NUMERICAL ANALISYS OF IMPACT PHENOMENON BETWEEN A FRANGIBLE PROJECTILE AND THIN METALLIC PLATES USED IN AIRCRAFT STRUCTURES

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Abstract: *This paper shows simulation results whose purpose is to study the impact occurrence between an anti-hijack pistol projectile and a thin metallic plate. The plate is made of aluminium alloy used in aeronautical structures. Laboratory tests permitted to analyse the mechanical behavior of the projectile's material. The shootings experiments have confirmed the expected impact behavior at given velocity. The model and simulation works were developped under AUTODYN/ANSYS. The simulation results are well proven by the experimental outcomes.*

Keywords: *terminal ballistics, FEM, frangible bullet, antihijack projectile, experiment*

1. INTRODUCTION

The projectile – target impact phenomenon is complex and is summed up in the study of involved materials submitted at a specific deformation ratio. The impact conditions may vary within a wide range and are a function of impact velocity, incident angle, projectile and target type [1]. The continuous developping trend in ammunition design and the needs for specialized ammunition bring in front new projectiles, made of new materials, with complex impact behavior. For these reasons we are dealing with a variety of terminal ballistics cases. Last period we faced a move from classical ammo to frangible ammunition, especially for training purposes, in order to reduce the risk. So that not only the ricochets are avoided but the toxicity of projectiles made of copper powder is less significant than the lead core bullets show [9].

This is the context of issuing on the market the anti-hijack ammo. The bullets are made on the basis of copper powder and polymeric binder. The mixture allows a dual behavior, with respect to target's nature: the impact with thin metallic plates produces a bullet smash, in a very short time and without target damage, while a penetration in soft targets (e.g. ballistic gelatin) occurs. In this paper we are focused on impact analysis between this kind of projectile and aircraft structure (aluminium thin deformable plates). Some experimental and laboratory data were used for buiding the simulation cases and for validating the results.

2. LABORATOY TESTS

The material used for anti-hijack bullets is a composite of copper powder in a polymeric matrix and has the property of being frangible due to a mixture of phases with weak adhesion properties [10]. For this reason, besides compression tests (for Young's modulus and yield stress determination) additional tensile tests were made (based on Brazilian disk test).

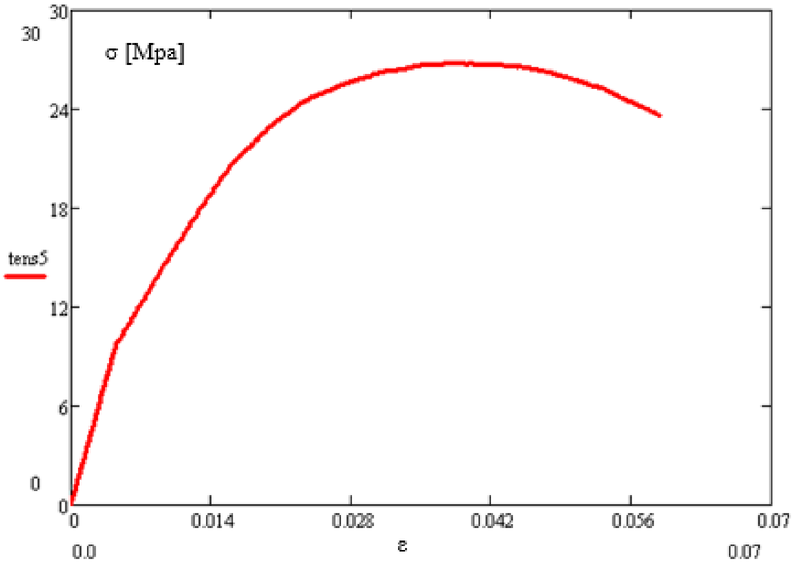

FIG. 1 Mechanical behavior of composite copper-polymer material

The experimental results show an elasto-plastic behavior. There are instantaneous deformations remaining after loading removal. Under the elasticity limit, only elastic deformations occur. A special case is the elasto-plastic model with a perfect plastic behavior. If the elasticity limit is reached, the material tension remains at elasticity limit level. This model can be well represented by a serial connection of a spring and a friction sleeve (Saint-Venant model).

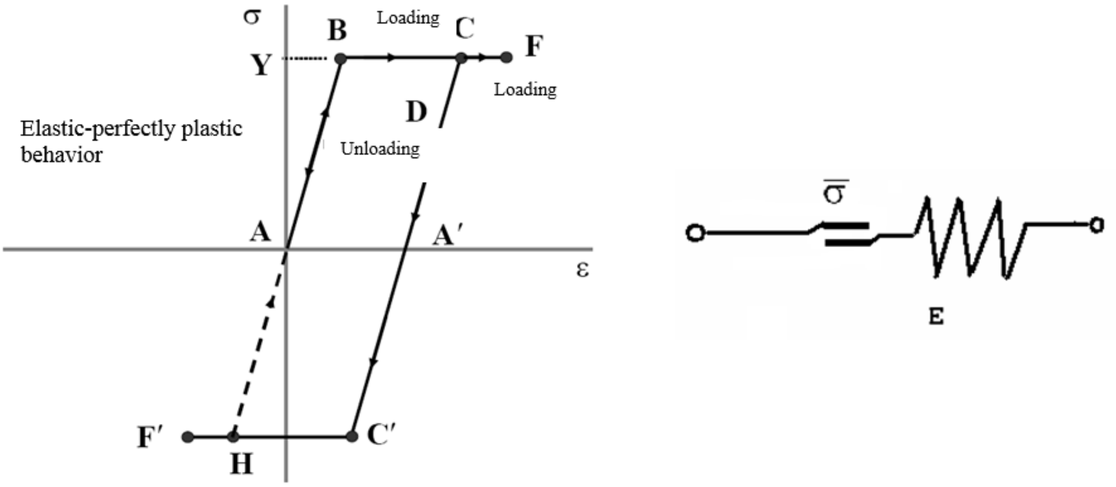

FIG. 2 Loading scheme of an elastic-perfectly plastic material and Saint-Venant model

Based on experimental results, the mechanical properties according to Saint-Venant model were defined, as in Table 1.

These data and the Saint-Venant model were used in the part dedicated to numerical calculus and impact simulations between anti-hijack projectiles and the metallic plates [11].

Table 1 Mechanical properties of tested material

Properties	Projectile material
Young modulus [GPa]	2,11
Yield stress [MPa]	26,58
Poisson coefficient	0,3
Tensile strenght [MPa]	6,20
Density [g/cm^3]	4,8

3. SHOOTINGS EXPERIMENTS

The composite projectiles were tested in real shootings against aluminium plates of 1,5 mm thickness. At nominal velocity, the bullets have proven their *nonpenetrating* behavior, as in Figure 3.

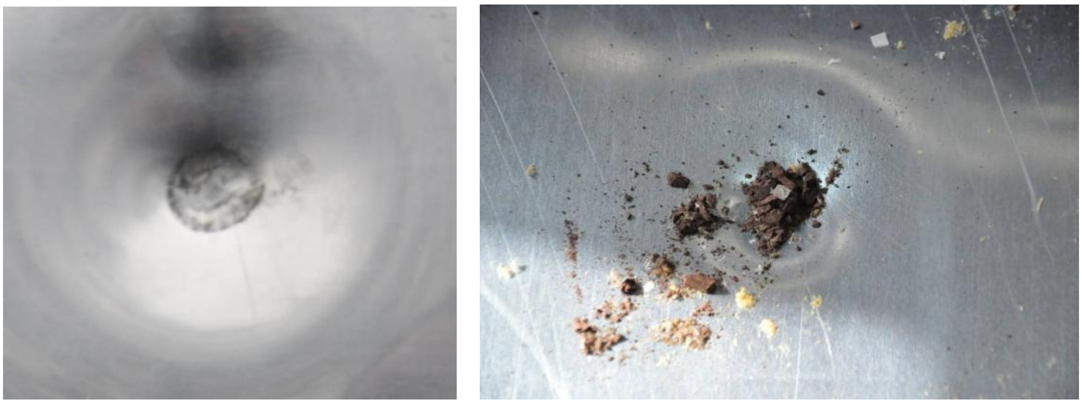

FIG. 3 Aluminium plate's shape after impact. The projectile breakage model

For comparation purposes and validation of simulation results, a cross-sectional view of an impacted aluminium plate (1,5 mm thickness) were measured. The center shows a displacement of 8,11 mm and the plate thickness at the greatest deformation plate is 1,25 mm. Figure 4 shows the profile of impacted plate.

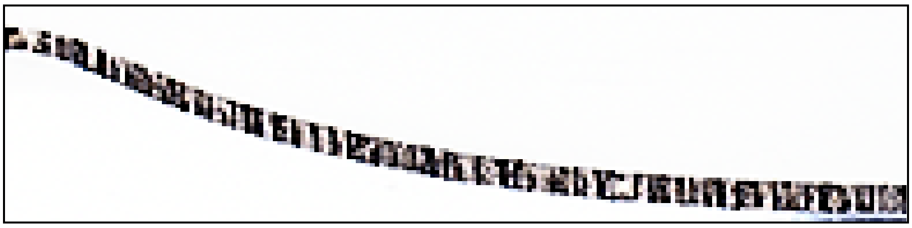

FIG. 4 Real profile of an impacted aluminium plate of 1,5 mm thickness

A profile function was found by measuring the displacements at several distances from the center. Using mathematical regression algorithms, the profile function that includes the measured points was found as follow:

$$f(x) = 8{,}11 \cdot e^{-0{,}028 \cdot x^{1{,}5}} \quad (1)$$

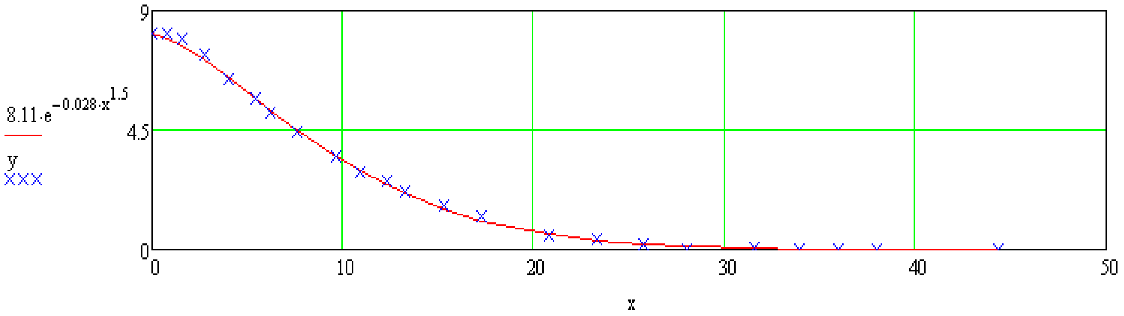

FIG. 5 The impacted profile's approximation function and measured points on the profile. The maximum value of the function is 8,11 mm – the impact center displacemet

4. NUMERICAL MODEL

The model was built under Autodyn, considering a 3D nonlinear formulation. All involved materials have nonlinear behavior.

The code allows the use of the three solvers: Lagrange, Euler and SPH. Due to specific behavior of the materials and the characteristics of impact phenomenon, we decided to use the Lagrange solver for the impacted structure. For the projectile deformation, we have used both Lagrange and SPH solvers. The numerical studies considered the similar case as in real shootings, i.e. anti-hijack projectile impact with aluminium plates of 1,5 mm thickness. Table 2 comprises the model configuration.

Tabelul 2 Model configuration

Configuration		Type	Material	Solver	Innitial conditions
1	Projectile	Anti-hijack	Copper powder in polymeric matrix	Lagrange	V0 = 330 m/s
	Target	Al plate 1,5 mm	Al 2024 T3	Lagrange	Shell; V0 = 0 m/s
2	Projectile	Anti-hijack	Copper powder in polymeric matrix	SPH	V0 = 330 m/s
	Target	Al plate 1,5 mm	Al 2024 T3	Lagrange	Shell; V0 = 0 m/s

For the projectile we have used an elastic – perfectly plastic material model. The characteristics are given in Table 3. For the aircraft structure material we have used a material model which allows shell elements discretization (uniform stress and strain in plate's depth) for reducing the solving time. The chosen model was completed with the characteristics of aluminium 2024, T3, according to French standard 9048 AIR - Conditions de controle des produits lamines en alliages d'aluminium utilises dans les constructions aerospatiales).

Tabel 3 Johnson-Cook constitutive constants for aluminium 2024-T3

Material	Density (kg/m^3)	Specific heat (J/kgK)	Melting temperature (K)	A (MPa)	B (MPa)	N	C	M
Aluminium 2024-T3	2770	875	775	265	426	0,34	0,015	1,00

The decission of using SPH solver for the projectile arised as a necessity in this kind of impact. The deformation and, eventually, penetration of the plate are dependent on the amount of transferred momentum and energy, as well as being dependent on the way in this transfer occurs.

The SPH solver does not require and erosion algorithm (as the Lagrange does). The fragmentation is accomplished by particles separation and without mass losses. The projectile discretization is shown in Figure 6. The chosen values have been obtained after a number of tests for checking the solving time and results quality.

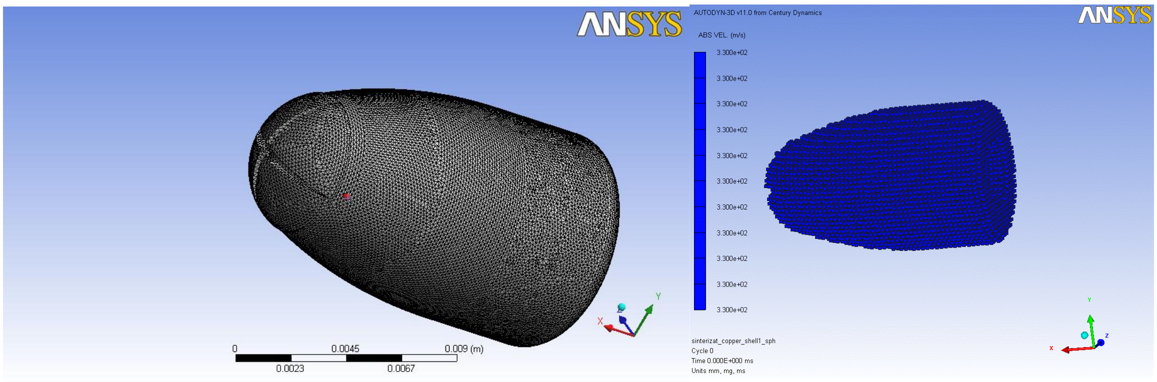

Fig. 6 Discretization of projectile: 235000 nodes for Lagrange solver; 78000 elements for SPH solver

For the plate model we have used shell elements of 1,5 mm thickness.

After solving the problem, we can obtain images and graphics related to deformed state, velocities and deformations fields, kinetic energy distribution etc.

5. SIMULATION RESULTS ANALYSIS

For a better understanding of the results we will present instantaneous pictures both for the projectile and for the plate. Regarding the plate, we are interested in deformation evolution, looking for penetration/nonpenetration events. Also, the way in which the projectile is fragmented, the shape and size of the fragments are of interest.

The simulated projectile behavior coresponds to the real one. The Lagrange approach with erosion option catches its breakable character and the fragmentation. However, the fragments are affected by erosion algorithm, being totally consumed. In real tests we obtained several fragments of different sizes.

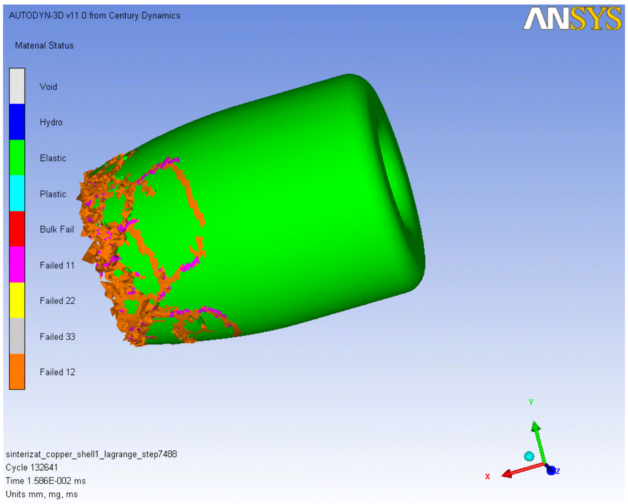

FIG. 7 Projectile's nose fragmentation. Side view

The impact phenomenon lasts 0,1 ms. Thus, at 0,15 ms the bullet is eliminated from the simulation. A critical analysis of the energy transfer between the bullet and the plate is needful.

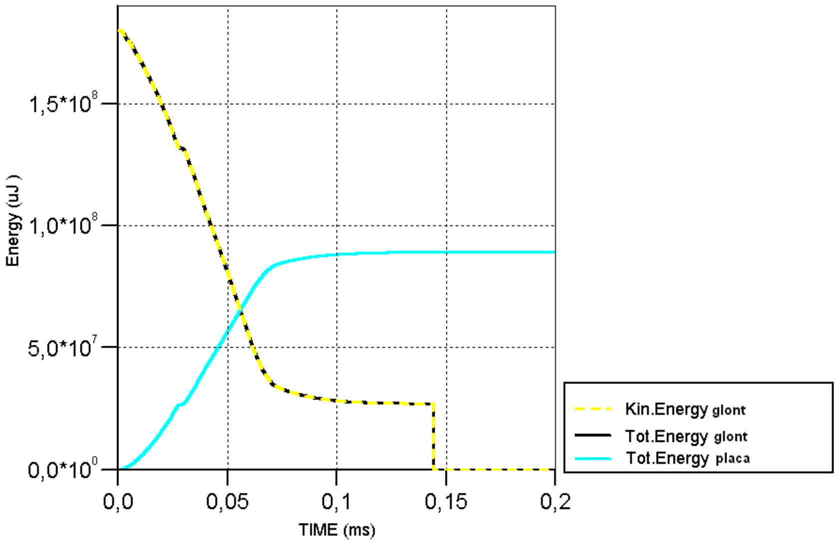

FIG. 8 Energy transfer at impact in Lagrange approach

First, we observe that the total energy of the bullet is similar with its kinetic energy evolution, so that the bullet material doesn't faces a deformation work or an elastic energy. This is because of the rapid erosion of the nodes. This is a condition imposed by the breakable nature of the material. Also, we meet an elimination from the model of the associated energy, excepting the kinetic energy of the nodes. So that, even if the model is functional, it doesn't respect the principle of energy conservation. In Figure 9 the *free* nodes evolution at a given moment can be observed as having inertia. As they are released from the network, some of them go beyond the aluminium plate and quickly disperses. However, this unrealistic event comes with a momentum transfer to the plate. As we already noted, the energy transfer is finished at 0,1 ms, even the simulation shows that the projectile is fully consumed by erosion at 0,64 ms. As a conclusion, the Lagrange approach leads to an incomplete energy transfer from the free nodes to the plate and even unrealistic, as the plate does not break, nor crack.

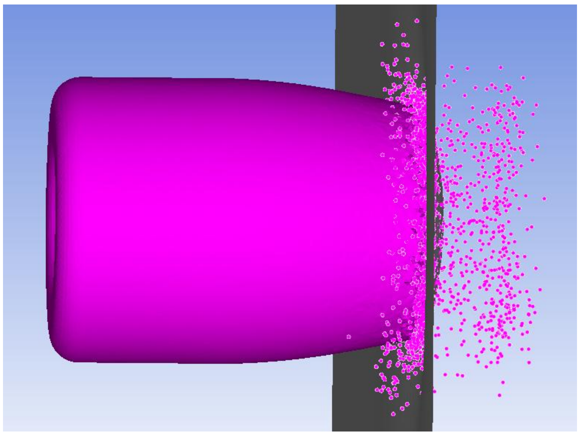

FIG. 9 Free nodes behavior within impact phenomenon. Lagrange approach

The results shows a maximum displacement of 9,47 mm in the impact center, at 0,176 ms.

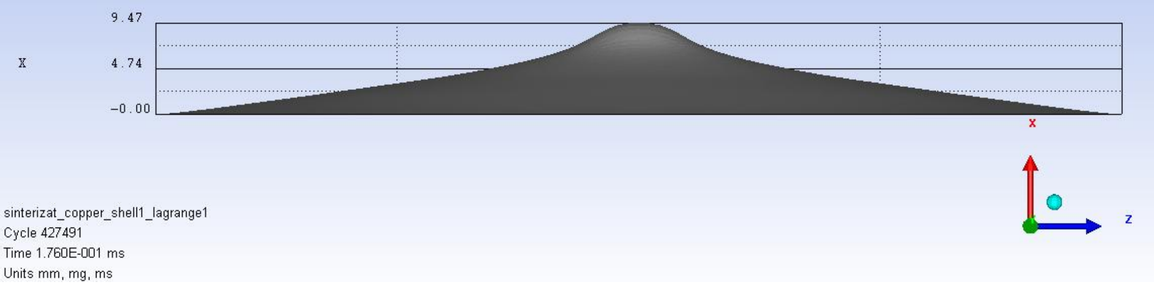

FIG. 10 Plate profile after maximum displacemet of impact center occurs

For getting the final profile of the plate, the artificial amortization of the movement is used (an Autodyn built-in option). So that the nodes velocities are reduced gradually to zero. Solving the problem with the option of artificial amortization allows us to estimate the final form of the plate and the impact point displacement.

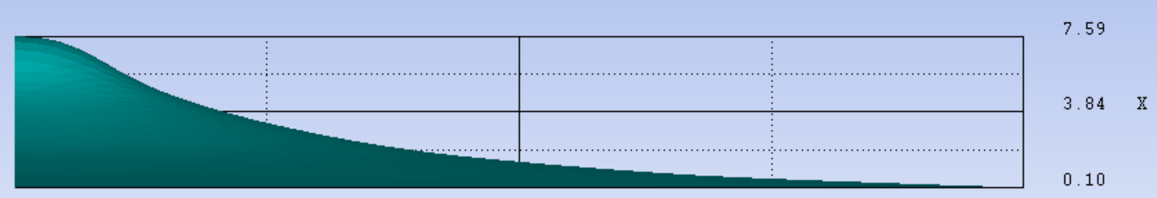

FIG. 11 Final plate profile. Lagrange approach

So, the total displacement in impact center is 7,59 mm, with a plastic deformation of 0,32 and a remained thickness of 1,17 mm. An interpretation based on strenght limit of the material, allows to conclude that the impact will not provoque cracks.

When simulating of the same phenomenon with SPH solver, we were especially focused on bullet behavior at impact. The images succession the cracks in projectile can be seen, simultaneously with fragments occurrence. Some fragments are projected in radial directions, while the remaining go ahead, on the impact direction. The same excessive fragmentation happened. In this case, this is because the solver cannot handle big size fragments. Because the bullet material doesn’t face any erosion, we can observe an increasing of the impact surface, up to 1,45 times the bullet caliber. This has correspondence in reality, while in Lagrange approach the impact surface remained restricted to the bullet caliber.

From the projectile velocity evolution (the projectile not being anymore a true bullet, but a cloud of dust, as it was transformed in fragments), we can see that the interaction time with the plate lasts up to 0,22 ms. From this point on, no change in velocity happened. The final velocity value is negative, due to a forward movement of the plate after maximum deformation. The plate starts an oscillatory movement. The same fact can be observed in energy evolution diagram of the plate and projectile. All these let us note that the energy conservation principle is respected this time.

For the deformation shape evolution we have used again a virtual displacement transducer placed in impact center. The results show that a maximum displacement in impact center occurs, up to 10,23 mm, at 0,17 ms.

Using the same amortization algorithm as in previous case, the final displacement of the impact point is at 8,5 mm, with a plastic deformation of 0,18 and a thickness of 1,28 mm. again, the strength limit is not reached and no cracks occur.

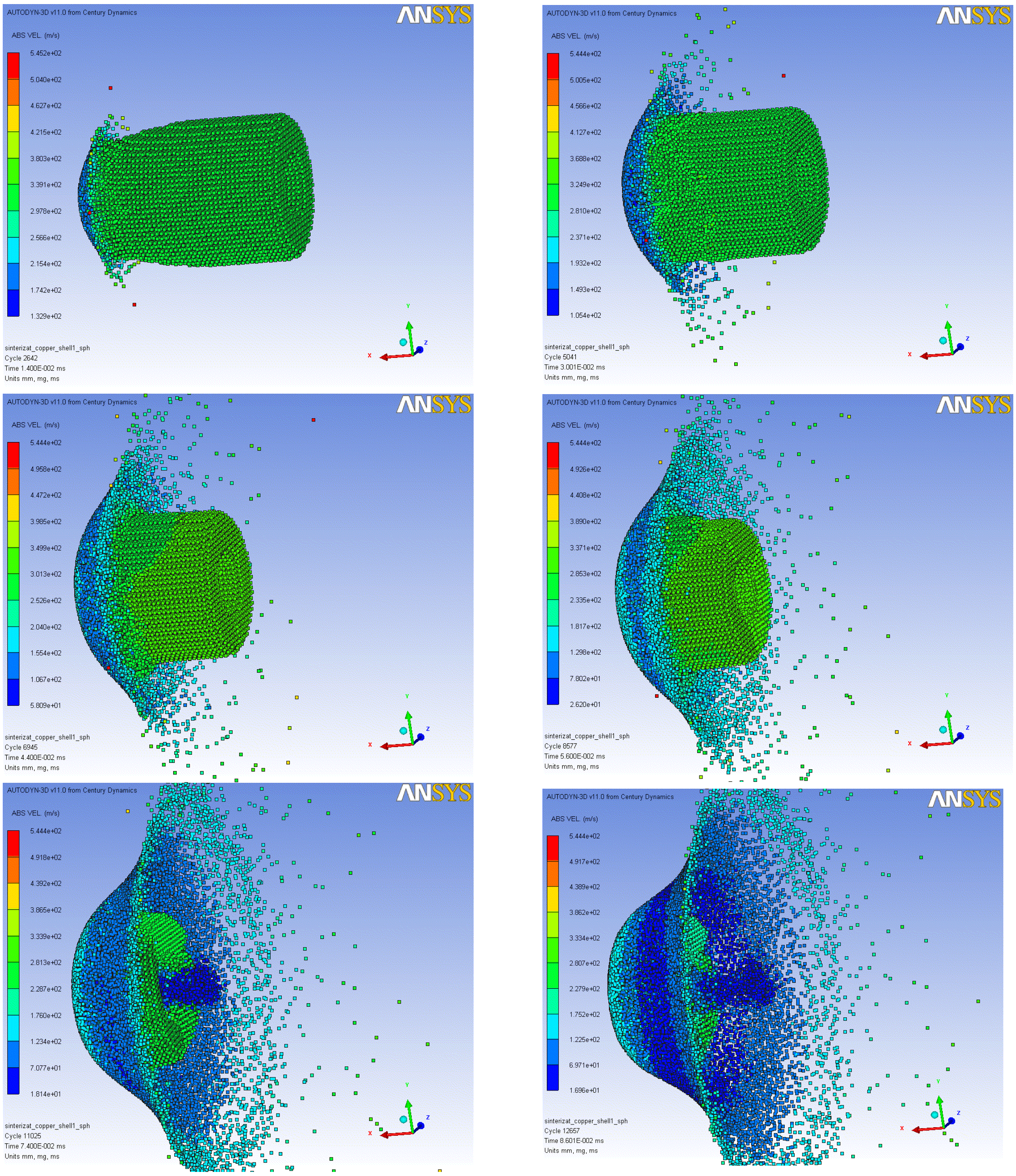

FIG. 12 Projectile fragmentation at impact. Gradual instants

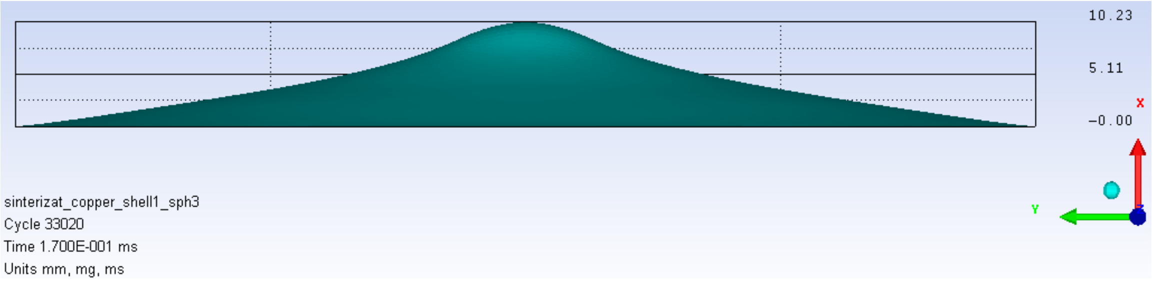

FIG. 13 Plate's profile at maximum displacement of the impact center

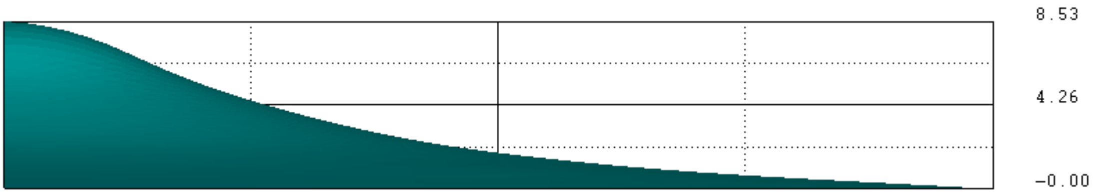

FIG. 14 Plate's final profile. SPH approach

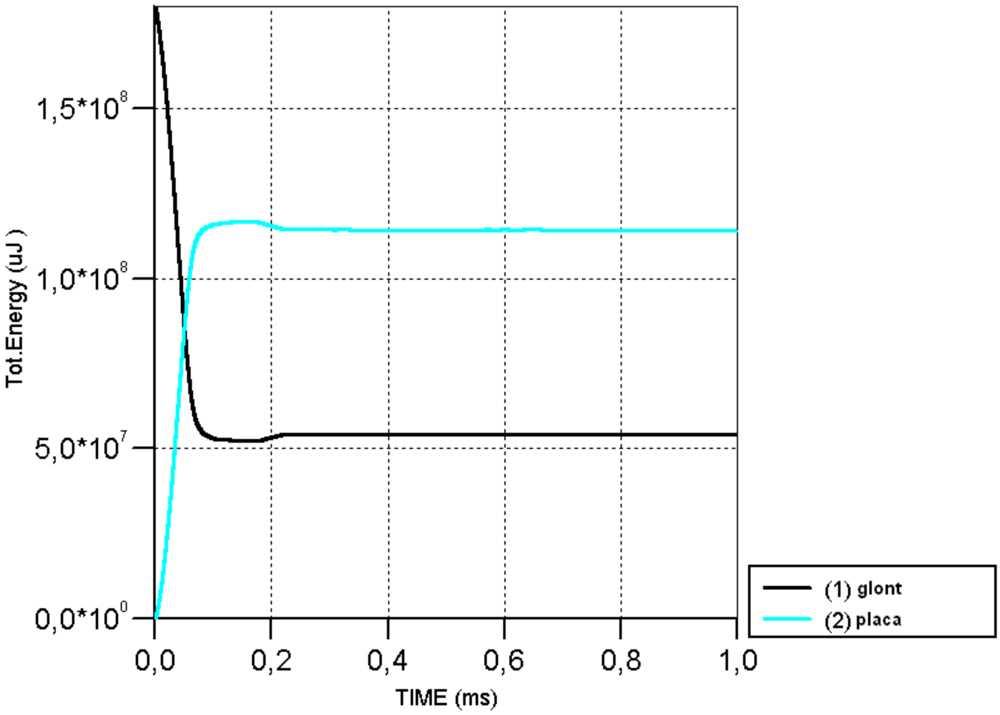

FIG. 15 Total energy transfer; bullet (black) and plate (green)

A greater displacement in SPH approach then the Lagrange case can be explained by a greater amount of energy transferred to the plate: 115 J in SPH approach versus 89 J in Lagrange approach. However, in the impact center the deformation is smaller in the SPH case then in Lagrange one. This is only an apparent contradiction. The fact is explained by the greater impact surface using SPH, so an even distribution of energy whose effect is less bending of the plate. So that, in SPH case we have greater deformation but less effort on the impact center.

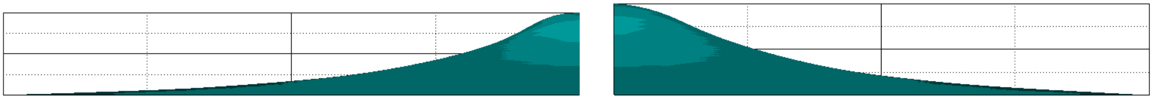

FIG. 16 Final plate's profile: Lagrange (left) vs SPH (right)

The measured data of maximum displacement and plate thickness are within the range delimited by the simulation results in the two cases. The significant differences between the two approaches are in plate's profile shapes. Regarding this, the SPH case has a better match with experimental results.

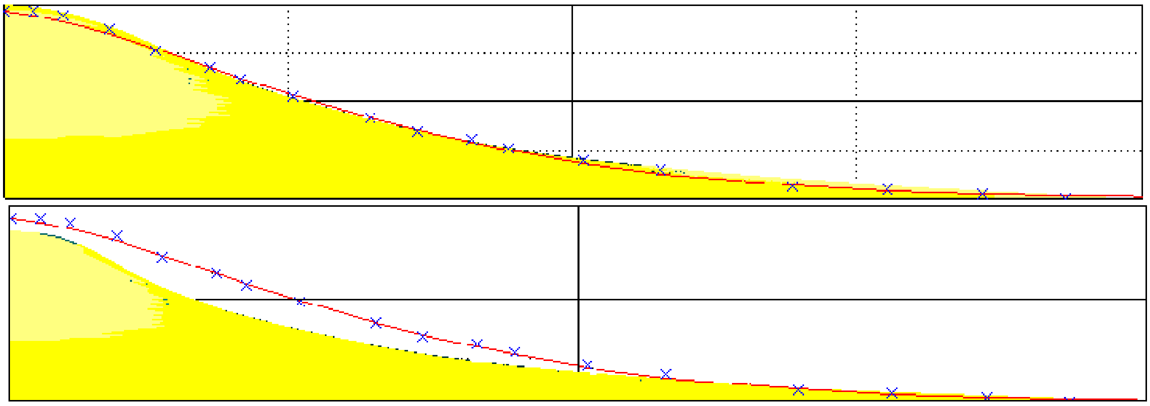

FIG. 16 Final plate's profile. Match level of real test with simulation. SPH (up) vs Lagrange (down)

5. CONCLUSIONS

The two numerical methods used in our study offers the advantage of a good model for impact analysis between a frangible projectile and an aluminium plate. The simulation results are close to experimental results. However, for a very good analysis, additional data are required: material real characteristics, constitutive models and appropriate solver for each material. Laboratory tests have proven the breakable (frangible) behavior of copper powder mixed with polymeric binder. The data were processed for finding the material model as being elastic-perfectly plastic, with tensile limit lower than yield limit. The SPH model was find better than Lagrange model in the case of projectile, because of inaccuracy of the last one in accurate reproduction of the impact steps and material's behavior.

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