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Numerical Simulation of Tank Behavior to a Inner Explosion

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Abstract

This paper presents a numerical study regarding the behavior of a tank, when an inner explosion occur. This explosion could be the result of any high energy material type. The initiation point of an explosion is very important, especially in the case of an inner explosion, because from such a point the shock waves begin their moving. In this paper the influence of the initiation point position is researched, using one of the most used way by finite element method. The finite element method is applied using special material model, one of the most used equation of state and a methodology which is implemented in some professional programs.

Key words: *explosion, shock wave, material model, finite element method*

Introduction

Any chemical compound, mixture, or device, having the primary purpose to function by an explosion could be named an explosive. Three types of explosions exist: nuclear, mechanical and chemical. This paper is referring only to third type, namely, to chemical explosion.

A chemical explosion is caused by an extremely fast conversion of a solid or liquid compound into hot gases having a much greater volume than the substances from which they are generated. Exothermically reacting shock waves are classified into two types: detonation waves and deflagration waves.

Detonation waves are supersonic and compressive and deflagration waves are subsonic and expansive. The phenomena of detonation is that initial process of an explosion, being a very rapid and stable chemical reaction, which proceeds through the explosive material at a speed, called the detonation velocity.

For majority high explosives, detonation velocity range is from 5,000 to 8,000 meters per second. The detonation wave converts the solid or liquid explosive into a very hot, dense, high-pressure gas. The volume of this gas, which had been the explosive material, is then the source of strong blast waves in air, acting upon different structures, human being and others.

For quantifying blast effects as a result of other explosive than TNT, the mass of the explosive in question is converted into a TNT mass, using different criterions, most used being released kinetic energy, energetic density and released heat by detonation.

Blast Wave Characteristics

The effects of an explosion are primarily caused by the shock (or blast wave), which accompanies the explosion. A blast wave produces an overpressure (atmospheric pressure at standard sea level is 101 kPa) of 3...5 kPa and even more. This overpressure determines the damage degree. This is also determined by the distance from explosion or in other words, by the energy of explosion. In practice, both parameters, distance and explosion energy, are the main factors which are taken into account for damage evaluation.

The study of the blast parameters and of the blast effects starts from the blast wave characteristics, which propagates in the atmosphere (beyond the explosive mass) and from the interaction of this wave with a structure (mechanical structure, civil structure, human beings etc.). The interaction is analyzed considering an impulsive load (direct action upon a structure is much shorter than first natural frequency period), applied to a structure. The blast wave pressure in time is presented in the Figure 1 and versus distance in the Figure 2.

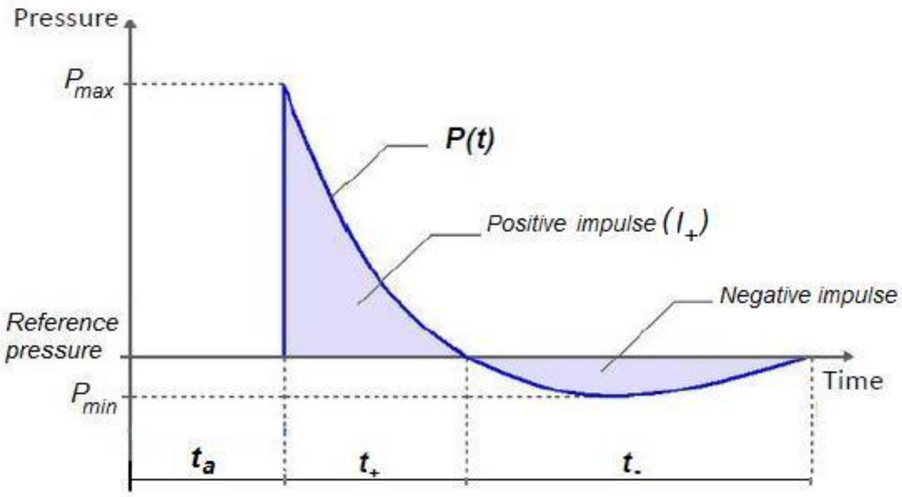


Fig. 1. The pressure function $P(t)$, in a point near the explosion

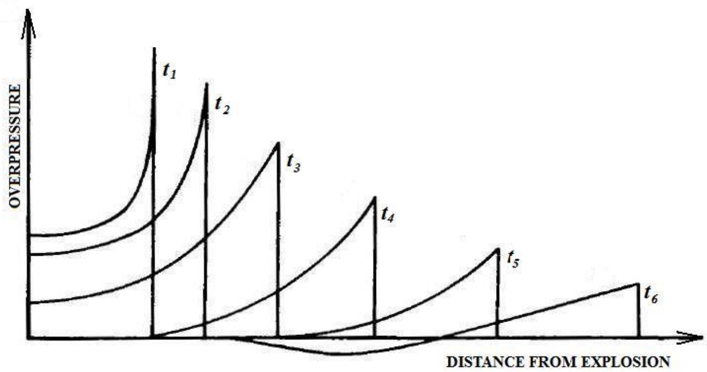


Fig. 2. Overpressure versus distance

The main parameters of an explosion are: peak positive overpressure (P_{pos}; $P_{\max}$), positive duration (t_{pos}; t_+), negative (under) pressure (P_{neg}; $P_{\min}$), negative duration (t_{neg}; t_-), wave decay parameter (b), the impulse (I) which can be referred to positive (I_+), negative (I_-) or total time period. All these parameters and others, can be referring to the incident (direct) pressure (P_i) or to the reflected pressure (P_r).

By the mechanism of wave formation, the reflected pressure parameters are higher than incident pressure parameters, they occur practically instantaneously and they influence the damage characteristics of the blast wave. Practically, $P_r = P_{\max}$.

The above blast wave parameters can be known by experimental methods, by numerical methods and by empirical formulas (established by numerous experiments and observations). A pure theoretical (analytical) approaching is practically impossible because the blast phenomena is a very complicated one, with many variables which are very difficult to be described by an equation system which to be successfully solved.

The blast loads on structures can be divided into two main groups based on the confinement of the explosive charge (unconfined and confined explosions) and can be subdivided based on the blast loading produced within the structure or acting on structures. This classification is presented in Table 1 and it is very important because each type of load need a specific approaching of analytical or numerical calculus.

Table 1. Blast loading categories

<table>
<tr><th colspan="4">Charge Confinement</th></tr>
<tr><th colspan="2">Unconfined explosion</th><th colspan="2">Confined explosion</th></tr>
<tr><th>Category</th><th>Pressure Loads</th><th>Category</th><th>Pressure Loads</th></tr>
<tr><td rowspan="2">Free Air Burst</td><td rowspan="2">Unreflected</td><td rowspan="2">Fully Vented</td><td>Internal shock</td></tr>
<tr><td>Leakage</td></tr>
<tr><td rowspan="2">Air Burst</td><td rowspan="2">Reflected</td><td rowspan="3">Partially Confined</td><td>Internal shock</td></tr>
<tr><td>Internal gas</td></tr>
<tr><td rowspan="2">Surface Burst</td><td rowspan="2">Reflected</td><td>Leakage</td></tr>
<tr><td rowspan="2">Fully Confined</td><td>Internal shock</td></tr>
<tr><td colspan="2"></td><td>Internal gas</td></tr>
</table>

This paper presents a particular case, namely, a fully confined explosion, when the structure, a tank made by steel thin plates, is loaded by an internal shock.

Numerical Calculus of the Explosion Effects on Structures

As numerical calculus is concerned, two numerical methods are validated being available today: finite element method (FEM) and free particles method (FPM), especially smoothed particle hydrodynamics (SPH). Finite element method is most used numerical method, but with some specific improvements regarding large deformations and strong non-linearity aspects which occur during explosion. So, a new finite element formulation was implemented in professional codes, named arbitrary Lagrangian Eulerian (ALE).

The Figure 3 illustrates the main differences between those three formulations of finite elements. As we can see, in ALE formulation, both mesh and grid are going to be moved and next to it, finite elements are deformed. Only this formulation is fitted to describe explosion phenomena, when large deformations, large strain and high strain rate occur. Without this formulation, any finite element program cannot run and especially correctly run. This finite element formulation is applied to air as well as to the explosive. Any structure, loaded by a blast wave, can usually be modelled by Lagrange formulation of the finite elements.

The developing of the finite element method, for blast wave effect calculus, lead to special material models for explosive and for air. The explosive material model takes into account those specific transformations from solid to gas and its behaviour like a fluid.

The air material model has to describe the real behaviour of the air. Such material models exist and they are implemented in many professional or dedicated finite element codes.

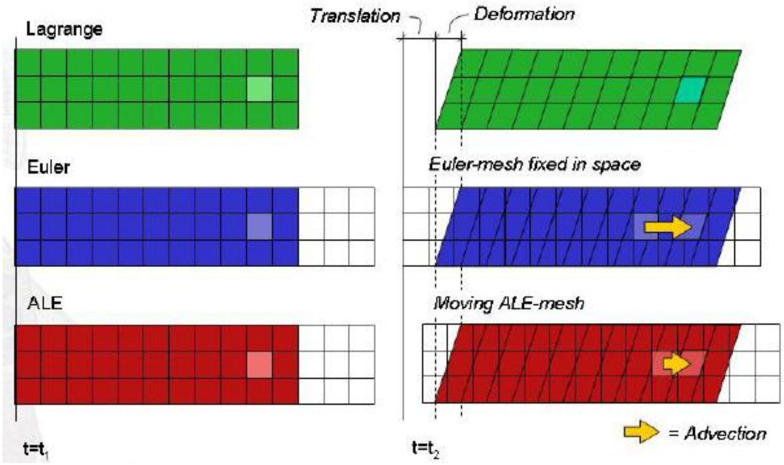


Fig. 3. Finite element formulations

In Ls-Dyna code, for explosive modelling, we can use a special material model named High_Explosive_Burn, which need an equation of state (EOS), which could be Jones-Wilkins-Lee (JWL) or Jones-Wilkins-Lee-Baker (JWLB). Also in Ls-Dyna code, for air modelling, we can use a special material model named Mat_Null, which also need an EOS of type Linear_Polynomial or Gruneisen type.

For the modelling of the fluid structure interaction (FSI), in the last period, a special numerical procedure was created and implemented. So, in Ls-Dyna code, this procedure is called Constrained_Lagrange_in_Solid. By this procedure, the FSI takes place between finite elements in ALE formulation (for explosive and air) and finite elements in Lagrangean formulation (for structure).

A special attention has to be paid to the boundary conditions; these consist in two kinds: boundary conditions coming from symmetry conditions (usually conditions representing the blocking of different degree of freedom) and an other kind regarding to the boundary surface of the air domain. For this type of boundary conditions, a special procedure was created, named boundary_non_reflecting, by which the blast wave can not be reflected inside of air domain; so, the blast wave has a normal behaviour, going far away beyond the boundary of air domain.

Numerical models with Finite Elements

There are some approaching ways for a numerical modelling of the explosion effects upon structures. ***A first way*** consists in modelling, by finite elements, the explosive, the air and the structure. ***The second way***, for the numerical modelling of the explosion effects upon a structure, consists in combining the empirical methods with numerical methods. There are a lot of empirical calculus relations, but their presentation here is beyond of this paper aim.

In this way, only the structure is modelled by finite elements and loading with blast wave pressure is made by special procedures, named in the Ls-Dyna code, Load_Blast, Load_Brode or Load_Blast_Enhanced (LBE). By this procedure (LBE), more than one explosion source can be taken into account, at the same time or at different explosion time.

All these procedures need key words, like Load_Segment, for applying the pressure on a specified surface. About explosion, only its type, its mass and its position must be provided, without any geometric or FE modelling.

Such a model has an important advantage regarding computer-time, and then it offers the possibility to use different blast wave profile, including an user defined profile.

For solving the adopted problem (a tank with an inner explosion), being a fully confined explosion, the easier and most efficient way of FE modelling is represented by the second way described above.

Material models for explosives

There are some professional programs which have in their material library dedicated material models for explosives. For instance, Ls-Dyna code - one of the famous professional program - has such material model named MAT_HIGH_EXPLOSIVE_BURN.

This material model, like others, uses an EOS and can simulate detonation by release controlling of the chemical energy. So, firstly, in the initialization phase, a lighting time t_1 is computed for each element by dividing the distance from the detonation point to the center of the element by the detonation velocity *D*. The burn fraction F is the maximum of values F_1 or F_2:

$$F_1 = \begin{cases} \dfrac{2(t-t_1)\cdot D\cdot A_{e\max}}{3v_e} & t > t_1 \\ 0 & t \le t_1 \end{cases} \tag{1}$$

$$F_2 = \frac{1-V}{1-V_{CJ}} \tag{2}$$

If F exceeds 1, it is reset to 1 and it is held constant. In the relation (1), t is the current time, *V* is the current volume, V_{CJ} is the Chapman-Jouguet relative volume.

The pressure in a high explosive FE is the product between F and the pressure calculated by adopted EOS (p_{EOS}), V is the relative volume and h is the internal energy density per unit initial volume.

Equations of state for explosives

For explosive materials some equations of state (EOS) are available: polytrophic (γ - law) EOS, Jones-Wilkins-Lee (JWL) EOS, Jones-Wilkins-Lee-Baker (JWLB) and Becker-Kistiakowsky-Wilson (BKW) EOS etc. The most used EOS are JWL and JWLB.

The JWL equation of state (3) defines pressure as a function of relative volume, V, and internal energy per initial volume, h, as:

$$p = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega h}{V} \tag{3}$$

where ω, *A*, *B*, R_1 and R_2 are user defined input parameters. The JWL equation of state is used for determining the pressure of the detonation products of high explosives. In the same aim, ***JWLB equation of state*** (4) is used, but the pressure of the detonation products is:

$$p = \sum_{i=1}^{5} A_i\left(1-\frac{\lambda}{R_i V}\right)\cdot e^{-R_i V} + \frac{\lambda h}{V} + C\left(1-\frac{\lambda}{\omega}\right)\cdot V^{-(\omega+1)} \tag{4}$$

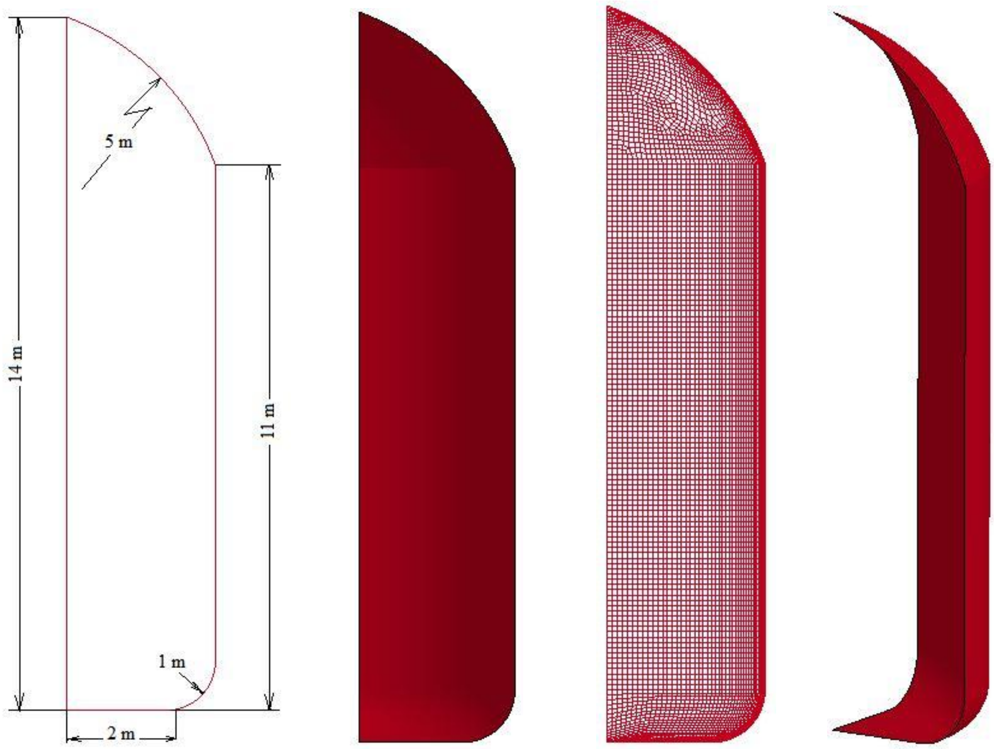
in which,

$$\lambda = \sum_{i=1}^{5} A_i\left(A_{\lambda i}V + B_{\lambda i}\right)\cdot e^{-R_{\lambda i}V} + \omega \tag{5}$$

where A_i, R_i, $A_{\lambda i}$, $B_{\lambda i}$, $R_{\lambda i}$, *C*, and ω are input constants defined for each explosive.

Numerical Analysis of Tank Behavior to a Inner Explosion

A hypothetical model was considered, having the dimensions presented in the Figure 4-a. Considering that the initial ignition point of explosion is placed just on the symmetry axis, a 2D axis-symmetric model could have been used - being the simplest one - but a 3D model was used for 1/4 of structure by reason of symmetry for a better post-processing of results. Details of the considered structure can be viewed in Figures 4-b, 4-c and 4-d.



a) b) c) d)

Fig. 4. Dimensions, geometrical and finite element models

The wall thickness of the tank is constant being of 2.5 mm. Such a structure can be properly modeled with the shell finite elements. So, the finite element type was SHELL163, taken from Ls-Dyna FE library. The material was a steel with elasto-plastic behavior and it was modeled by using the PLASTIC_KINEMATIC. The input material data are presented in the Table 2.

Table 2. Material property of the tank walls

Density	Young Modulus	Poisson Rate	Yield Stress	Tangent Modulus	Cowper-Symond Coefficients		Failure Strain
kg/m^3	MPa	---	MPa	MPa	C	P	---
7850	2.1e+6	0.29	450	0.0	0.0	0.0	0.20

There are some other proper material models (most known being JOHNSON_COOK), but the aim of this paper was only the presentation of an available calculus model together with researching the influence regarding the position of the explosion initiation point.

Occurred explosion inside of tank was equivalent with 20 kg of TNT. For this numerical study, this explosive and its initiate point was placed at different levels on the axis-symmetric axis: 1m, 3 m, 7 m and 11 m. Figures 5...8 present some results when the explosive is placed at 1 m above the bottom. Some results are presented below.

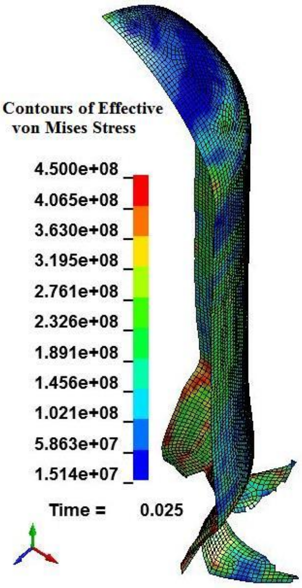


Fig. 5. The stress field on deformed structure

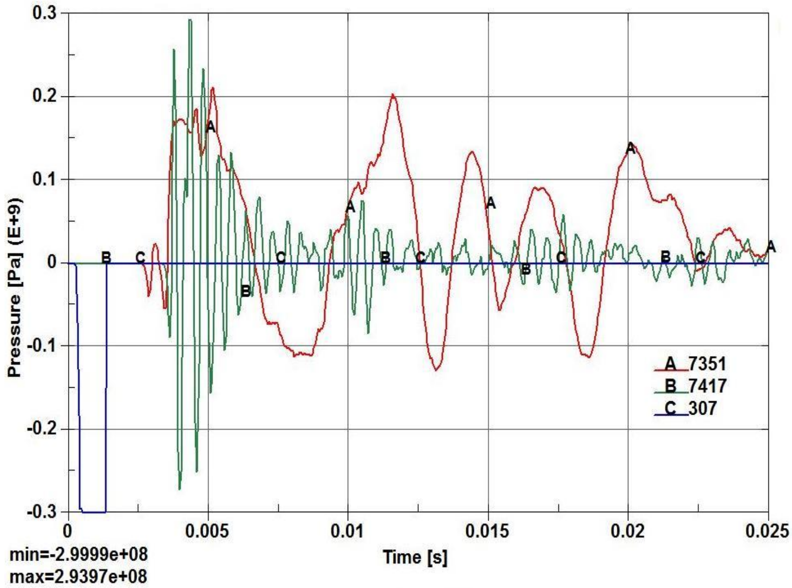


Fig. 6. Time evolution of the element pressure for three finite elements

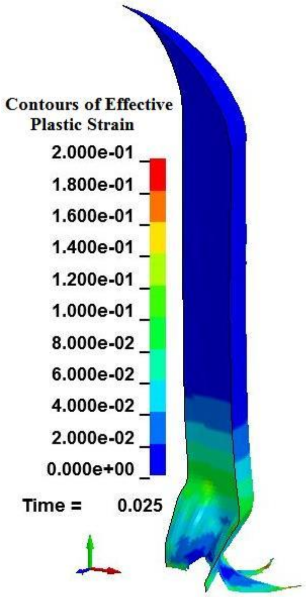


Fig. 7. Plastic strain field on deformed structure

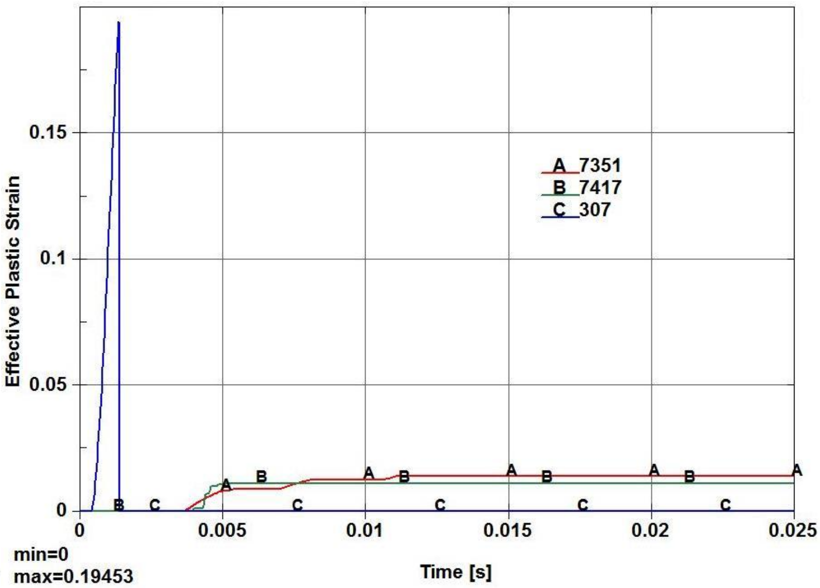


Fig. 8. Time evolution of the plastic strain of the same (specified) finite elements

The finite elements chosen for result postprocessing are in the middle of bottom (307), at the structure top (7417) and just on the upper side of cylindrical wall (7351), at center of structure.

Figure 9 and 10 present some results when the explosive is placed at 3 m above the tank bottom.

Conclusions

The numerical methods, like finite element method or newer free particle method under its version of smoothed particle hydrodynamics are able to simulate the explosion effects upon any structure or to calculate the parameters of detonation or of blast waves.

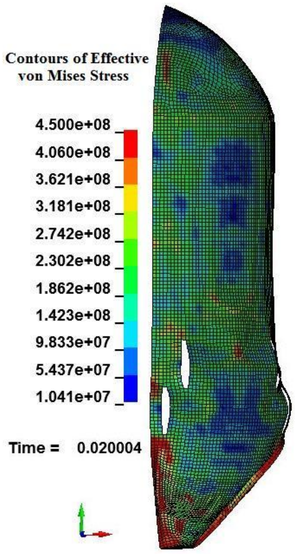


Fig. 9. The stress field on deformed structure

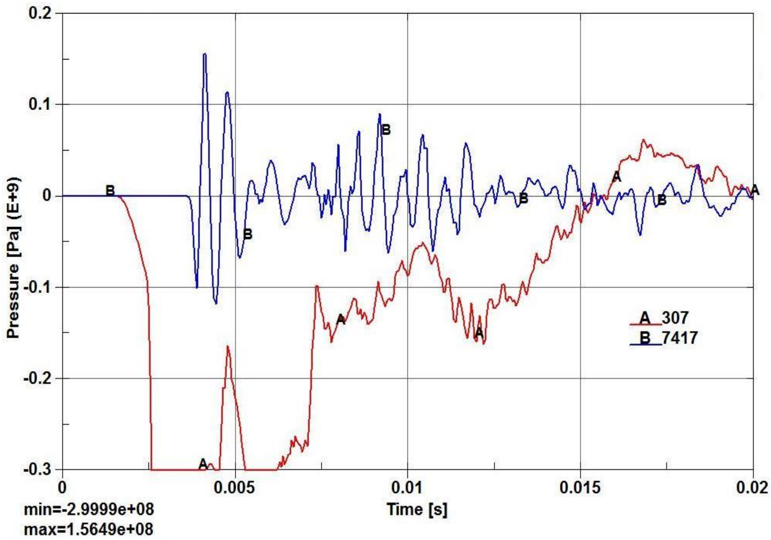


Fig. 10. Time evolution of the element pressure for two characteristic finite elements

This paper presents a model regarding the numerical modeling of an explosion inside of tank and also, which are the effect of explosive placement somewhere in the tank.

Unfortunately, this study is not based on experiment or on a real case, but surely, the model and methodology presented in this paper have a lot of analytical, experimental and numerical fundamentals, verified in other studies (protection against blast waves, ballistic protection for kinetic projectiles etc.).

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Simularea numerică a comportării unui rezervor la o explozie interioară

Rezumat

Această lucrare prezintă un studiu numeric privind comportarea unui rezervor, când se produce o explozie în interior. Această explozie poate fi rezultatul oricărui material exploziv. Punctul de iniţiere al exploziei este foarte important, în special în cazul oricărei explozii interioare, deoarece din acel punct îşi începe mişcarea unda de şoc. În această lucrare, influenţa poziţiei punctului de iniţiere este cercetată folosind unul din modele, una din cele mai utilizate ecuaţii de stare şi o metodologie care este implementată în unele programe profesionale.