I-BEAM STRUCTURE UNDER BLAST LOADING – EULERIAN MESH DENSITY STUDY

Łukasz Mazurkiewicz, Jerzy Małachowski

Military University of Technology, Faculty of Mechanical Engineering,
Department of Mechanics and Applied Computer Science
Kaliskiego Street 2, 00-908 Warsaw, Poland
tel.: +48 22 683-96-83, fax: +48 22 683-93-55
e-mail: lmazurkiewicz@wat.edu.pl, jerzy.malachowski@wat.edu.pl

Abstract

Dynamic response of an I-beam structure subjected to shock wave produced by the detonation of high explosive (HE) materials is presented in this paper. LS-DYNA, a 3-D explicit, finite element computer code is used to study this behaviour. A coupled analysis between Lagrangian formulation (solid material) and Eulerian formulation (gas medium) was performed. The latest extensive research in this area indicates that the finite element analyses of such problems require complex meshes for Euler and Lagrange formulation. This research is focused on Euler mesh density influence on coupled analysis results. The principal objective of this paper is to compare various mesh density Eulerian models in respect to accuracy and computing time and asses the limit of element size. The Eulerian domains (Air and HE) were developed with various element size from 10 mm up to 30 mm. Results from all the analysis cases show how the Eulerian mesh element size influences on the global response of the column. Models with coarse meshes give much lower dynamic response then models with finer meshes. The resultant velocity vectors were also presented to illustrate the characteristic of blast wave propagation. Moreover the numerical models computational efficiency was compared are respect of CPU Time. Models with complex meshes (below 20 mm) are very computationally expensive.

Keywords: *blast wave, FEM, Eulerian mesh*

1. Introduction

The problem of high explosives materials and the development of structures resistant to the shock wave have been very popular due to increasing terrorist activities in recent years. Bombing attacks are the most common terrorist attacks (Fig. 1) and its number is still growing (Fig. 2). In 2010 bombing incident victims count 6,595 dead and 21,151 wounded [1].

Due to increasing threat structures to resist blast effect are desired and an efficient method of analysis is required to develop that structure. Computational mechanics methods used in this research seem to be fully applicable to such problems.

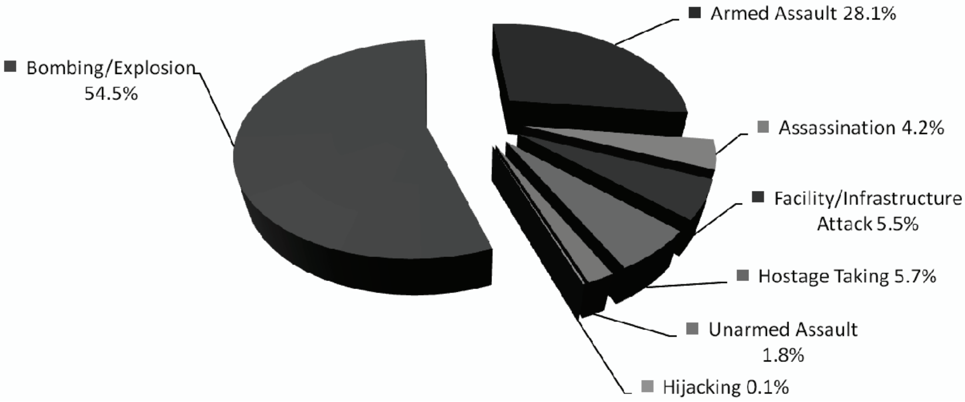

Fig. 1. Types of global terrorism attacks in 2007 [2]

Explosion is an exothermic reaction induced by external effects. This reaction result in mechanical interaction through the highly compressed hot gases. The surrounding medium generates a sudden pressure jump, reaching values of tens GPa. Also the velocity of detonation-wave propagation is usually within the range of 1000-10000 m/s [3].

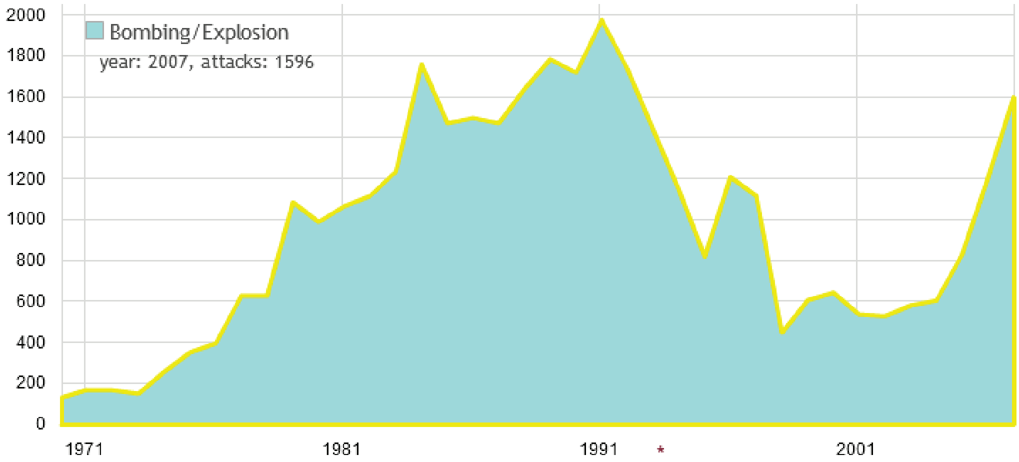

Fig. 2. Trends in global terrorism [2]

Such simulations require complex meshes with advanced constitutive material models capable of describing behaviour of air, the high explosive material (*HE*) and an engineering object subjected to blast wave resulted from the blast wave detonation. However, this very detailed description of the blast wave may be too computationally expensive [4].

This research is focused on Euler mesh density influence on coupled analysis results. The principal objective of this paper is to compare various mesh densities of ALE models in respect to accuracy and computing time and asses the limit of maximum element size.

2. Simulated problem

Dynamic response of a steel I-beam column to the effects of a blast load generated by 50 kg of TNT at 2 meters was analyzed. The columns are UC203x203x86 (A992 rolled shapes), have a height of 4.5 m and support a static axial load of 300,000 N (Fig. 3). Fixed-simple boundary conditions are assumed.

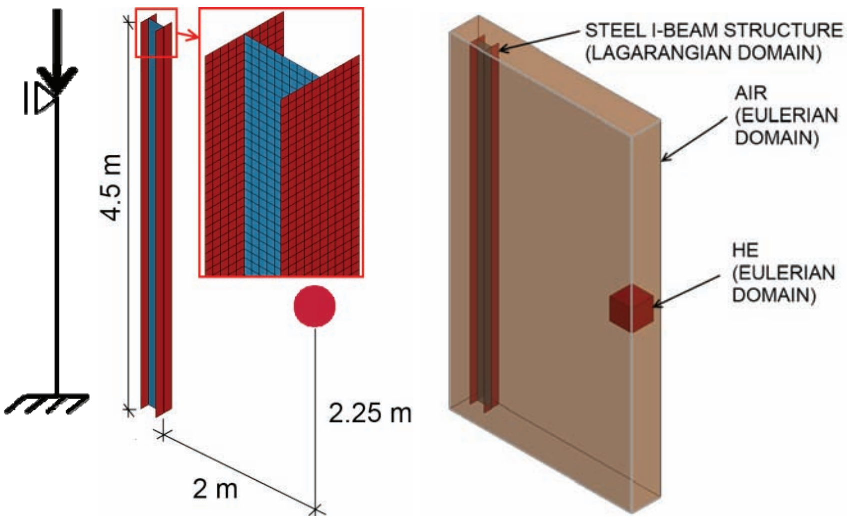

Fig. 3. Studied case

3. Discrete models

The steel column model was developed using shell elements in Lagrangian formulation. Due to the complexity of the constitutive material models the Belytschko-Lin-Tsay shell element with thickness stretch was implemented to describe the I-beam structure. Average element size of column modes is 20 mm.

The elastic-plastic material model with isotropic hardening was applied to describe the half cylindrical surface properties including strain rate effect. The Johnson–Cook model provides a satisfactory prediction of flow stress σ_{flow} for large strains and high strain rates when its dependence on strain rate is linear in semi logarithmic scale. The mathematical formula which describes this model is as follows [5]:

$$\sigma_{flow} = \left[A + B\left(\varepsilon^{p}\right)^{n} \right]\left(1 + C\, ln\, \dot{\varepsilon}_{*}^{p}\right), \tag{1}$$

where A, B, C, n = material constants and $\dot{\varepsilon}_{*}^{p}$ = effective plastic strain rate.

The detonation process of *TNT* high explosive material was implemented in the performed numerical tests through the automated programmed burn model, supported by LS-DYNA using so called “explosive burn” material model. The energy contained in the *HE* was assumed to be immediately released inside the front of detonation wave. The detonation requires modelling of the movement of the *PD* (product of detonation) after reaching successive locations by the *DW* (detonation wave) front. The Jones-Wilkins-Lee (*JWL*) equation of state was implemented in the applied explosive burn model. This equation of state has the following form [3, 6]:

$$p = A\left(1 - \frac{\omega}{R_1 \bar{\rho}}\right) exp\left(-R_1 \bar{\rho}\right) + B\left(1 - \frac{\omega}{R_2 \bar{\rho}}\right) exp\left(-R_2 \bar{\rho}\right) + \frac{\omega \bar{e}}{\bar{\rho}}, \tag{2}$$

where $\bar{\rho} = \rho_{HE} / \rho$; $\bar{e} = \rho_{HE}\, e$; ρ_{HE} = density of the high explosive; p = pressure of *PD*; e = specific internal energy of *PD* and ρ= density of *PD*. A, B, R_1, R_2, ω are empirical constants determined for specific type of a high explosive. All constants required are taken from literature [7] (Tab. 1):

The blast wave propagates in air medium. Column model and *HE* model were submerged within the air domain model. It requires defining the equation of state for air which is considered as simple ideal gas with linear polynomial equation of state [6]:

$$p = \left(C_4 + C_5 \mu\right) E, \tag{3}$$

where:

$\mu = \rho/\rho_0$,

C_4, C_5 - polynomial equation coefficients,

ρ - density,

ρ_0 - initial density,

E - internal energy.

The Eulerian domains (Air and *HE*) were developed with various element sizes from 10 mm up to 30 mm with assumption of perfectly cubical *HE* model. Analysis cases data is presented in Tab. 1.

The FE models of analysis cases with minimal (10mm) and maximal (30mm) element size are presented in Fig. 4.

4. Numerical analysis

LS-DYNA 3-D explicit, finite element computer code was used to study this behaviour. A coupled analysis between Lagrangian formulation (solid material) and Eulerian formulation (gas medium) was performed.

Tab. 1. Analysis cases data

Case name	Element size [mm]	HE elements per edge length	Total number of Eulerian domains elements
30 mm	31.304	10	193 200
27.5 mm	28.458	11	249 975
25 mm	26.086	12	316 800
22.5 mm	22.360	14	541 800
20 mm	19.565	16	776 160
17.5 mm	17.391	18	1 069 200
15 mm	14.906	21	1 763 055
12.5 mm	12.521	25	3 018 750
10 mm	10.098	31	5 698 575

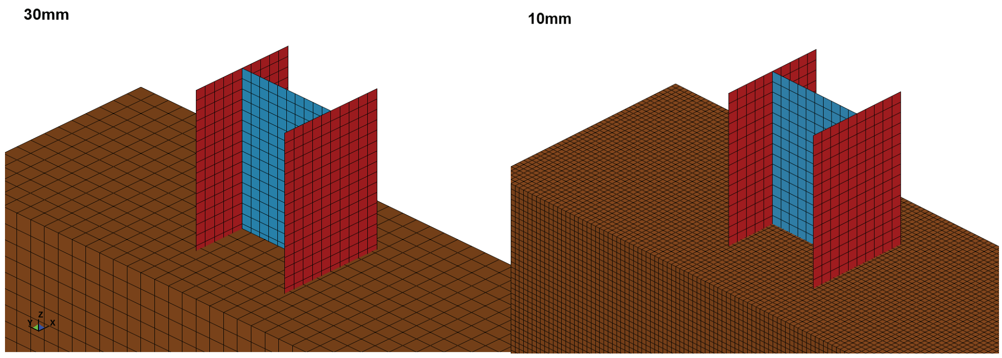

Fig. 4. Models of cases 10mm and 30mm

The ALE procedure consists of the following sequence of steps: the classical Lagrangian step and the advection step. The advection step is carried out with the assumption that changes in the positioning of nodes are only slight (very small) in comparison to characteristics (lengths of elements that surround these nodes). Another advantage of using this procedure is that the constant topology of the *FEM* grid is provided.

The governing equations for the fluid domain (Euler domain) describe the conservation of mass, momentum and energy:

$$\frac{dM}{dt} = \frac{d}{dt}\int_{V(t)} \rho dV = \oint_{S(t)} \rho(\underset{\sim}{w} - \underset{\sim}{v}) \cdot \underset{\sim}{n} dS \quad , \tag{4}$$

$$\frac{d\underset{\sim}{Q}}{dt} = \frac{d}{dt}\int_{V(t)} \rho \underset{\sim}{v} dV = \oint_{S(t)} \rho \underset{\sim}{v}(\underset{\sim}{w} - \underset{\sim}{v}) \cdot \underset{\sim}{n} dS - \int_{V(t)} \nabla p dV + \int_{V(t)} \upsilon \underset{\sim}{g} dV \quad , \tag{5}$$

$$\frac{dE}{dt} = \frac{d}{dt}\int_{V(t)} \rho e dV = \oint_{S(t)} \rho e(\underset{\sim}{w} - \underset{\sim}{v}) \cdot \underset{\sim}{n} dS - \int_{S(t)} p \underset{\sim}{v} \cdot \underset{\sim}{n} dS + \int_{V(t)} \rho \underset{\sim}{g} \cdot \underset{\sim}{v} dV \quad , \tag{6}$$

where, ρ = fluid mass density, p = pressure, $\underset{\sim}{g}$ = acceleration of gravity and e = total specific energy. The quantities M,Q and E are the total mass, total momentum and total energy, respectively, of a control volume $V(t)$, bounded by a surface S, which moves in the fluid (gas-air) with arbitrary velocity $\underset{\sim}{w}$ which may be zero in Eulearian coordinates or $\underset{\sim}{v}$ in Lagrangian coordinates. The vector $\underset{\sim}{n}$ is the outwards normal to the surface S.

The 2% of critical damping was applied to the model, damping coefficient was obtained from engenvalue analysis.

5. Results

Results from all the analysis cases show how does the Eulerian mesh element size influence the global response of the column (Fig. 5).

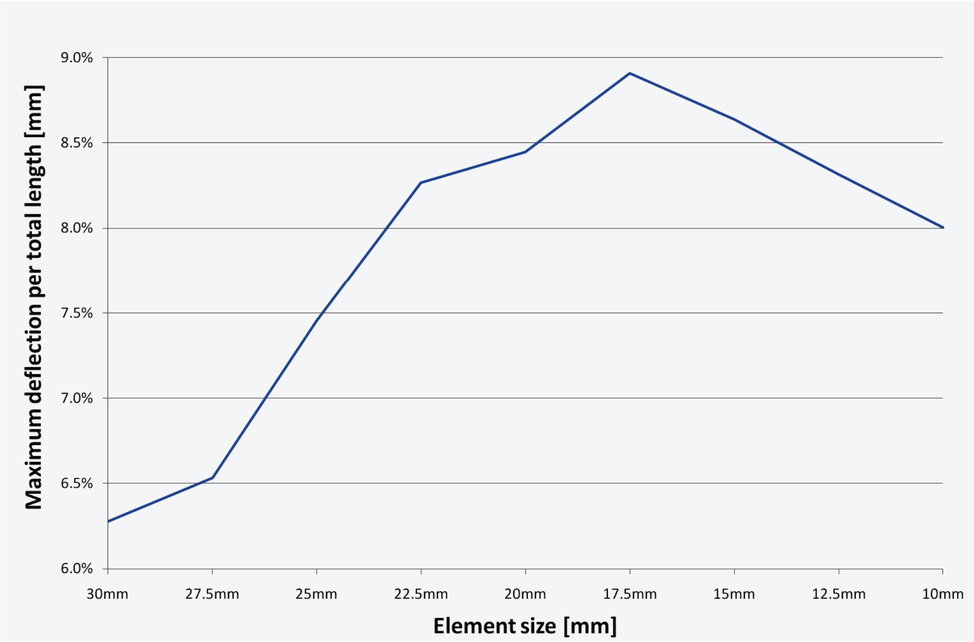

Fig. 5. Maximum column deflection in function of Eulerian mesh element size

It can be seen that models with coarse meshes results in the much lower deflections than models with element size about 20 mm. Further mesh densification gives an opposite effect. Under 17.5 mm of element size global structure response is also decreasing.

Element size influence is noticeable in Eulerian domain kinetic energy trend. Increasing the number of elements the kinetic energy of air and products of detonation are growing (Fig. 6).

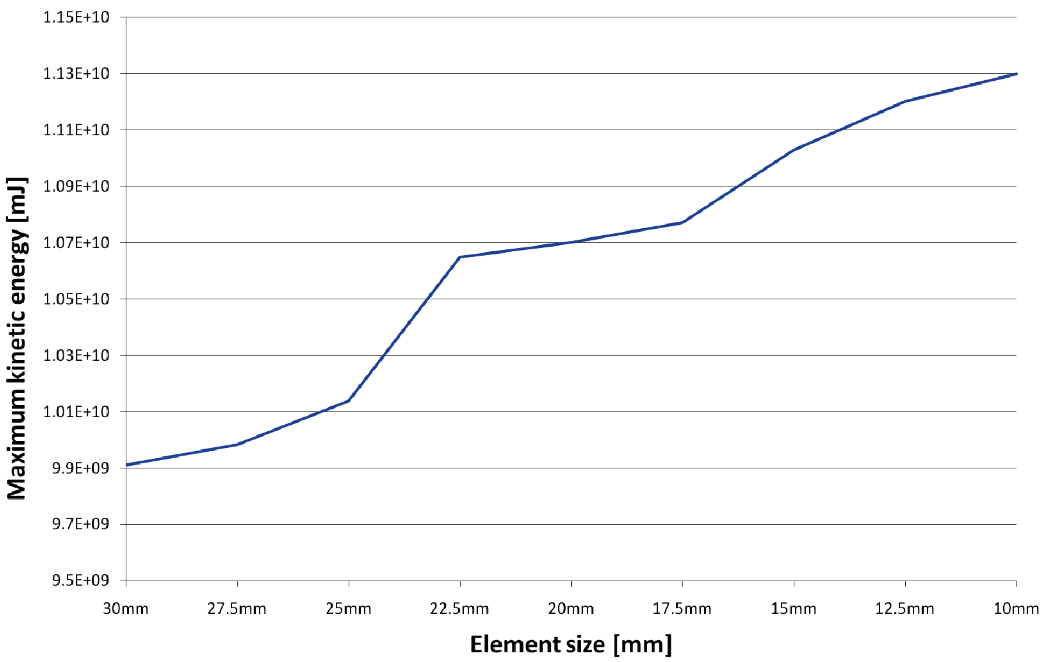

Fig. 6. Maximum Eulerian domain kinetic energy vs. element size

Deformation plot with map of Y-displacement for minimum and maximum deflection cases are presented in Fig. 7.

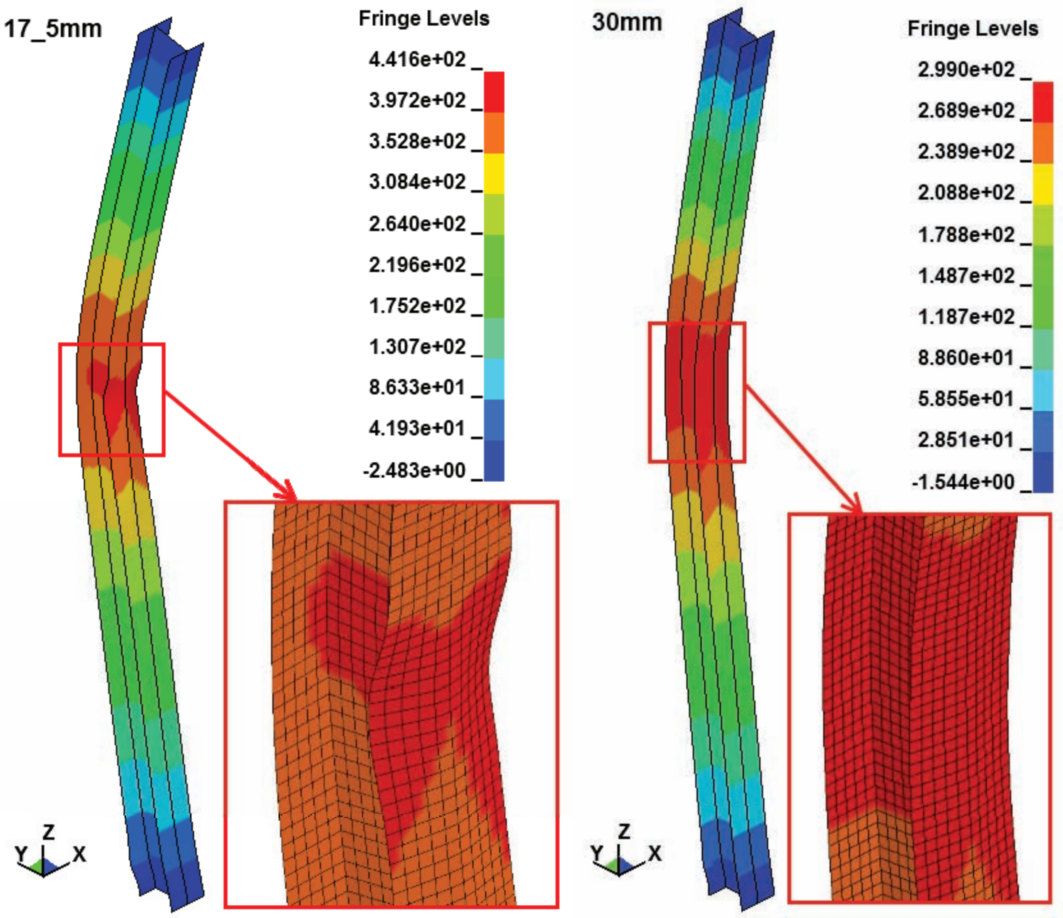

Fig. 7. Map of Y-displacement [mm]

Numerical results are also presented to illustrate the characteristic of the blast wave propagation. Fig. 8 show resultant velocity vectors for the analysis cases. It can be noticed that under 17.5 mm element size local flow effect around a body appears.

Numerical models computational efficiency was compared are respect to CPU Time (Fig. 9). Analyses were performed on multi-core cluster with the usage of 12 cores per analysis job.

It can be seen that models with complex meshes (below 20mm) are very computationally expensive.

6. Conclusions

Performed analyses confirmed the Eulerian mesh element size influence on the global response of the column. Models with coarse meshes give underrate response of the column subjected to the blast wave. Finer meshes result in increasing of the column deflection but with meshes under 17.5 mm element size local flow effect around the column appears and the response is decreasing. Also element size differences between Eulerian and Lagrangian meshes which influence on coupling process can be probable cause. Further investigation will be carried out within stated problem to explain this phenomenon.

Nevertheless the results shows that mesh element size in blast wave interaction study should not exceed 20-22.5 mm which leads to significant decrease of global response and models with that mesh density have acceptable computational time.

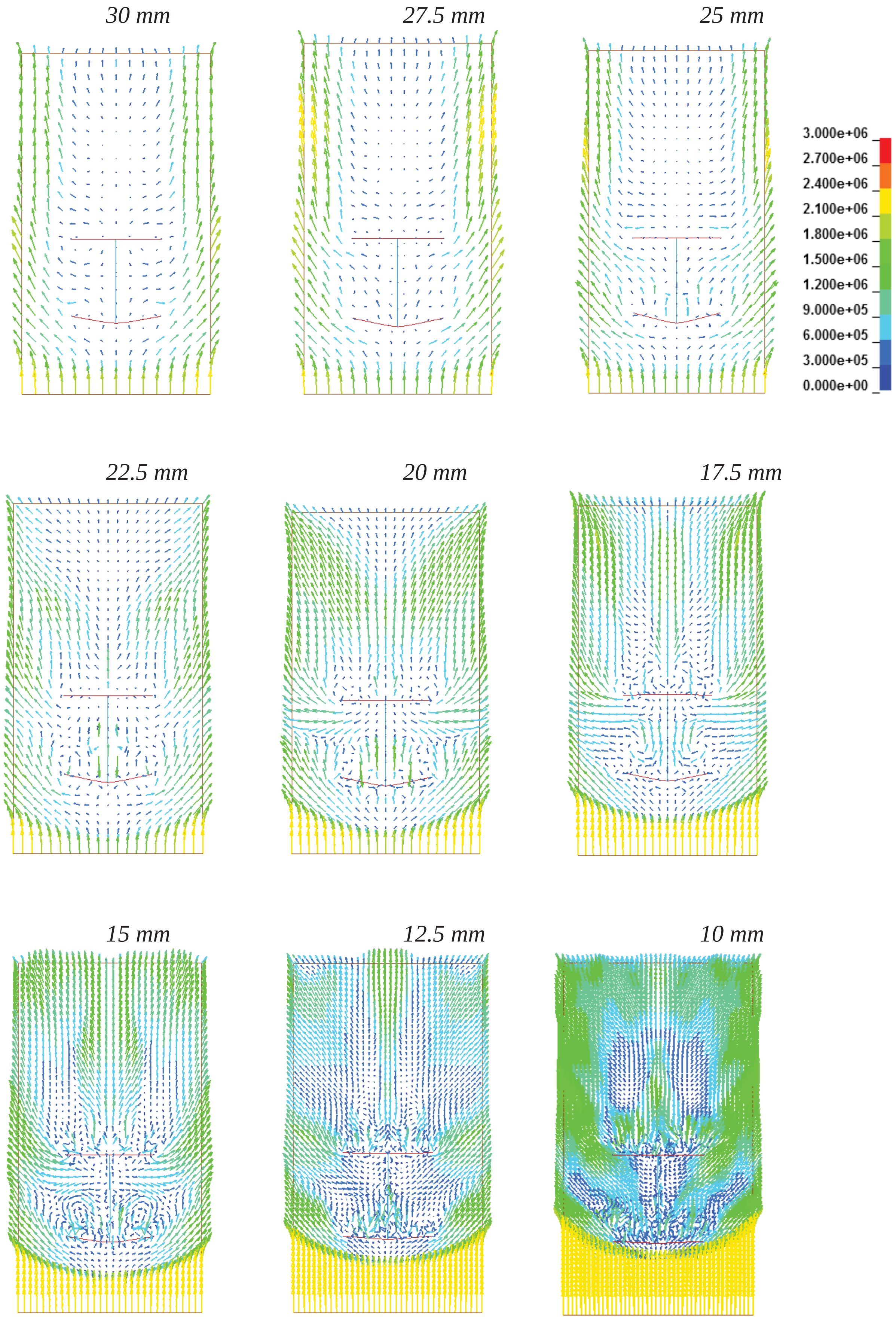

Fig. 8. Velocity vectors at 0.001 s [mm/s]

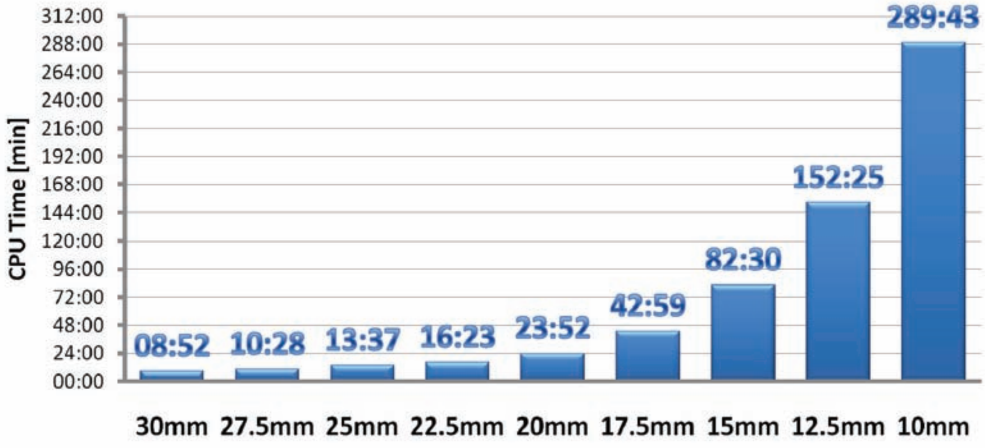

Fig. 9. Computational time of analysis for studied cases.

Acknowledgement

The research was carried out under a research grant from Polish Ministry of Science and Higher Education. This support is gratefully acknowledged.

References

[1] Worlwide Incidents Tracking Systems, National Counterterrorism Center (NCTC), *https://wits.nctc.gov*
[2] Global Terrorism Database (GTD); *http://www.start.umd.edu/gtd/features/GTD-Data-Rivers.aspx*
[3] Wlodarczyk, E., *Fundamentals of detonation*, Military University of Technology, Warsaw 1995.
[4] Malachowski, J., *Modelowanie i badania interakcji ciało stałe-gaz przy oddziaływaniu impulsu ciśnienia na elementy konstrukcji rurociągu*, BEL Studio, Warszawa 2010.
[5] Malachowski J., *Influence of HE location on elastic-plastic tube response under blast loading*, Shell Structures Theory and Applications, Vol. 2, pp. 179-182, 2010.
[6] Hallquist, J. O., *LS-DYNA. Theory manual*, Livermore, California 2006.