by the nodal masses model of the bird, it was observed that those depends on the viscous damping coefficient in the Contact Algorithm and, therefore, the value of this parameter has to be carefully chosen referring to experimental evidence before being used.

Required CPU-time (Tab. 1)

With regard to the required CPU-time, the comparison among the different models was made considering the early 1.4 *ms* of the event – which is the limit reached by the simulation performed with the FE model of the bird before the significant drop in time step caused by the huge distortion in the mesh of the bird (Fig 4a).

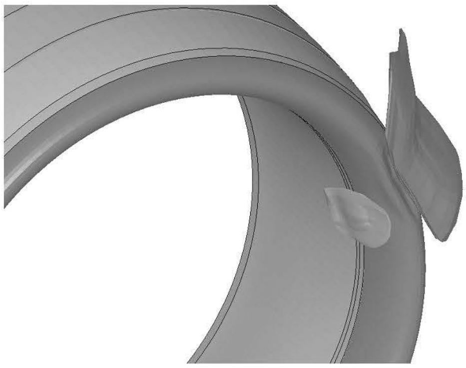
Referring to the CPU-time required by the FE model of the bird (Tab 1), the simulations performed with the ALE model lasted more than three times and those performed with the SPH and nodal masses models about one third. These results are not surprising. In fact, it is known that the efficiency is at the same time the main drawback of the ALE and the main benefit of the meshless models.

Table 1. Relative required CPU-time.

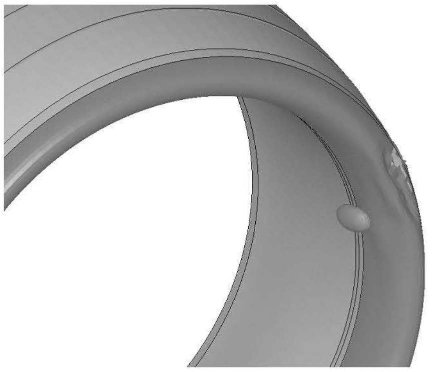
	Bird model			
	FE	ALE	SPH	NM
Relative CPU-Time	*1.00*	*3.18*	*0.33*	*0.29*

Discussion

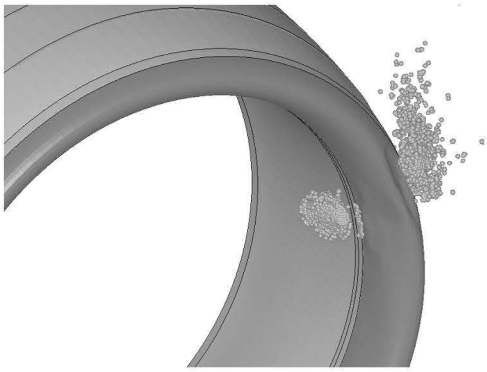
With regard to the results obtained some remarks can be done on the four models investigated.



(a) Lagrangian FE model of the bird



(b) ALE model of the bird



(c) SPH model of the bird

(d) Nodal masses model of the bird

Figure 4. Multiple birdstrike using different models of the bird – time = 1.4 *ms*.

FE model. The FE model of the bird gives an accurate description of the event in the early stages of the impact. In absence of large distortions of the mesh of the bird, this model provides results reliable and coherent – as shown for numerous cases documented in scientific literature. Indeed, the use of this model to develop new structures or verify existent component is not only justified but also recommendable. Nevertheless, when the event involves large distortions the FE model fail and therefore other model seem recommendable.

ALE model. The ALE approach, customary, has one of its typical applications in birdstrike analysis. The computation efforts (CPU-time and memory usage) required by the ALE approach, thought smaller than those required by a pure Eulerian approach, are the first constraint to the use of the ALE model of the bird.

With regard to the event considered, this approach allowed a normal termination of the analysis. Nevertheless, for features typical of the solver of the code used in the analyses, the behaviour of the ALE model was closer to that of a jelly body rather than to that of a fluid. Furthermore, as mentioned, the Eulerian mesh at the end of the simulation was so stretched that doubts on the accuracy of the solution rose.

SPH model. The SPH model of the bird allows a description of the event definitively commonsense. In particular, the scattering of the SPH particles after the impact is similar to that observed during birdstrike tests.

The SPH model, though based on the Lagrangian approach, differently from the FE model, does not suffer the distortions in the mesh of the bird and hence the simulations performed reached a normal termination. Furthermore, this model, differently from the Eulerian and ALE model, require somewhat small computational efforts.

Indeed, the results showed that, when appropriately validated, the SPH model makes it possible to analyse the multiple impacts with a *confidence*, which comes from the underlying consolidated theory. Merits and defects of the SPH method are well known and therefore it is possible to *argue* about the correctness of the obtained numerical results.

Nodal masses model. The nodal masses discretisation is an unconventional and straightforward technique that was successfully used to model the bird. Indeed, this technique gave good results when considering the impact and the penetration inside the airframe of a bird after a straight impact.

Nevertheless, with regard to the case considered, the nodal masses model provides a somewhat poor description of the dynamic of the bird. As no (internal) interaction among the masses is defined, the nodes moved, impacted the intake and eventually were deflected or rebounded independently one from the others. Thus, the motion of the bird resulted in being somewhat unnatural.

Furthermore, differently from the SPH model, the nodal masses model has not an underlying theory and, therefore, it is difficult to judge the correctness of the results obtained.

On the other hand, this model has the remarkable advantage of the feasibility: the nodal masses model, in fact, may be readily implemented in various explicit codes. Furthermore, the nodal masses model requires negligible computational efforts and, in some cases, it is more stable than the SPH model.

Conclusions

Statistics show that, despite the efforts provided to avoid collisions between aircraft and birds, birdstrike still represents a threat for flight safety.

In particular, as the probability of a multiple birdstrike, (i.e. the simultaneous impact of two or more birds) is increasing, the development of analysis tools able to reproduce such an event is mandatory. Nevertheless, in scientific literature, analyses of multiple birdstrike are extremely rare.

In this research, using an explicit FE code, namely LSTC LS-Dyna, the simultaneous impact of two birds has been considered. In particular, four already validated bird models have been investigated: the customary FE model, the ALE model, the SPH model, and nodal masses model.

The obtained results were compared one with the others and advantages and disadvantages of the different models have been highlighted.

In particular, the FE model has shown to be a useful tool to develop new bird-proof tools but not particularly feasible for a multiple birdstrike analysis.

On the other hand, the ALE model suffers the large expansion of the Eulerian mesh to follow the motion of the bird, which led to a lack of accuracy. Furthermore, the amount of computational efforts required imposes severe limitations to the use of this model.

Better results were obtained with the SPH model of the bird, which has allowed reproducing the event in detail and without requiring remarkable computation efforts. Probably, the best choice (when properly validated) for codes which implement such a solver.

Similar in appearance, but different in the results, the nodal masses model has provided a description of the event somewhat unrealistic in some respect. Nevertheless, this model is trivial and can be readily implemented in any explicit FE codes. Therefore, it seems recommendable only when an *indicative* result is needed in a short time – regardless to the code used in the analyses.

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