Numerical simulation of soft-body impact on GFRP laminate composites: mixed SPH-FE and pure SPH approaches

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Abstract

Impact events involving laminate composites had been largely studied through computational approaches, due mainly to the technical difficulties and high costs associated with experimental tests, and the availability of highly sophisticated computational codes. In the present work, medium-to-high velocities impact events of 'dummy birds' against balanced S2-Glass/Epoxy laminate composites are simulated through LS-Dyna explcit finite element package. Pure and mixed formulation coupling finite elements (FE) and smoothed particle hydrodynamics (SPH) techniques is adopted to describe the motion of the impacted composite plate and the soft body projectile, respectively. The severe distortions and the damage induced on the plate by the impact imply the remotion of some elements of the mesh, in order to become possible the continuity of the simulation without adoopting very reduced timesteps. An alternative approach consisting of SPH formulation of both projectile and target plate is adopted and comparisons between the these numerical procedures are made.

Keywords: impact, laminate composites, Finite Element Method, Smoothed Particle Hydrodynamics, LS-Dyna.

1 Introduction

The impact of birds with aircraft structures is one of the main threats for flight safety. Due the considerable presence of birds in the vicinity of airports a large number of these bird strikes occur around the world. In the last two decades a significant expansion of the use of fiber reinforced composite materials in aeronautical industry has been verified, aiming to obtain structures with advantageous strength/weight ratios. However, the damage induced by impact in composite materials is an aspect that inhibits the application of this kind of material, since it is well known that composites are very

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susceptible to transverse impact. In the bird-aircraft impact the bird is characterized as a soft body, i.e. body with low rigidity/hardness, because the stresses generated are beyond the strength of the bird and generally below the strength of the target. Moreover, the bird behaves like a fluid in the impact event, and the effect are large area of the target [1]. Thus, the problem in consideration joins some very complex aspects, such as high strain rates, large deformations, complex constitutive relationships and damage/failure mechanisms, among others. Therefore, this complexity usually precludes the use of analytical solutions to solve this class of problems.

Considering that experimental tests ate both expensive and troublesome, computational methods have been extensively by the aircraft industry to minimize the number of experiments, aiming this way to reduce certification and development costs and support the design of efficient bird-proof structures. In this sense, nonlinear explicit codes based on Finite Element (FE) techniques have been successfully employed to a large number of problem in the field of Continuum Mechanics since late eighties. The LS-Dyna code [2] is a general purpose finite element code for non-linear structural dynamics, which has been largely employed to impact analysis [3–6]. Impact of bodies with low rigidity and hardness, as those considered in the bird impact analysis, has been treated in the aeronautical industry and research centers through the so-called 'substitute birds' [7, 8], materials whose mechanical behavior resembles real birds, with advantages in what it refers to the uniformity and repeatability of the experimental tests, usually conducted by using gas gun projectile launchers.

Recently, aiming to overcome the difficulties of Lagrangian description to handle large distortions of the mesh, it has been proposed in the literature the use of Smoothed Particle Hydrodynamics (SPH), a mesh less method developed initially to simulate astrophysical problems and later extended to several other applications in Computational Mechanics. Examples of the use of such technique, already incorporated to LS-Dyna [9], can be found in the works of Anghileri et al. [3] and Ryabov et al. [5]. Comparative studies of Lagrangian, Eulerian and SPH formulations have been presented by Schewer [10] and Buyuk et al. [11] in ballistic impact simulation, by Anghileri et al. [3] in fluid-structure interaction problems and, more recently, by Huertas [12] analyzing bird-strike events through LS-Dyna and three distinct formulations: Lagrangian, Arbitrary Lagrangian Eulerian (ALE) and SPH.

The present work presents a numerical simulation of the impact between a substitute bird and a glass fiber- reinforced polymer (GFRP), more specifically a S2-Glass/Epoxy composite plate, by using the LS-Dyna code. Due the lack of test data the material behavior of the idealized bird is approximated as that of the water, as suggested in the literature [4, 8]. Combinations of two different approaches to describe the motion of the bird are investigated, namely the classical Lagrangian FE and the SPH. The results obtained, as well as the computational performance of each method, are critically compared, and a qualitative comparison with experimental results obtained at Group of Solid Mechanics and Structural Impact (GMSIE/USP) is performed.

2 Problem description

The impact here considered is that of a circular cylindrical soft body, the plasticine ('play-doh' modeling compound) 'bird', which is horizontally launched on a vertically placed, circular composite plate, made of a continuous fiber-reinforced S2-Glass/Epoxy. The tested plate had a diameter of 250 mm

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and a thickness of 4 mm, whereas the circular cylinder, with 50 mm of diameter and 100 mm of length, observed the ratio diameter-to-height suggested in the literature [8]. The plate was placed over a rigid circular ring, i.e. clamped boundary condition was assumed and an initial velocity of 115 ms^{-1} was provided to the impactor to start the analysis. In order to save processing time, the cylinder was initially placed very close to the plate in the beginning of the numerical analysis, i.e. 6 mm from plate upper surface to the bird lower surface. In the present work the commercial package LS-Dyna was used to obtain the transient dynamic response of the plate during impact. The main aspects of the numerical simulation are described in the next sections.

3 LS-Dyna's numerical solvers

LS-Dyna [2] is a general-purpose finite element package to non-linear, dynamic analysis of transient field problems. In the present work this code was adopted to solve the dynamic equilibrium equations, as well as the contact between the two deformable bodies. Regarding to the formulations, Eulerian approach with non-deformable mesh, Lagrangian approach with deformable mesh, and Smoothed Particle Hydrodynamics (a mesh-free method) are available in the version 970, which was used in this work. The kind of problem considered in the present work is traditionally analyzed by using the Lagrangian approach. However, aiming to circumvent the above mentioned difficulties of this formulation, in particular to handle large deformations of the mesh, the new alternative represented by SPH is also considered in this work. To allow the comparison the same code was used, the constitutive models were kept constant, and just minor changes were done in the geometric modeling in the two simulations.

In the traditional **Lagrangian** description, widely used in problems of Solid Dynamics, the FE mesh is attached to the material. Consequently this kind of description possesses limitations to contemplate severe distortions of the mesh, due to numerical inaccuracies that may to harm or even to make impracticable the simulation. In these cases, the occurrence of negative-volume errors and hour-glass modes appearance are often related with the entangling of the mesh. Furthermore, the explicit, conditionally stable nature of the central difference scheme, the time integration algorithm adopted in this work, can lead to very reduced time-steps, considerably increasing the computational cost of the problem. An alternative to remove too distorted elements from the simulation is the so-called 'element erosion', usually based on a user supplied criteria [2]. In LS-Dyna some of these criteria are maximum principal strain (tension), minimum principal strain (compression) and minimum allowable time step. The main drawback associated to these criteria is that they are ad hoc by nature, as observed by Schwer [10].

SPH, on the other hand, is a mesh less method where a set of particles with their respective masses provides the discretization of the continuum without any connectivity among the particles [9]. The particles are the basis of an interpolating scheme based on the kernel function and some conditions in setting the initial particle masses and coordinates are required: the array of particles needs to be regular, for instance. In this framework the conservation equations are equivalent to terms expressing inter-particular forces and the smoothing kernel is usually defined in terms of a cubic B-spline. Due to nonexistence of a mesh, SPH is not affected by the problems caused by distortions in large deformation problems, as occurs in the traditional Lagrangian approach. Besides, this method shows another remarkable feature: a better representation of the fluid-like movement of projectiles with low rigidity/hardness, including their disintegration process. The compatibility between the SPH processor with the FE Lagrangian solver in LS-Dyna is ensured due the way as this new technique was implemented in the code, enabling the use of the classical LS-Dyna keywords (input data sets) and making easier the use of mixed approaches. On the other hand, there exist some remaining problems in the areas of accuracy and stability and of such formulation.

4 Numerical modeling methodology

As observed previously, both FE and SPH models were employed in the numerical simulations, either in isolated form or combined in a mixed approach. The contact-impact problem was modeled and solved on LS-Dyna version 970. All the numerical analysis were accomplished using a common PC (Pentium IV- 3 GHz CPU, 1024 MB RAM). A total of six different numerical experiments were conducted and are given in Tab. 1.

Table 1: Numerical models employed to simulate the soft body impact onto a composite plate.

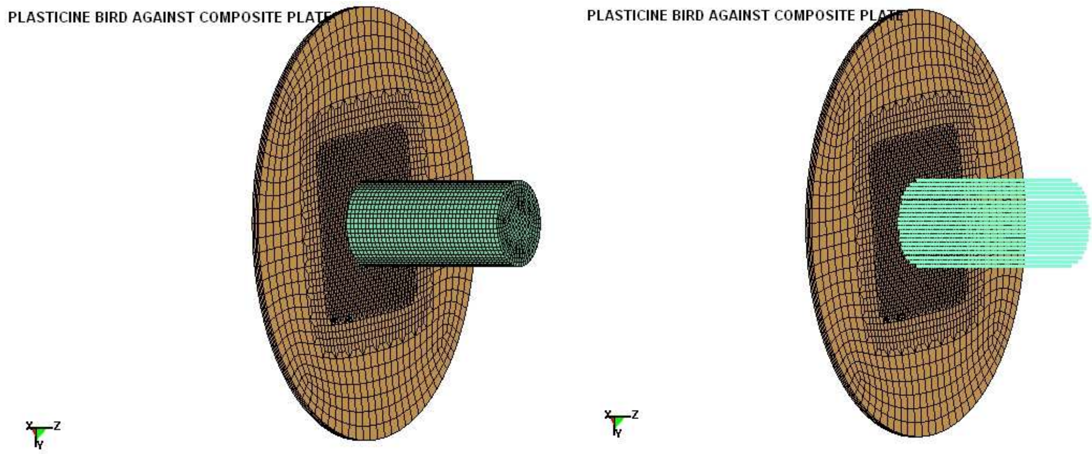
TEST CASE	PLATE NODES	PLATE ELEMENTS	BIRD NODES	BIRD ELEMENTS	PLATE PARTICLES	BIRD PARTICLES
A1 (PURE FE)	**18635**	**14712**	**6825**	**5680**	**none**	**none**
A2 (PURE FE)	**18635**	**14712**	**15378**	**13840**	none	none
B1 (MIXED)	**18635**	**14712**	none	none	none	**6825**
B2 (MIXED)	**18635**	**14712**	none	none	none	**13325**
C1 (PURE SPH)	none	none	none	none	**19760**	**6825**
C2 (PURE SPH)	none	none	none	none	**162315**	**6825**

4.1 Pure Finite Element model

The FE model of the plate used 8-node (brick) finite elements with one integration point. Due the use of reduced integration, the 'Flanagan-Belytschko viscous form with exact volume integration' option was employed to stabilize the zero strain-energy ('hourglass') modes (Hallquist, 2006). The plate was modeled with four element layers through thickness and clamped boundary conditions were assumed in its boundary. To model the impacting body in Lagrangian description were used meshes with 6825 nodes/5680 elements to test case 'A1', Fig. 1a, and 15378 nodes/13840 elements to test case 'A2', resulting from previous sensitivity analysis [13]. Some values recommended in the literature [12] for element erosion were used to the bird part, as well as a limit to minimum allowable time step and the failure criteria of the material model, as explained right after. These erosion procedures make the simulation more stable, but their use must be judicious in order to maintain coherence of the results [10].

4.2 Mixed model (FE + SPH)

In this simulation the plate was modeled by finite elements, whereas the bird model was generated with a set of equally spaced particles. As SPH was developed as an extra layer of the code, all LS-Dyna's features such as assignment of initial and boundary values, contact treatment and etc., can be used within the particles' context. Therefore the compatibility between FE and SPH in LS-Dyna's framework is complete, enabling mixed approaches. The same FE model employed previously to the composite plate was used again in the mixed model. The SPH parts of this model were comprised of 6825 and 13325 particles in the test cases 'B1', Fig. 1b, and 'B2', respectively. The SPH particles of model B1 were obtained from the bird mesh of model A1, whereas to model B2 a new set of particles was generated respecting the recommendation of to distribute the particles on a regular configuration [9].



(a) (b)

Figure 1: Perspective view of two computational models: a) CASE A2 (Pure FE); b) CASE B1 (Mixed FE + SPH).

4.3 Pure SPH model

The last two simulations, i.e. test cases 'C1' and 'C2', were performed solely with SPH approach. Therefore both the plate and the impacting bird were discretized through sets of particles. The same

SPH model used before in the test case B1 was adopted to model the bird, whereas two different discretization levels were adopted to the plate: the first one containing 19760 particles (test case C2) and the second, more refined, with 19760 particles (test case C1). The particle approximation algorithm adopted was the code's standard gather form [9] and to all remaining SPH input parameters were used the code's defaults.

4.4 Contact/Impact interaction

In the simulations with pure FE model and mixed model, it was adopted the contact option *CONTACT_CONSTRAINT_NODES_TO_SURFACE with the code's default values. In these simulations the bird was considered as the 'slave' surface and the plate as 'master' surface for contact verification purposes, i.e. to handle the interaction between the two colliding parts. In the pure SPH simulations the contact is automatically verified and there is no need to specify a *CONTACT card, since the code assumes that two SPH parts will always interact (contact).

4.5 Material modeling

LS-Dyna's material library includes over 130 models to represent the mechanical behavior of the material to be modeled. Of course that the more complex the material model is, the greater the necessity of input material parameters. So the availability of these parameters is an important factor to be considered when choosing a determined material model, as observed by some authors [6]. Moreover, this fact can lead to the need of simplifications and estimations, strategy that were also adopted in the present work. Regarding to failure and erosion associated to each constitutive model, LS-Dyna proceeds as follows: each of the failure options is applied independently, and once any one of them is satisfied, the element is removed from the calculation [2].

4.5.1 Composite plate

This work used S2-Glass/Epoxy plain weave composite laminates (balanced 0/90 cross-plies) manufactured by the Mechanics of Composites Laboratory of Federal University of Minas Gerais [14]. All available material data resulting from mechanical characterization tests at GMSIE, i.e. compressive/tensile static tests on an Instron machine and dynamic tests on Split Hopkinson Pressure Bar [15], were used to provide the representation of the material properties, shown in Tab. 2. The *MAT_COMPOSITE_FAILURE_SOLID_MODEL, which is based on the Chang-Chang failure criterion [16] was selected. This material card allows to consider the reduction of material properties due the damage process and the inter-ply delamination in the failure process, and thus resembles the composite material behavior verified experimentally.

The above mentioned material model in not available in the code to SPH parts. Therefore the constitutive model *MAT_PLASTIC_KINEMATIC was adopted in the simulations 'C1' and 'C2', in which the plate is also modeled in the SPH framework. Again, the experimental results obtained with the composite material here considered were used. Table 3 presents a list of the LS-Dyna's required input parameters to this model. Although considerably simpler than the previous model, *MAT_PLASTIC_KINEMATIC has an remarkable feature: it permits to consider the strain rate

Table 2: Physical properties of composite panels – MAT_COMPOSITE_FAILURE_SOLID_MODEL constitutive model.

Mass density	1425 kgm^{-3}
Elastic Modulus at in-plane fill direction, E_1	17 GPa
Elastic Modulus at in-plane warp direction, E_2	17 GPa
Elastic Modulus at out-of-plane direction, E_3	17 GPa
Poisson's ratio, υ_{21}	0.12
Poisson's ratio, υ_{31}	0.40
Poisson's ratio, υ_{32}	0.40
Shear modulus (in-plane), G_{12}	6.1 GPa
Shear modulus (out-of-plane), G_{23}	6.1 GPa
Shear modulus (out-of-plane), G_{31}	6.1 GPa
Shear strength (in-plane), S	60 MPa
Shear strength at plane 1-3, S1	60 MPa
Shear strength at plane 2-3, S2	60 MPa
Compressive strength at in-plane fill direction, XXC	325 MPa
Compressive strength at in-plane warp direction, YYC	325 MPa
Compressive strength at out-of-plane direction, ZZC	325 MPa
Tensile strength at in-plane fill direction, XXT	325 MPa
Tensile strength at in-plane warp direction, YYT	325 MPa
Tensile strength at out-of-plane direction, ZZT	325 MPa

effects on the material properties, which plays an important role when this kind of material is simulated.

The strain rate parameters C and P of Cowper and Symonds model permit to the model to scale the static failure stress with the factor:

$$1 + \left({}^{\dot{\varepsilon}}/_{C} \right)^{1/P} \tag{1}$$

This quite simple formulation, yet isotropic, allows to find the rupture stresses corresponding to each strain rate level. Other important parameter included in this model is the failure strain for eroding elements. Finally, the tangent modulus, obtained from the experimental stress-strain curve, permits to approximate the process of softening.

Table 3: Physical properties of composite panels – MAT_PLASTIC_KINEMATIC constitutive model.

Young's modulus, E	17 GPa
Yield stress, SIGY*	325 MPa
Tangent modulus, ETAN	-11459.16 Pa
Strain rate parameter for Cowper and Symonds model, C	1520.00
Strain rate parameter for Cowper and Symonds model, P	13.43
Poisson's ratio, PR	0.40

* actually the rupture stress, for composite materials are brittle and do not yield.

4.5.2 Plasticine cylinder

The substitute bird, made of plasticine compound, bahaves as a hydrodynamic material at higher pressures [17]. The selected material model to it was given by a combination of LS-Dyna's material card *MAT_NULL and the *EOS_LINEAR_POLYNOMIAL equation of state [2] as recommended in the literature to this kind of projectile [7, 8]. Thus, the pressure-dependent character of the material behavior is considered: at lower pressures the material behaves as isotropic elasto-plastic and at higher pressures as a hydrodynamic material, for which an equation of state relating the thermodynamic properties pressure and volume is adopted. An example of equation of state that has been largely used is the polynomial one, which was adopted in this work and has the following expression:

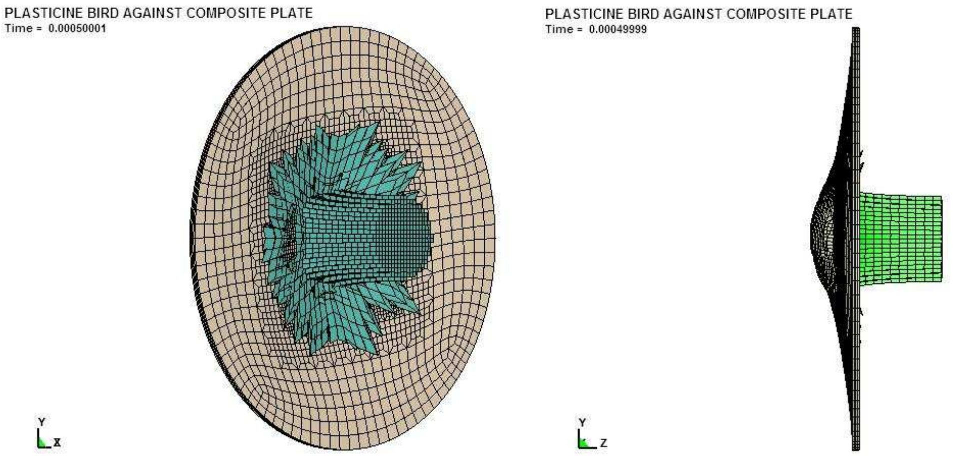
$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3, \quad \mu = \rho/\rho_0 - 1 \tag{2}$$

where C_0, C_1, C_2 and C_3 are material constants, ρ is the current density and ρ_0 is the reference initial density. Difficulties in the measurement of these constants have motivated to adopt a material behavior similar to water, such that: $C_0=C_2=C_3=0$, $C_1=2.2$GPa. In these values may be recognized the bulk modulus of water, C_1. It is worthwhile to emphasize that the specimen employed in the gas-gun experimental tests with is about ten times lighter than those adopted adopted for the most part of the references, that is 1.82 kg, which is a requirement for the design of aircraft wing structures.

5 Results and discussion

Figures 2, 3 and 5 to 8 illustrate the final deformed configuration as calculated by the different simulations. As commonly observed in soft body impact events in this velocity range, the damaged area encloses a considerable portion of the plate, greater even than impactor's cross section, because these soft materials flows over the structure, spreading the impact area. This behavior is clearly noted in these simulations and the projectile's disintegration is adequately represented by the simulations.

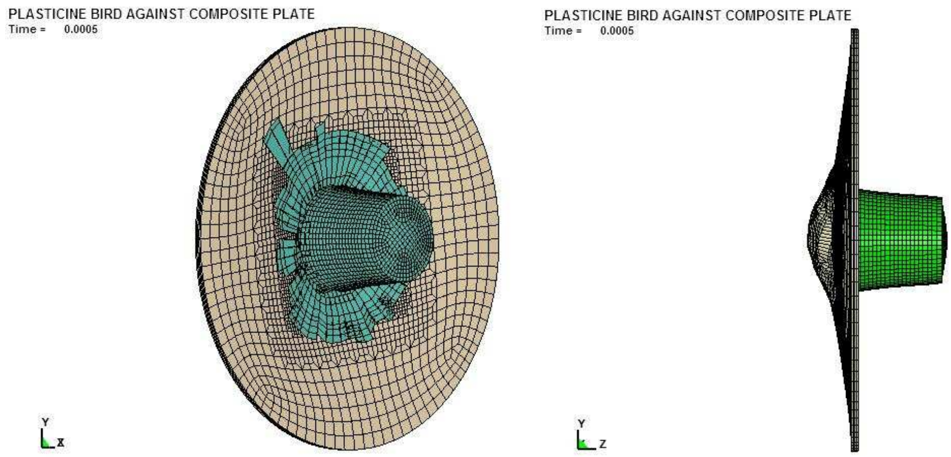
For comparison purposes next are presented in Fig. 4 some pictures of the experimental test showing the final configuration of the plate after the gas gun test. An overall good agreement between the results of the two simulations is verified. It can be seen in Figs. 2 and 3 that some finite elements have been removed from the bird due the failure criterion adopted, which includes element deletion. At this stage of the simulation the presence of some very distorted elements in the plate description indicate the beginning of the numerical instabilities that will eventually interrupt the processing.



(a) (b)

Figure 2: Final deformed configuration to CASE A1: a) perspective view; b) lateral view.

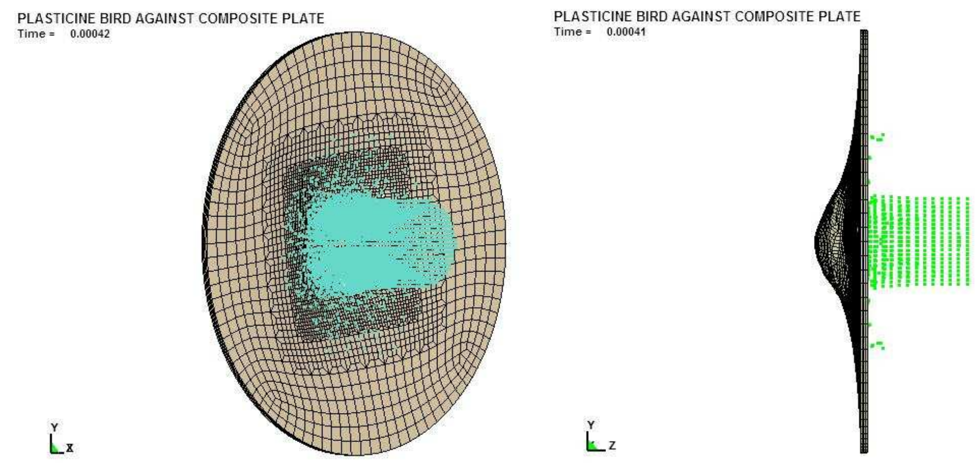
Observing the Figs. 7 and 8, a different deformation profile is verified, which is probably related to differences in the simulations regarding to element erosion, that was not needed in pure SPH approaches (cases C1 and C2). A simple quantitative comparison between the simulations is presented in Fig. 9, where the time variation of the displacement of the plate's central node (at lower surface) is depicted, numerically confirms the above mentioned. Furthermore, it can be observed that simulations A1, A2, B1 and B2 furnished similar curves.



(a) (b)

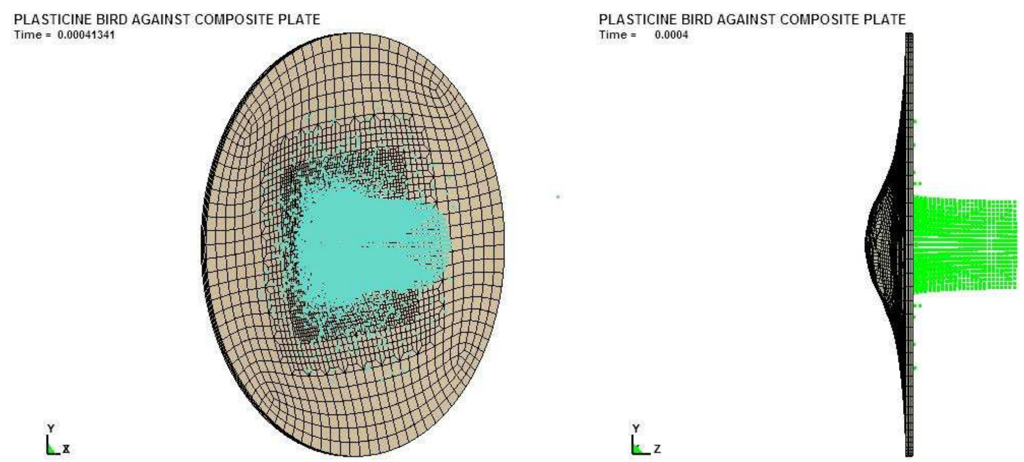
Figure 3: Final deformed configuration to CASE A2: a) perspective view; b) lateral view.

Figure 4: Plate's deformed configurations after the gas gun impact test: total view (left) and zoom views (center and right).



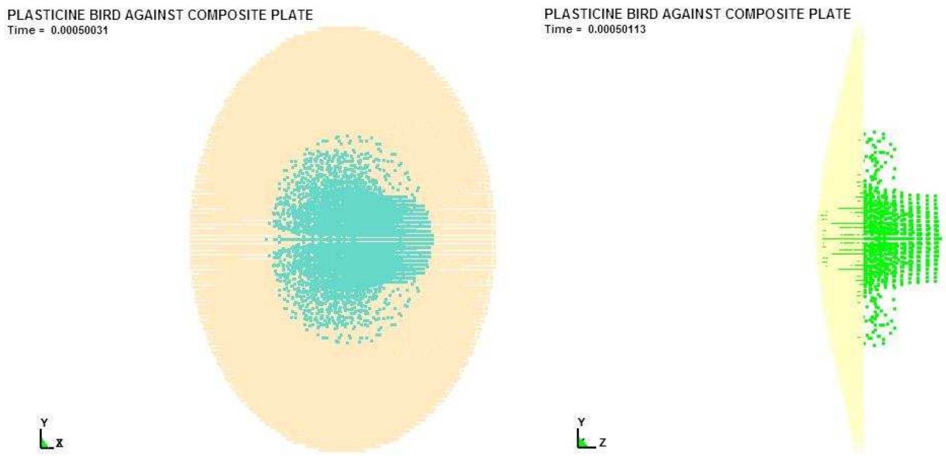
(a) (b)

Figure 5: Final deformed configuration to CASE B1: a) perspective view; b) lateral view.



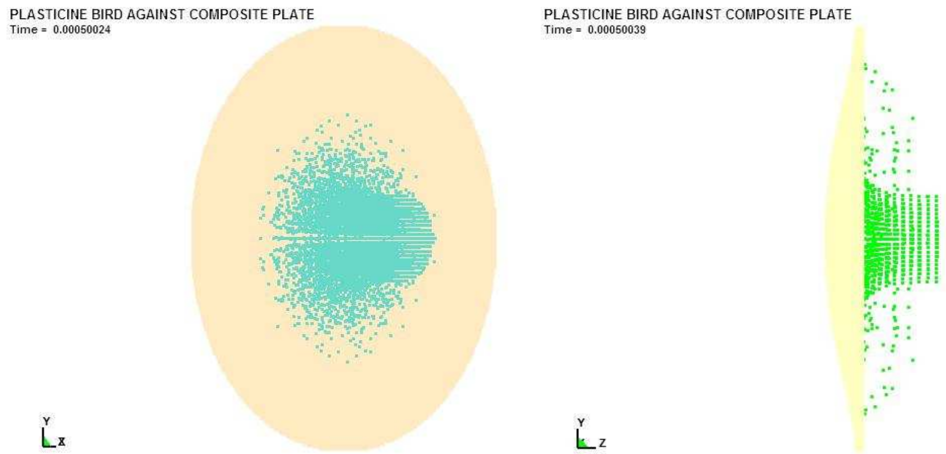
(a) (b)

Figure 6: Final deformed configuration to CASE B2: a) perspective view; b) lateral view.



(a) (b)

Figure 7: Final deformed configuration to CASE C1: a) perspective view; b) lateral view.



(a) (b)

Figure 8: Final deformed configuration to CASE C2: a) perspective view; b) lateral view.

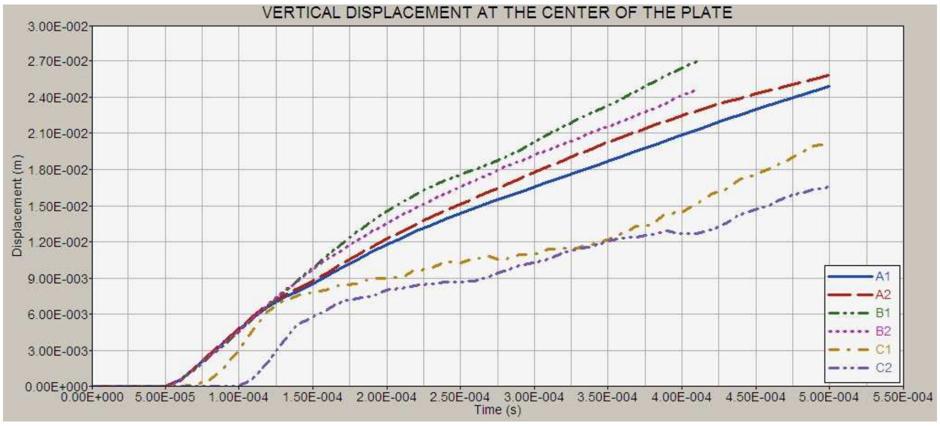


Figure 9: Curve displacement at plate's central node *versus* time to various test cases

The computational characteristics of the six simulations are presented in the Tabs. 4 and 5, in which it can be noted the way the timestep changed at every simulation, how the calculations ended, and the computational cost associated to all test cases. As expected, a considerable decreasing of stable timestep were verified in large-deformation simulations involving Lagrangian parts, whereas in the pure SPH runs the timestep remain almost constant. A normalized computational cost is defined to allow to compare the six test cases in a common basis, being the results presented in Tabs. 4 and 5.

6 Concluding remarks

In this work three numerical models to analysis the normal impact of idealized birds onto S2-Glass/Epoxy laminate composites have been developed by using LS-Dyna: finite element to both target and projectile in the first two analysis, finite element to target and smoothed particle hydrodynamics model to projectile in the second set, and a new approach: smoothed particle hydrodynamics to both domains in the third set. These models were qualitatively compared referring to a experimental test performed at GMSIE (USP) and advantages and disadvantages of the two models have been discussed. It was observed that LS-Dyna was able to capture the main patterns of the impact event and a reasonable qualitative correlation between numerical predictions and experimental results were obtained, although further improvements of the numerical models are necessary.

The LS-Dyna capacity to handle such complex problems with accuracy strongly depends on the knowledge of the material properties and the correct treatment of contact and failure phenomena. Despite these complexities, which are inherent to the problem, it can be considered that the obtained results are quite promising. Some issues like a better mechanical characterization of the materials, and additional instrumentation of the experimental tests with gas gun, allowing quantitative comparisons and aiming more integrated (numerical-experimental) approaches. Correlation for relevant impact

Table 4: Summary of the LS-Dyna's numerical analysis.

TEST CASE	INITIAL TIMESTEP (s)	FINAL TIMESTEP (s)	END TIME (s)	FINAL STATUS
A1	1.96E-07	1.53E-08	5.000E-04	normal termination
A2	1.96E-07	4.85E-09	5.000E-04	normal termination
B1	1.96E-07	5.87E-09	4.171E-04	interrupted(1)
B2	1.96E-07	4.94E-09	4.011E-04	interrupted(1)
C1	1.28E-06	1.28E-06	5.000E-04	normal termination
C2	6.44E-07	6.20E-07	5.000E-04	normal termination

(1) The reason of the interruption was the excess of brick elements eroded due to negative volume and a large number of failed elements as well. The reported 'end time' of these interrupted simulations mark the beginning of large variations in the ratio (total energy / initial energy), i.e. a considerable amount of energy loss, indicating numerical instabilities that generate non-physical results.

Table 5: Comparative of computational performance.

TEST CASE	ELAPSED TIME (s)	NUMBER OF NODES	NUMBER OF TIME STEPS	COMPUTATIONAL COST* (NORMALIZED)
A1	1662.00	25460	12699	1.25
A2	6168.00	34010	41925	1.00
B1	8834.00**	25460	11609	6.85
B2	6480.00***	31960	19242	2.33
C1	483.00	26585	391	9.02
C2	9169.00	169140	794	12.65

* COMPUTATIONAL COST = (elapsed time) / (total number of nodes) / (total number of time steps)
** simulation interrupted at time= 4.171E-04 s.
*** simulation interrupted at time= 4.011E-04 s.

parameters, such as inter-ply delamination area and contact forces are examples of such comparisons, that can be conducted when the suitable test data are available. These questions still remain open to be addressed as future works in this study. Additional theoretical studies regarding SPH approach are also needed, in oder to improve the accuracy of this promissing technique and to check the validity and feasibility of such numerical approach.

The SPH's computational cost was superior to that of FE analysis, although considering that the simulations ended at different times. As the size of the model is increased, the use of parallel processing may become mandatory due the large CPU requirements associated to the problem, specially if auto-adaptive analysis is adopted. This automatic adaption of mesh topology can be an alternative to overcome the limitation of Lagrangian formulation to follow large deformations, but is not applicable in LS-Dyna to all element types. The strategy of to remove the too distorted elements and replace them by SPH particles, already investigated by some authors, could provide to the model a good commitment beetween accuracy and computational efficiency but is not yet available in the code nowadays.

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References

[1] Abrate, S., Modeling of impact on composite structures. *Composite Structures*, **51**, pp. 129–138, 2001.
[2] Hallquist, J., *LS-DYNA3D Theoretical Manual*. Livermore Software Technology Corporation (LSTC): Livermore, 2006.
[3] Anghileri, M., Castelletti, L.M., Invernizzi, F. & Mascheroni, M., A survey of numerical models for hail impact analysis using explicit finite element codes. *International Journal of Impact Engineering*, **31**, pp. 929–944, 2005.
[4] Antoun, T.H., Gekfen, P.R., Holmes, B.S. & Kirkpatrick, S.W., Description of a six-inch gas gun facility for soft body impact. *Proceedings 43rd Annual Meeting of the Aeroballistic Range Association (ARA)*, 1992. Paper No. 50 (http://www.sri.com/poulter/composites/bird.html).
[5] Ryabov, A., Romanov, V., Kukanov, S., Shmotin, Y. & Chupin, P., Fan blade bird strike analysis using lagrangian, sph and ale formulations. *Proceedings of the 6th European LS-DYNA Users Conference*, 2007.
[6] Yen, C..F., Ballistic impact modeling of composite materials. *Proceedings of the 7th International LS-DYNA Users Conference*, 2002.
[7] Airoldi, A. & Cacchione, B., Modeling of impact forces and pressures in lagrangian bird strike analyses. *International Journal of Impact Engineering*, **32**, pp. 1651–1677, 2006.
[8] Johnson, A. & Holzapfel, M., Numerical prediction of damage in composite structures from soft body impacts. *Journal of Material Science*, **41**, pp. 6622–6630, 2006.
[9] Lacome, J.L., Smoothed particle hydrodynamics (sph): a new feature in ls-dyna. *Proceedings of the 7th International LS-DYNA Users Conference*, 2002.
[10] Schewer, L.E., Preliminary assessment of non-lagrangian methods for penetration/simulation. *Proceedings of the 8th International LS-DYNA Users Conference*, 2004.
[11] Buyuk, M., Kan, C.D.S., Bedewi, N.E., Durmus, A. & Ulku, S., Moving beyond the finite elements, a comparison between the finite element methods and meshless methods for a ballistic impact simulation. *Proceedings of the 8th International LS-DYNA Users Conference*, 2004.
[12] Huertas, C.A., *Robust Bird-Strike Modeling Using LS-DYNA*. Master's thesis, University of Puerto Rico,

2006.
[13] Azevedo, R.L. & Alves, M., Numerical simulation of bird strike impact against balanced fiberglass/epoxy composite plates. *Proceedings of the 19th International Congress of Mechanical Engineering*, Brasília (DF), Brasil, 2007.
[14] Ávila, A.F., Soares, M.I. & Silva Neto, A., An experimental investigation on nanocomposites under impact loading. *WIT Transactions on Engineering Sciences, Impact Loading of Lightweight Structures*, eds. M. Alves & N. Jones, pp. 89–102, 2005.
[15] Santiago, R.C., Azevedo, R.L., Alves, M. & Ávila, A.F., Mechanical characterization of glass/epoxy composite material with nanoclays. *Proceedings of the 19th International Congress of Mechanical Engineering*, Brasília (DF), Brasil, 2007.
[16] Chang, F.K. & Chang, K.Y., A progressive damage model for laminated composites containing stress concentrations. *Journal of Composite Materials*, **21**, pp. 834–855, 1987.
[17] Meyers, M.A., *Dynamic Behavior of materials.* John Wiley and Sons, Inc., 1994.

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