AN INNOVATIVE METHODOLOGY TO PREDICT REACTION OF COMPLEX WARHEAD TO FRAGMENT IMPACTS

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ABSTRACT

MBDA France, as Design Authority for Complex Warheads, has to justify the resistance of its equipment to multiple mechanical attacks. Thus, MBDA France with the help of Eurenco, has developed a way to predict reaction of warheads to fragment impacts.

This methodology consists in three steps:

- Construction of the Ignition and Growth model of explosives based on standard characterizations
- Validation of the reactive models based on available data to predict detonation
- Application of the reactive model to the complex warhead

In the frame of the development of a new warhead, this prediction and justification methodology has been implemented.

This paper proposes to present this work and its application to this new warhead. The construction and the validation of the reactive model will be presented and its application will be detailed. Numerical simulations have been performed on the complete warhead and a comparison with experiment results has been done.

CONTEXT: IMPORTANCE OF INSENSITIVE MUNITIONS

In the frame of the current geopolitical context, the importance of insensitive munitions has become more pronounced than ever. As tensions simmer and conflicts erupt in various regions around the world, the need for military forces to prioritize safety, reliability, and efficiency in their weaponry has become increasingly critical.

Insensitive munitions offer a crucial advantage in conflict zones, where the risks of accidental detonation are heightened due to unpredictable circumstances and volatile environments. The war in Ukraine has underscored the devastating consequences of accidental explosions, not only in terms of loss of life and injury but also in terms of collateral damage to civilian infrastructure and the environment. Insensitive munitions mitigate these risks by providing a higher degree of safety during handling, transportation, and storage, thereby reducing the potential for unintended harm to both military personnel and civilians.

The development and adoption of insensitive munitions remain essential priorities for defence agencies worldwide as they strive to address the challenges of modern warfare while safeguarding the well-being of both military personnel and civilian populations.

INTRODUCTION

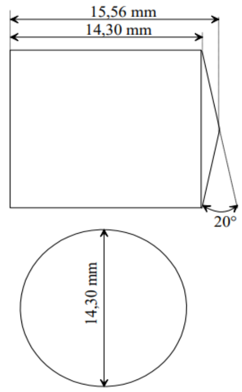
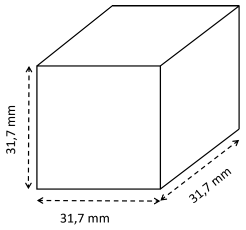
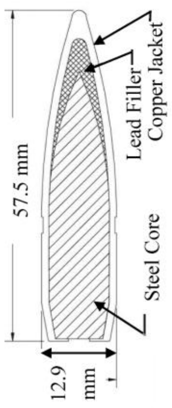
In the current context, MBDA France has to design new warheads taking into account this need of maintaining safety while enhancing performances, reducing at the same time development delays and costs. Thus, MBDA France with the support of EURENCO, has integrated an innovative methodology to predict as early as possible reaction of warheads to fragment impacts. This way allows us to optimize design and avoid specific tests in future developments.

This new methodology consists on relying on numerical simulation and fine modeling of metallic structures and explosive loading. In order to predict the risk of detonation of the warhead, an “Ignition and Growth” model is used to model the high explosive.

The reactive model is the one proposed by Lee and Tarver first in 1980 [6] and modified in 1985 [7]. Based on Lagrangian analyses, the authors explain that it is essential to consider kinetics in three stages: hot spot initiation, relatively slow onset of growth, completion of reactions. The model is detailed in the first part of the paper with the experimental identification of the parameters. In the second part, a validation of this model is proposed based on standard characteristics and available data. Finally, the application of a complex warhead is presented in the third part.

The three mechanical solicitations considered in this study are the impact of light fragment [1], the impact of heavy fragment [2] and the 12.7 mm bullet impact [3]. The following table presents the fragments in question.

Table 1: Fragments description

Fragment type	**Light**	**Heavy**	**Bullet**
Material	Steel	Steel	Steel, lead, copper
Mass	18.6 g	250 g	42.5 g
Velocity	1830 m/s	1650 m/s	850 m/s
Shape			

This methodology consists in three steps: construction of the Ignition and Growth model of explosives based on standard characterizations, validation of the reactive models based on available data to predict detonation, application of the reactive model to the complex warhead.

FIRST STEP: MODEL CONSTRUCTION

The first step of the methodology is to build the reactive model of the explosive. Reaction zone is modeled with one equation of state for the unreacted phase, another equation of state for the reacted phase and kinetics law. In its 1985 version, the model proposed by Taver et al. is written as follows with twelve parameters.

$$\frac{d\lambda}{dt} = I(1-\lambda)^b\left(\frac{v_0}{v}-1-a\right)^x + G_1(1-\lambda)^c\lambda^d P^y + G_2(1-\lambda)^e\lambda^g P^z$$

The John Wilkins Lee (JWL) equation of state of the unreacted material is as follows.

$$P(\mu,T) = A^r . e^{-\frac{R_1^r}{1+\mu}} + B^r . e^{-\frac{R_2^r}{1+\mu}} + R_3^r . \frac{T}{1+\mu}$$

The JWL equation of state of the reacted material is as follows.

$$P(\mu,T) = A^p . e^{-\frac{R_1^p}{1+\mu}} + B^p . e^{-\frac{R_2^p}{1+\mu}} + R_3^p . \frac{T}{1+\mu}$$

Identification of the parameters is based on a macroscopic approach Shock-to-Detonation Transition (SDT). The reactive model is calibrated to transcribe the depth of transition to the detonation of the studied explosive. The experimental configuration consists of transmitting a shock wave into the sample of explosive to be studied using a projectile. The explosive is machined into a wedge shape in order to measure at its periphery, the progression of the shock wave in the explosive, without influence of lateral detents, and to establish a flow diagram, most often using a slit camera or timing hands, as can be seen in following figure. This type of experiment is commonly called “pop-plot test” after the name of its author [8].

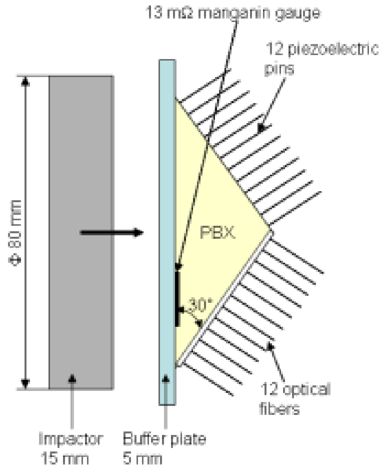


Figure 1: Pop-plot test description from [9]

The flow diagram makes it possible to determine the run distance X, depth of the explosive from which the transmitted shock wave transits to a detonation wave. It has been showed that run distance can be linked to the solicitation pressure P by the relation log(X) = a + b.log(P). By performing several tests at different pressure, we obtain the pop-plot curve of the studied explosive.

Thus, to build the reactive model of the explosive, several tests are performed, the flow diagrams are established. Several simulations are then carried out in order to establish the best set of parameters allowing all of the flow diagrams to be transcribed. The following figure shows an example for two different solicitations.

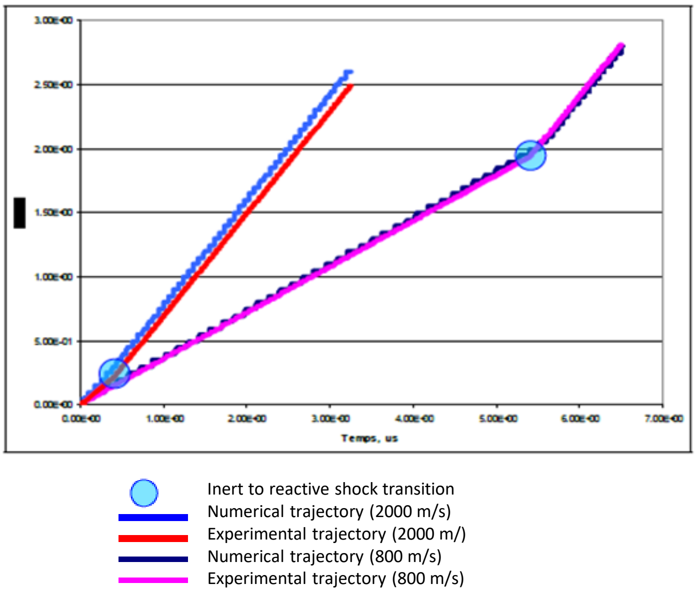


Figure 2: Flow diagrams obtained by simulation and experimentally

SECOND STEP: MODEL VALIDATION

The second step of the methodology is to validate the parameters obtained during the first step. To do this, we base our study on available standard characteristics: gap-test and several impact tests from the literature [5]. The objective is to simulate the tests and verify that the reactive model correctly transcribes the detonation threshold of the explosive.

The gap-test [4] does not participate in the determination of the parameters but can be used as a validation test. The RDX/wax donor used in the gap test is composed of two 40 mm diameter and 80 mm height cylinders. The explosive sample is a 40 mm diameter and 200 mm height cylinder. The acetate cards have a thickness of 0.19 mm and a diameter of 40 mm.

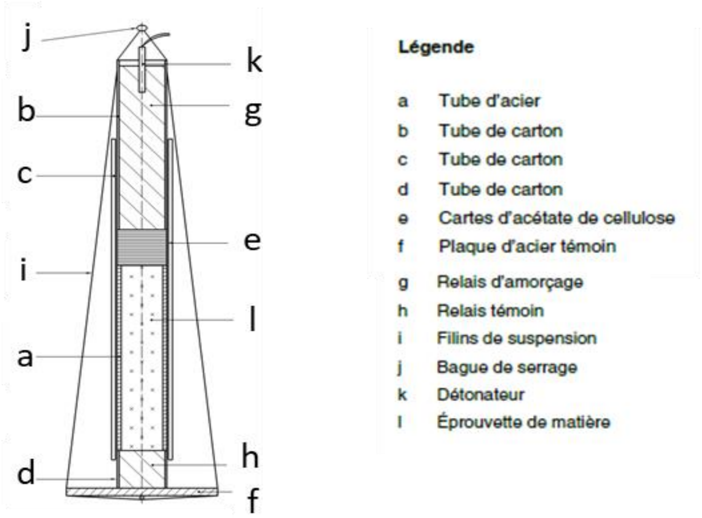
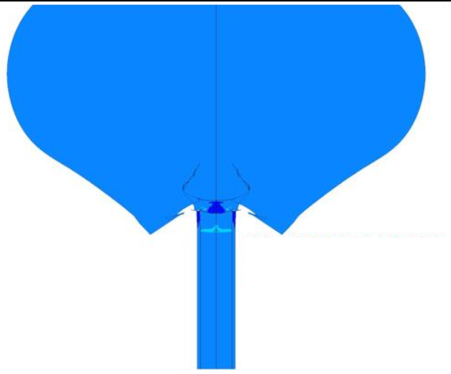
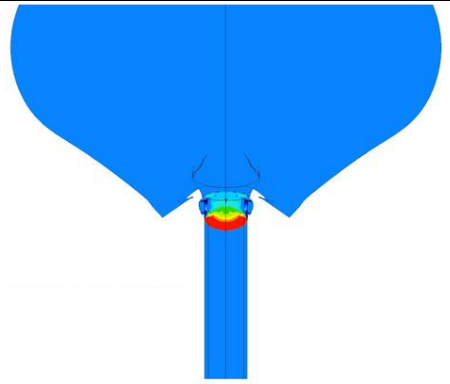


Figure 3: Gap-test description

The calculation has been carried out in 2D-axisymmetric representation with an element size of 0.5 mm side, in agreement with the mesh refinement used for the determination of the reaction kinetics parameters. The pressure peak at the entry of the explosive has an amplitude of 9 to10 GPa. As we can observe on the following figure, we have a Shock-to-Detonation Transition (SDT) with a stack of 160 cards but no transition for 165 cards.

Table 2: Gap-test simulations results

	
165 cards	160 cards
No transition to detonation	Transition to detonation

A discrepancy with the experimental data is observed, which predicts a limit of around 175 cards [newgates]. This difference of 10 cards is acceptable given the uncertainty we have in this test. Out of curiosity, this same simulation was carried out with a refinement of four elements per millimeter. We then see a seed limit between 165 and 170 cards, which makes it possible to highlight the influence of the mesh on the observed result by using the Lee-Tarver behavior law.

Projectile impact data on explosive samples placed behind a barrier are also available from the work of Collignon et al. [5]. A cylinder of explosive is placed behind an aluminum barrier 0.635 cm thick. The projectile is a steel cylinder with a diameter of 1.433 cm. In this case, the radius of the projectile is slightly lower than the thickness of the barrier, which indicates that the rarefaction of the waves coming from the edges of the projectile can potentially influence the loading received by the explosive.

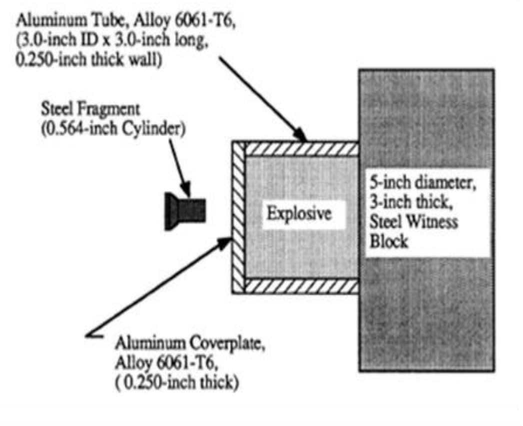
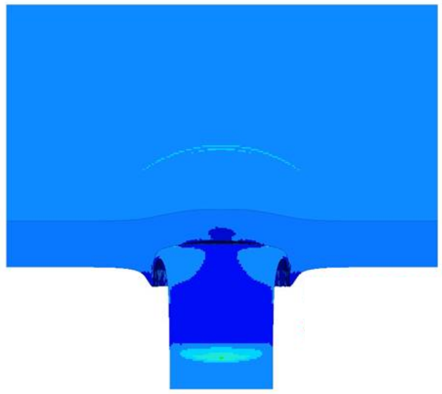
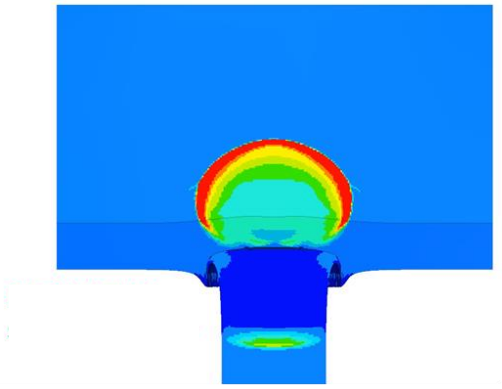


Figure 4: Impact tests description from [5]

With an element size of 0.25 mm, the reactive model predicts detonation for an impact velocity of 1417 m/s and non-detonation for 1357 m/s (see following table), which agrees with the experimental results.

Table 3: Impact test simulations results

	
1357 m/s	1417 m/s
No transition to detonation	Transition to detonation

The reactive model developed for our studied explosive provides relevant results for predicting SDT. Initially intended to be used with elements of size 0.5 mm, the model however seems more representative with elements of size of 0.25 mm. Thus, the reactive model can be used for prediction in unknown conditions such as fragment impacts.

THIRD STEP: MODEL APPLICATION

After validation during the second step, we now use the model for the prediction of SDT under specific conditions. As said in introduction, the present study focus on light and heavy fragments, and bullet impacts.

A simplified 3D model of warhead is considered for this study. This model consists of a standard stack of materials as shown in the following figure.

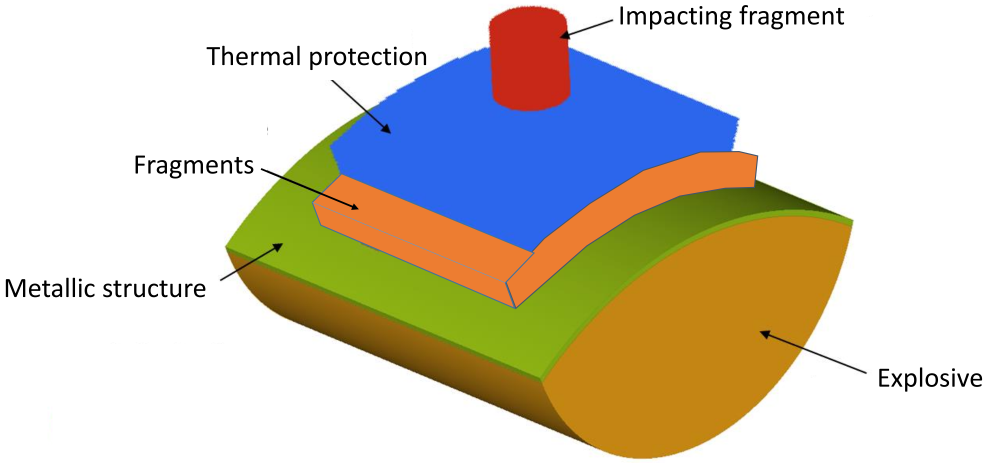


Figure 5: Simplified 3D model

The size of the elements is close to 0.5 mm in order to limit calculation times, while previous work indicated that an element size of 0.25mm was preferable. However, the fragment being relatively large comparing to the critical diameter, the shocks generated by the impact are therefore long and the influence of the element size remains low.

The impacting fragment and the thermal protection are meshed in Smoothed-Particle Hydrodynamics (SPH) with a centered cubic model and a particle gap of 0.03 cm for the impacting fragment and 0.025 cm for the thermal protection. Concerning the mesh of the fragments, the structure and the explosive, elements of size 0.025-0.03cm are preferred in the direction of impact. The radial size of the elements in the fragments is increased to 0.05 cm to ensure a ratio of number of SPH particles/Lagrangian surface area sufficient for good interaction between the thermal protection and the fragments. For the explosive, the area closest to the point of impact is meshed with 0.025 cm elements in order to respect the prerequisite of the reactive model. Outside of this area, a mesh derefinement was applied to save the total number of elements. The size of the modeled zone is dimensioned so that the reflected waves on the free surfaces do not have time to disturb the elements at the entry of the explosive.

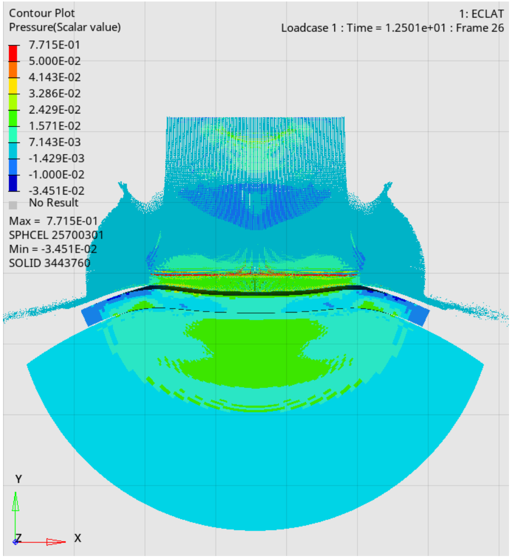
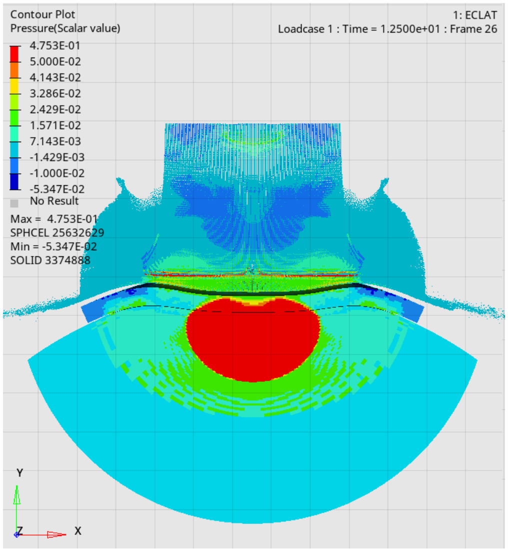
The simulations of the three identified cases were carried out under these conditions. The following table presents the results obtained.

Table 4: Simulation results

Fragment type	**Light**	**Heavy**	**Bullet**
Velocity	1830 m/s	1650 m/s	850 m/s
Result	No transition to detonation	Transition to Detonation	No transition to detonation

The following figure presents contours of pressure in the case of heavy fragment impact.

Table 5: Heavy fragment impact simulations

	
1300 m/s	1400 m/s
No transition to detonation	Transition to Detonation

In order to validate our methodology, tests have been carried out on prototypes representative of the simulations. The results are presented in the following table.

Table 6: Test results

Fragment type	**Light**	**Heavy**	**Bullet**
Theoretical velocity	1830 m/s	1650 m/s	850 m/s
Experimental velocity	1809 m/s	1667 m/s	878 m/s

Experimental result	No transition to detonation	Transition to Detonation	No transition to detonation

The test results are consistent with the predictions made by simulation and make it possible to validate the application of the methodology to our warheads.

CONCLUSION

The methodology presented in this paper is based on the use of a well-defined and validated reactive model for the explosive loading. Application to complex warheads has been also verified thanks to a consistent comparison between the simulations and experimental data.

MBDA France now considers this methodology validated and usable for future applications. It is first necessary to determine the parameters of the reactive model for the considered explosive, to validate it on available and relevant data and to apply it to the definition of the warhead. Considering the IM aspect from the beginning of development makes it possible to reduce development delays and costs by reducing the number of tests, and meet the needs driven by the current geopolitical context.

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