Impact of soft body materials, an experimental and numerical approach using a Hopkinson tube: application to substitute bird.

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1 Abstract

This work shows a combined experimental-numerical methodology for helping in the developing of soft body material modelling subjected to high velocity impact. In this case, it is applied to substitute bird application. In particular it has been used a Hopkinson tube attached with a steel plate in which the substitute birds are impacted at different velocities. The Hopkinson tube is instrumented by means of several strain gauges. These data will be used to compare with the numerical simulations in order to validate the numerical material model. Prior to this, the numerical model of the Hopkinson tube has been validated with an experimental modal analysis. For the bird substitute it has been used a numerical model based on a linear polynomial equation of state. In order to reproduce the high deformations experienced by the substitute bird in the impact process, the Smooth Particle Hydrodynamics (SPH) technique has been used. After the analysis of the results, it can be concluded that the combined experimental-numerical methodology proposed successfully can be used to validate the numerical models for simulate the behavior of soft impactor when subjected to high velocity impacts. In addition it has been used to analyze the influence of several parameters such us the impact angle, also analyzing the robustness of the experimental methodology.

***KEYWORDS: Soft body impact, SPH, Experimental test, Numerical modeling, material behavior, Hopkinson tube, Bird substitute impacts.**

2 Introduction

Industries such as Aeronautic and Aerospace permanently seeks to optimize structural components due to the high requirements demanded to the aircrafts for both safety and reliability. Moreover, these industries are continuously improving their structures in order to reduce the weight of the aircraft, which matches with the social challenge of achieving a more sustainable transport. These improved structures can be subjected to severe case of loads to accomplish the certification requirements. In order to assure the certification, traditionally it has to be performed several experimental tests to validate the design. The high cost of the experimental tests forced the engineers to implement numerical tools to improve the designing process. However these numerical tools need reliable material models to produce accurate results. Thus developing test to obtain reliable experimental data to validate material models are a key point for the engineers.

Test load cases for aeronautic structures are extensive but among others, impact is one of the most concerning loads to which a structure is subjected. Different materials could impact on the structure during the landing and takeoff operations, which can lead to damages in the structures. Events such as the US Airways Flight 1549 in which after struck a flock of canada geese the plane suffer several damages and lost all engine power, landing in the Hudson river; or the case of Concorde that due to a tyre impact one of the fuel containers catch fire; are examples in which such type of loads promotes the lost of structural integrity. This menace has been reported by the authorities: literally from an EASA 2011 report "*A critical safety issue for the design of primary aircraft structures is vulnerability and damage tolerance due to foreign object impact from bird strike, hail, tyre rubber and metal fragments*",[1] highlighting the impact threat as a key factor in the design of composite structures.

Several authors study such type of events, from an experimental and a numerical point of view, using different types of impactors. The impacts caused by quasi-non-deformable bodies (metal fragments), or highly deformable (hail, bird) have been studied in some depth. Concerning to the later, these impactors flow over the structure, spreading the impact load; so as the material models increase in complexity to capture the physics of the impactor, it requires for reliable damage prediction in aeronautical structures the use of more complex experimental technique to obtain appropriate for developing appropriate modeling techniques.

In this work, a combined experimental-numerical methodology is presented to validate the material model implemented for the impactor subjected to high impact velocity; applying it to a real case of study: the bird impact. Instead of use real birds for the experimental campaign, substitute birds (SB) made from gelatin are used, avoiding the spread of properties related with the different bird species. The SB are launched against a Hopkinson tube in order to measure the impulse induced and the stress pulse generate in the tube, at different impact velocities.

3 Experimental setup

In order to accelerate the simulated bird, a one stage light gas gun was employed, which uses pressurized air (or helium) to impel the projectile through 20 meters long, 60 mm caliber barrel (Fig. 1). The impact velocity, in the range between 70-150 m/s, was measured by means of a laser sensor placed between the barrel muzzle and the target. These laser barriers are also used to trigger the high speed cameras and the data acquisition system that registers the strain measured by the strain gauges. The measurement of these gauges located at 350 mm form the impact point in the Hopkinson tube give information about the intensity of the force induced by the simulated bird. The tube is 6 m long with 80 mm of diameter and 2 mm of thickness made of Aluminum AW6060 T66. At the ends of the tube, two impact plates are attached to be used as a target for the impactor. These plates are screwed to a piece of aluminum which join the plate to the tube. The strain signals were stored by a data acquisition system (DEWETRON DEWE-800) with a sample rate of 1·MHz. Similar facilities are employed by the NASA for impact test measurement [2].

Fig.1: Uc3m impact laboratory

The SB was made by gelatine in the UC3M lab facilities. The gelatine employed, “250 Type A Ordnance Gelatin” from Gelita® is recommended to reproduce the behaviour of organic tissue under ballistics conditions due to its mechanical properties. The shape of the impactors is obtained pouring the gelatine into a mold designed and manufactured using 3D print process, the dimensions are 56.5 mm of diameter and 160 mm long as is presented in the work of Budgey [3], giving as a result a SB of 350 g (aprox).

In addition to the simulated bird impacts, a modal analysis of the Hopkinson tube has been done in order to validate the numerical model of the facility. To this end, the modal frequencies of the Hopkinson tube have been measured by means of an accelerometer and an instrumented hammer. The hammer impact at the same location of the SB and the accelerometer measure the response of the tube under the hammer impact in the longitudinal axis, obtaining the frequency response of the structure and hence its modal frequencies.

4 Numerical simulations

The numerical model for the Hopkinson tube and the substitute gelatine bird was implemented in LS-Dyna. The Hopkinson tube was modelled using solid elements, while the SB was modelled using a mesh-free approximation (SPH). Prior to simulate the impact, the numerical model of the Hopkinson tube was validated by means of comparing the modal frequencies experimentally measured and numerically obtained. In this section the numerical model of both tests are explained in detail.

4.1 Numerical model of the modal analysis of the Hopkinson Tube

Prior to simulate the impact of the SB, in order to validate the Hopkinson tube numerical model, a modal analysis has been done to be compared with the experimental results. For this purpose, the modal package included in the implicit module **(*CONTROL_IMPLICIT_DYNAMICS, *CONTROL_IMPLICIT_EIGENVALUE,*CONTROL_IMPLICIT_GENERAL,*CONTROL_IMPLICIT_SOLVER**) of LS-Dyna was employed. The Hopkinson tube has been modelled by 5 different parts analogously as the experimental setup: 1 aluminium tube, two aluminium adaptors and finally two steel plates. All the parts are modelled using solid elements and with elastic materials (**`*MAT_ELASTIC`**) (table 1). The different components of the facility have been attached using a contact tied formulation (**`*CONTACT_TIED_SURFACE_TO_SURFACE_ID`**). As it was said previously, in the experimental test only longitudinal modes are obtained, therefore it has been restricted the displacement of several nodes avoiding the obtainment of flexural modes.

Part	**Material**	**Density [kg/m^3]**	**Young modulus [GPa]**	**Poisson Coefficient [ ]**	**Number of solid elements**
Tube	Aluminum	2500	70.6	0.28	6400
Screw adaptors	Aluminum	2500	71	0.3	2006
Steel plates	Steel	7850	210	0.3	15776

Table 1: Hopkinson tube materials

4.2 Numerical model of the SB impact on to Hopkinson Tube

The numerical simulations of the simulated bird impact use the aforementioned Hopkinson tube model, but in this case the SB impactor has included and the explicit module of LS-Dyna has been employed. The complete numerical model can be observed in figure 2.

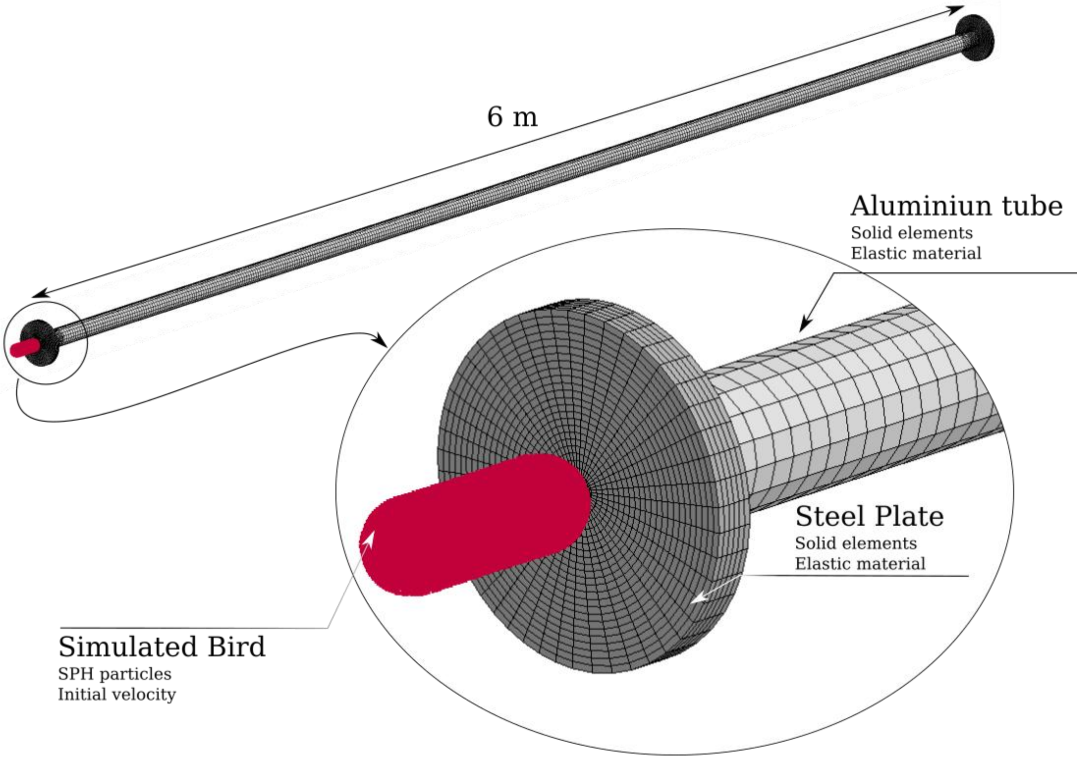


Fig.2: Numerical Model of the simulated bird impact against a Hopkinson tube

The SB was defined using the smooth particle hydrodynamics technique (`*SECTION_SPH` 15872 particles), this meshfree approximation was selected due to the large deformation suffered by the SB during the impact. The constitutive behaviour of the gelatine was modelled as a fluid like material (`*MAT_NULL`) with a polynomial equation of state (`*EOS_LINEAR_POLYNOMIAL_TITLE`), the material properties were obtained from the literature ([4][5]). The material cards:

```
*MAT_NULL_TITLE
Gelatine
$#     mid        ro        pc        mu     terod     cerod        ym        pr
         4 1000.0000     0.000 1.0000E-3     0.000     0.000     0.000     0.000
*EOS_LINEAR_POLYNOMIAL_TITLE
EOS
$#   eosid        c0        c1        c2        c3        c4        c5        c6
         1     0.000 2.2500E+9     0.000     0.000     0.000     0.000     0.000
$#      e0        v0
     0.000     0.000
```

Finally, contact between the simulated bird and the steel plate (used as a target) was defined (`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID`) and the impact velocity was defined as the velocity measured in the experimental tests (`*INITIAL_VELOCITY_GENERATION`).

In order to compare the numerical simulations and the experimental measurements, elements located analogously as the strain gauges (350 mm form the impact point between SB and steel plate) in the experimental were tracked (using `*DATABASE_ELOUT` and `*DATABASE_HISTORY_SOLID_SET`) to be compared with the experimental measurements.

5 Results

5.1 Modal analysis of the Hopkinson tube

The results from the modal analysis of the Hopkinson tube from experimental tests and numerical simulations are compared in table 2. The table 2 shows the 6 firsts longitudinal modals frequencies of the tube; all the frequencies are faithfully predicted by the numerical simulations, the errors associated by the numerical predictions are around 10 %.

Experimental [Hz]	Numerical [Hz]	Error [%]
164	180,18	9,8
470	517	11
838	931	11,1
1220	1365	11,2
1620	1804	11,1
2020	2244	11,1

Table 2: Experimental and numerical longitudinal modal frequencies of the Hopkinson tube

Taking into account the numerical results of the modal analysis of the Hopkinson tube it is possible to state that it is validated and it can be used for the impact simulations.

5.2 Impact simulations of SB against Hopkinson tube

The strain gauges measurements in the experimental tests are compared in terms of stress, assuming elastic behaviour in the Hopkinson tube, with the numerical results. Figures 3 and 4 show the stress time history results of 2 different impacts velocities (100 and 150 m/s). The experimental and numerical curves show a good agreement between them: a sudden compression at the beginning of impact followed by a gentle compression diminution, and finally another increase compression pulse arrival. The first decrease corresponds with the compression waves generated by the impact and transmitted through the steel plate, aluminium adaptor and the tube. The whole projectile impacts in a interval of time that is approximate equal to t=L/v where L is the length of the projectile and v is the impact velocity. The maximum compression is obtained approximately when the end of the cylindrical part of the projectile hits the plate. Moreover it can be seen how as the impact velocity is greater the maximum compression is obtained earlier, confirming this effect. Then the compression diminishes until the reflected wave at the opposite end of the tube reaches again the strain gauges, the superposition of both elastic waves promotes an increase in the compression. Not only the trend, but also the minimums values are well predicted by the numerical simulations.

The first compression predicted by the numerical simulations are gentler than in the experimental test, but the maximum compression it is similar to the experimental tests at both impact velocities. The reflected wave that promotes the superposition reaches before in the numerical simulations the strain gauge location. It is possible that the reflection phenomena in the simulations are magnified, possibly due to the tied joints between the parts are idealized.

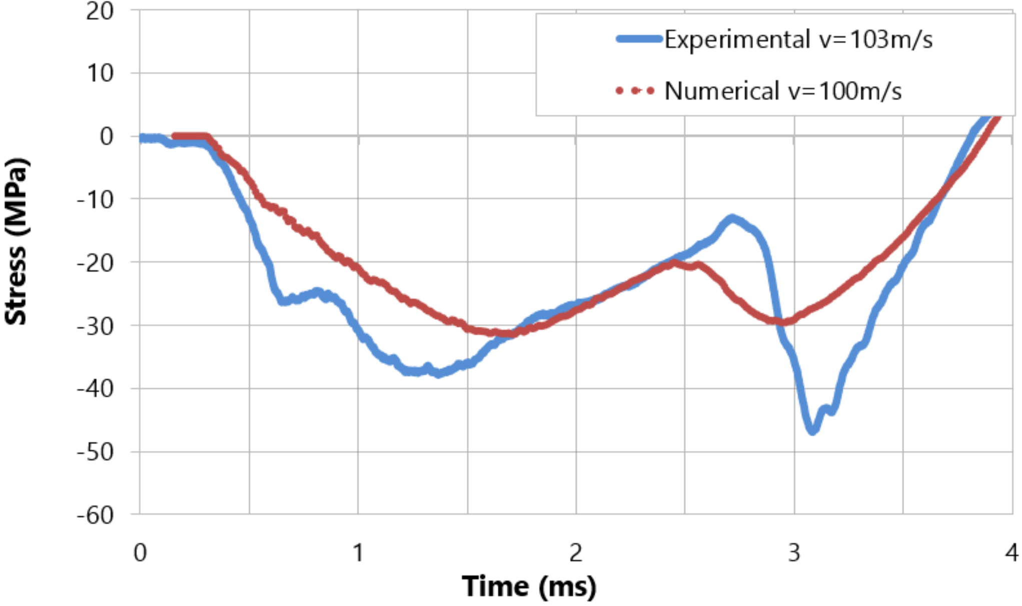


Fig.3: Simulated bird impact against Hopkison tube at 100 m/s

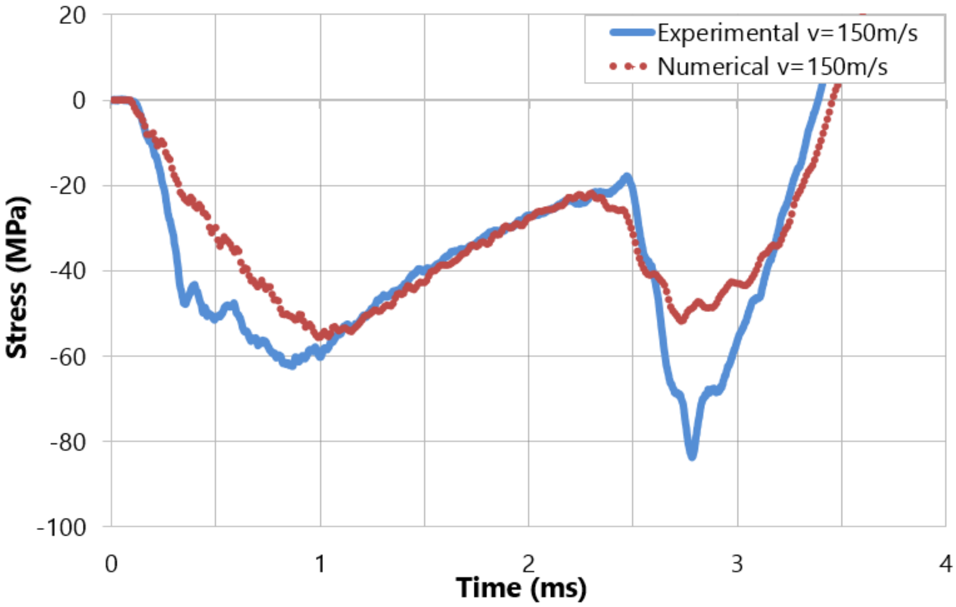


Fig.4: Simulated bird impact against Hopkison tube at 150 m/s

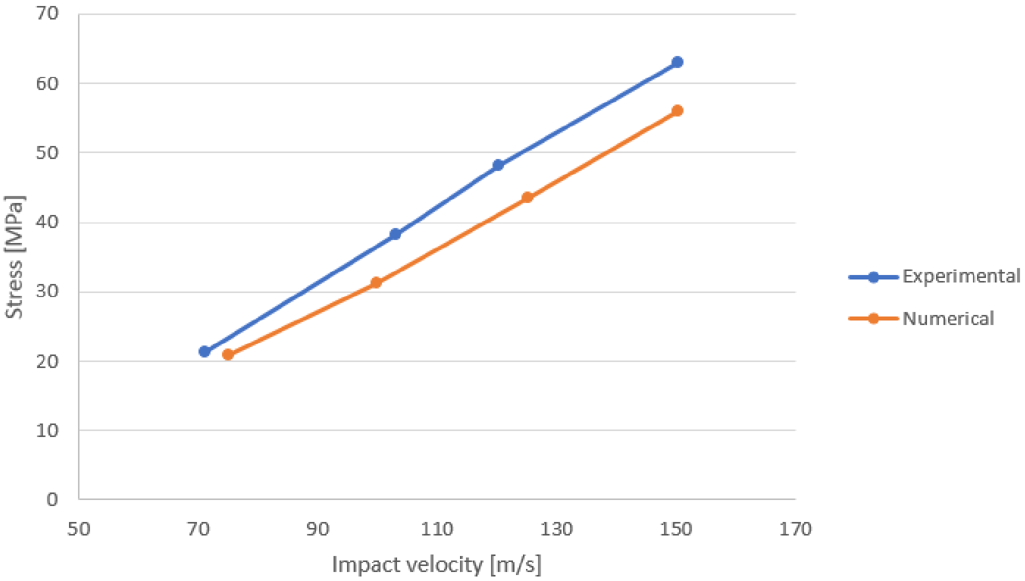


Fig.5: Experimental and numerical maximum compression stress against impact velocity

The maximum compression stress values, experimental and numerically obtained, for all impact velocities are shown in Fig. 5. It can be observed that the maximum stress varies from less than 20 MPa to more than 60 MPa, for the cases with a higher kinetic energy. Fig. 5 also shows how the maximum stress increase as the impact velocity raises. As it can be seen, the numerical model not only predicts adequately the maximum stress values, but captures the aforementioned trend.

In order to study the simulated bird impact phenomenon, not only the stress induced by the SB projectile should be predicted by the numerical simulations, but also the general behavior of the material should be represented. Birds impactors flow over the structure, spreading the impact load; thus it is necessary that the numerical model predict faithfully how the SB deforms during the impact. Fig. 6 shows different frames of the high-speed video recorded during the impact of an SB and the corresponding numerical frames. It can be observed that the numerical model is capable of reproducing, qualitatively, the spreading of the SB along the steel plate as the impact develops.

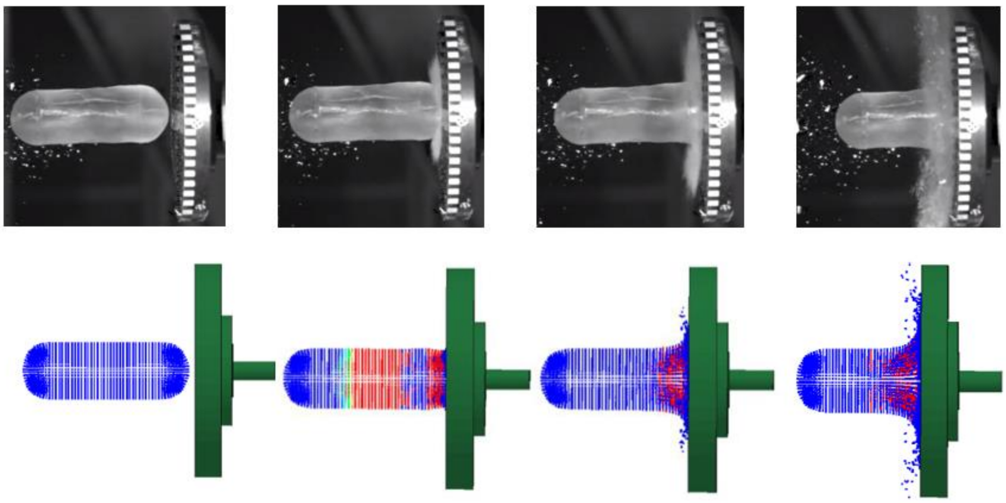
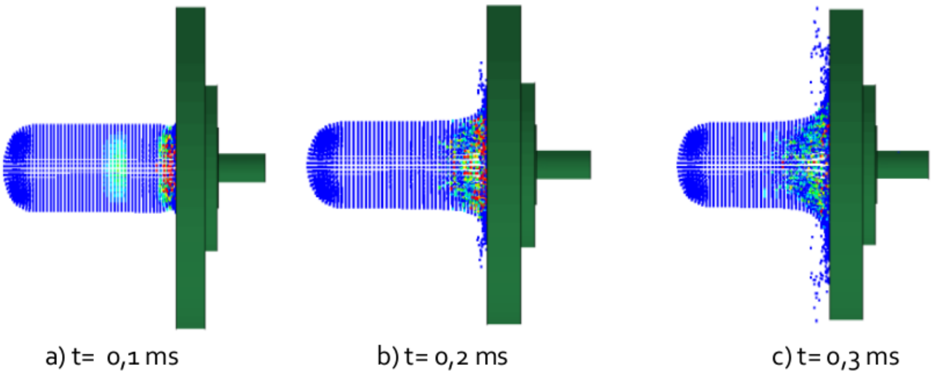


Fig.6: Comparison between numerical and experimental images

The numerical model can be used also to analyze the different phases experienced in a bird substitute impact (Fig. 7). At the first instant of the impact, it is obtained the maximum pressure that it can be obtained with the Hugoniot pressure ($P_H=\rho_0 u_s u_p$). Then the projectile starts to deform in an axial direction in what is called the flow phase. In this phase, the pressure decays and it can be obtained with the stagnation pressure ($p_s=\rho V^2/2$). The phase has the same duration as the projectile is impacting against the rigid plate. This phase is characterized by a homogenous pressure contour inside the projectile.



a) t= 0,1 ms b) t= 0,2 ms c) t= 0,3 ms

Fig.7: Different phases observed in the numerical subsititute bird impact

Finally it is included the numerical force registered in the contact surface of the plate. The force is obtained using the intfor file where the registered force can be obtained in the whole surface. It can be seen a steep increase in the force created by the initial impact, and the maximum pressure and therefore force it is obtained confirming what it has been said previously. Then the flow phase starts characterized by a constant pressure field. If the theoretical average force it is obtained ($F=mV^2/L$) [6], for this case it is a value of 49.9kN. It can be seen that the results matches perfectly with the theoretical value. Moreover, it can be confirmed that the contact time can be obtained approximately by t=L/v (in this case t=1.06 ms).

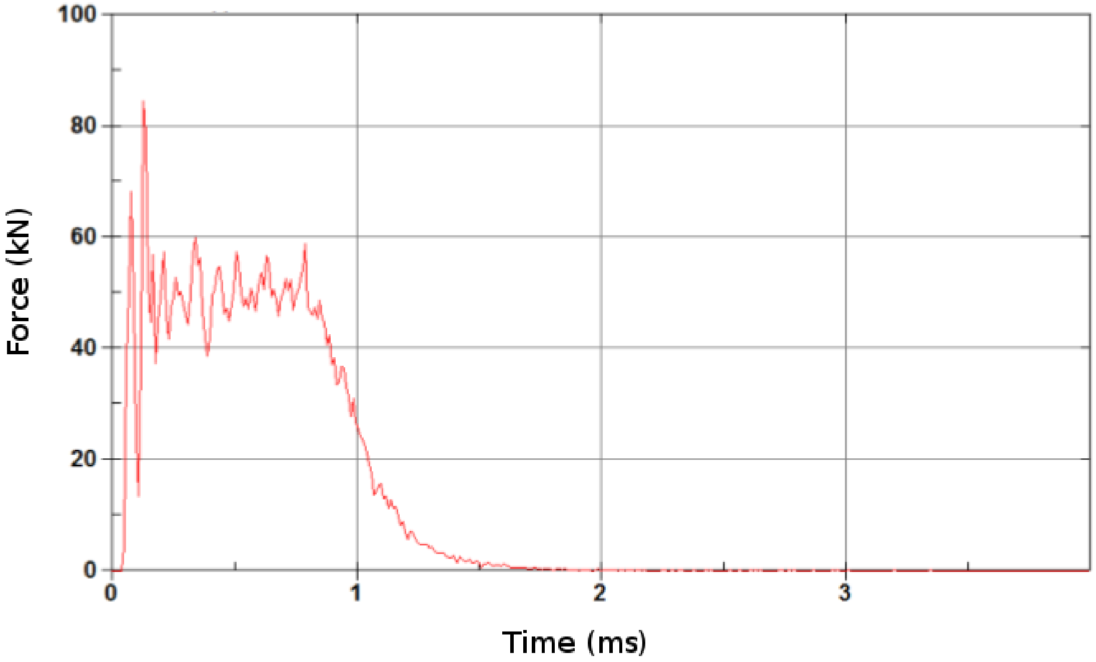


Fig.8: Force obtained in the contact surface of the plate at 150 m/s

According to the aforementioned results, it can be concluded that the numerical model is validated. In addition, the numerical results show the capability of the SPH approach to reproduce the impact phenomena. The validation performed enable the use of the model proposed to analyse more complex problems.

6 Numerical study of the influence of the impact angle

Once the numerical model was validated it can be used for analyze different parameters: as for example the influence of the impact angle. Moreover, small differences at the SB impact angle are detected during the experimental tests so it will be used for study the robustness of the experimental facility. Therefore the numerical simulations are used to study the influence of this parameter in the strain gauges measurements. To this end, a set of numerical simulations is designed varying the SB impact angle as can be observed in figure 7 simulations varying form 15º to 45º has been performed at 100 m/s.

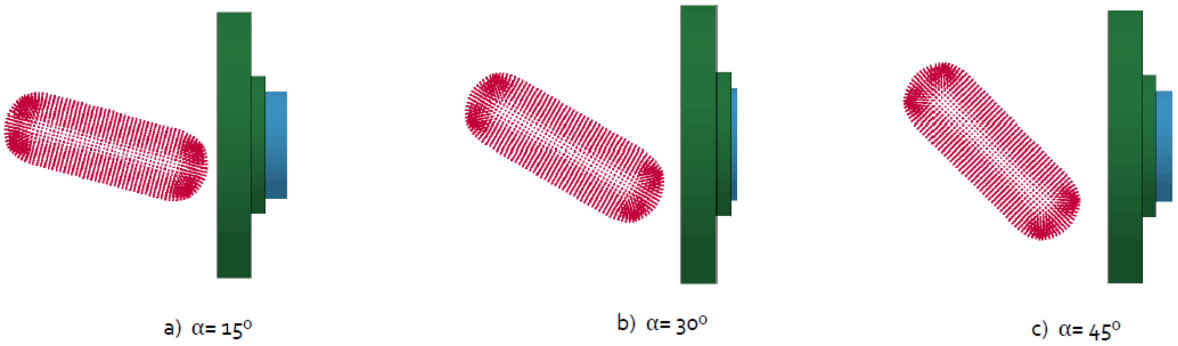


Fig.9: Numerical simulations varying the SB impact angle

Figure 8 shows the variation of the maximum compression stress in the Hopkinson tube as a function of the impact angle of the simulated bird. It can be seen an increase trend in the stress as the angle rises. This trend can be related with the amount of gelatin that impact at the beginning of the impact, as the angle increases the amount of SB or the projected area increases as the stress does. Nevertheless the increase of the stress is less than 10 % for an angle of 45º which can be explained because the projected are is not as crucial as the momentum of the projectile. In the experimental it has not been detected any deviation higher than 15º, so the results allows to assure a high robustness of the experimental setup against changes of the angle of the impactor.

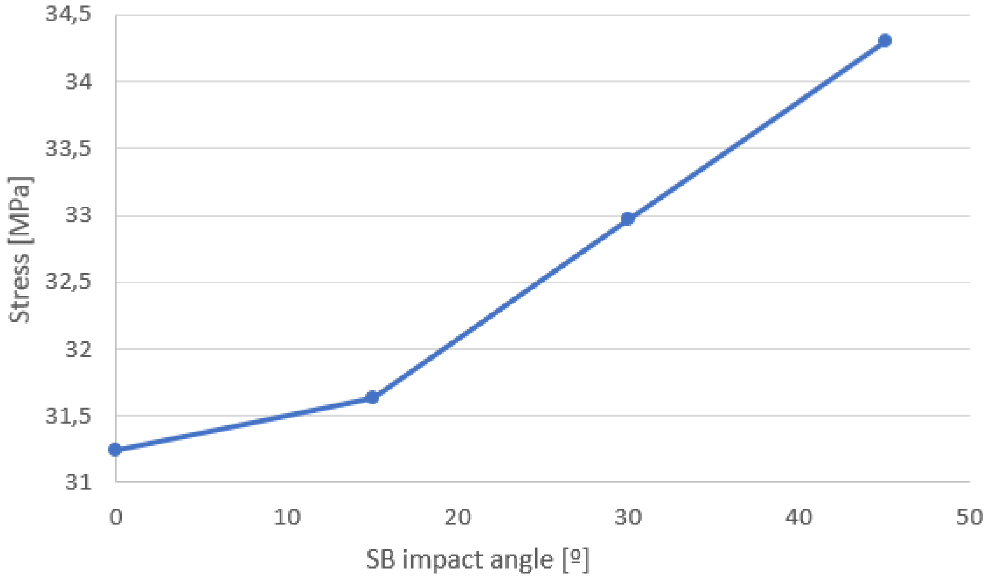


Fig.10: Maximum compression stress predicted in the hopkinson tube against SB impact angle

7 Summary

The combined experimental-numerical methodology has been proved to be useful for material model characterization under impact conditions. Moreover the numerical simulations have been proved to be adequate for analyzing the influence of impact parameters and studying the robustness of the experimental facilities under experimental deviations.

As a summary, it has been included the steps followed in the methodology:
- Experimental modal analysis of the Hopkinson tube
- Numerical modal analysis of the experimental setup to assure the validity of the numerical model
- Experimental impact test of SB against Hopkinson tube
- Numerical impact simulations using a impactor model from the literature
- Analyze of the influence of impact angle and study of the robustness of the facilities by means of numerical simulations

8 Literature

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