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High explosive simulation using arbitrary Lagrangian-Eulerian formulation

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Abstract

A number of studies are underway at DRDC Valcartier looking at damage inflicted by improvised explosive devices (IEDs) in order to design retrofits to protect military vehicles and their occupants. Throughout these studies, numerical tools were developed to allow better modelling of blast wave interaction with vehicles. In this study, an Arbitrary Lagrangian Eulerian formulation was used to treat shock wave propagation in the air. The numerical model was first explored by comparing the numerical results (pressure and impulse) with experimental data found in the literature and second with numerical solutions based on the conventional weapons calculation software (CONWEP). Various parametric studies were also conducted in order to correlate numerical results more closely to the experimental data and also to assess for model independence upon mesh characteristics. The developed numerical model will be used to conduct a vulnerability study on a light armoured vehicle.

Résumé

Un programme de recherche est en cours à RDDC Valcartier afin de réduire la vulnérabilité des véhicules blindés légers face aux engins explosifs improvisés *IED* et pour concevoir une protection pour ces véhicules ainsi que leurs occupants. Dans ce programme, des outils numériques ont été développés pour permettre de mieux modéliser l'interaction de l'onde de choc avec les véhicules. Dans cette étude, un modèle basé sur la formulation *Arbitrary Lagrangian Eulerian* a été utilisé pour traiter la propagation de l'onde de choc dans l'air. Les résultats du modèle numérique ont été validés de deux manières : des données expérimentales provenant de la littérature et les résultats des calculs du logiciel CONWEP. Une vaste étude paramétrique a également été entreprise afin de corréler les résultats numériques avec les données expérimentales. De plus, l'indépendance du modèle numérique par rapport au maillage a été évaluée. Le modèle numérique développé sera utilisé pour entreprendre une étude de vulnérabilité sur un véhicule blindé léger.

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Executive summary

High explosive simulation using arbitrary Lagrangian-Eulerian formulation:

Amal Bouamoul; Tuong-Vi Nguyen-Dang; DRDC Valcartier TM 2008-254; Defence R&D Canada – Valcartier; October 2008.

The study of highly time-dependent and non-linear phenomena such as material failure of a light armoured vehicle subjected to high explosive blast or improvised explosive devices (IEDs) requires better modelling of blast wave propagation, intensity and its interaction with structures. The goal of developing such models is to provide efficient methods for assessing vehicle structural vulnerability to blast and to assist in the design of protection for present and future vehicles.

In this study, the Arbitrary Lagrangian Eulerian formulation was used to treat the shock wave propagation in the air. Comparisons with experimental results from literature and CONWEP predictions were made in order to explore the numerical model. Several parametric studies were conducted. As a result, the model was optimised by the means of an artificial bulk viscosity together with an optimized mesh coarseness, geometry and explosive mass scaling factor. The developed model will be used to conduct a vulnerability study on a light armour vehicle.

Sommaire

High explosive simulation using arbitrary Lagrangian-Eulerian formulation:

Amal Bouamoul; Tuong-Vi Nguyen-Dang; DRDC Valcartier TM 2008-254; R & D pour la défense Canada – Valcartier; Octobre 2008.

L'étude des phénomènes non linéaires et ceux qui dépendent du temps tels que la rupture de la coque d'un véhicule blindé léger soumis au souffle d'un explosif ou des aux engins explosifs improvisés *IED* exige de modéliser précisément la propagation, l'intensité et l'interaction de l'onde de choc avec les structures. L'objectif de développer de tels modèles est de fournir des méthodes efficaces pour évaluer la vulnérabilité structurale des véhicules au souffle et aider à la conception de la protection des véhicules présents et futurs.

Dans cette étude, un modèle basé sur la formulation *arbitrary Lagrangian Eulerian* a été utilisé pour modéliser la propagation d'un explosif dans l'air. Une comparaison avec des résultats expérimentaux provenant de la littérature et de CONWEP a été faite afin de valider le modèle numérique. Plusieurs études paramétriques ont été réalisées. En conséquence, le modèle a été optimisé à l'aide du coefficient *Bulk* de viscosité, un accoisement de la résolution de maillage et un facteur d'ajustement pour la masse de l'explosif. Le modèle développé sera utilisé pour entreprendre une étude de vulnérabilité sur un véhicule blindé léger.

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1 Introduction

In an effort to protect military vehicles and their occupants from damage inflicted by improvised explosive devices (IEDs), a number of studies are underway at DRDC Valcartier including modelling blast wave propagation and its interaction with structures. Damages to a vehicle result from material deformation at high strain rate and fragments impact. Structural solutions for these physical phenomena require a fully coupled fluid-structure interaction algorithm, equation of state for explosive and constitutive models for materials and explosives.

In this memorandum, the LS-DYNA code was used to investigate the possibility of numerically modelling the blast wave formed from a detonation of an explosive and its propagation in air. The LS-DYNA code was chosen for its ability to handle all at once, blast wave formation and propagation, fully coupled fluid-structure interaction and material deformation at high strain rate. The developed model will be then used to explore the vulnerability of the LAV III vehicle under specific explosive charges.

1.1 ALE formulation

A hydrocode is a finite element algorithm for the modelling of fluid flow at all speeds in mechanics of continuous media. It can therefore be used to treat various rheological models of material behaviour at high strain rate. Hydrocodes can be based on either Lagrangian or Eulerian formulation.

In a classical Lagrangian formulation, the computational mesh defines the geometry of the problem. At each time step, variables of interest are computed on every node and the mesh is updated to account for material deformation. When materials undergo large deformations over short periods, elements from the mesh become distorted, thereby degrading accuracy.

In an explicit code, the time step between each cycle is determined by the smallest element length or feature, according to the Courant-Friedrich-Levy (CFL) condition, which states that the time step should be smaller than the time needed for the wave of interest to span an element. CFL condition is given in Equation 1.

$$\Delta t \langle \frac{\Delta x}{C_s} \qquad (1)$$

Where, C_s is the sound speed, Δx is the element width and Δt is the time step. Unfortunately, this condition often results in an increase of computational time to a prohibitive value. Moreover, large node displacement might lead to premature ending of the calculations when negative element volumes are obtained. Thus, high strain-rate problems involving large fluid distortion cannot be solely resolved with Lagrangian formulation.

The second approach is the Eulerian formulation. In this approach, the computational grid is fixed in space while material passes through it. Among problems that are encountered when using Eulerian formulation to solve large deformation problems are the difficulty to simulate the interaction of multiple materials that may occupy one element.

From the brutal expansion of the gaseous reaction products of an explosive results a shockwave leading to a highly stressed state. Therefore, significant deformation of the continuous medium (and of the mesh) is inevitable and blast analysis cannot be achieved using Lagrangian or Eulerian formulations. An alternative to the classical formulations is a combination of both Lagrangian and Eulerian methods. This method is called the Arbitrary-Lagrangian-Eulerian formulation (ALE). In the latter approach, there are two phases in each cycle. The Lagrangian approach is first used followed by an advection phase were flows are taken into account and mesh regularity is controlled by remapping nodes to their initial position (with regard to the Eulerian frame). In other terms, the ALE approach combines the advantages of both the Lagrangian and Eulerian formulations, namely the precision of boundary displacement and handling of distortions, respectively.

In this study, the LS-DYNA hydrocode, which is a finite element algorithm for the study of very intensive loading on materials and structures, was used to simulate the detonation of high explosive using ALE approach.

1.2 Typical blast wave of high explosive

Blast waves are associated with rapid energy release processes such as explosions. Detonation of a high explosive (HE) is achieved by compressing and heating of the constituents. As a result, a chemical reaction is triggered and propagated supersonically at the Chapman-Jouget velocity through the explosive. The violent expansion of the gaseous products generates a strong shock wave that propagates into the ambient medium. Shock waves are created because the sound speed increases with increasing temperature in a compressible flow. As a matter of fact, the wave travels faster than the sound speed in the ambient medium. The various properties of the fluid (density, pressure, velocity and Mach number) fluctuate almost discontinuously. In atmospheric conditions, with idealized specific heat ratio $\gamma = 1.4$, the density and pressure across the shock increase whilst the speed decreases and the shock weakens as its Mach number decreases. When the flow Mach number becomes sonic $M = 1$, the jump in pressure, density and speed vanish and the shock fades away.

The typical pressure versus time curve at a stationary point (in the inertial reference frame) is presented in Fig. 1. The positive compression phase is characterized by a peak overpressure, p_s, above that of the ambient medium, p_o. The pressure immediately decays, as a function of time from its peak value. A negative expansion phase follows where the pressure drops below the ambient level. The time at which this shock occurs is termed the time of arrival, t_a. The duration of the shock, t_d, is the time between the time of arrival and the time at which the pressure reaches that ambient pressure. Another non-negligible aspect of a shock is its specific impulse, I, the momentum imparted in a blast (Eq. 2). It can also be viewed as the area under the pressure-time curve. Its magnitude often determines structural damage and injuries caused by the blast.

The duration of the shock increases with the distance from explosion, whereas the peak pressure decreases. With high-energy blasts, subsequent minor pressure maxima following the main one can be recorded although they are often disregarded because they occur with decreasing amplitude and are rapidly damped in the air. As the primary blast wave is moving outward, the expansion wave travels inward. When reflected at the blast center, the then created outward-moving shock wave is referred to as the secondary shock. Tertiary shock can sometimes be observed since the cycle of compression and rarefaction is recurring periodically. Finally, reflections on grounds, walls or obstacles are much more likely to cause secondary and tertiary shocks than reflection of shock on itself.

The internal structure of a shock front can be approximated by means of an equation of state together with the Rankine-Hugoniot relations that are based on the conservation of mass, momentum and energy through an adiabatic shock. These relations enable thermodynamic variables to be determined downstream as well as upstream.

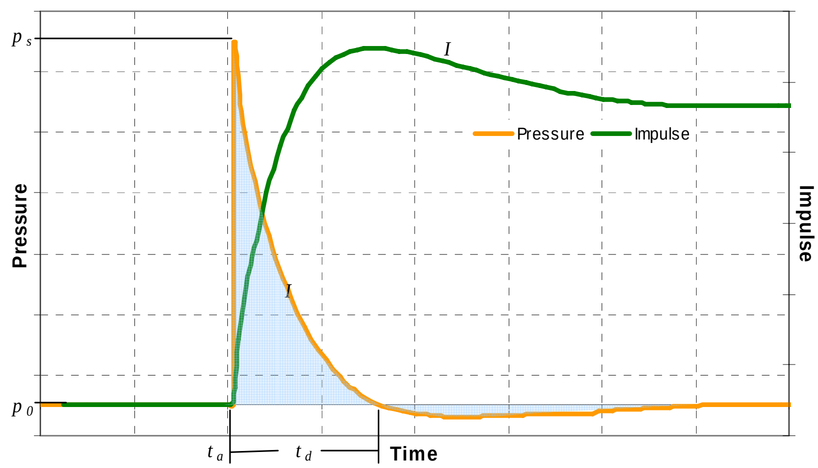

Figure 1: The typical pressure versus time curve at a stationary point

$$I = \int_{t_a}^{t_a+t_d} P(t)dt \qquad (2)$$

1.3 Artificial bulk viscosity

Although they are mathematically treated as discontinuities, shocks do have a narrow thickness on the order of a few collision mean free path in the ambient gas. For air at STP, the mean free path is estimated to 70 nm. Thus, to keep the accuracy of the results, the mesh size should be scaled until the shock is resolvable by each individual element. In practice, this method is not viable because the algorithm is requested to handle a massive amount of calculation. In fact, the size of the mass-stiffness matrix increases with the number of computational zones. Furthermore, the equations of conservation of mass, momentum and energy across a shock require that kinetic energy be transformed into internal energy or heat. In the absence of physical viscosity in the immediate vicinity of the shock, an artificial unphysical one was added to dissipate the excess of energy. This has the effect of thickening the shock and smearing the discontinuity into a smooth transition zone, and thus, the shock is automatically captured on the computational mesh.

As implied by its designation, the artificial viscosity possesses the basic properties of a real viscosity. This is a requirement to avoid significant unphysical results [Ref. 1]. That is:

- it generates entropy and decreases kinetic energy (dissipative);
- it varies uniformly with the velocity field;
- it vanishes with uniform compression and rotation;
- and, it vanishes with sufficient expansion.

In LS-DYNA code [Ref. 2], the artificial viscosity is formulated as follows:

$$
\begin{aligned}
q &= \rho l \left(C_o l \left(\sum \frac{d\varepsilon_{kk}}{dt} \right)^2 - C_1 a \left(\sum \frac{d\varepsilon_{kk}}{dt} \right) \right) && \text{if } \sum \frac{d\varepsilon_{kk}}{dt} \langle\ 0 \\
q &= 0 && \text{if } \sum \frac{d\varepsilon_{kk}}{dt} \geq 0
\end{aligned}
\qquad (3)
$$

Where *q* is added to the pressure term in the momentum and energy equations [Ref. 2], C_o and C_1 are dimensionless constants, *l* is a characteristic length given as the cubic root of the volume, $\sum \frac{d\varepsilon_{kk}}{dt}$ is the trace (summation over the diagonal of the matrix) of the strain rate tensor, ρ is the density and *a* is the local speed of sound.

2 Air blast model

ALE formulation was used to treat high explosive blast propagation. An air-blast model was developed with the LS-DYNA version 970, revision 6763.169 explicit code. All calculations were performed on Linux Workstation platform with Linux 2.4.21 operating system. The ALE blast model was explored by two means: comparison with experimental data published in open literature [Ref. 3] and comparison with numerical solutions based on a pure air blast calculation of above ground air-blast (no ground or reflections on obstacles were considered) of high explosives using CONWEP code [Ref. 4]. Various parametric studies were also conducted in order to correlate numerical results more closely to the experimental data and to assess model independence upon mesh characteristics.

2.1 Spherical domain

Air-blast geometric model consists of two concentric spheres, the inner one being the explosive and the outer one representing the air (Fig. 2).

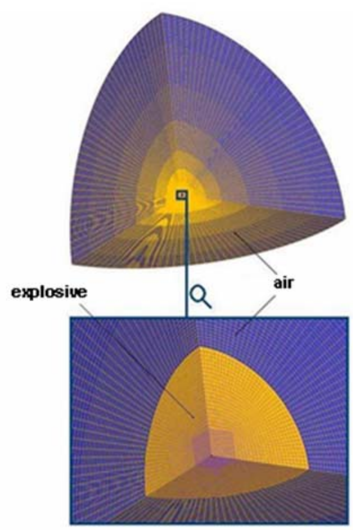

Figure 2: Finite element model with coarse mesh

A spherical explosive burst generates spherical blast waves expanding radially outward from the point source. Thus, for the modelling of the ambient medium, this geometry was preferred so as to ease radial wave propagation through the mesh. Given the problem symmetry, simplification of the model was possible by considering a sphere octant. As a result, symmetry conditions with 3 degree of freedom were set on nodes lying on every cutting plane. Moreover, initial pressure loading and non-reflecting boundary conditions corresponding respectively to the *LOAD_SEGMENT and *BOUNDARY_NON_REFLECTING cards in the LS-DYNA input deck were applied to all elements on the air-sphere free surface. Hence, pressure waves were dissipated from the mesh at the boundaries, therefore modelling an infinite domain.

Air and explosive were discretized into hexahedron elements. Care had been taken to keep element lengths within reasonable range with the aim of maximizing computational precision without degrading the time step. The sphere octant was approximately 3 m radius and totalizing 302 000 elements, 270 000 for the air and 32 000 for the explosive. The element volume varied between $1.2E^{-10}m^3$ and $6E^{-4}\,m^3$. The explosive modelled for the purpose of this exploration was C4. Its radius was 0.0407 m with mass 0.454 kg (1 lb). C4 was modelled with the *MAT_HIGH_EXPLOSIVE_BURN card and with the Jones-Wilkins-Lee (JWL) equation of state (Eq. 4).

$$P_s = A\left(1-\frac{w}{R_1V}\right)e^{-R_1V} + B\left(1-\frac{w}{R_2V}\right)e^{-R_2V} + \frac{w}{V}E \qquad (4)$$

Where *P* is the pressure and the subscript ‘‘s’’ denotes reference to isentropic compression or expansion. *A*, *B*, R_1, R_2 and *w* are constants which the performance values are given in Table 1. V and E are the specific volume and the internal energy. In table 1, ρ, p_{CJ} and V_d are mandatory for the *MAT_HIGH_EXPLOSIVE_BURN model.

Table 1: C4 and air equation of state parameters

C4 PARAMETERS		AIR PARAMETERS	
A, (Pa)	609.8 E9	γ	1.4
B, (Pa)	13.0 E9	E_o, (Pa)	2.5 E5
R_1	4.5	ρ_o, (kg/m^3)	1.23
R_2	1.4	p_c	0
E, (Pa)	9.0 E9	μ_c	0
w	0.25		
V_d, (m/s)	8193		
ρ, (kg/m^3)	1600		
p_{CJ}, (Pa)	2.8 E10		

Likewise, the ambient air was modelled with the *MAT_NULL card and with the gamma law through the linear polynomial equation of state (Eq. 5).

$$p = (\gamma - 1)\frac{\rho}{\rho_0}E \tag{5}$$

Pressure cut-off (P_c) is used to limit the amount of pressure that can be generated by tensile loading. In *MAT_NULL card, this pressure was set to zero since air do not allow tension. Similarly, since the inertial forces were dominant, the flow was assumed to be inviscid and thus the dynamic viscosity coefficient μ_c could be omitted. It is worth of note that both explosive and air used ALE formulation.

Pressure history from the numerical model was recorded at 200 kHz and 1.52 m from the center of explosion likewise the experimental one. Note that no artificial viscosity was used for these calculations. Comparison of the results with CONWEP and experimental data [Ref. 3] showed mediocre correlation (see Fig. 3). The pressure jump did not occur and the pressure value rose smoothly over a relatively long time lapse (~ 0.5 ms). The CONWEP peak pressure is 3.4 E5 Pa, the experimental peak pressure is 2.8 E5 Pa and the obtained numerical peak pressure is 1.8 E5 Pa (representing -36% relative error). The numerical impulse is 44% less than the CONWEP impulse. In order to lighten the report, only comparisons with experimental result were made. The second peak of pressure observed in the experimental data was du to the reflection from the support of the charge (not ground) and was not modelled numerically.

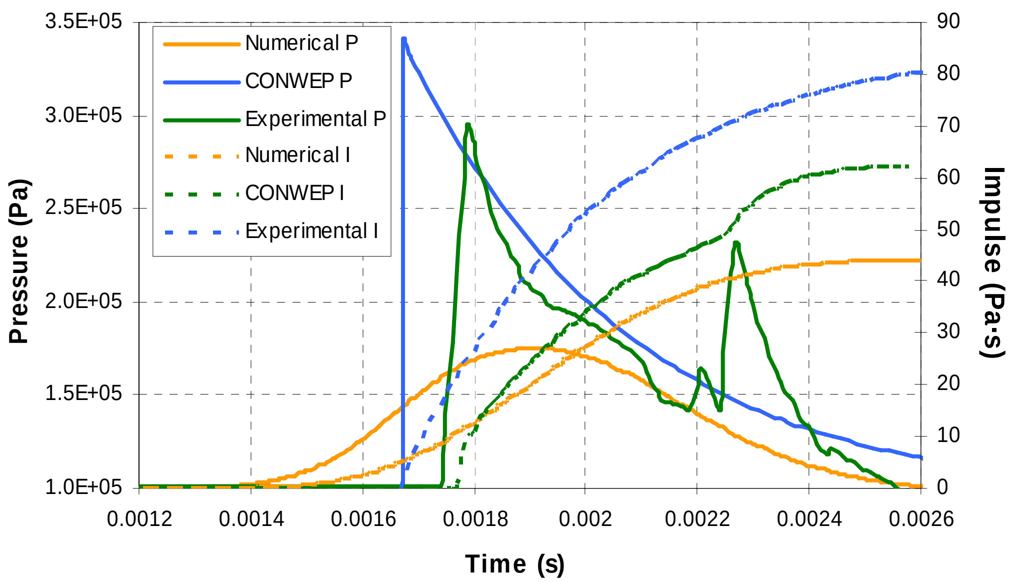

Figure 3: Comparison of numerical results (coarse mesh) with CONWEP and experimental data from Ref. 3 (1 lb C4). In the legend, P means pressure and I the impulse

2.1.1 Mesh sensitivity analysis

A series of meshes with various coarsenesses were created in order to conduct mesh sensitivity analysis. Details concerning these meshes are summarized in Fig. 4. Element ratio (its length divided by its width) was kept below 3:1 to ensure a three-dimensional analysis.

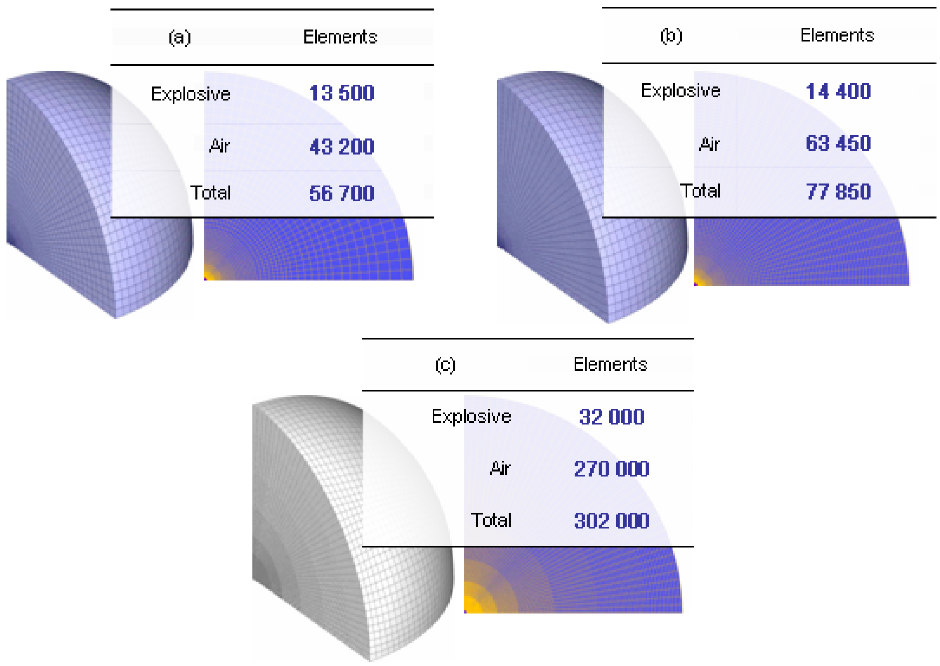

Figure 4: Total elements in coarse mesh (a), fine mesh (b) and very fine mesh (c)

As expected, better agreement between numerical and experimental results was achieved with increased mesh resolution. However, accuracy did not significantly increase from a 77 850-elements mesh to a 302 000-elements mesh (corresponding to a ~4 factor), whereas the calculation cost increased appreciably. The elapsed time increased from 15 minutes to 1 hour 26 minutes and the memory usage quadrupled, all for a gain in accuracy on the peak pressure of only 9% (Fig. 5). Two experimental impulse curves were given in Fig. 5 (with and without support for the explosive). Since the support was not modelled, the numerical impulse was compared with the impulse curve corresponding to the one without the explosive support. For the three meshes, the impulse curves were different but with the same finale total impulse which was equal to 44.2 Pa.s representing -16% relative error regarding the experimental impulse (equal to 52.6 Pa.s). Only impulse curve of the coarse mesh is given in Fig. 5. Computational time and total memory usage for an explicit solution, when solving with single precision and using one processor are presented in Table 2. In addition, double precision calculations increased computational costs drastically without significantly affecting the results.

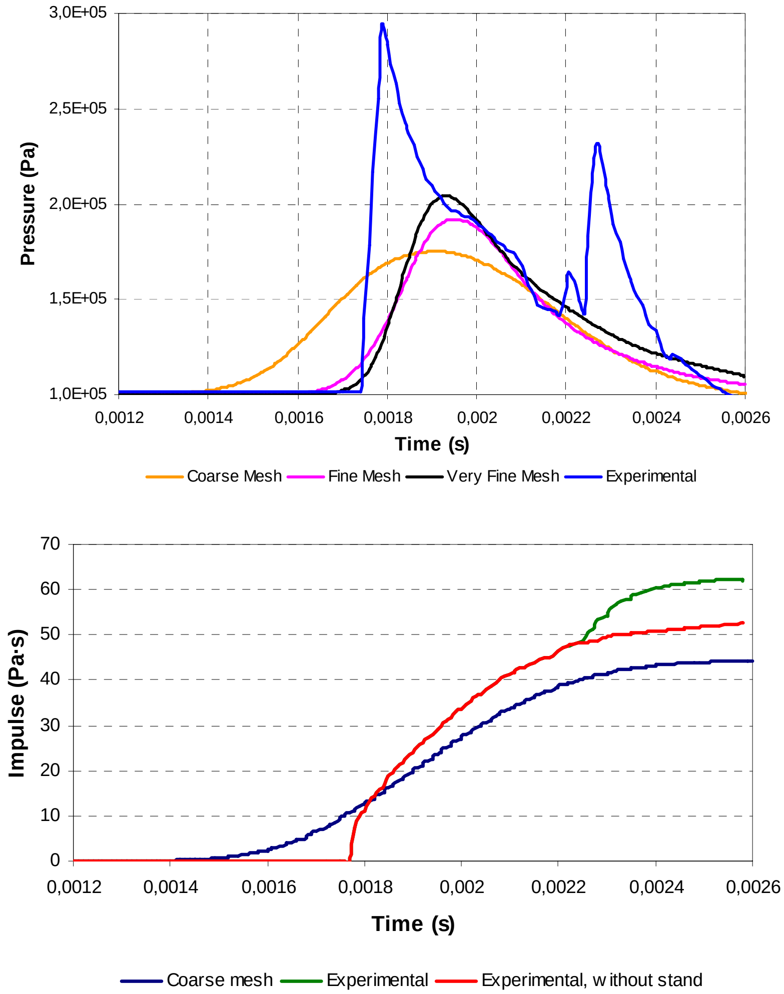

Figure 5: Pressure and impulse profiles for different mesh and from experiments (1 lb of C4 with stand)

Table 2: Computational cost and relative errors for various mesh-coarseness

	COARSE MESH	FINE MESH	VERY FINE MESH
Elements	56 700	77 850	302 000
Elapsed time	13 min 21 s	14 min 56 s	1 h 26 min 02 s
Relative Error on peak overpressure	-36%	-31%	-27%
Relative Error on total impulse	-16%	-16%	-16%

2.2 Cube domain

A cube-shaped domain with identical boundary conditions as the spherical and the same amount of explosive (1 lb of C4) was also used to assess numerical independence upon mesh geometry. Air and explosive were discretized into hexahedron elements. To achieve an effective comparison, element size in the cubic domain was matched with the dimensions of the elements at 1.52 m radial distance from the center coordinate in the spherical model. Figure 6 shows the cubical mesh model. Results were found to be identical, thus confirming numerical independence between these two types of meshing. For the following simulations, cube-shaped domain was used over the spherical-shape domain for flexibility of a cube to be meshed easily.

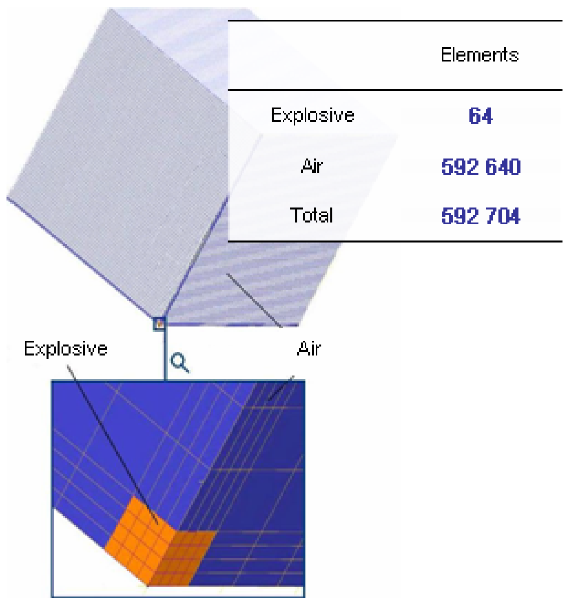

Figure 6: Cubical mesh

2.2.1 *CONTROL_BULK_VISCOSITY

Artificial viscosity was added to the model using the *CONTROL_BULK_VISCOSITY card. For improved results, a parametric study was performed to determine the quadratic coefficient C_o and its linear counterpart C_1 (see introduction, Section 1.3 for an insight of the subject). LS-DYNA default values are respectively 1.5 and 0.06. Various combinations of the coefficients were evaluated ($0.01 \le C_o \le 0.35$ and $0.001 \le C_1 \le 2.5$). As shown in Fig. 7, the peak pressure and the duration of the shock are both affected by artificial viscosity, whereas the total impulse is not. Better agreement with the experimental data was achieved when those coefficients were kept small, as high values resulted in excessive spreading of the shock. Oscillations behind the shock front intensify was observed when $C_o \le C_1$. The maximum peak pressure, 2.17 E5 Pa, was obtained with $C_o = 0.09$ and $C_1 = 0.001$. Therefore, the use of artificial viscosity results in a 4.5% improvement in the accuracy of the calculated peak pressure with a good approximation on the duration and pressure profile.

Other parameters had also a positive effect on the pressure recorded. With the *ALE_REFERENCE_SYSTEM_SWITCH card, the time switches back and forth from the Eulerian to the Lagrangian reference system. As a result, the mesh expands and contracts in the vicinity of the shock. With the modifications stated above, the relative error on the peak pressure was reduced from -36% to -22.5% (the maximum numerical peak pressure is equal to 2.17 E5 Pa).

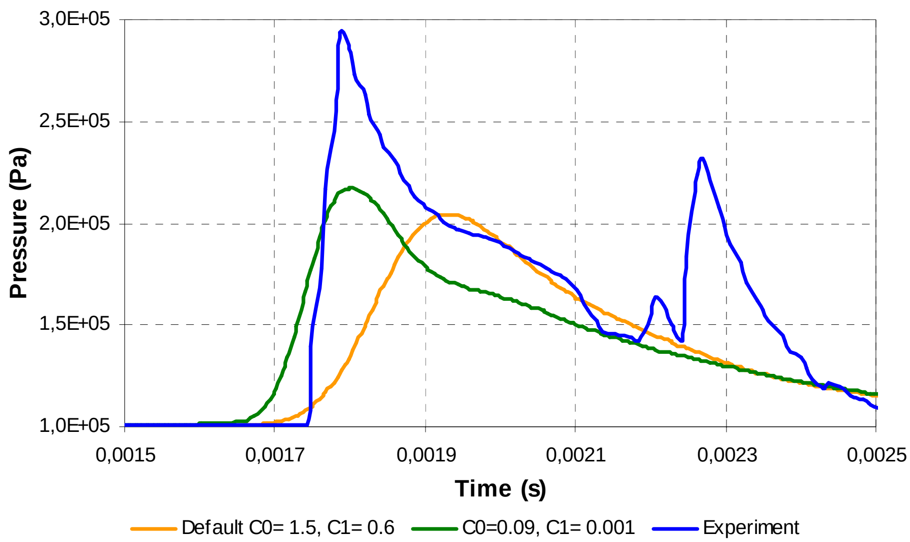

Figure 7: Comparison between experimental data and two different bulk viscosity values: the LS-DYNA default and the one used in this study

Because of the discrepancy between the experimental and the numerical pressure, a compensating scaling factor had to be prescribed to the explosive mass, the determination of its value being discussed in the next sub-section.

2.2.2 Explosive mass scaling

Using a cubic model developed previously, a parametric study was again conducted. The correlation between experimental data and the numerical model for the peak pressure and the impulse variable was assessed for various values of the explosive weight. Some inaccuracies were introduced into the results due to the mesh coarseness and to the inherent inaccuracy of the technique used to pick elements at various distances. In effect, the distance from the center of explosion is calculated on nodes although pressure is accounted in the centre of elements. Thus, uncertainties were caused by an over or underestimation ($\pm 0.0167m$) of the distance from explosion.

The relative error between the maximum experimental overpressure and the numerical model was computed for scenarios in which the explosive mass (l lb of C4) was multiplied by a factor. Good results were obtained when this factor was equal to 1.18 as shown in Fig. 8.

Finally, the simulation of small explosives (containing only a few elements) is to avoid as the inherent coarseness of the mesh may perturb the simulation of the pressure build-up in the explosive at detonation, thereby introducing a substantial error in the measured pressure of the surrounding air. Similarly, large radius explosives have to be modelled with care, for inexactness of the simulation data might arise due to near field effects.

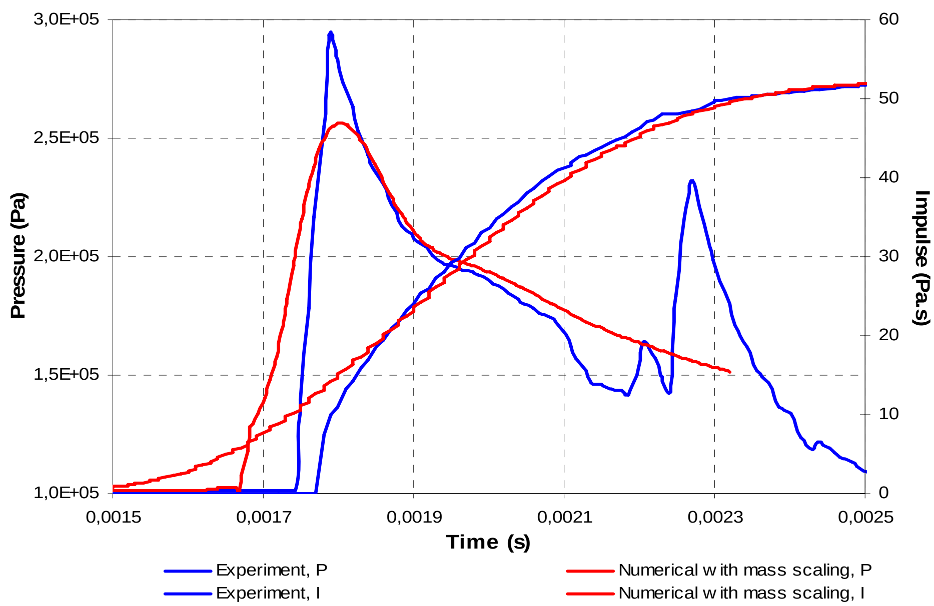

Figure 8: Comparison between experimental and the numerical pressure and impulse profile using a mass-scaling factor

3 Conclusion

A high explosive blast model had been created using an arbitrary Lagrangian Eulerian formulation. Comparisons with experimental results from literature and CONWEP predictions were made in order to validate the numerical model. Several parametric studies were conducted. As a result, the model was explored by the means of an artificial viscosity together with an optimized mesh coarseness, geometry and scaling of explosive mass. Good correlation between the numerical results and experimental data was obtained when using the right combination of solution parameters and multiplying the explosive mass by a factor equal to 1.18.

Further simulations must be conducted in order to simulate well the shock wave from an explosive using an ALE formulation (without using a mass-scaling factor). This may be done by modelling the explosive as a spherical shell that contains high-pressured air with specific profiles. The model developed in this work will be used to explore the vulnerably of the LAV III under specific blast loads.

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List of symbols/abbreviations/acronyms/initialisms

a	Local sound speed
ALE	Arbitrary Lagrangian-Eulerian
C_1	Dimensionless constant
CFL	Courant-Friedrich-Levy
C_o	Dimensionless constant
CONWEP	Conventional weapons calculation software
C_s	Speed of sound
E	Internal energy per unit volume
E_0	Initial internal energy per unit volume
HE	High explosives
I	Impulse
IEDs	Improvised explosive devices
JWL	Jones-Wilkins-Lee equation of state
l	Cubic root of volume
M	Mach number
p_0	Ambient pressure
p_c	Pressure cutoff
p_{CJ}	Chapman-Jouget pressure
p_s	Peak pressure
q	Added pressure due to Bulk viscosity
R	Mass-scaling factor
STP	Standard temperature and pressure
t_a	Time of arrival

t_d	Duration of the shock
V_d	Detonation velocity
V	Specific volume
w	Constant for JWL EOS
γ	Ratio of specific heats
μ_c	Dynamic viscosity coefficient
ρ	Density
ρ_0	Initial density
Δx	Element width
Δt	Time step
$\sum \frac{d\varepsilon_{kk}}{dt}$	Trace of the strain rate tensor

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A number of studies are underway at DRDC Valcartier looking at damage inflicted by improvised explosive devices (IEDs) in order to design retrofits to protect military vehicles and their occupants. Throughout these studies, numerical tools were developed to allow better modelling of blast wave interaction with vehicles. In this study, an Arbitrary Lagrangian Eulerian formulation was used to treat shock wave propagation in the air. The numerical model was first explored by comparing the numerical results (pressure and impulse) with experimental data found in the literature and second with numerical solutions based on the conventional weapons calculation software (CONWEP). Various parametric studies were also conducted in order to correlate numerical results more closely to the experimental data and also to assess for model independence upon mesh characteristics. The developed numerical model will be used to conduct a vulnerability study on a light armoured vehicle.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

High explosive, Blast, ALE formulation.

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