MODERN APPROACHES IN NUMERICAL CALCULUS OF THE EFFECTS OF EXPLOSIONS ON STRUCTURES

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Rezumat. Într-o manieră sintetică, această lucrare prezintă cele mai importante caracteristici ale unei explozii şi cele mai folosite formule empirice de calcul ale parametrilor undelor exploziei, în cazul general al exploziilor aeriene. Lucrarea de asemenea prezintă unele modele numerice şi cele mai noi proceduri de calcul a parametrilor exploziei şi a efectelor acesteia asupra structurilor. Modelele şi exemplele prezentate în această lucrare se bazează pe folosirea programului Ls_Dyna. Elementele finite utilizate sunt în formulare arbitrară Lagrange-Euler (ALE) şi de asemenea mai este folosită şi formularea multi-material arbitrar Lagrange-Euler (MMALE). În final, oferă unele modele valide pentru simularea numerică a unei explozii.

Cuvinte cheie: unda exploziei, explozie, FEM, metode numerice, ALE, MMALE.

Abstract. This paper presents in a synthetic way the most important characteristics of an explosion and the most used empirical formulas for calculus of the blast wave parameters, in the general case of an air explosion. The paper also presents some numerical models and the newest procedures used for blast wave parameter and effect calculus upon structures. The models and examples presented in this paper are based on using of Ls_Dyna code. The used finite elements are in arbitrary Lagrangian formulation (ALE) and the procedure of multi material arbitrary Lagrangian formulation (MMALE) is also used. Finally, the paper offers some valid models for numerical simulation of an explosion.

Key words: blast wave, explosion, FEM, numerical procedure, ALE, MMALE

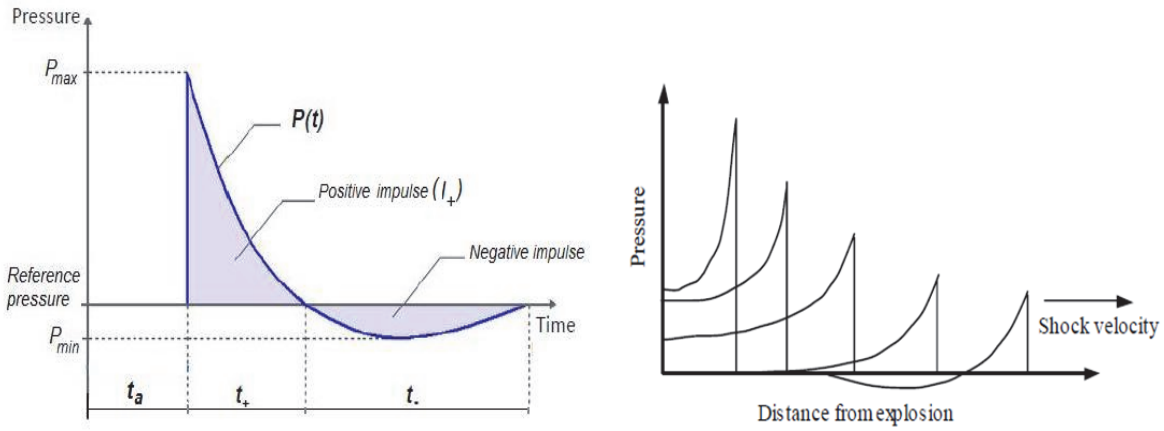
1. INTRODUCTION

By explosion a high energy is released, in a very short time and most important parameters of the air are modified, generating a pressure wave of finite amplitude (Figure 1). The nature of the explosion energy is beyond of this paper, being of physical, chemical or nuclear nature. This paper presents an engineering approaching regarding blast parameters for air explosion (surface burst included) and regarding the effects of the blast wave upon structures.

The detonation of a condensed high explosive generates hot gases under pressure up to 300 kilo bar (30 MPa) and a temperature of about 3000 up to 4000C°. The explosion effect is the result of the interaction between blast (incident and reflected) wave and a structure or other obstacle.

The Figure 2 presents the formatting of the incident and reflected waves, in the case of an air explosion. In such cases, the reflected waves have higher parameters than incident waves, where the coefficient c_R has values between 2 to 10 ($p_{ref} = c_R p_{inc}$).

Figure 3 illustrates the evolution in time of the incident and reflected waves. In the case of a surface explosion, the incident and reflected waves merge instantly. There is no region of regular reflection.



a) b)

Fig. 1. The pressure vs. time (*a*), and vs. distance (*b*), in a point near the explosion.

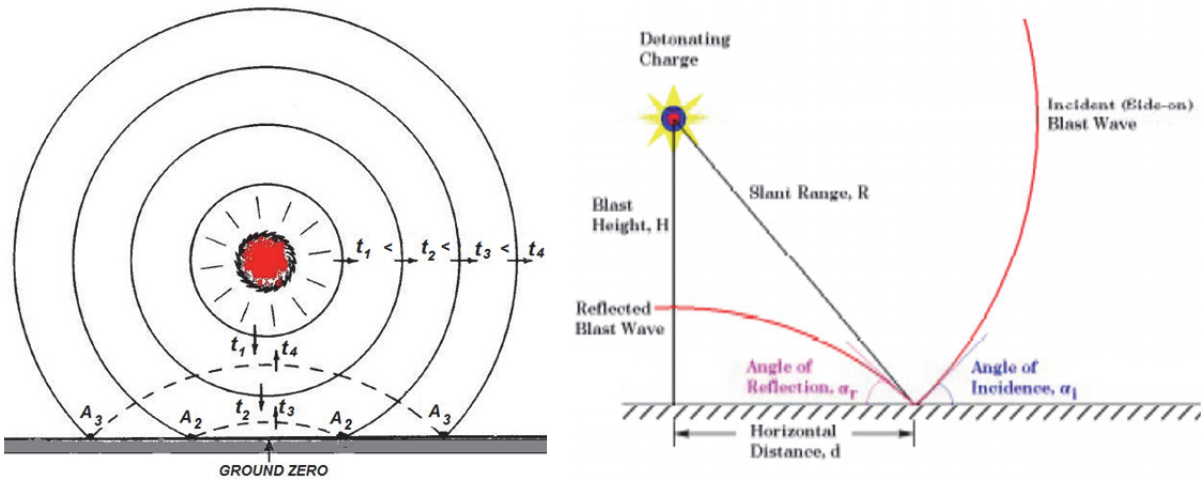


Fig. 2. Incident and reflected waves in the case of an air explosion.

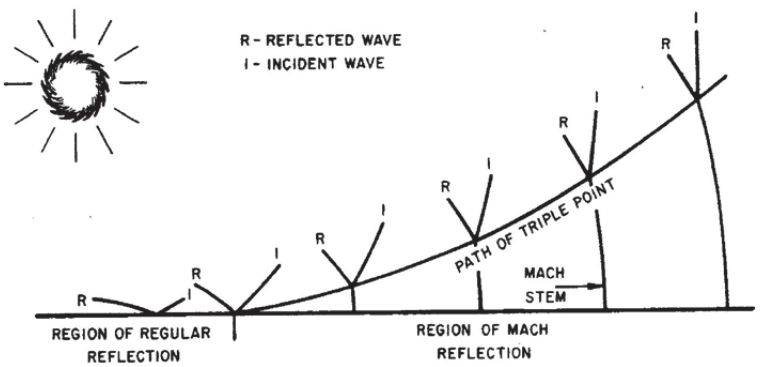


Fig. 3. Evolution of the incident and reflected waves.

The main parameters of an explosion are: peak positive over pressure (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). Generally:

$$P(t) = P_i(t) + P_r(t) \tag{1}$$

The equation (2) can take into account the angle of incidence θ, of the blast incident and reflected pressure, by relation:

$$P(t) = P_i\left(1 + \cos^2\theta - 2\cos\theta\right) + P_r\cos^2\theta \tag{2}$$

When θ is negative (the surface is not facing the point of explosion), then pressure load is just incident pressure. By the mechanism of wave formation, the reflected pressure parameters are higher than incident pressure parameters, they occur practically instantaneously and they determine the damage characteristics of the blast wave. Practically, in this case, $P_r = P_{\max}$.

Explosion calculus has two main aspects: the calculus of blast wave parameters and the calculus of blast wave effect upon structures, human body, civil constructions etc.

Next to experimental methods, all these calculus aspects can be solved by empirical relations or by numerical methods. The most efficient way for explosion calculus consists in combining the empirical and numerical calculus.

2. EMPIRICAL CALCULUS OF THE BLAST WAVE PARAMETERS

There are various empirical relations for the blast wave parameters calculus, all of them being based on experiments. Almost all researchers are referring to spherical charge detonated in air, when the explosive has a spherical shape and is placed somewhere above the ground at a distance h. In the case of an explosion at ground level (surface explosion), the explosive is considered like a hemispherical charge and the parameters could multiplied with a factor grater 1 and less 2. An universal normalized description of the blast effects and parameters can be given by scaling distance Z *(Hopkinson-Cranz)* relative to the ratio:

$$Z = \left(\frac{E}{P_0}\right)^{\frac{1}{3}} \tag{3}$$

where E is the released energy [J/kg] and P_0 is the ambient pressure [Pa].

Experimentally, and from the above relation, all air blast effects and parameters follow the same scaling law, expressed by the scaled distance *Z:*

$$Z = \frac{R}{W^{1/3}} \tag{4}$$

where R is the is the distance [m] from the explosion point to a considered point (where the parameters or effects of blast waves are calculated) and W is the charge weight [kg]. So, the scaled

distance Z is independent of the type of explosion (nuclear or non-nuclear), is independent of the kind of explosive etc.

In the empirical formulas, for blast wave parameters calculus or for blast wave effects calculus, the different simplified models of the blast wave profile are adopted, like in the Figure 4.

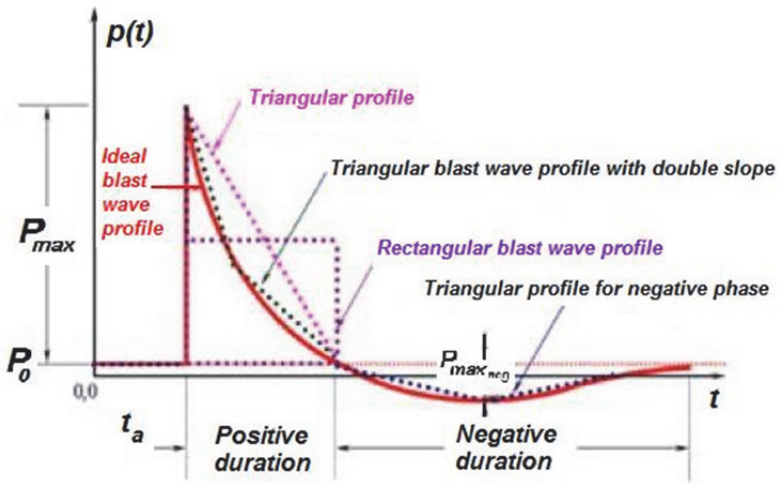


Fig. 4. Simplified models of the blast wave profile.

Analytically, the ideal blast wave profile was first time modeled by Friedlander in 1946 by relation (6), where t_+ is the positive duration.

$$P(t) = P_{\max}\left(1 - \frac{t}{t_+}\right)e^{-\frac{t}{t_+}} \tag{5}$$

An other relation - modified Friedlander – was adopted (relation no. 6), by introducing of the decay parameter b:

$$P(t) = P_{\max}\left(1 - \frac{t}{t_+}\right)e^{-b\frac{t}{t_+}} \qquad \text{gt5v} \tag{6}$$

The decay parameters (a and b) are different in positive (t_+) and negative ($t_$) durations, so, relation (6) becomes:

$$P(t) = P_{\max}\left(1 - \frac{t}{t_+}\right)e^{\left(-a\frac{t}{t_+}\right)} + P_{\min}\left(1 - \frac{t}{t_-}\right)e^{\left(-b\frac{t}{t_-}\right)} \tag{7}$$

In time, many empirical formulas for blast wave parameter calculus appeared (Brode-1955, Newmark & Hansen-1961, Baker-1983, Bulmash & Kingery-1984, Mills-1987, Beshara-1994, Mays & Smith-1995, Randers-Pehrson & Bannister-1997, Henrych, Held, Kinney & Grahm, Sadovskiy, Bajic and many others), starting from the requirement of a better and better concordance with the experiment.

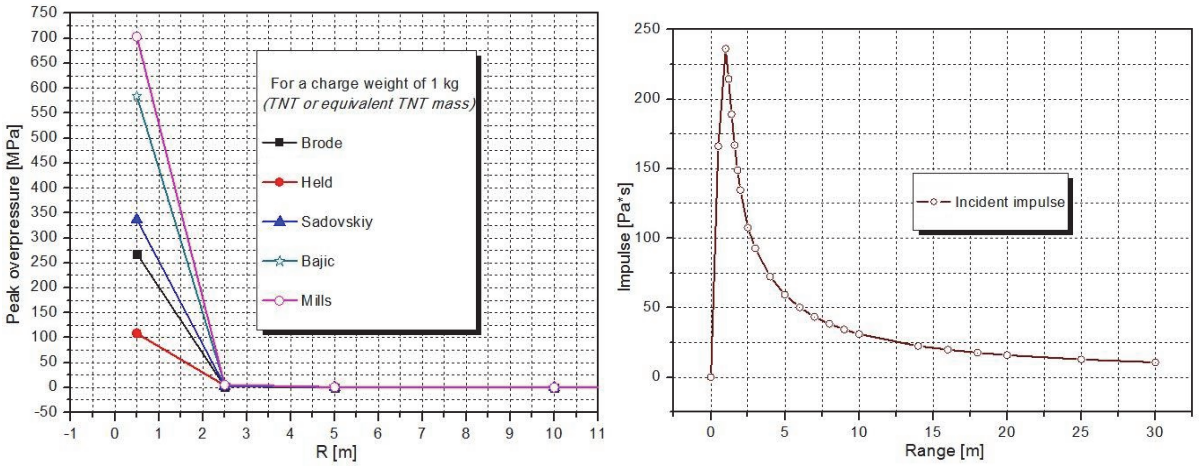


Fig. 5. Peak overpressure and positive impulse vs. distance *R*.

The Figures 5…8 present some of the most important blast wave parameters ($P_{\max}$, I_+, b, $t_+ \equiv t_{pos}$) and their variations with scaled distance Z, or physical distance $R \equiv Range$, in the case of air explosion of 1 kg TNT explosive. The empirical relations used for above graphical representations and others for determining of other parameters, can be easily got from specific technical literature.

For example, by Brode, peak over pressure ($p_{\max}$) can be calculated with relations (8). For $0.10 < P_{\max} < 10$, relation (8a) is recommended,

$$P_{\max} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} \tag{9a}$$

and for $10 < P_{\max}$, relation (8b).

$$P_{\max} = \frac{6.7}{Z^3} + 1 \tag{9b}$$

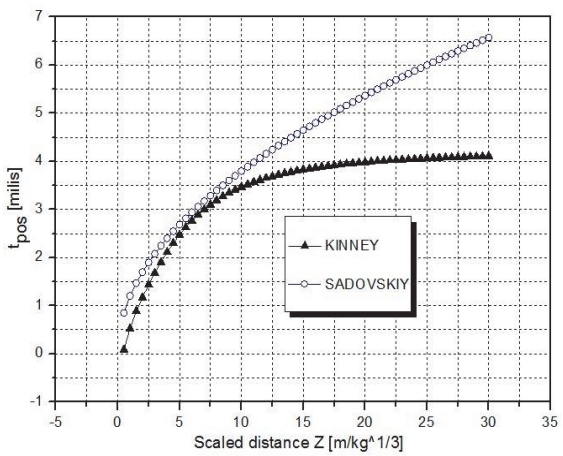


Fig. 6. Positive duration of the blast wave.

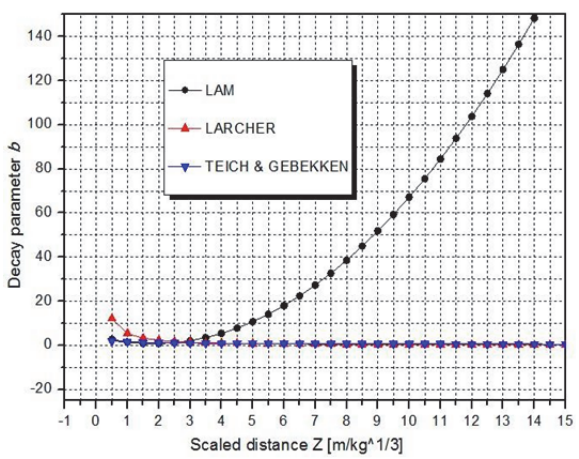


Fig. 7. Decay parameter variation with scaled distance.

3. NUMERICAL CALCULUS OF THE EXPLOSION EFFECTS ON STRUCTURES

As numerical calculus is concerned, two numerical methods are validated being available: 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).

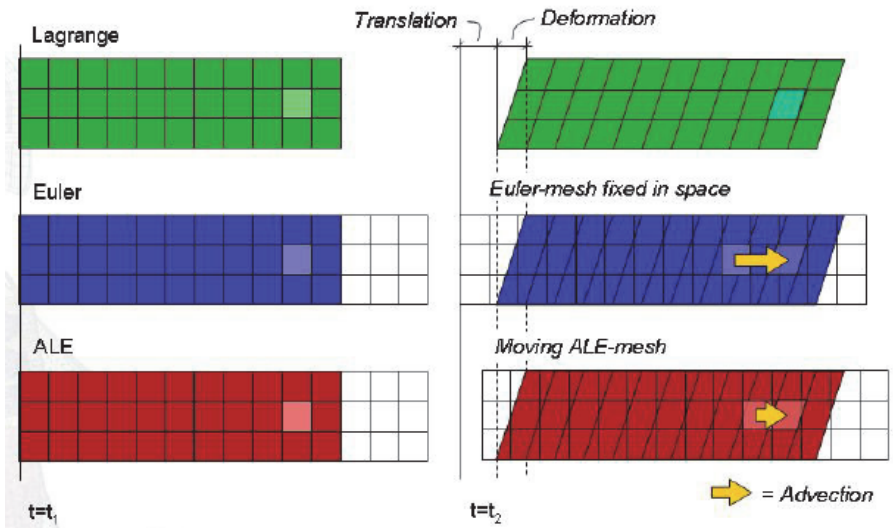


Fig. 8. Finite element formulations.

The Figure 8 illustrates the main differences between those three formulations. 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 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 finite element codes.

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 can be Jones-Wilkins-Lee (JWL) EOS or Jones-Wilkins-Lee-Baker (JWLB) EOS. 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.

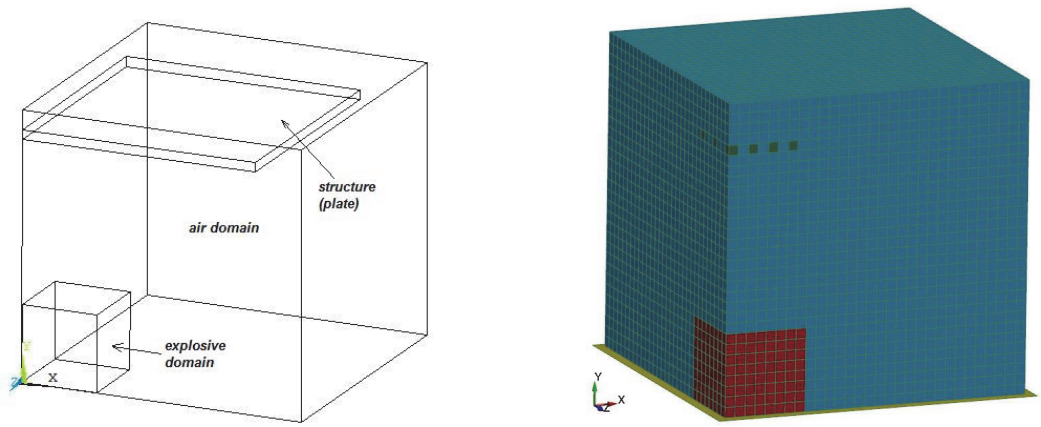
For the modelling of the fluid structure interaction (FSI), in the last period, a special numerical procedure was created and implemented. So, in Ls-Dyna code, this procedure is called Constrained_Lagrange_in_Solid. By this procedure, the FSI takes place between finite elements in ALE formulation (explosive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

Of course, FSI could be modelled by contact procedure between blast wave and structure, but in this case ALE formulation is not available and next to it, a large computer-time is necessary; then, the program cannot run a longer period (only very short time) because large deformations appear, the shape of finite elements can become no acceptable for numerical calculus and so on. Nowadays, this procedure is not used in professional programs which can model an explosion for its parameters or its effects upon structures.

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 of the explosive, of the air and of the structure. Figure 9-a shows three domains, which will be meshed in finite element (Figure 9-b). In this figure we can see only a part (1/4) of entire problem representing an explosive just on the surface (plane xoz) and a plate being included in the air domain.



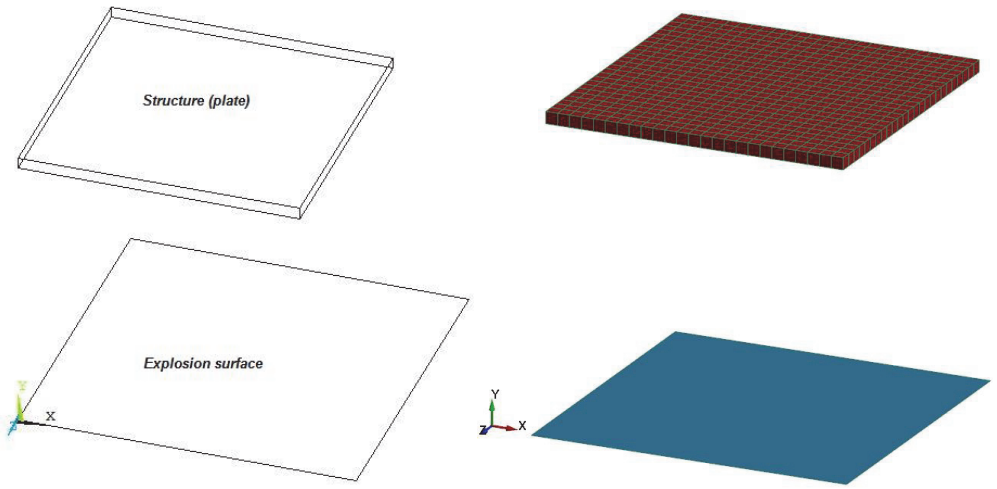
a) b)

Fig. 9. All domains modelled with finite elements.

An other way for the numerical modelling of the explosion effects upon a structure, consists in combining the empirical methods with numerical methods. 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 time explosion. 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 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. A big disadvantage

exist: the blast wave effect over a structure shadowed by the first structure cannot be calculated. The reflections cannot be accounted. Only o surface with a direct viewing to the charge can be loaded.

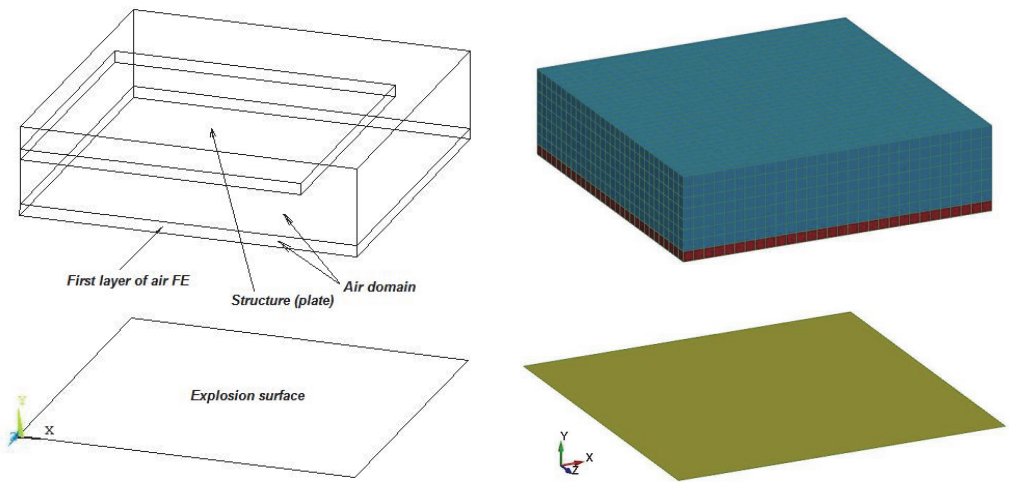


a) b)

Fig. 10. Domains and FE model, for second way modelling.

The newest way for the numerical modelling of the explosion effects upon a structure, consists in coupling those two ways described above. In this third way, the main disadvantage of the second way is got out and the main advantage of a shorter computer-time is available.

By introducing of a new concept – Multi-Material Arbitrary Lagrange Eulerian (MM-ALE) – the user can model the action of more material (resulting or moved by explosion), upon a structure. In the Figure 11, we can see the specific domains of modelling as well as the finite element model. The air domain includes the structure, but it has smaller dimensions, being around the structure (one or more). The first layer of finite elements of the air domain is modelled like a different material but practically, it's the loaded face of the air domain.



a) b)

Fig. 11. Domains and FE model, for third way modelling.

4. ILLUSTRATIVE EXAMPLE

The structure consists in a simple plane plate, with edges clamped, loaded by a blast wave resulting from an explosive quantity placed under plate, in the middle point, at a distance of 50 cm, as we can see in the Figure 12. The adopted calculus model was only 1/4 of structure presented in Figure 12, because two symmetry planes exist.

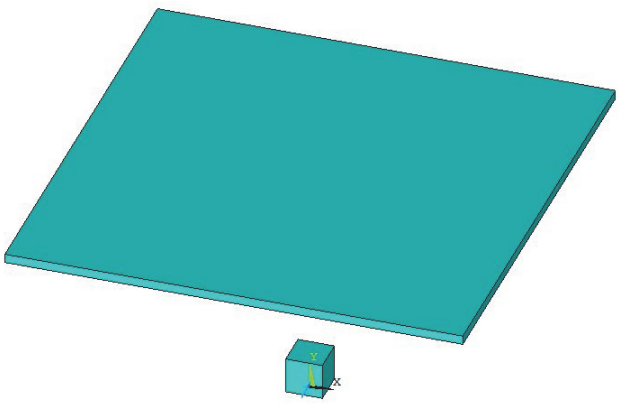


Fig. 12 . A model for blast effects calculus.

Table 1

Comparative results

ALE SvM [Pa]	Time [s]	BLAST SvM [Pa]	*Error %*
8,571E+08	2,225E-03	8,851E+08	*3,27*
ALE UY [m]	**Time [s]**	**BLAST UY [m]**	***Error %***
3,995E-02	1,750E-03	3,988E-02	*-0,18*
ALE Pressure [Pa]	**Time [s]**	**BLAST Pressure [Pa]**	***Error %***
5,062E+08	2,33E-03	5,062E+08	*0,00*

Both first two approaching ways, ALE and only Lagrangian formulation, can be successfully used, but the computer time as well as the possibility to model large structure are very different.

The Table 1 presents some results (equivalent von Mises stresses and displacements along Y-axis and blast pressure), in a comparative way, for those two approaching possibilities. There is a good concordance between those two ways.

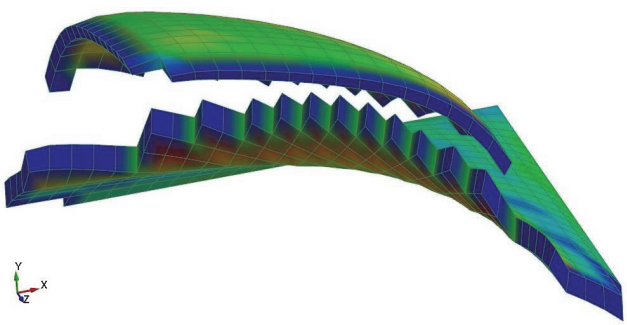


Fig. 13. Deformation state and von Mises stress field.

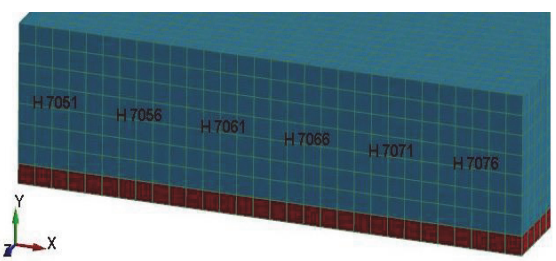


Fig. 14. Selected finite elements.

Figure 13 shows von Mises stress field, on the deformed plate (fractured) at the end of analysis time. In the Figure 15, the pressure profiles, applied on the selected finite elements (Figure 14) are presented. This pressure is just the pressure applied on the plate finite elements and the effect can be seen on the Figure 13.

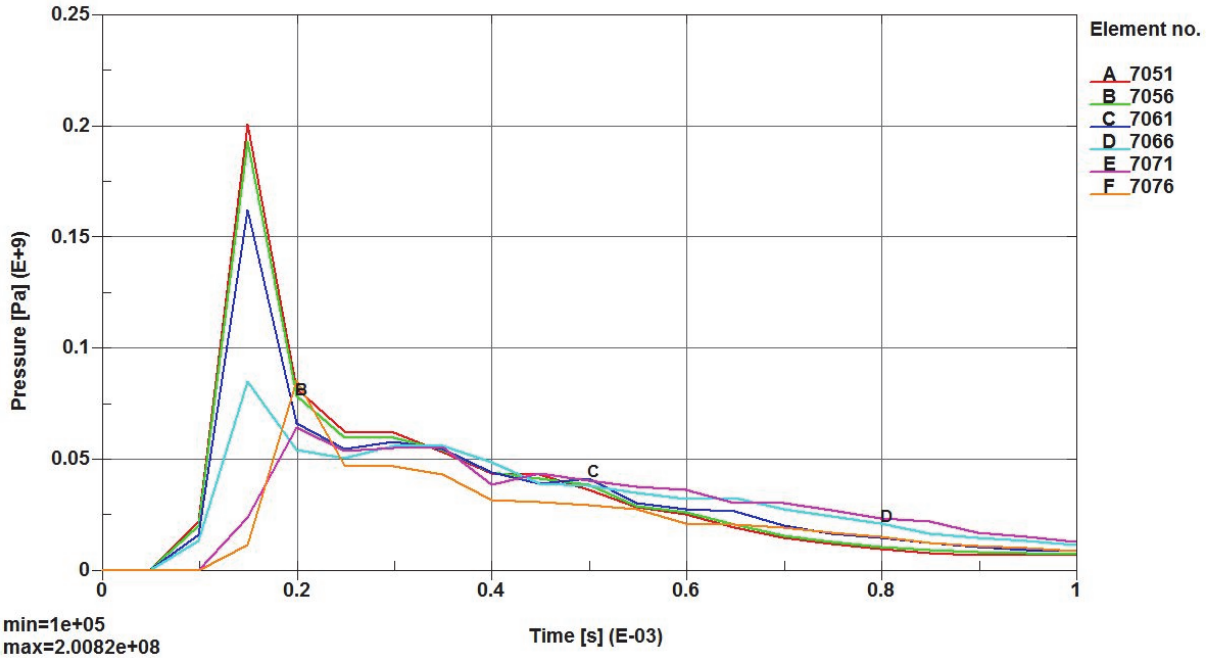


Fig. 15. Blast wave profiles on the selected finite elements

5. CONCLUSIONS

The modern approaching of the numerical calculus regarding the blast wave effects consists in combining the empirical formulas with finite element analysis, using special procedures. The core of this new formulation is presented above, together with main advantages.

Next to the deep, large and modern knowledge, who wants to develop such a study, has to be based on some experiments, because there are many values and options that have to be adopted as right as possible. Then, for using an efficient numerical analysis, a professional code is necessary.

Our results are based on Ls-Dyna code, this program being one of the most powerful and fitted for such problems. Finally, we hope that our work to be useful for researchers in the blast wave parameters and effects calculus area, by concept formulations and offered models.

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