Experiments and Simulations of Explosives: Shock Wave Propagation around a Convex Structure

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Abstract

IRSN provides technical support to the relevant French authorities involved in the security of nuclear material, nuclear facilities and in the transportation of nuclear material. In order to improve its knowledge on blast wave propagation, IRSN has set-up a laboratory scale able to perform detonations of solid explosives against rigid structures (no damage or deformation). In July, 2017, the 7th experimental campaign was conducted on this set-up to study the shock wave propagation around a convex structure. Several configurations were tested, involving a charge of 50 g of TNT equivalent and a horizontal half cylinder. The pressure data obtained have been compared with simulations performed using LS-DYNA® and OURANOS (French software developed by CEA). Concerning simulations, a process of validation was conducted on both software programs, in order to test mesh choices (mesh size, structured or unstructured mesh…) and boundary conditions (mesh boundaries, coupling…).

Introduction

IRSN is a French public institute with industrial and commercial activities, placed under the joint authorities of the Ministries of Defense, Environment, Industry, Research, and Health. It is the national expert in nuclear and radiation risks, and its activities cover all the related scientific and technical issues.
IRSN is entrusted, among others, to assess and conduct researches in the area of the protection of nuclear facilities and transport of radioactive and fissile materials against malicious acts. In this context, IRSN establishes projects and studies to improve its knowledge of blast characteristics and weapons effects.

In 2006, IRSN designed and built an experimental set-up to achieve non-destructive shock wave propagation studies on a small scale. This set-up is composed of a modular table, sensors and targets able to perform the detonation of solid explosives up to 64 g of TNT equivalent. It was used to conduct six experimental campaigns between 2006 and 2011 ([1]).
In 2017, a new experimental campaign was set up to investigate blast wave propagation around a convex structure ([2]). The present paper summarizes some of these experimental tests, and introduces additional numerical simulations realized using two different software programs: LS-DYNA and OURANOS (French eulerian software program developed by Atomic Energy and Alternative energies Commission (CEA)). The objectives of this work intend to improve IRSN knowledge about blast characteristics whenever an explosion occurs near critical infrastructures, and to evaluate software capability to reproduce experiments.

Experimental Campaign

The blast table has been principally designed to study shock waves reflection phenomena and interaction with different non deformable structures. It measures 1.6 x 2.4 meters and features an array of mounting holes that facilitates the placement of modular 0.4 x 0.4 x 0.05 m wooden plates, and pressure transducers (see Figure 1).

For this campaign, eleven piezoelectric pressure transducers (Kistler, 603B (0-200 bar)) are mounted on an elastic support inserted in the holes provided for this purpose. Each pressure transducer is calibrated prior to the tests with its amplifier and connection cable.

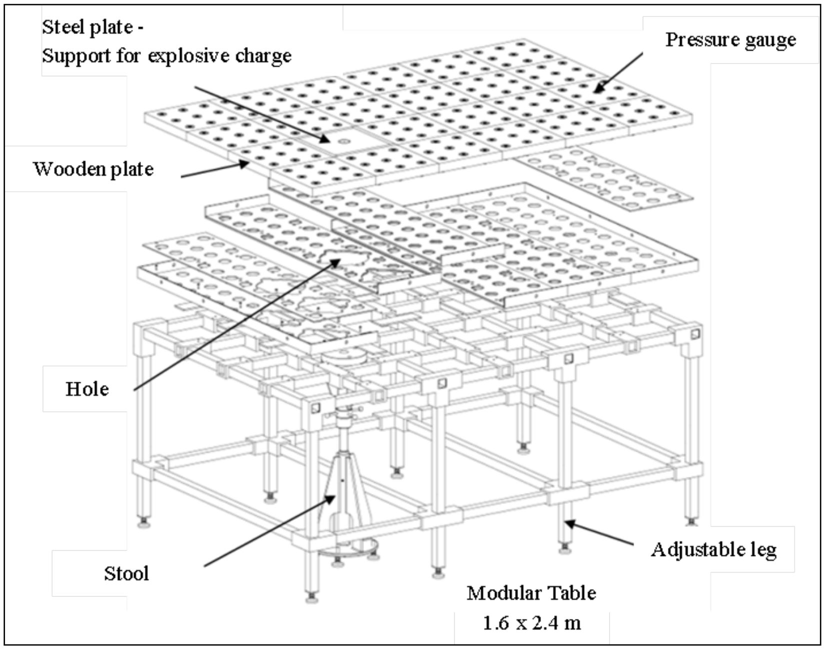
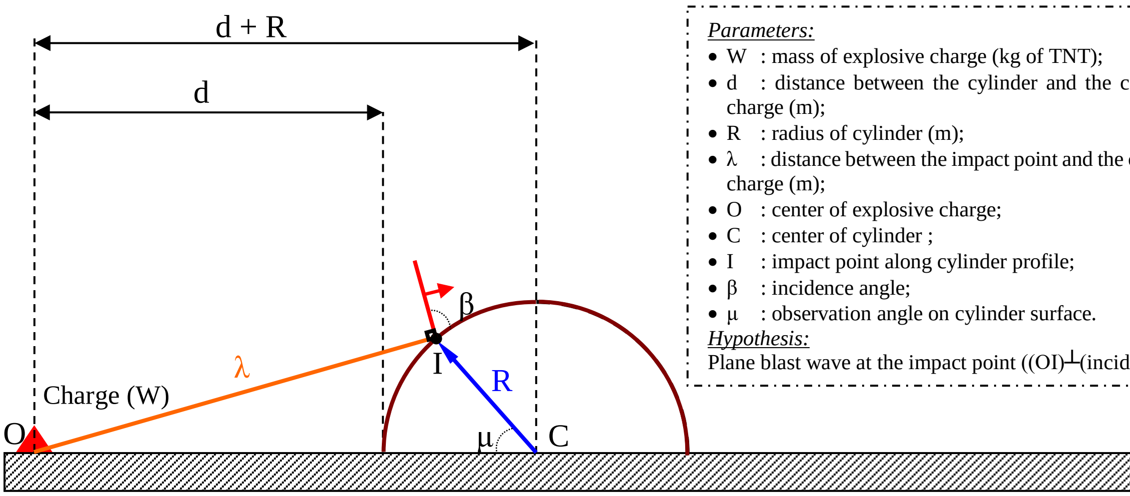


Figure 1: Schematic view of the laboratory scale table

Experimental campaigns are performed at the Ariane Group's research center located near Paris (Vert-le-Petit, France). Ariane Group handles all the experiment pyrotechnics and also provides the data recording system (NICOLET Genesis data acquisition system, sampling rate of 5 MHz). During experiments, the modular table is mounted and placed at the center of a closed bunker, so as to avoid the perturbation from shock reflection on the bunker walls.

The main objective of the 7th campaign is to study the interaction of a blast wave with a cylindrical surface. For that purpose, a set-up using a wooden semi-cylindrical target lying on the table has been chosen (see Figure 2, [3]).



Parameters:
- W : mass of explosive charge (kg of TNT);
- d : distance between the cylinder and the center of the charge (m);
- R : radius of cylinder (m);
- λ : distance between the impact point and the center of the charge (m);
- O : center of explosive charge;
- C : center of cylinder ;
- I : impact point along cylinder profile;
- β : incidence angle;
- μ : observation angle on cylinder surface.

Hypothesis:
Plane blast wave at the impact point ((OI)⊥(incident wave)).

Figure 2: Diagram of the experimental configuration involving a semi-cylinder

The target is sufficiently rigid to withstand repeated blast loading without damage nor deformation. The cylinder, with a diameter of 0.4 m, has the same length than the table in order to avoid bypass of the shock wave at cylinder endpoints (see Figure 3). Pressure gauges can be placed at the cylinder surface due to the holes created in the section that faces the blast.

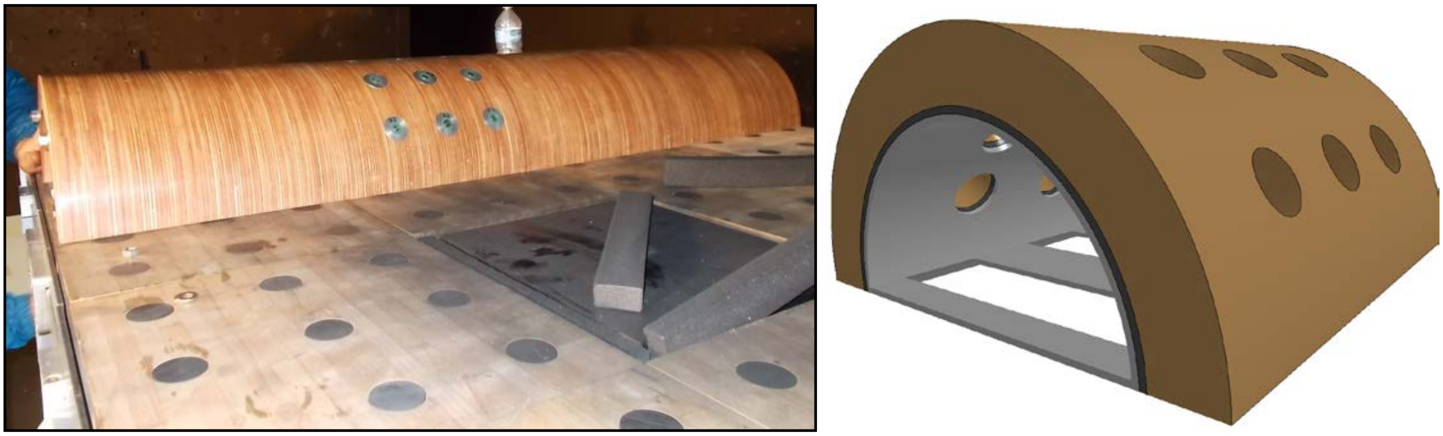


Figure 3: View of the wooden half cylinder lying on the table with holes for sensor positioning

The explosive charge is a Hexomax® hemisphere, initiated from the bottom using electrical detonators. For this work, the mass used is 50 g of TNT equivalent, placed directly on the table, on the dedicated steel plate (see Figure 4).

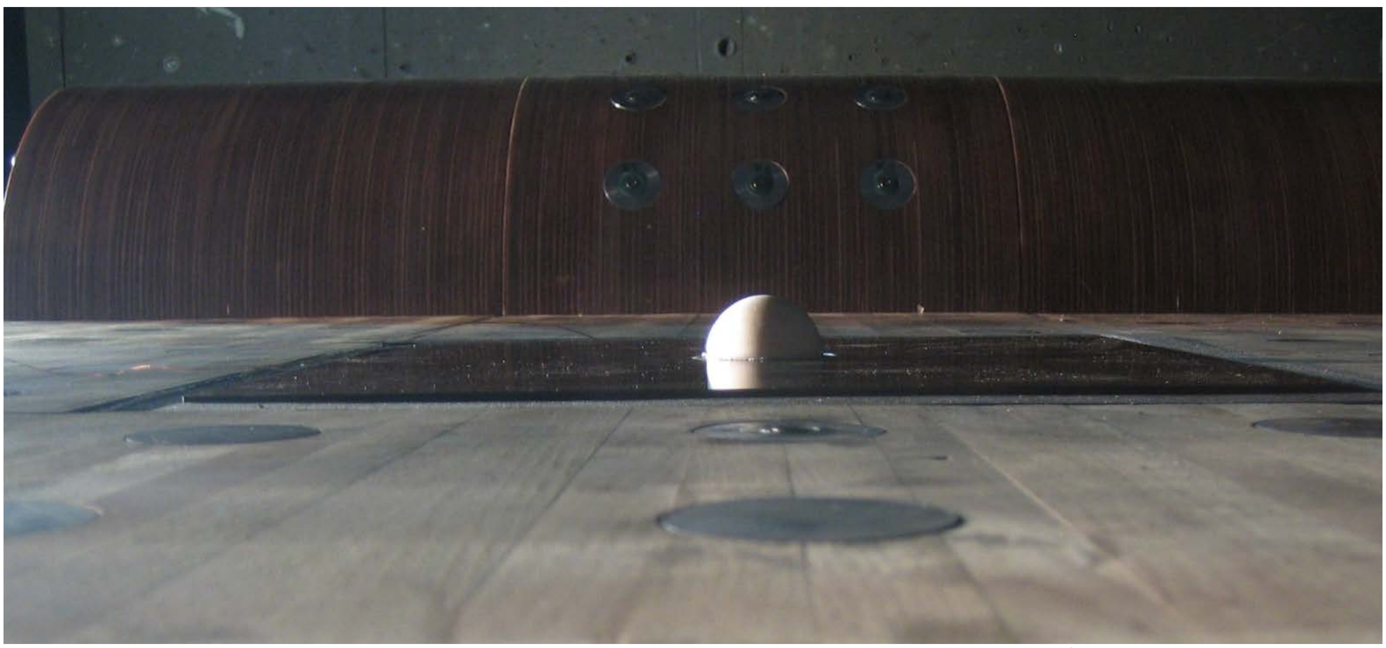


Figure 4: Example of initial configuration of the experiment with the Hexomax® hemisphere

For this experimental campaign, three trials with different configurations have been performed:

1. A free field test, in order to characterize the explosive charge and check the TNT equivalent,
2. A configuration n°1 with the cylinder placed at 0.6 m from the center of the charge,
3. A configuration n°2 with the cylinder placed at 0.4 m from the center of the charge.

The distance of 0.6 m used in configuration n°1 is the minimum distance beyond which it is assumed that the 2D axisymmetric effects begin to be non-effective in a numerical simulation. When this kind of configuration (very long cylinder) is simulated using 2D axisymmetric dimension, a torus is then modeled instead of a cylinder which can have consequences on the results at a small distance (artificial containment area). This point will be investigated in the second part of the study with the comparison between simulation and experiment.

The distance of 0.4 m used in configuration n°2 is the approximate limit of detonation products area [3]. The objective is here to maximize the shock wave on the cylinder without disturbing it by detonation products arrival. In this case, a 2D axisymmetric modeling could cause a pressure increase due to the reason explained above.

Calibration of Numerical Simulations

After this experimental campaign, an additional phase of numerical simulation was realized. The aim is to compare pressure data obtained during the tests with simulations realized with two different software programs: LS-DYNA and OURANOS, a French eulerian code developed by CEA, which specialized in blast and weapon effects among others.

In order to make a fair comparison, modeling choices and software options were as similar as possible, while trying to make the most of each code regarding numerical resolution options (for example, numerical scheme is not the same between the two software items). LS-DYNA and OURANOS simulations have been run on different working stations, making it difficult to compare computation time. The comparison presented in this paper will only concern the evolution of the positive phase of the shock wave: maximum of positive overpressure and positive impulse.

For both software programs, 2D axisymmetric MMALE models have been developed for all configurations in order to be able to achieve a sufficient mesh size on a 16 cores workstation. For air, a perfect gas behavior is used with an initial pressure of 101325 Pa. For the explosive, a modeling with Johnson-Wilkins-Lee equation of state is used. A scale factor of 0.4 is applied on the CFL condition for the calculation time.

Regarding the differences between the two codes, they principally concern the eulerian calculation scheme. For OURANOS, a Godunov ([4]) scheme is used. For LS-DYNA, a bulk viscosity model for shock treatment (finite element method) is used; a Van Leer advection method is chosen ([5]).

In order to calibrate models and make a first comparison between the two codes, a preliminary configuration (not experimentally tested) using more classical characteristics has been simulated: a free field air blast with 1 kg of TNT. The objectives are to check if a mesh size of 4 mm/kg$^{1/3}$ is able to provide peaks of pressure with relatively small diffusion, and to compare the results with data from literature.
In this regards, numerical models of a 10 m by 10 m domain with a structured square mesh have been prepared for the detonation of a 1 kg TNT sphere. Results in terms of maximum of overpressure and positive impulse have been compared with two different reference sources: Kinney & Graham ([6]) and TM5-1300 ([7]). Pressures are extracted from the simulation along the X-axis. Figure 5 presents these comparisons depending on the reduced distance from the charge.

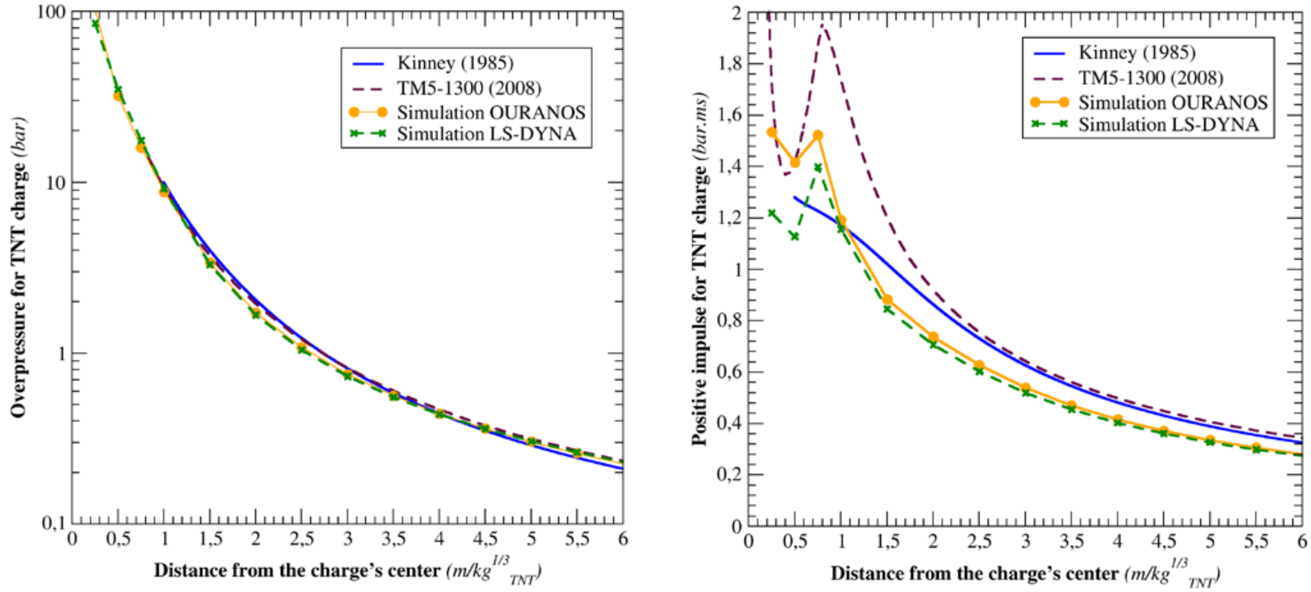


Figure 5: Overpressure (left) and impulse (right) versus reduced distance for preliminary configuration (TNT)

For the maximum of overpressure, the comparison shows that LS-DYNA and OURANOS give very similar results in all areas (from 0.25 to 6 m/kg$^{1/3}$). Both software programs are able to produce a peak of overpressure with a maximum very close to the literature references (only a few percent of error). These observations confirm the choice of the mesh size of 4 mm/kg$^{1/3}$ of TNT. Regarding the positive impulse, for a reduced distance above 1 m/kg$^{1/3}$, results are very similar between the two codes but always underestimate the values from Kinney and TM5-1300. For smaller distances, OURANOS seems to give a higher impulse, closer to the TM5-1300 reference than LS-DYNA.

Using the same model, a study of the effects of the mesh shape has been performed. The aim is to quantify the differences for a spherical shock wave induced by a structured square mesh depending on the angle. These differences are simulated for two distances (1 and 5 m/kg$^{1/3}$) and for several angles (0°, 20°, 45°, 70°, 90°), as it is explained on Figure 6.

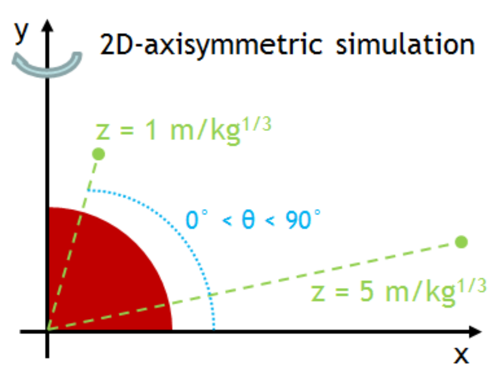


Figure 6: Diagram explaining sensors positions in the mesh shape study

Regarding OURANOS, only the square structured mesh has been tested because it is the one recommended for eulerian calculations in this software. As for LS-DYNA, two meshes have been tested; one square structured mesh and another one with a butterfly mesh perfectly fitting the charge surface. A view of the two types of meshes (square or butterfly) is available on the following Figure 7.

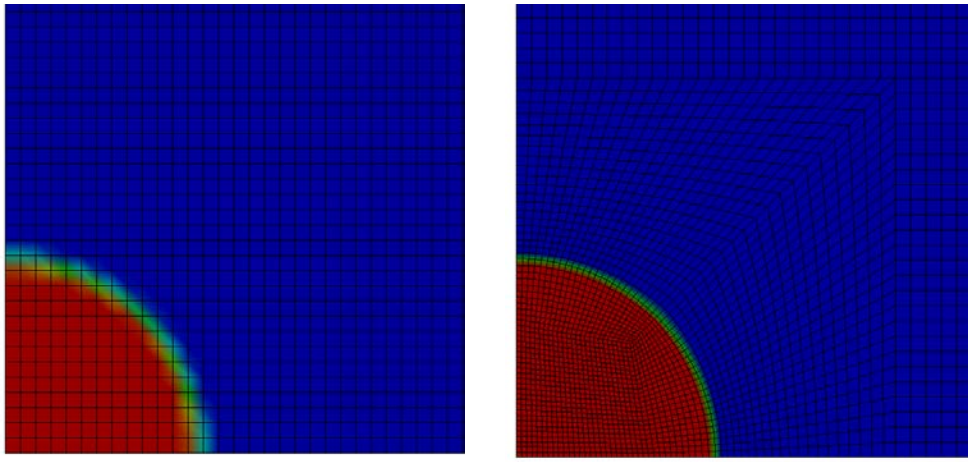


Figure 7: Views of LS-DYNA structured square mesh (left) and butterfly mesh (right) near the charge

A comparison of the results in terms of maximum of overpressure and impulse in the positive phase has been done for all angles. A summary of maximum relative errors is presented in the following Table 1. These errors are calculated with the difference between minimum and maximum values observed for all angles at a same distance.

Distance ($m/kg^{1/3}$)	**Data**	**OURANOS Square mesh**	**LS-DYNA Square mesh**	**LS-DYNA Butterfly mesh**
1	Overpressure	≈ 7-8 %	≈ 24-25 %	≈ 4-5 %
	Impulse		> 40 %	≈ 2-3 %
5	Overpressure	≈ 1-2 %	≈ 9-10 %	
	Impulse		< 1 %	

Table 1: Summary of maximum errors due to sensors positions for all meshes

This comparison shows that LS-DYNA presents a dispersion of the results more important than OURANOS for a structured square mesh for short distances. Regarding LS-DYNA, it seems to be highly recommended to use a butterfly mesh to reduce the error in this area. Therefore in the present study, all LS-DYNA models will be performed with a butterfly mesh to initialize properly the spherical shock wave.

Comparison between Simulations and Experiments

The first three trials of this experimental campaign are in free field, involving a charge of 42 g of Hexomax® (50 g in TNT equivalent). To compare experimental results with simulation in this work, the chosen method consists in keeping the best two trails (regarding literature standards Kinney & Graham and TM5-1300), in order to make an average and consider an experimental uncertainty of 20 %.

Numerical simulation models have been developed for this configuration using the mesh size validated in the previous case (4 $mm/kg^{1/3}$ of TNT, so for this case a mesh size of 1.86 mm). The domain size is 2 m by 2 m, and the JWL equation of state for Hexomax® is provided by Ariane Group based on a Cheetah 2.0 calculation (thermochemical code developed by LLNL, [8]).

Figure 8 presents a comparison between simulation and experiment in terms of maximum of overpressure and positive impulse depending on the distance from the center of the charge.

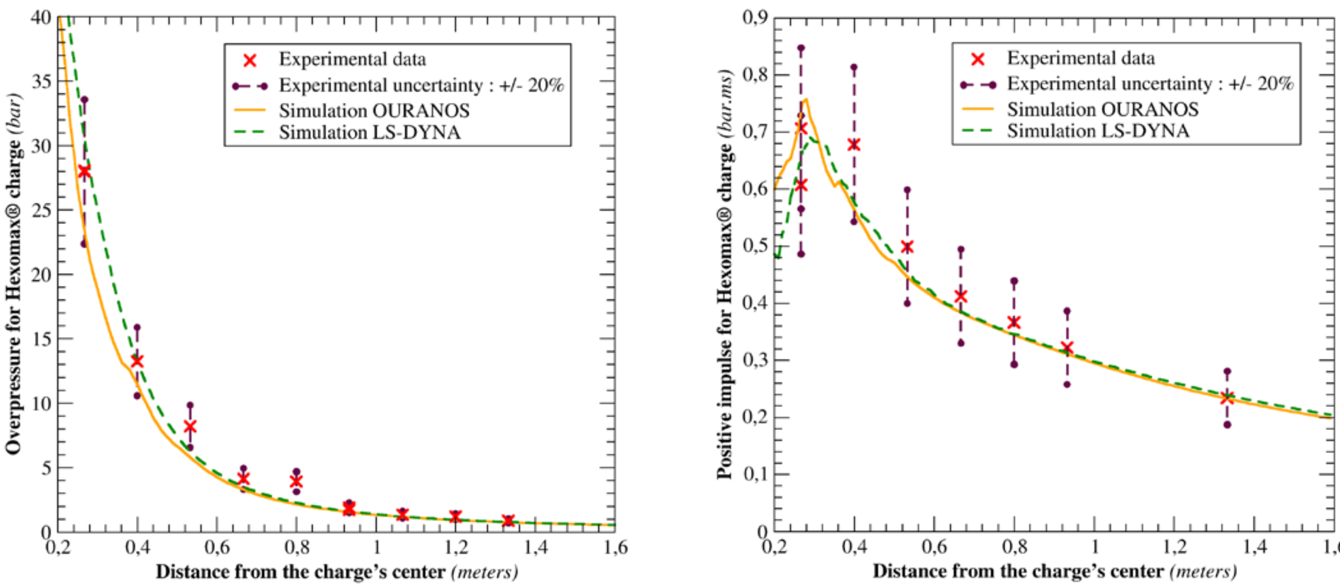


Figure 8: Comparison between simulation and experiment in terms of Overpressure (left) and Impulse (right) for free field experimental configuration (Hexomax®)

Concerning the overpressure, the comparison shows that values obtained by both software programs fall within the experimental uncertainty for most of the points. LS-DYNA seems to give a smoother evolution with the distance than OURANOS, with higher values close to the charge. Regarding the impulse, both software programs give the same behavior with values always in the experimental uncertainty. As observed before with TNT simulations, greater values are obtained for OURANOS close to the charge for the impulse.
These results show that LS-DYNA and OURANOS are able to reproduce detonation of Hexomax® charges in free field compared to these experiments on a small scale.

After these free field tests, two more complicated configurations have been performed involving a half cylinder lying on the experimental table (three shots each). This cylinder, of a diameter of 0.4 m, is placed at 0.6 m from the center of the charge in configuration n°1 and 0.4 m in configuration n°2. The comparison between simulation and experiment was based on five sensors placed on the cylinder and two sensors located upstream and downstream the cylinder. Moreover, in order to evaluate software capability to reproduce the maximum of reflected pressure, a point is added in the curves at the bottom left of the cylinder (the location where the shock wave hits first the structure) based on an estimation by Kinney (estimation of incident overpressure with equivalent mass of TNT) and TM5-1300 (estimation of reflected coefficient). In this paper, only overpressures are compared for the two configurations, impulses being processed and analyzed at this time.
Concerning these configurations, numerical models of a fluid domain of 2 m by 2 m have been created. In these models, a major difference exists between LS-DYNA and OURANOS concerning the cylinder treatment. In OURANOS, a structured square mesh is used for the entire domain, and the cylinder is modeled by a "fictitious fluid" acting as a fixed rigid body. In LS-DYNA, mesh boundaries follow the cylinder surface with a "slip" condition. These two different kinds of modeling are shown in the following Figure 9.

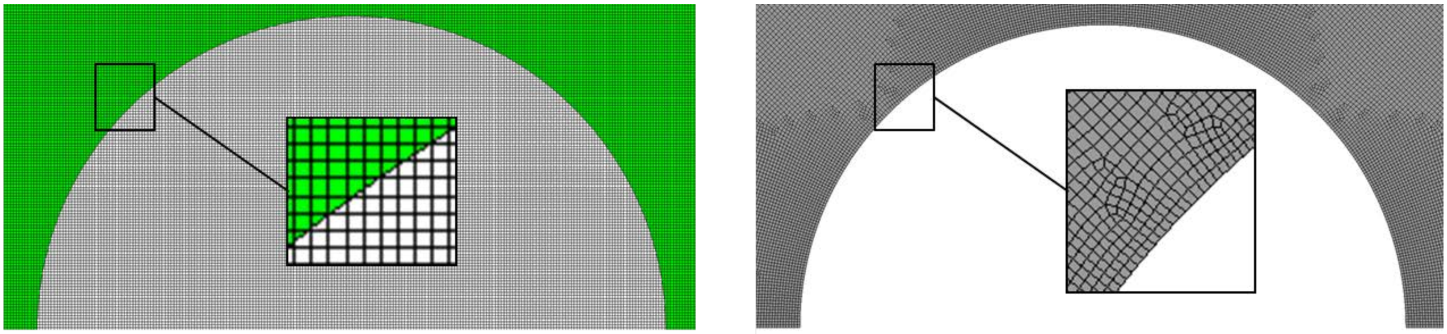


Figure 9: Comparison of cylinder modeling between OURANOS (left) and LS-DYNA (right)

As it is shown in the following Figure 10, multiple reflections occur during the shock wave propagation. This view of the simulation of configuration n°1 (cylinder at 0.6 m from the center of the charge) confirms that detonation products do not seem to have any influence on the blast interaction with structure.

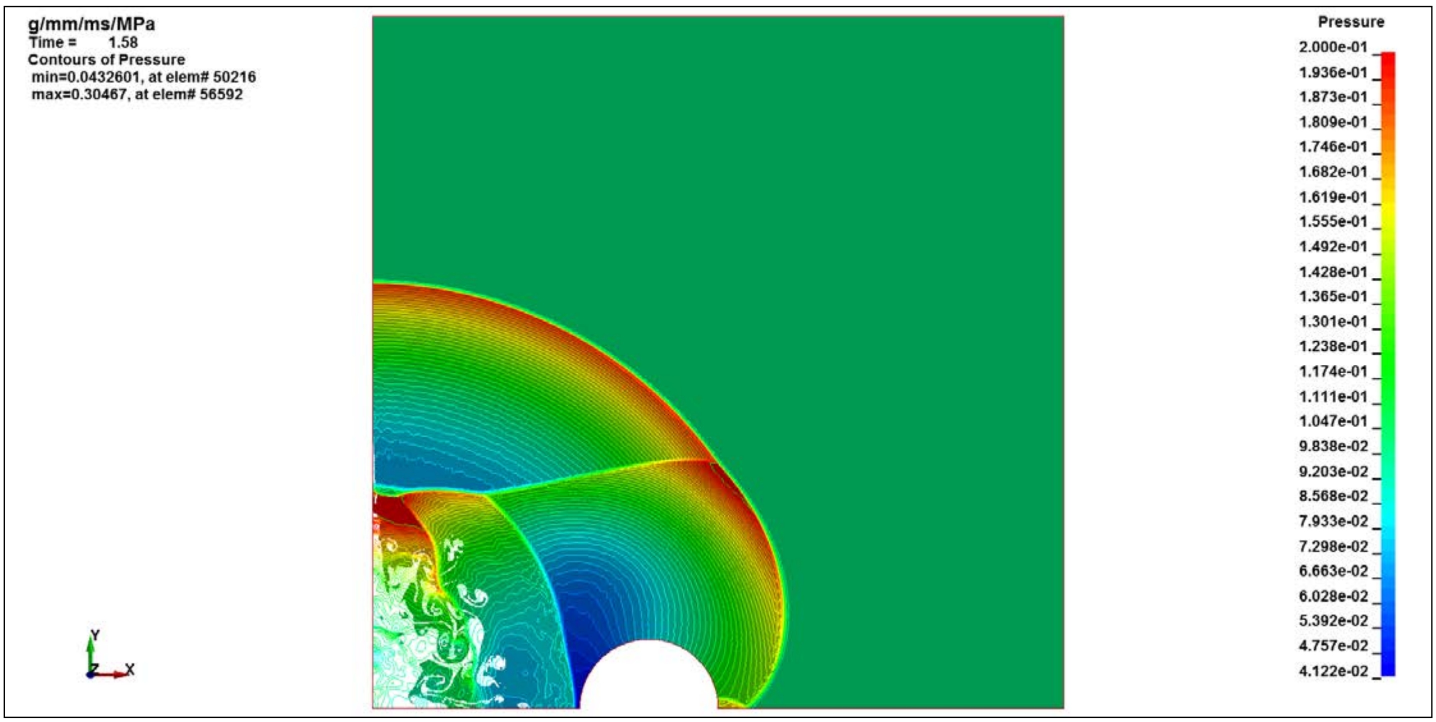


Figure 10: View of multiple reflections of the shock wave and detonation products in LS-DYNA calculation (configuration n°1)

A comparison of the overpressures between simulation and experiment is presented in Figure 11 for configuration n°1. As the distance between the charge's center and the sensor increases, the overpressure decreases until the shock wave reaches the cylinder. The reflected pressure causes a peak centered at the exact position of the beginning of the structure, where the reflection coefficient is maximum. Then, as the shock wave propagates around the cylinder, the overpressure highly decreases to achieve a relaxation phase on the back side. Downstream the cylinder, the overpressure increases again a little bit due to the reflection on the ground.

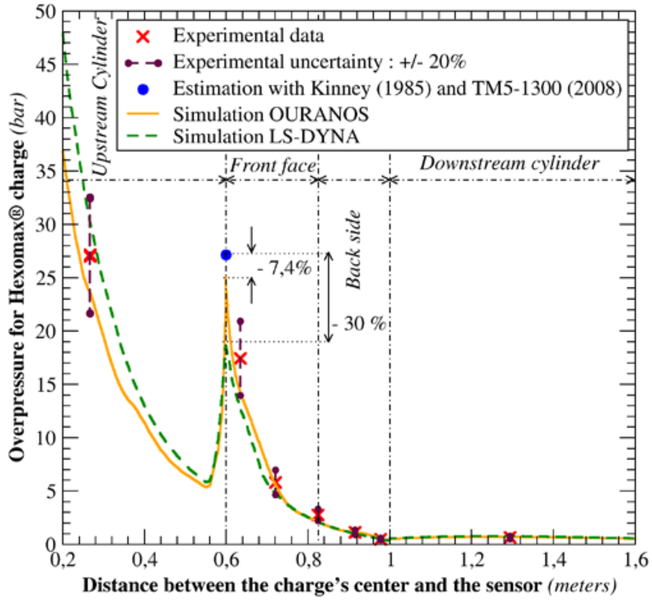


Figure 11: Comparison between simulation and experiment in terms of overpressure for experimental configuration n°1 (cylinder placed at 60 cm from the charge's center)

The comparison between simulation and experiment shows that LS-DYNA and OURANOS both give overpressures within the experimental uncertainty for all points. As observed before, LS-DYNA calculates a higher pressure peak close to the charge than OURANOS, in the free field area upstream the cylinder. However, at the cylinder's surface, LS-DYNA seems to underestimate the reflected pressure. In fact, for the peak value, the difference between simulation and estimation is much higher for LS-DYNA than for OURANOS.

The same comparison is presented in Figure 12 for configuration n°2. A similar evolution of the overpressure is observed for this case, with a greater pressure peak on the cylinder due to the proximity of the charge.

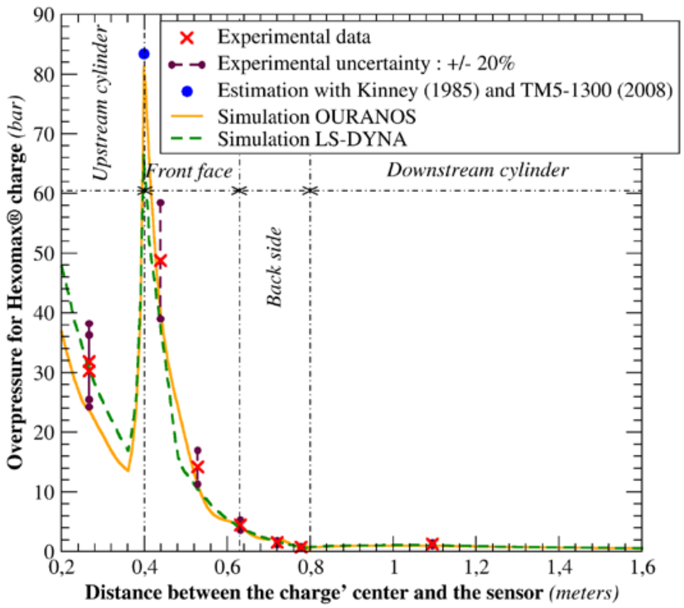


Figure 12: Comparison between simulation and experiment in terms of overpressure for experimental configuration n°2 (cylinder placed at 40 cm from the charge's center)

For this configuration, the comparison between simulation and experiment also shows that LS-DYNA and OURANOS both give overpressures within the experimental uncertainty for all points. Observation made for configuration n°1 about an underestimate of the reflected pressure on the cylinder is also applicable in this case in a similar proportion. Contrary to what it was expected, a pressure increase due to the artificial containment effect (2D axisymmetric dimension models a torus in place of a straight cylinder) is not observed. This point has to be confirmed by a 3D simulation of configuration n°2, in order to find out whether other effects do offset this 2D axisymmetric containment effect or not.

Conclusion

In order to improve its knowledge on blast wave propagation, IRSN has developed a laboratory scale set-up able to perform detonations of solid explosives against rigid structures. In July, 2017, the 7th experimental campaign was conducted on this set-up to study the shock wave propagation around a convex structure. Three configurations have been tested, involving a charge of 50g of TNT equivalent: one configuration in free field and two configurations with a horizontal semi-cylinder placed at 0.6 m and 0.4 m from the charge's center.
After a calibration phase, the pressure data obtained by experiment have been compared with results from simulations performed using LS-DYNA and OURANOS (French software program developed by CEA). This comparison has shown that both software programs are able to give results in the experimental uncertainty of 20 %. However, in terms of reflected pressure on the cylinder, OURANOS seems to give higher results, with a lower error compared to estimation made with literature references.

This work will be completed by a comparison between simulation and experiment for the positive impulse (experimental results are not yet processed for cylinder configurations). Additional simulations (3D dimension) and experiments have to be conducted to confirm these first results based on pressure sensors. In particular, an experimental campaign implementing a technology able to visualize the shock wave propagation could make possible a better understanding of phenomena and a more precise evaluation of software programs capability to reproduce them.

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