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ANALYSIS OF SELECTED STRUCTURAL COMPONENTS SUBJECTED TO BLAST WAVE

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Abstract

The phenomenon of high-energy explosion of a substance such as the mixture of flammable gases, explosives, etc. is highly exothermic chemical reaction that causes a blast wave consisting of hot gases at high pressure. Very complex nature of the phenomenon of detonation, affects the need for advanced methods of analysis. In the present work analysis of two steel columns (I-section and tubular section) subjected to the blast wave are presented.

The columns have similar values of the moments of inertia and mass per unit length. To describe the complex phenomena occurring in gas medium the Eulerian formulation was used. The steel structures were described using Lagrangian formulation. Interaction between domains was achieved by numerical coupling algorithm with implemented penalty function. From the results from all the analysis cases, the dynamic response of structural elements was obtained. Permanent deformation and the amount of absorbed energy are of special interest in this study. The resultant velocity vectors were also presented to illustrate the characteristic of blast wave propagation.

Keywords: *ALE formulation, blast wave, dynamic response, structural component*

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. In 2010 death toll of bombing incidents counted 6,595 and 21,151 people were 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, especially finite element analysis, used in this research, seem to be fully applicable in such problems. In opposition to other methods of blast response analysis, based on theoretical substitute models (e.g. SDOF) this method include the fluid structure interaction and is sensitive to the shape of interacting surface.

In the present work analyses of two steel columns (I-section and tubular section) subjected to the blast wave are presented. The main aim of this study is to assess the section shape influence on the dynamic response of narrow columns. The authors expect that the narrow front face of the components and the significantly higher charge standoff results in similar blast resistance with no significant influence of section shape.

2. Simulated problem

Dynamic response of steel columns (I-section and tubular section) subjected to the blast load generated by 50 kg of TNT at 2 meters was analyzed. The columns have similar values of the moments of inertia and mass per unit length, have a height of 4.5 m and support a static axial load of 300,000 N (Fig. 2). Fixed-simple boundary conditions are assumed.

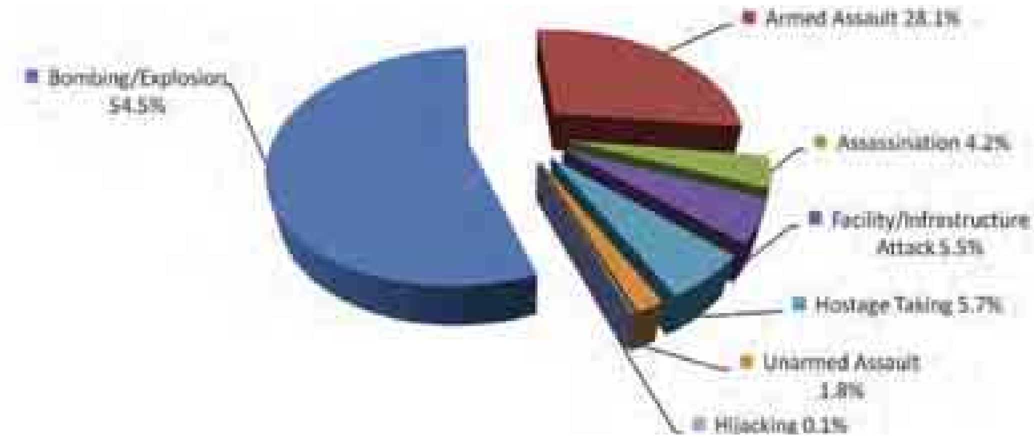

Fig. 1. Types of global terrorism attacks in 2007 [2]

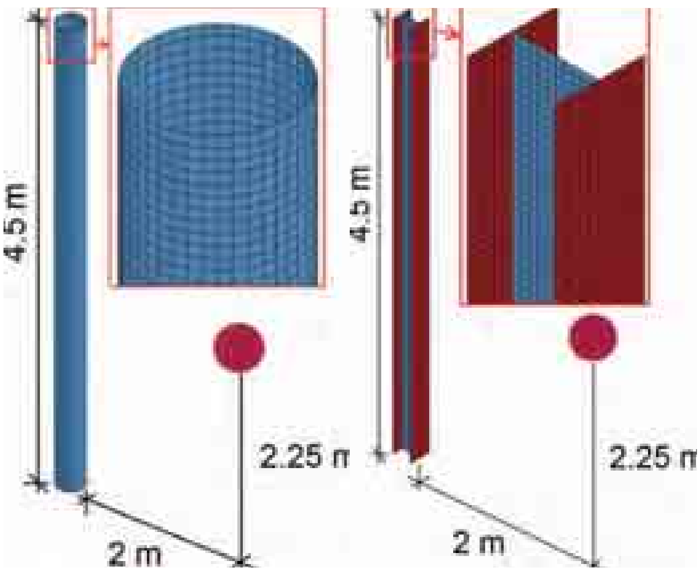

Fig. 2. Studied cases

3. Discrete models

The steel columns models were 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 steel structures. Average element size of column modes is 20 mm. The elastic-plastic material model with isotropic hardening was applied to describe the structural components 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 [5] (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 and C_5 = polynomial equation coefficients, ρ = density, ρ_0 = initial density, E = internal energy.

The characteristic length of the element representing the Eulerian domain was assessed in previous study [7] and is assumed to be 20 mm.

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.

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 [3]:

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

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

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

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.

5. Results

From the analyses results dynamic responses and deformations of structural elements were obtained. Permanent deformation (Fig 3, 4) and the amount of absorbed energy (Fig. 5) are of special interest in this study. The global response of the columns is similar but the local differences are noticeable. The boundary conditions and the local buckling effect results in different deformation of the part in the middle and bottom of components. The column deformation profile shows also a translation of the maximum deflection point to the bottom of the column.

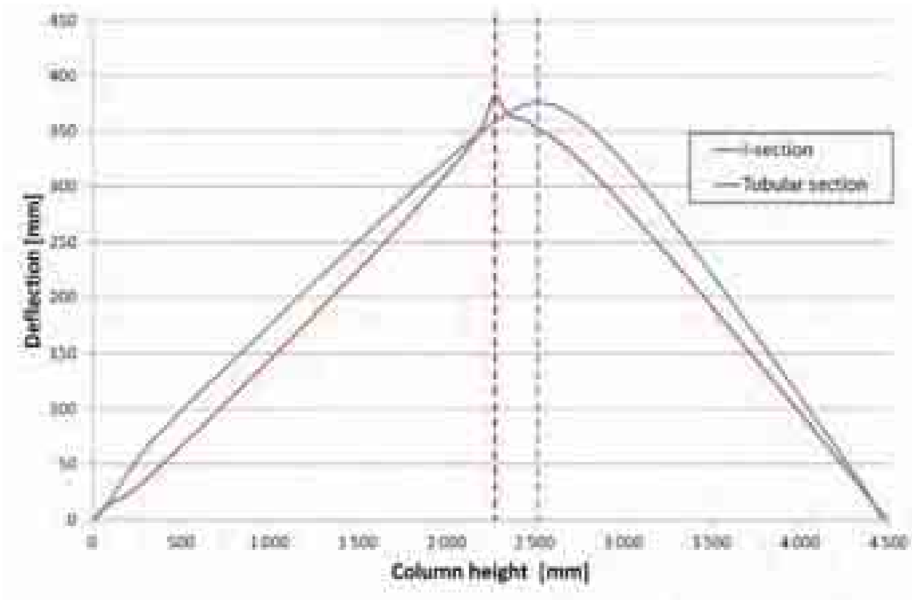

Fig. 3. Column deformation profile at maximum deflection

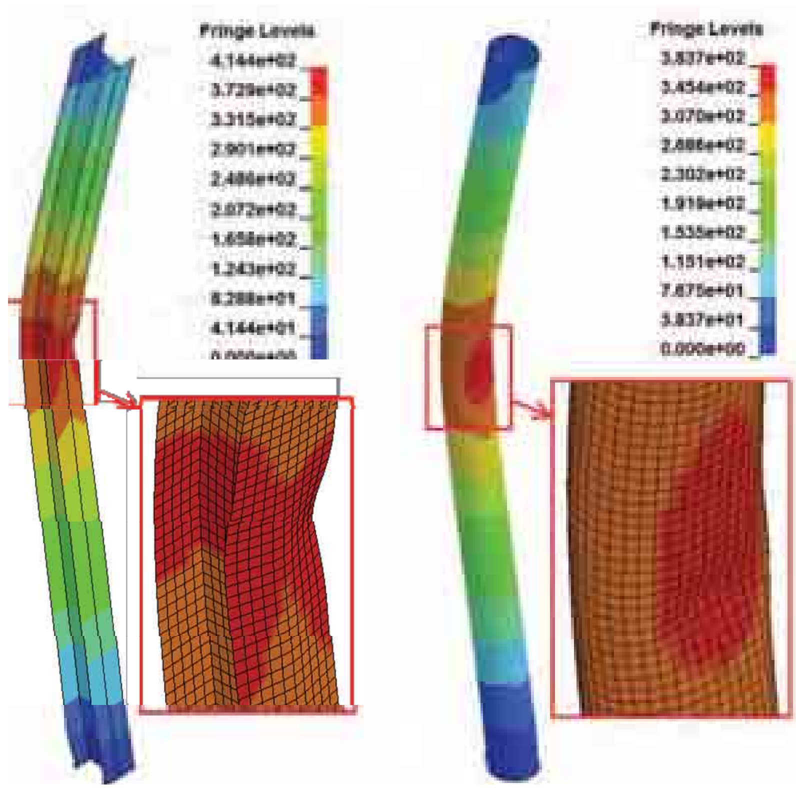

Fig. 4. Displacement map at maximum deflection [mm]

The most noticeable differences appear in the energy comparison study. The amount of the absorbed energy is significantly higher for the I-section case (Fig. 5). This is caused by the higher deformation of the section flanges.

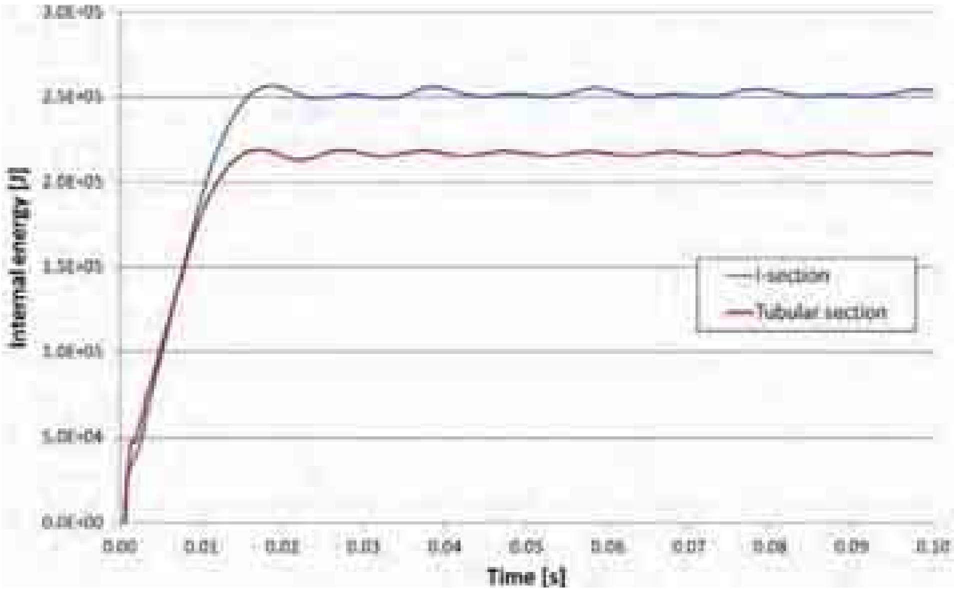

Fig. 8. Energy absorbed by structure

The resultant velocity vectors were also presented to illustrate the characteristic of blast wave propagation (Fig. 6). At the early stage of deformation, the blast wave propagation character is similar in both cases. It is also noticeable that the way of deformation in the first analysis case results in streamlining the section whereas in the second analysis case the section is getting flatter.

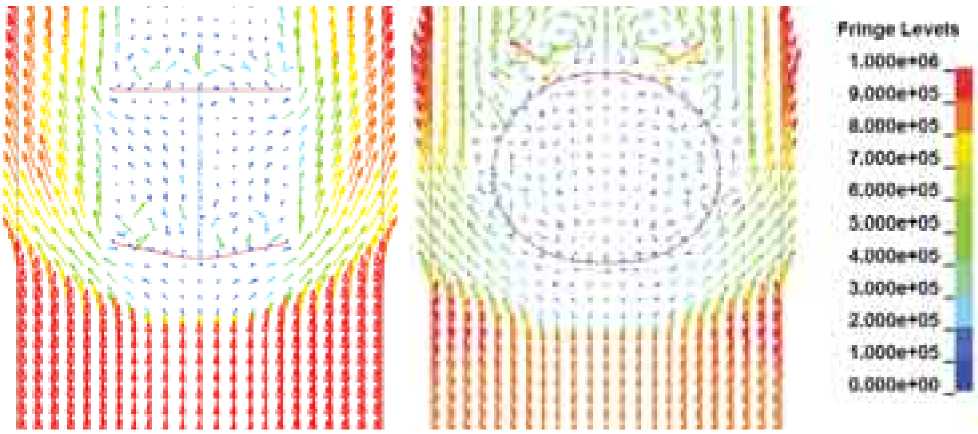

Fig. 6. Resultant velocity vectors [mm/s] for Eulerian domain at t=0.002s

6. Summary

The main aim of this work was to assess the dynamic response of two structural components with different section shapes (I-section and tubular section) but similar stiffness. Obtained results indicate that similar momentum of inertia and mass per unit length effects in comparable characteristic of global deformation. It means that there is no reasonable cause to optimize the external shape of protective panels against blast wave. The optimization of the internal structure of a panel can probably results in better blast resistance improvement than the optimisation of external shape. The streamline profile of a column is meaningless when the column has the narrow front face and the charge standoff distance is relatively high.

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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.

[7] Mazurkiewicz, Ł., Małachowski, J., *I-Beam Structure Under Blast Loading – Eulerian Mesh Density Study*, Journal of KONES Powertrain and Transport, Vol. 18, No. 3, pp. 245-252, 2011.