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Numerical simulations of an explosion confined inside a cylindrical pipe made of aluminium alloy Al6061-T6

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SUMMARY

Simulation of the behaviour of structural components subjected to high explosive detonation is one of the current challenges in the field of numerical simulation. Along with experimental tests, numerical analysis is necessary to give an in-depth insight of this event, as well to reduce costs for some further experimental tests. High values of strain rate, temperature and pressure, together with failure phenomenon, govern the complex interaction between the explosion and the structure involved. In a scenario of this type, capabilities and performance of the numerical software used are crucial to the quality and the outcome of the simulation. Besides the simulation itself, this paper provides a comparison between different finite element programs such as ABAQUS, AUTODYN and LS-DYNA in an explosion event. In the event descibed in the paper, the behaviour of tube made of aluminium alloy Al6061-T6 and filled with explosive material is under investigation. A fully coupled Eulerian and Lagrangian formulation is used together with a complete mechanical behaviour and constitutive equations of all the materials involved in the simulation (aluminium alloy Al6061-T6, explosive C4, air). Finally, results and comparison between the mentioned numerical solvers will be reported and critically discussed.

Key words: *explosive detonation, cylindrical pipe, numerical simulation, Al6061-T6, high strain rate.*

1. INTRODUCTION

The explosion process is a very complex matter to be described and to simulate due to intrinsic non-linearity. Several papers deal with explosions simulating the phenomenon by using specific and dedicated software. However, there are very few articles which compare different software analyzing such a complex scenario as a benchmark. The fact that a high non-linearity of the phenomena can be managed with different strategies thus obtaining dissimilar results makes this topic scientifically alluring. Therefore, the aim of this paper is to give a comparison of the results of three different solvers regarding this particular issue. Computational time, other than final results, is also one of the challenges which are important in simulation of such a dynamic event.

Out of the most popular software in this research field, the following solvers were used: AUTODYN, LS-DYNA and ABAQUS. The AUTODYN software is a part of ANSYS AUTODYN and plays a crucial role in the entire software package ‘ANSYS Workbench’ in the simulation of high-speed impacts and high-energy explosion. As regards high speed and high deformation analyses, compared to AUTODYN, LS-DYNA provides less specific features, but is capable of simulating almost every type of multi-physics scenario. Finally, ABAQUS is also a structural design and verification software now in fast evolution towards multi-physics applications.

2. NUMERICAL ANALYSIS

In the present work, finite element (FE) models were generated with the help of the three software in order to simulate the explosion process in entirety. For all simulations, the three software were installed in a Windows Server 2008 Enterprise *64 bit*. The hardware support consists of two 'Xeon 5620-4 Cores @ *3800 Mhz'*, mounted on a motherboard EVGA SR-2 dual-socket 1366, with *48 GB* of RAM installed.

Due to the particular geometry of the application and the ability of the software to operate on complex simulations (coupled Lagrangian/Eulerian formulations) using axial-symmetric geometries in 2D, only a semi-section of the tube and the explosive contained in it was modelled in AUTODYN and LS-DYNA. However, in ABAQUS software (V. 6.11), where there is lack of the possibility to simulate the explosion with a 2D geometry, the creation of a full, three dimensional model was needed. Moreover, the coupling of Eulerian and Lagrangian approaches allows the exploration of the characteristics of two types of geometry (3D and 2D).

As for the FE discretization, two different kinds of mesh were used, namely Lagrangian and Eulerian mesh. The Lagrangian mesh is designed mainly for the discretization of solid objects, it follows the contours of the reference geometry thus allowing a desired accuracy in approximation of the local stress and strain level. The Lagrangian discretization is, however, strongly correlated to the initial geometry: if the discretized object goes under significant deformation and self-penetrations and the elements are highly deformed, the convergence of the analysis is no longer guaranteed. In the Eulerian approach, the mesh remains unchanged and does not follow the deformation of the material included in the cells, on the contrary, a balance equation for the calculation of energy and mass transfer between each of the cells is verified at each step time. In that case, the simulation is faster and more stable. On the other hand, in the boundary zones, the mesh does not follow the reference geometry, but is limited to the calculation of the volume fraction of the total volume of the cell that is inside or outside the boundary line. Therefore, the Eulerian mesh offers no particular accuracy in the local approximation of the simulated phenomenon. Thus, discretizing the metal pipe using Lagrangian mesh, and the other components (explosive C4 and air) using the Eulerian mesh gives excellent results, fast simulations and stable analysis.

Other essential factors that had to be taken into consideration were air zone and boundary conditions. The area surrounding the tube was considered an air zone of sufficient size so that the phenomenon is not influenced by the conditions of the space outside the tube. On the contour of this zone, the condition of 'outflow' has been applied (Figure 1), which means that the fluid is free to overcome the Eulerian external boundary (in terms of mass and energy) without re-entry. A symmetry boundary constraint was used, which is illustrated as a yellow line in Figure 1, for both simulations made in AUTODYN and LS-DYNA. The ABAQUS simulation presents the same conditions of 'outflow' in the outer faces of the air zone, but no symmetry constraint is needed.

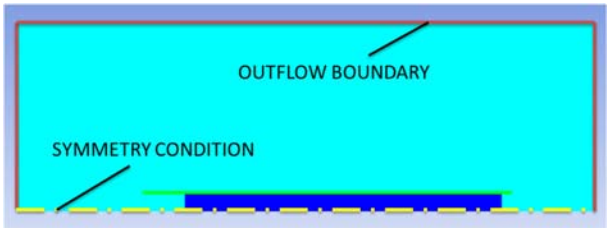

Fig. 1 Boundary and symmetry condition

2.1 Material behaviour

In order to describe the constitutive law for aluminium alloy Al6061-T6, Johnson-Cook (JC) model [1] was adopted. The JC model is a phenomenological model and it can be expressed as:

$$\sigma_{eq} = \left(A + B\varepsilon_{eq}^{n}\right)\left(1 + C\ln\dot{\varepsilon}_{eq}^{*}\right)\left(1 - T^{*m}\right) \quad (1)$$

where σ_{eq} is the equivalent stress, ε_{eq} is the equivalent strain, A, B, n, C and m are material constants, and $\dot{\varepsilon}_{eq}^{*} = \dot{\varepsilon}_{eq}^{*}/\dot{\varepsilon}_{0}$ is the dimensionless strain rate where $\dot{\varepsilon}_{eq}$ and $\dot{\varepsilon}_{0}$ are the strain rate and reference strain rate, respectively. T^{*} is a dimensionless temperature and is given as $T^{*}=(T-T_r)(T_m-T_r)$, where T is the absolute temperature, T_r is the room temperature and T_m is the melting temperature. Material data for the target material (Al6061-T6) are shown in Table 1.

Table 1 Constitutive material data for Al6061-T6

Density	*2,703 [Kg/m^3]*
Young's modulus	*70,000 [MPa]*
Shear modulus	*2,566 [MPa]*
Poisson's ratio	*0.33*
Specific heat	*0.896 J/g-°C*
Ref. strain rate	*319.5 [s^{-1}]*
Melting temp.	*925 [K]*
A	*110 [MPa]*
B	*147 [MPa]*
n	*0.19760*
c	*0.11126*
m	*1.34*

Fracture was one of the factors that had to be taken into account as well. Johnson-Cook fracture criterion [1] was chosen to describe the failure phenomenon of the tube. JC failure can be expressed as:

$$\varepsilon_f = \left[D_1 + D_2 \exp\left(D_3 \sigma^*\right)\right]\left[1 + D_4 \ln \dot{\varepsilon}^*_{eq}\right]\left[1 + D_5 T^*\right] \quad (2)$$

where $\sigma^* = \sigma_m / \bar{\sigma}$, is the stress triaxiality ratio; $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3) / 3$, is the mean stress; and $\bar{\sigma}$ is the effective stress or the von Mises equivalent stress ($\sqrt{3/2}$).

Constants D_1, D_2, D_3, D_4 and D_5 are the constants of this failure model and corresponding value for Al6061-T6 are shown in Table 2.

Table 2 Fracture criterion for Al6061-T6

D_1	0.35860
D_2	0.71100
D_3	-2.08800
D_4	0.01100
D_5	1.60000

However, in order to define the characteristics of the explosive, three parameters such as density, detonation velocity and Chapman-Jouget pressure are necessary and are shown in Table 3.

Table 3 Explosive C4 data

Density	1,601 [Kg/m^3]
Detonation velocity	8,193 [m/s]
Chapman-Jouget pressure	28,000 [MPa]

Moreover, in such a very high strain rate applications, the equation of state is necessary to describe the phenomenon correctly. To that end, the Gruneisen equation of state with cubic shock velocity-particle velocity is used (Eqs. (3) and (4)) and it defines pressure for compressed materials as:

$$p = \frac{\rho_0 c^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{a}{2}\mu^2\right]}{\left[1 - \left(S_1 - 1\right)\mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{\left(\mu + 1\right)^2}\right]^2} + \left(\gamma_0 + a\mu\right)E \quad (3)$$

and for expanded materials as:

$$p = \rho_0 C^2 \mu + \left(\gamma_0 + a\mu\right)E \quad (4)$$

where C is the intercept of the V_s–V_p curve; S_1, S_2 and S_3 are the coefficients of the slope of the V_s–V_p curve; γ_0 is the Gruneisen gamma; α is the first order volume correction to γ_0; and $\mu = \frac{\rho}{\rho_0} - 1$ [2]. The corresponding data for aluminium alloy Al6061-T6 regarding to EOS are shown in Table 4.

Table 4 Gruneisen EOS data for Al6061-T6

C	5.24e+6
S_1	1.40
Gama	1.97

Also, in order to define equation of state for explosive C4, the Jones-Wilkins-Lee (JWL) equation of state is used for explosive [3] and it defines the pressure as:

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \quad (5)$$

The corresponding data for explosive C4 are shown in Table 5.

Table 5 JWL equation of state data for explosive C4

A	6.098E+05 [Mpa]
B	1.295E+04 [Mpa]
R_1	4.50
R_2	1.40
ω	0.25
E_0	9000 [MJ/m^3]

2.2 AUTODYN model

The numerical model developed in AUTODYN includes all parties that are involved in the explosion: the tube made of aluminium alloy Al6061-T6, an explosive C4 and air. The assembly is shown in Figure 2: the detonation point is marked with the red circle.

The air was modeled in an area outside the tube and was formed of elements of the Eulerian type. The tube was inserted inside the air, and modelled with Lagrangian elements (blue, Figure 2). The tube is *350 mm* long with a diameter of *38.1 mm* and a thickness of *3.175 mm*. Inside the tube, the explosive component is modelled as a solid cylinder, with radius equal to the inner radius of the tube and a length of *300 mm* (green, Figure 2). The explosive is modelled with a mesh of the Eulerian type. The interaction between the two types of elements (Lagrangian and Eulerian) is implemented by the program during the simulation. Since, as it was pointed out before, the Eulerian mesh does not follow the contour of the geometry contained in it, it is important to generate a mesh dense enough to reproduce reliable local pressures and temperatures on the walls. Similarly, it is essential to have a well refined mesh in tube to represent well the stresses and calculate the damage.

The size, the number and the type of the elements involved in the simulation are shown in Table 6.

Table 6 Element type and dimensions overview (AUTODYN)

PART	Number of elements		Dimensions of elements	Type of mesh
	Axial direction	Radial direction		
Tube (Al6061-T6)	350	4	1x0.79375 mm	Lagrangian
Air	550	225	1x0.79375 mm	Eulerian
C4	300	20	1x0.79375 mm	Eulerian

The point of detonation is illustrated in Figure 2 as a red point positioned on the axis of symmetry, at *5 mm* respect to the first section of the explosive. The detonation starts at *t=0*.

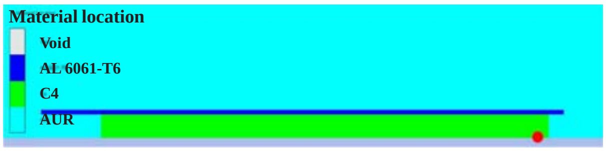

Fig. 2 AUTODYN bi-dimensional axial-symmetric model

2.3 ABAQUS model

The ABAQUS simulation includes all parties involved in the explosion: a tube made of aluminium alloy Al6061-T2, an explosive C4 and air. The assembly is shown in Figure 3, the detonation point is marked with the red point. In the ABAQUS simulation the model is a full, three-dimensional model.

The air and the explosive are made of Eulerian mesh while the tube is made of Lagrangian elements. The geometry dimensions, mesh size and element type are almost the same with respect to the previous case, but here the elements are solid (Figure 3). Regarding the tube, the element size in the tangential direction depends on the local radius, as well.

Table 7 Element type and dimensions overview (ABAQUS)

PART	Element dimensions	Type of mesh
Tube (Al6061-T6)	1x0.79375x.func(radius) mm	Lagrangian
Air	1x0.79375x0.79375 mm	Eulerian
C4	1x0.793750.79375 mm	Eulerian

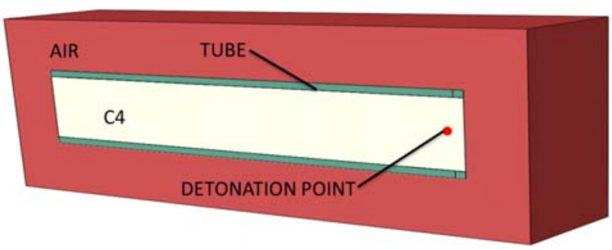

Fig. 3 ABAQUS a slice of the full 3D model

2.4 LS-DYNA model

To model the event in LS-DYNA, ALE (Arbitrary Lagrangian-Eulerian) 2D elements were used to discretize the explosive and air. To this end, a multi-material ALE formulation (ALEFORM=11) was considered. However, for the tube modelling, Lagrangian mesh was used. The dimensions of the elements in this model are identical as in AUTODYN, displayed in Table 6.

To define the detonation velocity and pressure, HIGH_EXPLOSIVE_BURN card was used. Also, the evolution of explosive C4 after ignition is describe by the Jones-Wilkins-Lee (JWL) equation of state, therefore EOS_JWL card is used in order to define detonation.

Another challenge in such a complex analysis is the definition of fluid-structure interaction. The Lagrange and Euler elements were coupled using a penalty method, CONSTRAINED_LAGRANGE_IN_SOLID. This mentioned coupling methods, in comparison to other coupling methods, gives researchers freedom to create an optimal mesh for both Lagrangian and Eulerian parts.

The LS-DYNA model is shown in Figure 4.

Fig. 4 LS-DYNA bi-dimensional model

3. RESULTS AND DISCUSSION

For all the three simulations, detonation started at time *t=0*. A pressure wave propagated across the tube from one side to the other, as illustrated in Figure 5.

The explosive pressure caused the deformation of the tube and made it to expand until the total failure. In Figure 6, a sequence of the deformation process of the tube in fixed time intervals is shown.

In order to evaluate the behaviour of the tube against the explosive in such a complex event, different aspects can be discussed. The first is the measure of the axial distance from the detonation point and the time at witch the tube deforms radially till reaching an external radius of *33 mm*. The second parameter is strictly related to the first since it measures the advancing speed of reaching the external radius of *33 mm* at the same time steps the previous ones had. The third is the angle of the tube walls during the expansion at each time step.

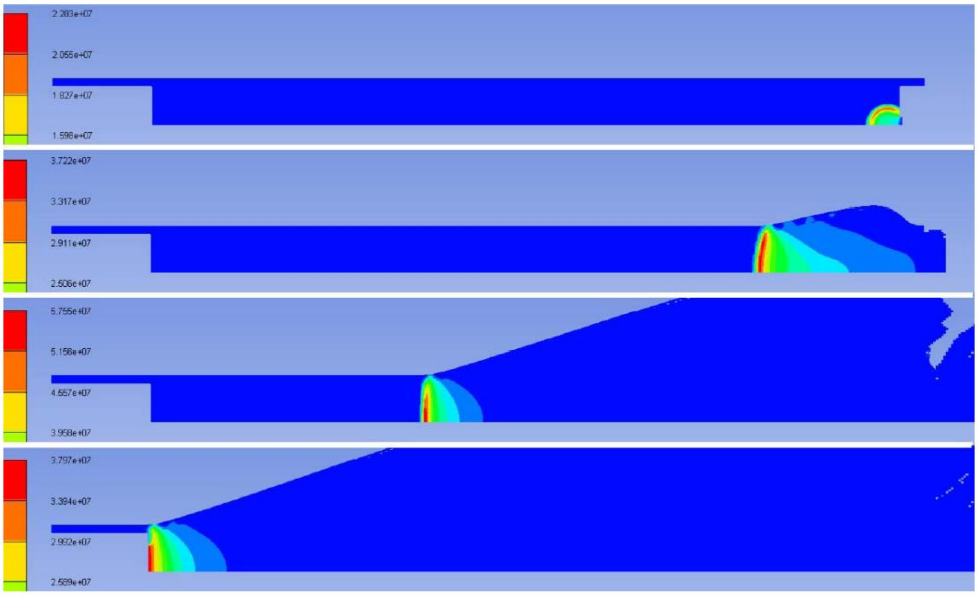

Fig. 5 Presure wave propagation

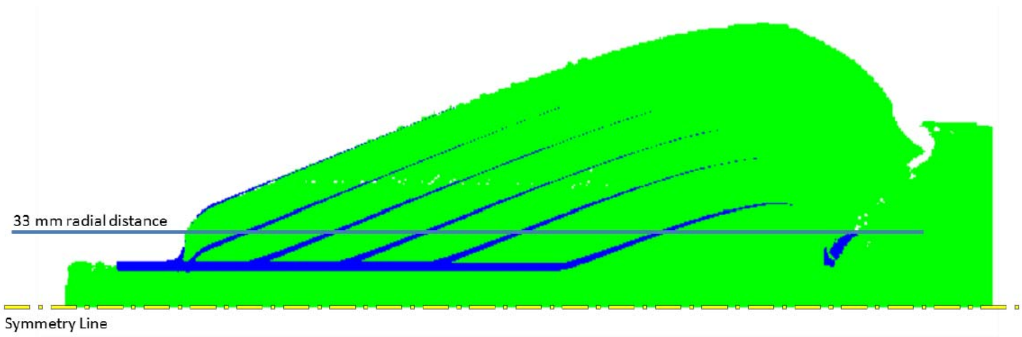

Fig. 6 Deformed shape of the tube wall during the explosion process

Figure 7 shows time versus axial distance from the detonation point at witch the tube deforms radially till reaching an external radius of *33 mm*: the data from the three software are presented simultaneously. Comparing the results obtained from different software, it is evident that the results of LS-DYNA and AUTODYN are very similar to the ones acquired by ABAQUS (that is a full 3D simulation). A noticeable difference is evident only in the first part of the curve, which is attributable to the fact that a curvature shape of the tube walls affects the measurement in the very first instants of the phenomenon, exemplified in Figure 6. Since the advancing front deforms in a straight shape after same time instances, there is no curvature effect on the further measurements.

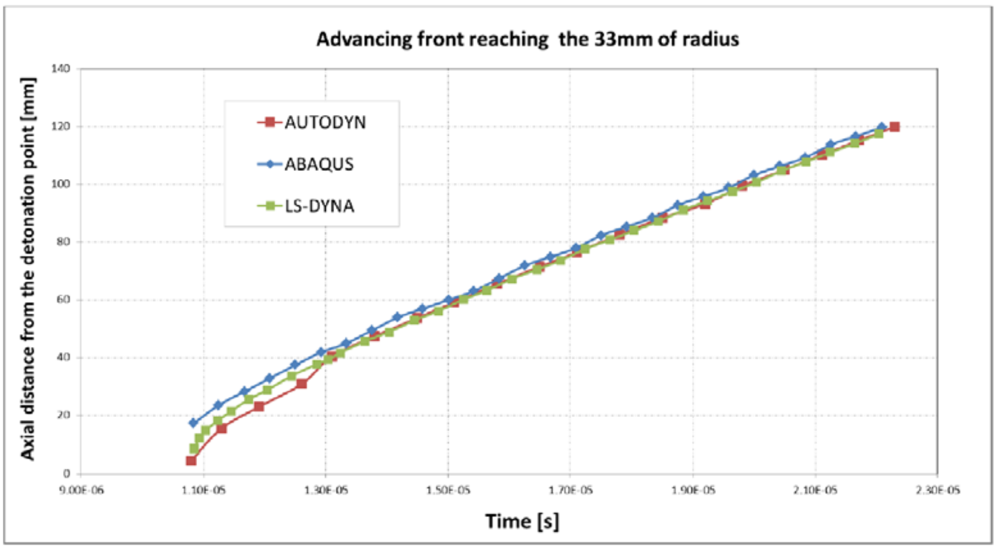

Fig. 7 Axial distance from the detonation point and the time at witch the tube deforms radially till reaching an external radius of 33 mm

The curvature effect is noticeable even in the advancing speed measurements, because the curve is calculated on the data of the previous curve, the errors in the first time steps are more evident (Figure 8). Despite this, the overall results are reasonably similar for the two dimensional simulations (AUTODYN and LS-DYNA) and prove very close to the ABAQUS ones.

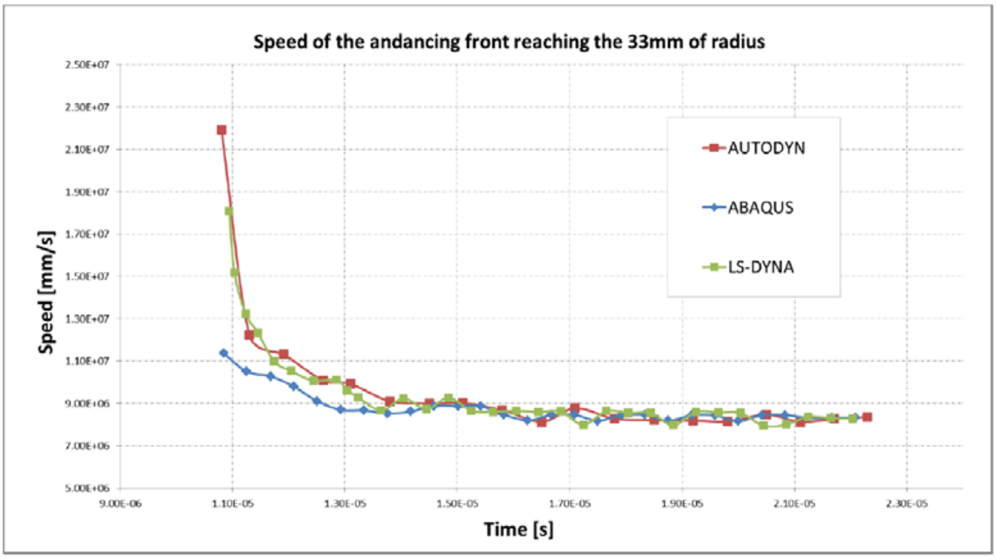

Fig. 8 Advancing speed of the front

In the Figure 9 the behaviour of the external angle of the deformed tube wall is illustrated. In this case the results are almost identical despite of making two dimensional or three dimensional analysis or using different software: the differences are less then *2%* which can also be in part due to error in measurement, taken upon a not perfectly straight wall.

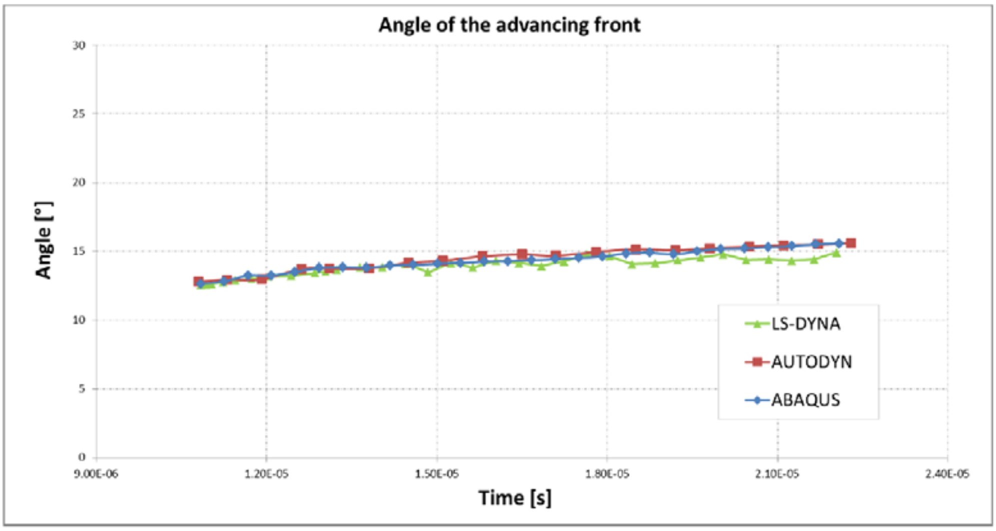

Fig. 9 Angle of the deformed tube wall

Finally, it is arguable that the results are comparable, i.e. similar, despite the fact that the software have diverse environments to describe and simulate the event. Also, if the advantage of using the axial-symmetry model is taken into consideration, very good results were obtained with a significant reduction of the computational time. In fact, considering the simulation time needed by the programs to compute all processes, the three dimensional simulation made in ABAQUS needed more than a day with 8 real cores used, while AUTODYN and LS-DYNA needed less than half hour with 4 cores used. In conclusion, since the results of all three software are very similar and also the computational time for 2D analysis are significantly less than the 3D one, the 2D models prove to be the most efficient and are highly recommendable.

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NUMERIČKA SIMULACIJA EKSPLOZIJE OGRANIČENE UNUTAR CILINDRIČNE CIJEVI NAČINJENE OD ALUMINIJSKE SLITINE AL6061-T6

SAŽETAK

Simulacija ponašanja strukturnih komponenti izloženih visoko eksplozivnoj detonaciji jedan je od suvremenih izazova u polju numeričke simulacije. Uz eksperimentalne testove, numerička analiza je nužna kako bismo podrobnije opisali događaj eksplozije te tim saznanjima umanjili troškove budućih eksperimentalnih istraživanja. Visoke vrijednosti prirasta deformacija, visoka temperatura i tlak zajedno s fenomenom otkazivanja strukturnih komponenti upravljaju složenim procesima interakcije eksplozije i strukture. U ovakvome scenariju, simulacijske mogućnosti i izvedba numeričkog softvera ključne su za kvalitetu i ishod simulacije. U ovome se radu također pruža usporedba različitih softvera temeljenih na metodi konačnih elemenata kao što su ABAQUS, AUTODYN i LS-DYNA za simulaciju događaja eksplozije. U radu se razmatra ponašanje cijevi načinjene od aluminijske slitine tipa Al6061-T6 napunjene eksplozivnim materijalom. Koriste se uparena Eulerova i Lagrangeova formulacija uz uporabu konstitutivnih jednadžbi zakona ponašanja materijala relevantnih za simulaciju eksplozije (aluminijska slitina Al6061-T6, eksploziv C4 i zrak). Naposlijetku će se iznijeti i kritički sagledati rezultati te usporedbe različitih numeričkih rješenja.

Ključne riječi: *eksplozivna detonacija, cilindrična cijev, numerička simulacija, Al6061-T6, brzi prirast deformacija.*