Improving the performance of shaped charges and passive ballistic protections

CAE models evaluated using two commercial solvers

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In this technical article, the authors discuss the development of CAE models for simulating the behavior of shaped charges, devices used in various industrial sectors, against two types of target – a monolithic steel target and a multi-layer steel-ceramic target – in order to better understand the physics of penetration. These models can be used to improve the designs for structurally hardening passive ballistic protections or for maximizing the effects of the shaped charges. The models used are applied using two consolidated commercial solvers, LS-DYNA® and ANSYS® Autodyn®, and the article provides information on the strategy and the numerical models adopted in the analyses.

The shaped charge is a particularly effective device used in various industrial sectors. In particular, it is used to make holes or cuts in hard-to-work materials, or when the technical crews cannot intervene directly – either for practical reasons, or in dangerous work environments, such as demolitions and mining excavations. The core of this type of device is a metal liner that is rapidly deformed and projected against the target following detonation of the surrounding explosive. The ability to simulate the whole phenomenon using dedicated solvers enables engineers to better understand the physics of penetration and, therefore, to increase the precision of the design. The numerical study presented in this article compares the results obtained using two consolidated commercial solvers, LS-DYNA® and ANSYS® Autodyn®, and details the peculiarities of the cases.

The impact of a high-speed shaped charge's jet onto a target and its subsequent penetration are characterized by fast dynamic phenomena that are quite challenging to simulate. Computational studies related to shaped charges are typically addressed through the so-called hydrocodes, or numerical solvers able to predict the behavior of materials in such extreme conditions.

Two of the most widely used commercial codes in this context, namely Autodyn [1] and LS-DYNA [2], were used to reproduce some experimental tests based on strictly confidential data. As a result, this article only qualitatively describes the computational outputs. However, information is provided on the strategy and models adopted, which can be useful for the structural hardening of the passive ballistic protections or, alternatively, to maximize the effects of the shaped charge.

Overview of the experimental tests and numerical analyses

Before performing the numerical analyses described, data relating to a series of experimental tests using standard shaped charges that were carried out by a RINA Group company, were collected and evaluated. This was done to predict the effects of the impact of the jet produced by such charges on passive ballistic protections. In particular, we studied two specific target configurations: monolithic blocks made of ductile materials, and sandwich structures (assemblies of several layers of both ductile and brittle materials). One of the main findings of the campaign was an important decrease in the depth of the hole

produced in the multi-layer configuration with brittle layers, compared to the monolithic target composed of ductile material only.

The detailed computational analyses were done on a monolithic steel target and a multi-layer steel-ceramic target. These configurations were studied numerically using a shaped charge placed directly in contact with the target structures. Due to the confidential nature of the experimental tests, we first set up an equivalent charge, detailed in the following section, and then used it to simulate the newly introduced configurations by adopting the Arbitrary Lagrangian [3][4] Eulerian [5][6][7][8] (ALE) approach [9][10], and a mixed ALE-SPH (Smoothed Particle Hydrodynamics) [11][12][13] approach respectively.

Autodyn was used for configuring the equivalent charge, whilst LS-DYNA supported the numerical verification on the monolithic target. With regard to the multi-layer configuration, which is of major interest to the present study, Autodyn was the only numerical means used.

The model of the equivalent charge

Since all data related to the experimental campaign are confidential, it is not possible to provide the geometry and the physical parameters of the materials making up the tested shaped charge. Therefore, to build a meaningful numerical model, it was necessary to create of an equivalent charge, defined like the shaped charge and producing the same penetration for a reference target as recorded during the experimental campaign.

We selected the penetration of the monolithic target of standard steel as a reference and obtained the equivalent charge in two stages, hereinafter referred to as identification and calibration, which were performed in sequence. In the identification stage, the equivalent charge was set up following the guidelines for the design of conical shaped charges. These simulations were performed using the ALE method and modelled the shaped charge and the target respectively using Eulerian and Lagrangian sub-grids. In the calibration stage, the depth of the hole obtained in the identification phase was aligned with the one actually produced, by correctly tuning one of the most influential parameters of the charge.

Identification and calibration of the equivalent charge

The device consists of an external cylindrical aluminum casing containing a certain amount of explosive material (TNT), and whose front side presents a conical cavity that houses a copper liner of a certain charge diameter (CD). The materials selected for the identification of the equivalent charge are listed in Table 1 and are included in the Autodyn library.

Regarding the equations of state (EOS)[14] for the materials, the Shock model was used for the liner, target and casing, whilst the Jones-Wilkins-Lee (JWL) was adopted for the TNT. Regarding the strength models, the Steinberg Guinan model was used for the target and casing, the Multilinear Hardening model for the liner, and High Explosive Burn for the explosive.

Model part	Autodyn material
Casing	AL 2024-T4
Explosive	TNT
Liner	COPPER
Target	STEEL 1006

Table 1 - Materials used for the identification of the equivalent charge

The geometrical axial symmetry of the charge made it possible to implement a 2D case representing only one sector of the device, as shown in Figure 1, by assigning the axial symmetry boundary condition to the axis along which the jet is supposed to travel. This assumption is commonly accepted by computer aided engineering (CAE) experts because the metal jet moves at high speed and at a sufficient distance from the edges of the donor system (target). Furthermore, this assumption is even more true because the direction of the jet is orthogonal to the target surface. The concept of axial

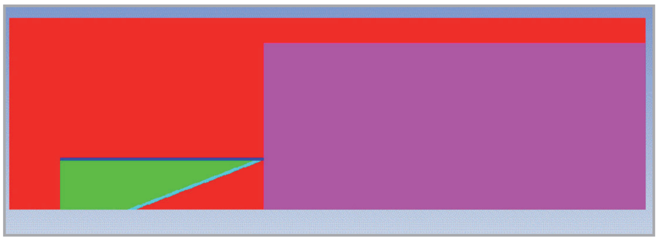

Fig. 1 - 2D model of the shaped charge

symmetry allows the analyst to significantly reduce the required computational time while maintaining adequate calculation accuracy of the solution.

To better illustrate the actual case simulated, Figure 2 graphically represents the complete shape by applying a 270-degree revolution to the bi-dimensional mesh. The portion of the mesh filled with air was initialized using the sea-level ambient condition and an outflow condition was imposed at its boundaries. Moreover, the target was constrained by fixing some nodes of the rear edge of the target, while the detonation was assigned to a set of nodes of the cells filled with TNT. A first set of simulations was carried out after properly modifying the refinement of the mesh to obtain a case providing mesh-independent outputs (a mesh sensitivity study), with the intention of assessing the generated case. Once obtained, the smallest elements of the mesh were less than 1mm in size. Then, the density of the liner was suitably adjusted to finally obtain a penetration with a relative percentage error below 4%.

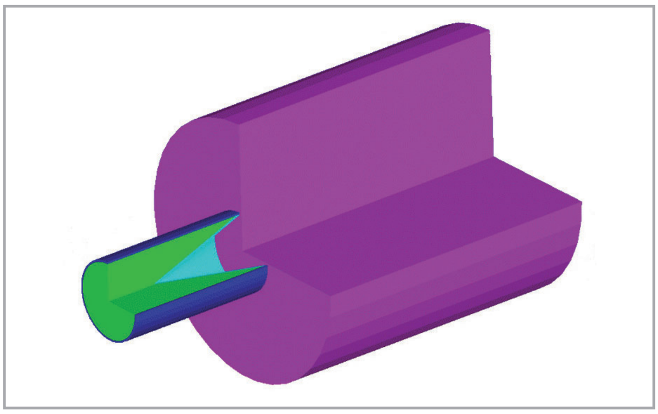

Fig. 2 - Example of the model revolved by 270° (mesh filled with air is not visualized)

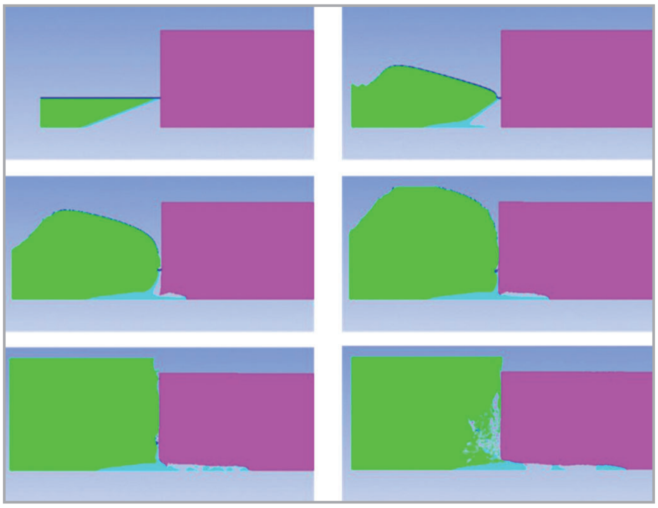

Fig. 3 - Detonation sequence on the monolithic steel target (mesh filled with air is not visualized)

Figure 3 illustrates the shape and depth of the crater generated in the monolithic target by the metal jet. The images show, from top left to bottom right, the charge detonation's evolution and its interaction with the steel donor system. For the sake of clarity, the portion of the model filled with air has not been represented. It is interesting to note that the model was able to generate a good representation of the ductile behavior of the perforated material.

The final settings of the shaped charge, namely those obtained at the end of the calibration stage, were used as a reference to build-up the LS-DYNA case and to perform the simulations detailed in the following sections.

Comparison with experimental data

Monolithic steel target

The LS-DYNA case was set up using the setting from the Autodyn case such as numerical grid refinement level, physical parameter values and the EOSs used, whenever possible. With regard to the material models and the EOSs used in LS-DYNA, the Gruneisen equation paired with the Johnson Cook strength model were used for the metallic parts. In particular, these relate to the external shell and to the liner, while the steel target was modelled using a simplified version of the Johnson Cook model, which excludes thermal effects. Regarding the environment, the air properties were described using the linear polynomial EOS and specifying its density. Finally, the High Explosive Burn model combined with the JWL equation of state were used to implement the properties of the TNT. Similar to the previous case, Figure 4 depicts some images of the materials' location during the simulation, starting from the initial configuration up to the maximum depth of the jet's penetration.

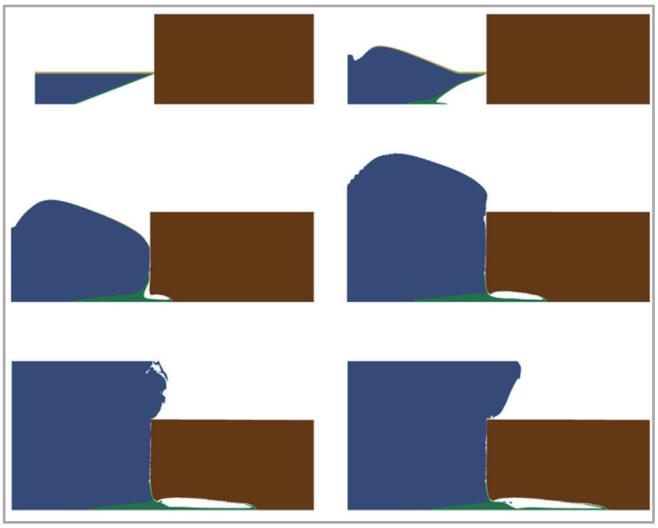

Fig. 4 - Detonation sequence against the monolithic steel target (LS-DYNA)

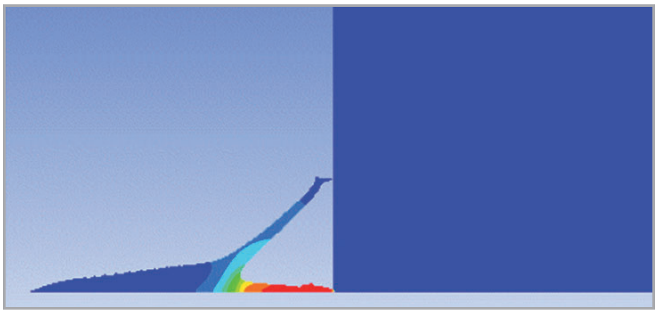

Fig. 5 - Velocity distribution of the jet

Figure 5 shows the distribution of the copper jet's absolute velocity. The picture emphasizes the fact that the detonation phenomenon does not completely develop because of the proximity of the charge to the target. This leads to the incomplete generation of the jet, with two relevant parts that partially penetrate the metal. In this configuration, the velocity of the tip at the moment of the impact is about 4500 m/s. Table 2 compares the depth of the hole, expressed in CD, recorded during the experiment and the values obtained by the different numerical simulations. As you can see, the LS-DYNA output is in good agreement with the other ones, and thus confirms the consistency of the numerical framework.

Experimental case	Autodyn (ALE)	LS-DYNA (ALE)
2.18	2.07	2.06

Table 2 - Results obtained for the monolithic steel target

Multi-layer steel-ceramic target

To simulate the brittle behavior of the ceramic layer appropriately, considered to be of fundamental importance taking into account the results of the experimental tests, the ALE method was coupled with SPH in Autodyn. The SPH method considers the elements constituting the model to be composed of free particles that, without being anchored to any mesh (mesh free method), include all the characteristics of the constituting material. Particularly in the case of high-speed impacts, the use of the SPH method allows an accurate reproduction of the response of brittle materials, including the phenomenon of destruction and the fragmentation of the elements. The entire charge was thus represented as the sum of three SPH blocks, while the target was modelled as a series of two Lagrangian steel layers and an SPH ceramic layer.

The set-up of the EOS and resistance models of the various materials involved followed the indications present in the literature and in the solver's theory manual [14][15][16]. With regard to the multi-layer configuration, the physical characteristics of the ceramic protection were extrapolated from the information provided in the materials sheet and were then inserted into the solver by modifying the properties of the material already present in the library. The case was defined by a single SPH domain containing the different parts of the charge and the protective ceramic layer. Subsequently, the two Lagrangian portions were positioned in such a way as to obtain the sandwich structure used in the experimental tests.

The contacts between the plates of different materials were managed by means of specific settings that guaranteed the stability of the result of the numerical solution. The series of images in Figure 6 shows the evolution of the jet formation phenomenon and its impact against the multi-layer target. It is interesting to note the brittle reaction of the ceramic plate whose fragments influence the jet's progression by absorbing part of the kinetic energy.
The penetration values, i.e. those reached experimentally and obtained by numerical analysis, are shown in Table 3. Although a larger discrepancy was evaluated than the one determined for the monolithic configuration (due to the lack of information available to customize the ceramic models), the depths of the holes are in good agreement. The results obtained demonstrate the ability of the CAE predictive model that was developed to assess the depth reached by the jet in a multi-layer target. Secondly, they also confirm the effectiveness of using such ceramic structures for passive ballistic protection to counteract the action of a shaped charge.

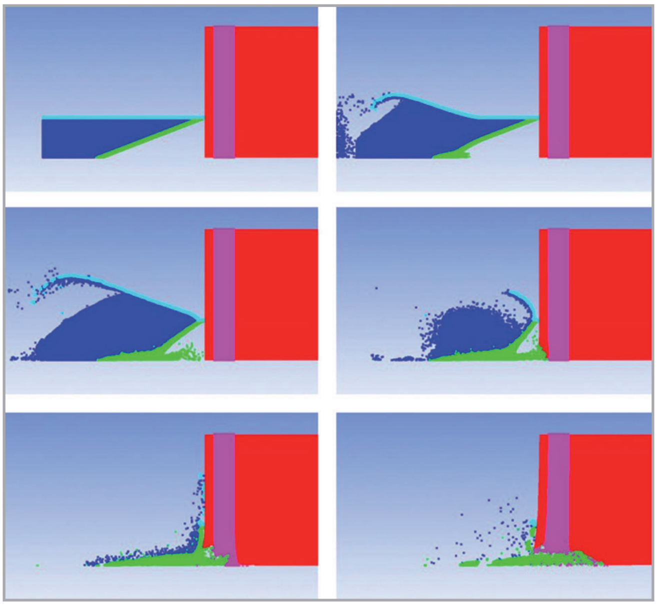

Fig. 6 - Detonation sequence against multi-layer target (Autodyn)

Experimental case	Autodyn (ALE-SPH)
0.53	0.77

Table 3 - Results obtained for the multi-layer target

Conclusions

This article describes the development of CAE models whose goal is to simulate the formation of jets from shaped charges and predict their penetration into passive ballistic protective structures. These numerical models are based on the use of a device defined as an equivalent charge, which was calibrated using the results obtained from experiments on a monolithic metal target.

Predictive models were then used to reproduce the experiments carried out on both a single-block steel target and a multi-layer protection composed of a ceramic layer sandwiched between two steel plates. In the end, a good alignment was obtained between the numerical results and the penetration values recorded during the tests. The discrepancies determined may be due to the lack of data necessary to customize the models adopted for the characterization of the material behavior (e.g. equation of state and strength model).
This study confirms the consistency and accuracy of the CAE predictive models and, thus, their effectiveness for tackling multi-layer metallic-ceramic structures.

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