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► **To cite this version:**

Aravind Rajan Ayagara, André Langlet, Gregory Girault. Fluid Structure Interaction between plate and blast waves : Numerical simulations. 24e Congrès Français mécanique, Aug 2019, Brest, France. hal-02568204

HAL Id: hal-02568204

<https://hal.science/hal-02568204v1>

Submitted on 8 May 2020

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Fluid Structure Interaction between blast and waves : Numerical simulations

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Résumé :

Cette étude présente un modèle numérique de l'interaction fluide-structure, capable de simuler la réponse d'une plaque à une explosion aérienne. Le calcul a été effectué en deux phases. Depuis l'explosion jusqu'à la plaque, la propagation des ondes de chocs est modélisée en 1D par l'analogie de ballon. Après l'impacte d'onde, le calcul est réalisé en 3D par projection des résultats 1D en 3D. Cette méthodologie est capable de reproduire la phénomène de réflexion des ondes, la formation de pied de mach. La plaque d'aluminium est modélisée avec la loi de comportement élastique-plastique. La répartition des contraintes sur la plaque dépasse la limite élastique. Donc, une loi de comportement couplée avec une loi d'endommagement pourrait donner des résultats précises et l'information sur l'évolution d'endommagement de la plaque.

Abstract :

This study, presents a numerical methodology for fluid-structure interaction between blast waves and plate using the LS Dyna explicit code. The numerical simulation was executed in two stages, (i) a one dimensional calculation was carried out using the balloon analogue and, (ii) the results of 1D calculation were remapped to three dimensions. The explosive used in this study was a mixture of propane and oxygen. The 3D model was able to reproduce the complex reflection phenomenon of shock waves, including the mach stem. A more refined mesh for the air domain shall produce accurate representation of this phenomenon. The aluminum plate was modeled using an elastic plastic constitutive law without damage. Results show that the stress in the plate are beyond its yield limit, therefore, an external damage law coupled to the constitutive law will further improve the results by giving us vital information on damage evolution and rupture.

Mots clefs : Air blast, Fluid-Structure Interaction, Mach Stem, MMALE, LS Dyna.

1 Introduction

The interaction of blast waves with a thin plate is investigated in this study. A blast wave originating from high explosives have a unique effect, known as the primary blast. This is due to the impact of over-pressurized waves on a structure and can be divided into 4 processes as follows

1. the detonation process of explosive
2. propagation of shock waves in the atmosphere around
3. reflection of shock waves from the obstacle (plate)
4. response of the plate and its consequences in the domain below the plate.

According to [1] and [2], the reflection of blast wave from a flat surface can be described accurately by mathematical equations (coalescence of incident and reflected waves at the triple point). One the blast waves impacts the structure, it resembles a fast moving discontinuity, followed by a continuously evolving non-uniformly distributed pressure.

There are two methods for simulation of blast loads (i) using empirical formulas and TNT energy equivalence and (ii) the compressed balloon analogue. The first method uses non linear equation of state such as JWL equation of state for the mechanics of explosion with an equivalent TNT energy and has been successfully implemented in [3]. Due to the difference between gaseous and solid explosives, this methodology might lead to discrepancies in the results. Therefore, the compressed balloon analogue was chosen in this study. The principle of balloon analogue method is that the gaseous explosives are confined in balloon of certain radius and are separated from the ambient atmosphere by an fictitious membrane. The detonation is achieved by inducing a spark to the mixture set to the Chapmann-Jouget pressure. The successful application of this analogue can be seen in [4] and [5].

The explosion process is very complicated since, this process divides the fluid domain into in-homogeneous parts through a thin reactive zone and does induce large deformations. Due to this reason, the numerical simulations of explosion using classic numerical methods is very difficult. For which, the ALE or Eulerian Multi-Material formulations can be used as an alternative approach [6].

As said above, the explosive used in this study is a mixture of propane and oxygen ($C_3H_8 + 5O_2$), which consists of two different elements. Therefore, a Multi-Material Arbitrary Lagrange-Euler (MMALE) formulation was chosen in this study. Thanks to the interface tracking algorithm in MMALE method, it is capable of tracking the interfaces between the explosive gas and the surrounding air. This cannot be achieved by ALE method. In the MMALE formulation, the FE mesh moves independently to the material flow and each element can allow the solver to track different materials. The working principle of MMALE is explained in detail in [7] and [6] and the equations are presented here for the sake of ease.

Let us consider a variable f . It's time derivative in the referential coordinate system can be expressed as

$$\frac{df(\mathbf{X}, t)}{dt} = \frac{\partial f(\mathbf{x}, t)}{\partial t} + (\mathbf{v} - \mathbf{w}) \cdot \text{grad}f(\mathbf{x}, t) \quad (1)$$

here, \mathbf{X} is the Lagrangian coordinate, \mathbf{x} is the ALE coordinate, \mathbf{v} is the particle velocity vector and \mathbf{w} is the velocity vector of the reference coordinate. Then the equations conservation of mass, momentum

and energy in ALE coordinates can be written as

$$\frac{\partial \rho}{\partial t} + \rho \operatorname{div} \mathbf{v} + (\mathbf{v} - \mathbf{w}) \operatorname{grad} \rho = 0 \quad (2)$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} - \mathbf{w}) \overline{\operatorname{grad}} \mathbf{v} = \operatorname{div} \overline{\overline{\boldsymbol{\sigma}}} + f \quad (3)$$

$$\rho \frac{\partial e}{\partial t} + \rho (\mathbf{v} - \mathbf{w}) \operatorname{grad} \cdot e = \overline{\overline{\boldsymbol{\sigma}}} \overline{\operatorname{grad}} \mathbf{v} + f \cdot \mathbf{v} \quad (4)$$

To solve the equations 2 to 4 in ALE form, there are two ways. The first is to solve fully coupled equations for fluid mechanics and the second is by using Operator-Split method. The first methods cannot handle multiple materials in the fluid domain, therefore, the later was chosen in this study. Each time step calculation in an Operator-Split method is divided into two phases, with an interface tracking algorithm intervention between each phase. In a nutshell, a time step in Operator-Split method consists of a Lagrangian phase, an intervention of interface tracking algorithm and the advection phase or transportation phase. The advection phase in this study was carried out through second order van-Leer algorithm.

Since, the fluid mechanics problem is compressible, we need an Equation of State (EOS) for the fluid domain. Apart from these, for the interaction between solid and fluid domains at the point of contact, we might also need the Constrained-Lagrange-in-Solid card of LS-Dyna.

2 Numerical Simulations

The model consists of an aluminum plate of 0.5 mm thickness, which is subjected to blast loads originating from an explosion at 283 mm above the plate. The explosive is a mixture of propane and oxygen and is enclosed in a hemispherical soap balloon of 62.5 mm radius.

The numerical simulations were carried out using the LS Dyna explicit hydrodynamic code. The simulation was divided into two parts for the sake of time saving. The first part was calculation of pressure variation in one dimension and the second was remapping the one dimensional results into three dimensions. In fact, the three dimensional model was carried out on $1/4^{th}$ scale of real case.

To simulate explosions and propagation of shock waves, one must need equations of state for both explosive and air. There are different equations of state available in LS Dyna. Since, the compressed balloon approach followed here is applicable for gaseous mixture explosive, we had chosen a linear polynomial equation of state for explosive gas and also air. A linear polynomial equation of state is expressed as follows

$$p = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_5 \mu + C_6 \mu^2) e \quad (5)$$

The constants C_0 to C_6 are user defined and μ is expressed in terms of relative volume as follows

$$\mu = \frac{1}{v_r} - 1 \quad (6)$$

If the gases are considered as perfect gas, then the constants of Eq.5 have to be considered as follows

$$C_0 = C_1 = C_2 = C_3 = C_6 = 0 \text{ and}$$

$$C_4 = C_5 = \gamma - 1$$

Therefore, the pressure for an ideal gas using the linear polynomial equation of state can be rewritten in terms of specific heats γ as

$$p = (\gamma - 1) \frac{\rho}{\rho_0} e \quad (7)$$

ρ and ρ_0 are the densities at a given iteration and initial density respectively. The equations of state for explosive and ambient air are given below

Domain	$C_4 = C_5 = \gamma - 1$	e
Explosive	0.2715	16 MJ.m ⁻³
Air	0.4000	0.0 MJ.m ⁻³

TABLE 1 – EOS properties for explosive gas and air

2.1 1D model

The 1D FE model consists only of explosive balloon and the ambient air of standalone distance, meshed with beam elements. The NULL material model was used for both air and explosive. The reason for using NULL material model is to avoid the calculation of deviatoric stress components.

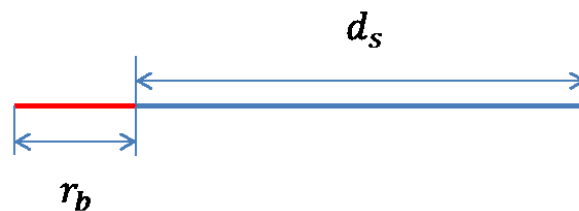


FIGURE 1 – 1D Model with explosive (red) and ambient air (blue)

Here, r_b is the radius of the balloon which was considered 65.5 mm and d_s is the standalone distance 283 mm. Since the material model NULL requires only the initial densities for this problem, the densities of explosive gas and air were considered to be 1.474 kg.m⁻³ and 1.290 kg.m⁻³ respectively. Other than these constituents, the 1D model was also provided with the ALE module. A Multi-Material ALE group was declared for explosive and ambient air domains.

2.2 3D model

The three dimensional model consists of two domains (i) the ambient air above and below plate (see Fig. 2a) and (ii) an aluminum plate of 0.5 mm thickness (see Fig2b).

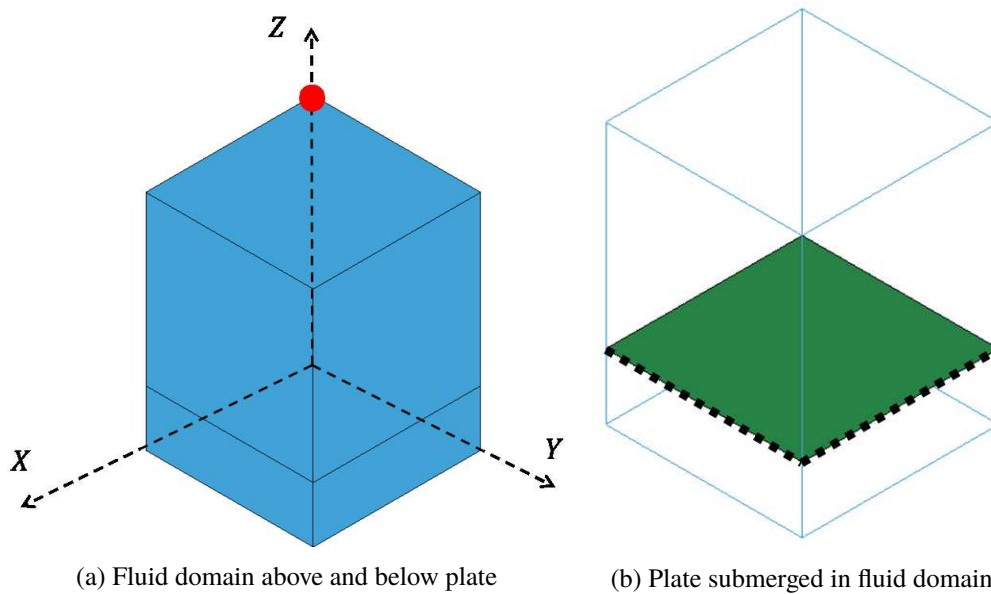


FIGURE 2 – Fluid and Solid domains in the 3D model

The fluid domain were meshed with 8 node hexahedral solid elements whilst the plate was meshed with shell elements. For the sake of accuracy, fully integrated shell elements with 5 integration points were considered. The plate was modeled using elastic-plastic law with following properties

Property	value
Density ρ [$\text{Kg}\cdot\text{m}^{-3}$]	2780.00
Young's Modulus E [GPa]	73.00
Yield Strength σ_y [MPa]	268.97
Poission's Ratio ν	0.33

TABLE 2 – Properties of aluminum plate

2.2.1 Boundary and Initial conditions

Since the model was considered to be axi-symmetric with symmetry boundary conditions along the XY and YZ planes and the other faces of air domain were provided with non-reflecting boundary conditions. Where as the dotted black lines in Fig. 2b, represent the clamped boundary condition of the plate.

The initial condition for the 3D model was the solution of 1D model.

3 Results

It is interesting to see the variation of pressure with respect to space and time. For example the red and green curves in Fig. 3a are recorded at explosion point and at $z = d_s/4$ which are respectively the results of 1D calculation. The variation in pressure with respect to depth below the plate is shown in Fig. 3b.

The Fig. 4, shows the corresponding pressure contours in the atmosphere above the plate. We can notice that the simulation is capable of reproducing the complex reflection of shock wave including the incident

wave (solid black line), the reflected wave (dotted black line) and the mach stem where incident and reflected waves meet (vertical black line) at $t = 6.097 \times 10^{-3}$ s. Similarly, the pressure contours below the plate are presented in Fig. 5. These are represented in the form of Isosurfaces for the sake of clarity. The range of pressure was fixed so that the wave propagation below the plate could be seen clearly. Note that the white blank space in Fig. 5 is due to the pressure values out of the range presented in the figure.

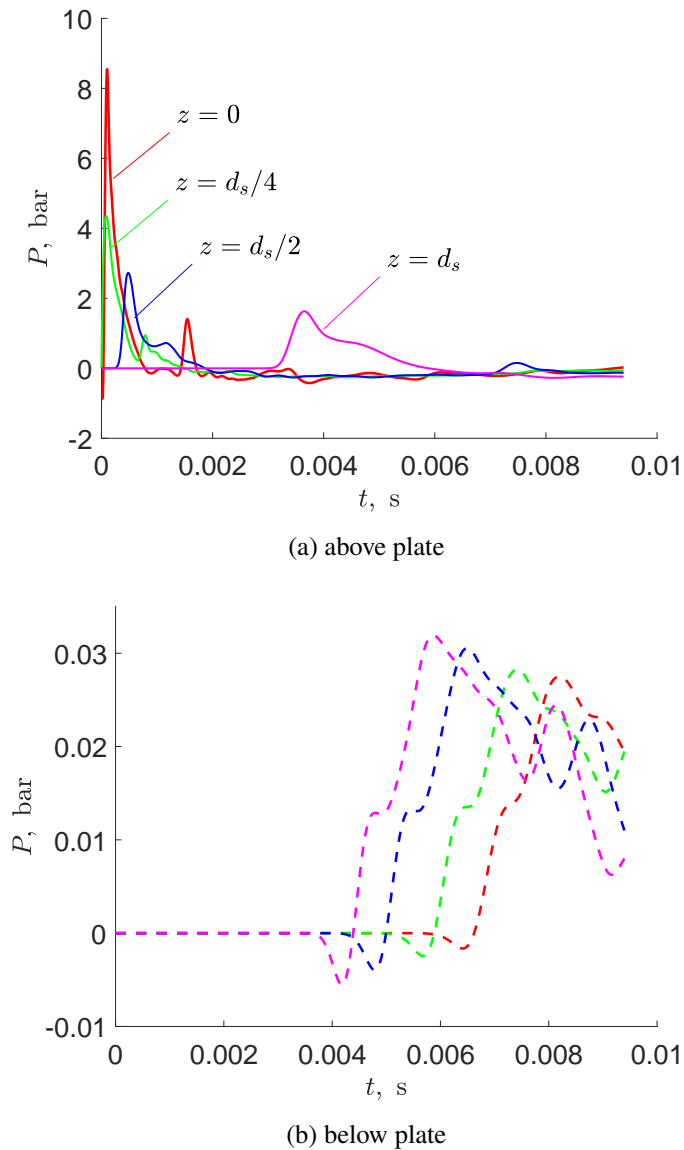


FIGURE 3 – Pressure curves in air

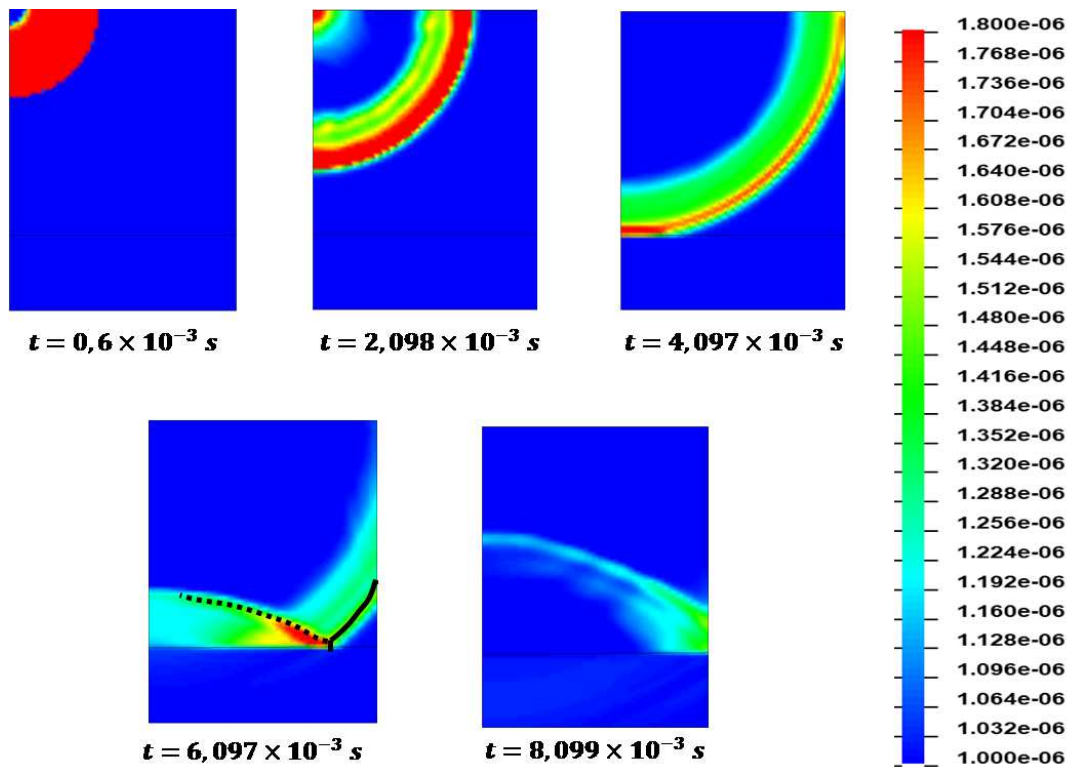


FIGURE 4 – Contours of pressure above the plate in Mbar

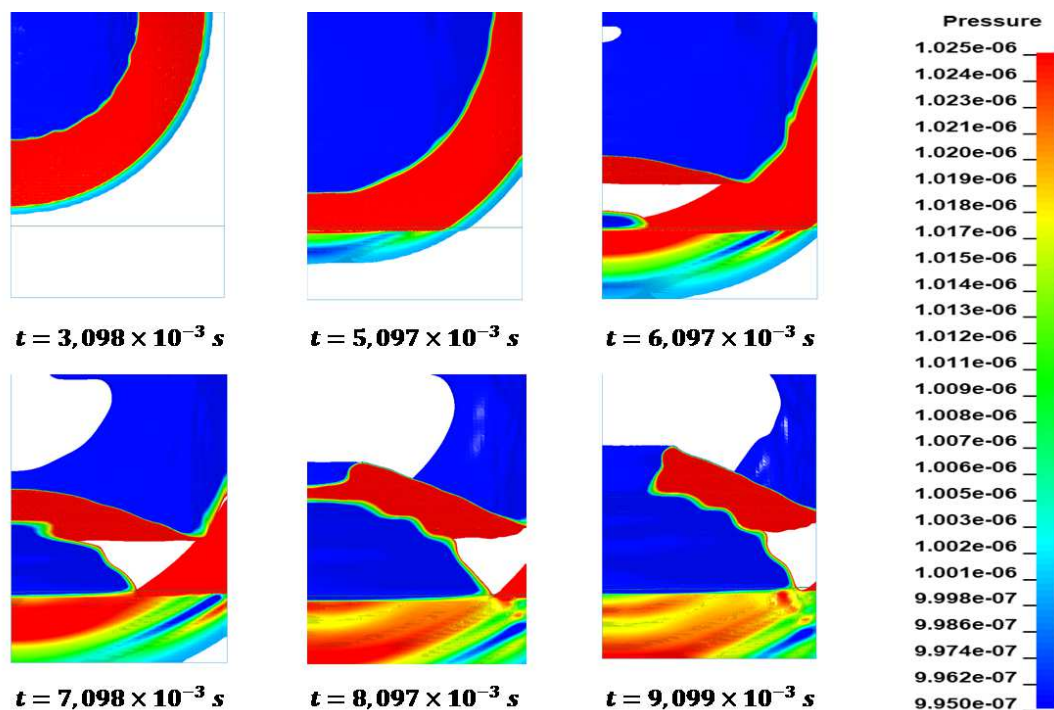


FIGURE 5 – Iso Surfaces of pressure below the plate in Mbar

The variation of pressure along the length of plate about X axis is shown in Fig. 6. The curves in solid line represent the pressure above the plate whereas the curves in dots represent the counterpart below the plate. The positive peak pressure in the curves below the plate represent the propagation of load front in

the fluid below due to the deflection of plate. Meanwhile, the variation of von-mises stress in the plate is presented in Fig : 7. We were able to notice the reflection of waves in the plate from the fixed (clamped) end. This can clearly be seen between time instances $t = 8.097 \times 10^{-3} \text{ s}$ and $t = 1.000 \times 10^{-3} \text{ s}$ i.e. till the end of calculation.

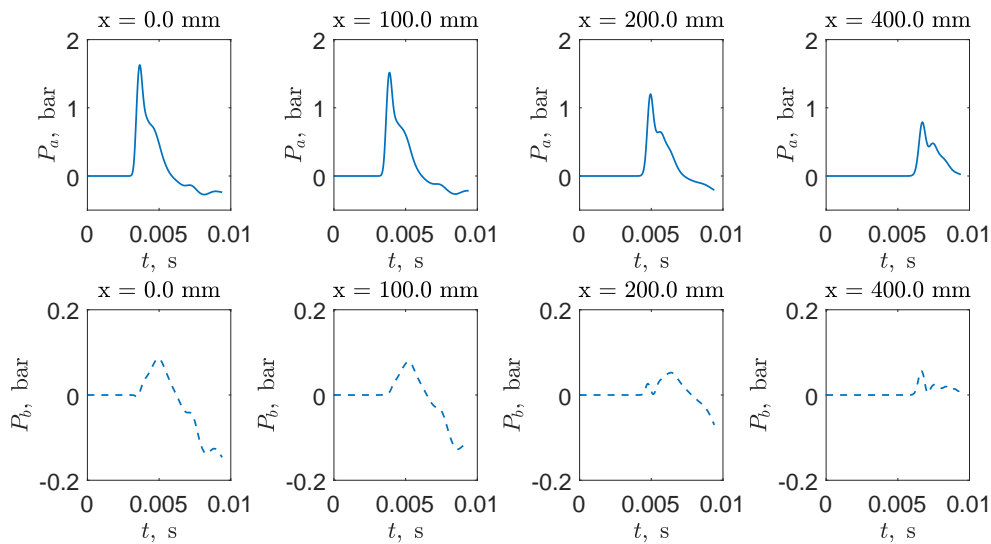


FIGURE 6 – Pressure curves at different X on either side of plate

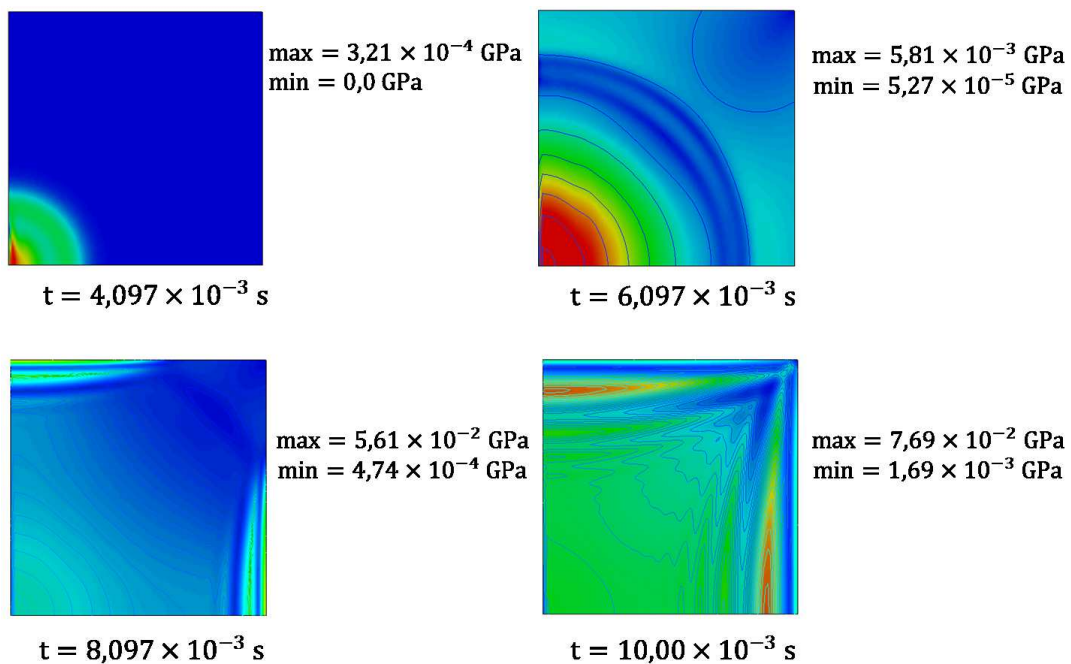


FIGURE 7 – von-mises stress contours on plate

4 Conclusions

We were able to successfully implement the balloon analogue in the LS Dyna explicit code. Consideration of linear polynomial equation state for a perfect gas gives coherent results. The use of ALE1D for one dimensional calculation and remapping the results for three dimensional from 1D results is a time effective method. The three dimensional model with current mesh size was able to reproduce the complex reflection phenomenon of shock wave including the mach stem formation. The current configuration had proved that the plate starts to yield, therefore if the model is coupled with an external damage law will produce the evolution of damage and rupture of plate if possible.

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