Effect of blast wave on chosen structure – numerical and experimental study

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***Abstract*—** This paper is based on non-linear finite element analysis of the effects of the blast wave on structures, caused by the detonation of explosive materials. Dynamic response of a pipeline subjected to the shock wave produced by the detonation of high explosive materials is presented in this paper. Coupled Euler and Lagrange formulation are used in the finite element analysis of such problems to accurately represent the detonation phenomenon. Preliminary results allow for detailed analysis of the blast wave propagation and its influence on the pipeline.

***Keywords*—** safety, explosive, pipeline, numerical analysis, blast, coupling

I. Introduction

THE earth gas is both one of the most essential heat-energy carriers and the basic raw material for the chemical industry. As a heat-energy carrier, most commonly it is used in households. Recently, it has become a major source used to generate electricity. Long-distance gas transportation is performed under high pressure, in the form of liquefied natural gas by pipelines. Only after having the gas delivered at its destination, it is decompressed to reach the distribution-pressure level. This fact is of great significance to the safety of gas transportation to end-users. The gas transportation safety is extremely sensitive to any acts of terrorism. In practice, it is impossible to safeguard and protect any gas-transmission pipelines that spread out over thousands of kilometres against terrorist attacks. What can and should be done is to minimise its susceptibility to probable attacks, i.e. to minimise effects of the most disadvantageous variants of terrorist attacks against the gas transmission pipelines.

The safety of gas delivery via gas transmission pipelines can be increased under the above-mentioned conditions by the following means [17]: diversification of power supply sources into separate urban agglomerations, the construction of suitably dislocated gas storage facilities, provisions for supplying end-users with gas from different sources, owing to the ring-shaped structure of the gas transmission system, suitable dislocation of engineering workshops furnished properly to quickly restore serviceability of the gas pipeline after the terrorist attack and high energy absorbing systems of protective layers [4,6,9,13,14].

When setting about to analysing possible terrorist actions against gas transmission pipelines, one should assume that terrorists who want to achieve their goals would not confine their actions to sabotage alone to effect economic impairment of the state. They would rather, or even above all, try to effect the mass neurosis in the society to force the State authorities to make some definite concessions. The above assumed to be a starting-point for the analysis of possible terrorist actions aimed at gas transmission pipelines implies the necessity of giving estimates on: components of the gas transmission pipelines most susceptible to terrorist attacks, points of attacks where the greatest hazards to human beings and environment, as well as economical losses would be provoked, points of attacks that could paralyse the whole country, and hence, the State's functioning, locations, times, and ways of performing terrorist attacks that, on the one hand, would threaten society to the greatest degree possible, whereas on the other hand, evoke the sense of the State's helplessness. Results of the above-suggested assessments would become a starting-point for the analyses of: possible ways of reducing the harmfulness of potential terrorist actions, the cost of preventive actions.

Past our team investigations on pipeline was primarily focused on investigation of geometric flaws, which may be detected in oil or gas transporting pipeline by a PIG calliper during a regular inline maintenance inspection. Such common flaws include dents, folds, and local buckles. The proposed research method was based on numerical simulation and analysis using the Finite Element Method (FEM). Laboratory tests were often conducted for a comprehensive verification of the FE models, their mechanical properties, and the methodology used [1,11]. Dents, folds and off-round imperfections were developed in labs using strength testing machines in samples of weldless thin-walled pipes. Such experiments were conducted under strict control, enabling measurements of deformations and strains in selected points located on external surface of the pipe wall. Experimental research on deformations and strains, conducted for bended pipes, allowed for verification of strains and stress distributions obtained from numerical studies. These laboratory based verification efforts resulted in significant improvements of the initial FE models and in increased confidence in final data obtained from computational

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mechanics.

Full-scale experimental testing of the effects of explosion on conventional structures is prohibitively expensive. A solution to these problems is offered by modern computational tools like FEM. Recently developed features of commercial FE codes allow, at a low cost, the numerical simulation of high explosive (HE) blasts to be repeatedly run and compared. Results from fluid pressure and blast wave simulation studies were published and discussed in several recent publications [3,4,10,12,15,16]. Such simulations require complex meshes with advanced constitutive material models capable of describing the behavior of air, the high explosive material (HE) and an engineering object subjected to blast wave resulted from the blast wave detonation.

The effect of a terrorist attack on a bus structure was studied by Morka [10]. The principal objective of his paper was to explore capabilities and usefulness of FEM for assessment of structural bus response and survivability of the passengers under a suicidal terrorist attack on the bus. A study concerning a protective capacity of containment structures subjected to blast wave is presented by Cichocki [4]. In this study impulsive loading placed underwater interacted with protective underwater structure to secure pipelines from a terrorist attack. The author of the paper implemented computer code with explicit solution [5]. The obtained results allowed to find the best protection in term of its effectiveness.

The main goal of this research was focused on establishing effective simulation methodology to study the influence of shock wave caused by explosion on pipeline systems.

II. Numerical Assessment of Detonation Process

A. The nature of detonation

Explosives produce violent exothermic reactions induced by external effects [10,15]. These reactions result in mechanical work through the evolution of highly compressed hot gases. The explosive material, filled with the gas generated products, are highly compressed at the surface. The surrounding medium generates a sudden pressure jump, reaching values of tens GPa. Another element of extremely high importance throughout this process is velocity of the detonation-wave propagation, usually within the range of 1000÷10000 m/s. Gas products of detonation, high reaction rate, and the exothermic nature of the blast, are the most fundamental factors responsible for strong and destructive effects of explosion [16].

Classic physical theory describes the shock wave as a surface of strong discontinuity where thermodynamic parameters (pressure, density, internal energy, mass velocity, entropy, temperature) are undergone a sudden and jumping changes. Equations involving these parameters in the initial state (before shock front) and on the shock wave front can be derived with the mass, momentum and energy conservation laws, including equation of state (EOS) [5,10,15]. Material properties in respect of shocks propagation are often characterized by Hugoniot Adiabat (HA) in one of the following forms: $p_H = f(\rho_0, p_0, \rho_H)$ or $p_H = f(u_0, p_0, u_H)$; where subscript "*0*" refers to the initial state, whereas "*H*" – to the shock front. Pressure, density and mass velocity were denoted by p, ρ, u, respectively. The detailed forms of the HA can be obtained empirical or analytical based on given EOS. Every HA is located over the Poisson Adiabat (PA) because of entropy change in the shock wave front. The typical shock front thickness in the gases is in the order of several free paths of the molecules. Shockwaves propagate with the velocity exceeding the local sound speed of the material before the front. The value of this velocity depends on the shock intensity (pressure on the front), stronger shocks travel faster. Every expanding shock diminishes as it overcomes successive distance from the originating point except the converged shockwaves. The geometric factor and entropy production are responsible for the shock intensity diminishing. The shock intensity declines together with increasing of the distance from the originating point r in relations increases. The diminishing rate varies between $(1/r)$ and $(1/r^3)$, depending on the front geometry.

B. The numerical description of detonation process

The detonation process from numerical point of view can be be implemented through the automated programmed burn model, supported by LS-Dyna [5]. In this model, it is assumed that the velocity of the Detonation Wave (DW) and the thermo-dynamical parameters on DW front are known [10]. This data is considered as a material properties related to a specific kind of HE. Additionally, the appropriate shape of the DW front must be defined based on the way of initiation of detonation. The best DW front shape is the surface of a sphere if the initiation of detonation begins in the center point of HE charge. In the proposed detonation model, the fundamental assumption will be made that the energy contained in the HE is immediately released inside the front of detonation wave. That energy is released as a result of the chemical reaction: $HE \rightarrow PD + Q$, where Q represents the heat effect of this reaction and PD are products of detonations. In addition, 100 % of HE mass transfers to PD. Under all above conditions, modeling of the detonation process leads to the description of the movement of the PD after reaching successive locations by the DW front. The Jones–Wilkins–Lee (JWL) equation can be used to characterize the products of detonation of the high explosive. The JWL equation of state used in the model has the following form [4,5,8,10,15,16]:

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

where, $\bar{\rho} = \rho_{HE}/\rho$, $\bar{e} = \rho_{HE} e$, p is the pressure of PD, e is the specific internal energy of PD and ρ is the density of *PD* and

R_1, R_2, A, B, ω are explosive's constants for specific type of *HE* available in references [4,10,115].

III. Interaction between blast wave and tube element

The state of affairs recently observed in world-wide proves that terrorist actions are possible at any time, first and foremost because gas/petroleum products transmitting systems remain easy of access. In the case of simulation of the processes given consideration, the problem to be solved is the selection of constitutive models suitable for materials used while constructing pipelines and components of infrastructure. The author introduces some problems related to interactions between the gas and the solid body, a tube's component subjected to some strong dynamic pulse (load) effected by the detonation of explosives. The LS-Dyna non-linear explicit computer code was used for all computational simulations in this studies and is particularly well suited to this type of study as it can simulate the blast using the Arbitrary Lagrangian Eulerian (ALE) formulation to model the actual blast pressure wave and investigate the interaction between gas body (blast wave) and solid body (tube element).

A. Coupling problem

The ALE procedure consists of the following sequence of steps: the remap step and the advection step. The advection step is carried out on 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 constant topology of the FEM grid is provided. This accuracy is reached owing to the algorithm applied to transform the solution from the deformed grid to the smoothed one. The algorithm performs the procedure with the accuracy to the lows of the second order. While approached theoretically, the ALE procedure contains the Euler formulas as a subset. These formulas allow some parameters to be determined for more than one material in a single element. However, any increase in the number of materials results in the increase in the number of indispensable material parameters (constants, coefficients, etc. The effect is that the cost of one step grows dramatically. The scope of problems that could be handled with the ALE procedure depends on how much the algorithms 'responsible' for the smoothing of the FE grid are complicated, and only on that. In the course of performing the Eulerian step most of the time is spent on computations related to the transmission of the material between adjacent elements; only a slight part of it is consumed to solve the problem of where and how the FE grid should be modified. The advection algorithms in use nowadays are complicated and time-consuming; however, they have afforded elimination of errors that had occurred in the earliest algorithms of accuracy of the first order (false oscillations in results gained, no stability, a limited scope of parameters, etc.). Generally, the following steps can be distinguished in the ALE procedure:

1. Performing a classical Lagrangian step,
2. Performing an advection step, with the following 'sub-steps' included:
   a. making a decision on which nodes should be relocated,
   b. relocation of extreme nodes,
   c. relocation of the internal nodes,
   d. recalculation of all variables as referred to elements,
   e. reevaluation of the momentum, and velocity updating.

The governing equations for the fluid domain (Euler domain) describe the conservation of mass, momentum and energy. The integral form of these equations is very well described in [2] and presented as follows:

$$\frac{dM}{dt}=\frac{d}{dt}\int_{V(t)}\rho dV=\oint_{S(t)}\rho(\underset{\sim}{w}-\underset{\sim}{v})\cdot\underset{\sim}{n}dS \tag{2}$$

$$\frac{d\underset{\sim}{Q}}{dt}=\frac{d}{dt}\int_{V(t)}\rho\underset{\sim}{v}dV=\oint_{S(t)}\rho\underset{\sim}{v}(\underset{\sim}{w}-\underset{\sim}{v})\cdot\underset{\sim}{n}dS+ -\int_{V(t)}\underset{\sim}{\nabla}pdV+\int_{V(t)}\upsilon\underset{\sim}{g}dV \tag{3}$$

$$\frac{dE}{dt}=\frac{d}{dt}\int_{V(t)}\rho edV=\oint_{S(t)}\rho e(\underset{\sim}{w}-\underset{\sim}{v})\cdot\underset{\sim}{n}dS+ -\int_{S(t)}p\underset{\sim}{v}\cdot\underset{\sim}{n}dS+\int_{V(t)}\rho\underset{\sim}{g}\cdot\underset{\sim}{v}dV \tag{4}$$

where, ρ is the fluid mass density, p the pressure, $\underset{\sim}{g}$ the acceleration of gravity and e the 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.

From numerical point of view the solution of the above procedure is able with the systems of equations based on operator split method [2,5]:

1. Lagrangian step:

$$\begin{aligned}\dot{u}^{n+1/2}&=\dot{u}^{n-1/2}+\Delta t\,\underset{\sim}{M}\left\{\underset{\sim}{f}^{ext}-\int\underset{\sim}{B}^{T}dV\right\}\\ u^{n+1/2}&=u^{n}+\Delta t\dot{u}^{n+1/2}\end{aligned} \tag{5}$$

2. Mesh smoothing:
   Eulerian: Mesh is returned to original configuration
   ALE: Mesh is moved to a prescribed manner
3. Advection phase
   Van Leer scheme for history variable
   Interface reconstruction for volume fractions
4. Mixture theory
   Volume fraction weighted stress
5. back to "Lagrangian step"

Every variable has to be 'transported'. These variables comprise, among other ones: velocity, density, internal energy, six components of the stress and plastic-strain tensors, and kinematic strengthening. It should be noted that velocity has to be 'transported' separately, because it is referred to nodes, not to elements like other variables. In LS-Dyna system the Van Leer scheme is used to calculate the values of the solution variables in the transport fluxes to archive second order accurate monotonic results. In this scheme Van Leer replaces the piecewise constant distribution with a higher order interpolation function, $\phi^n_{j+1/2}(x)$ that is subject to an element level conservation constraint. The value of ϕ at the element centroid is regarded in this context as the average value of ϕ over the element instead of the spatial value at $x_{j+1/2}$ [5]:

$$\phi^n_{j+1/2} = \int_{x_j}^{x_{j+1}} \phi^n_{j+1/2}(x)dx \tag{6}$$

To determine the range of ϕ $\left[\phi^{min}_{j+1/2}, \phi^{max}_{j+1/2}\right]$ for imposing the monotonicity constraint, the maximum and minimum values of $\phi^n_{j-1/2}$, $\phi^n_{j+1/2}$ and $\phi^n_{j+3/2}$ are applied (Fig. 1). Monotonicity can be introduced by two different ways. The first is to require that the maximum and minimum values of $\phi^n_{j+1/2}(x)$ fall within the range determined by the three elements. The second is to restrict the average value of ϕ in the transport volumes associated with element $j+1/2$. In each step of this algorithm the slope of function describing transported values ϕ is determined by assuming the maximum permissible values at the element boundaries.

For regular mesh, one-dimensional advection methods is be extended to two and three dimensions by using a sequence of one-dimensional sweeps along the logically orthogonal mesh lines. According to procedure described in [5] the advection scheme in LS-Dyna is performed isotropically. The fluxes through each face of element *A* are calculated simultaneously based on the following expression [5]:

$$\phi^{n+1}_A = \frac{1}{V^{n+1}_A}\left(V^n_A \phi^n_A + \sum_{j=1}^{6} f^{\phi}_j\right) \tag{7}$$

More details associated with this method is described in the following references [2,3,5].

To properly perform the process of coupling the fluid medium (gas) and the solid one, a suitable number of points of integration on the border between these two areas should be selected. Otherwise, the so-called artificial outflow of gas and its transfer through the Lagrangian medium may occur (Fig. 2). The coupling between these areas is produced with a method based on the penalty function [5].

B. Model description

During this study the case with the detonation of explosive placed on the pipe were analyzed. The shape of the explosive material was a rectangular prism. The elastic-plastic material model with isotropic hardening was applied to describe the pipe properties including strain rate effect. The yield condition and basic formulations are very well described by Hallquist [5]. The strain rate effect was accounted for using Cowper and Symonds model, which scales the yield stress, by strain rate dependent factor. The final form for σ_y is as follows [5]:

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/P}\right](\sigma_0 + \beta E_P \varepsilon^p_{eff}) \tag{8}$$

where *p* and *C* are input constants and $\dot{\varepsilon}$ is the strain rate. The radius of the yield surface σ_y includes the initial yield strength σ_o and the growth $\beta E_P \varepsilon^P_{eff}$ .The value of plastic strain rate was calculated as a difference between the total and the elastic strain rate. The effective plastic strains are defined as:

$$\varepsilon^p_{eff} = \int_0^t \left(\frac{2}{3}\dot{\varepsilon}^P_{ij}\dot{\varepsilon}^P_{ij}\right)^{1/2} dt \tag{9}$$

Fracture of the pipe subjected to the wave blast was also taken into consideration using a simple strain criterion. Failure was initially assumed to occur in this model if:

$$\varepsilon^p_{eff} > \varepsilon^p_{max} \tag{10}$$

where ε^p_{max} was user defined.

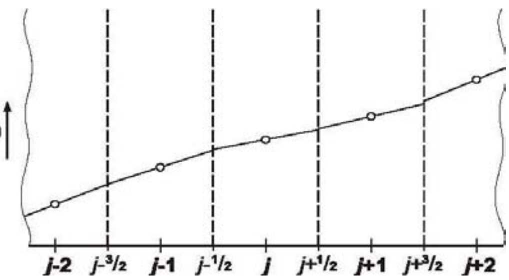

Fig. 1 The piecewise distribution of ϕ value [5]

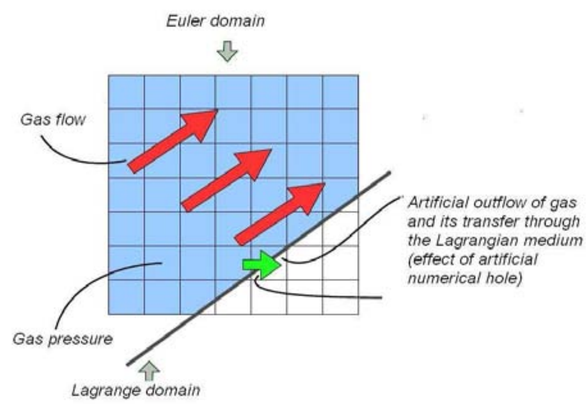

Fig. 2 The process of coupling the fluid medium (gas) and the solid one - the so-called artificial outflow of gas and its transfer through the Lagrangian domain

Stresses for elastic-plastic material are integrated incrementally in time based on Jaumann stress rate procedure [5]:

$$\sigma_{ij}^{n+1}=\sigma_{ij}^{n}+r_{ij}^{n}+\sigma_{ij}^{\nabla n+1/2}\Delta t^{\nabla n+1/2}$$
$$\sigma_{ij}^{\nabla n+1/2}\Delta t^{\nabla n+1/2}=C_{ijkl}\ \Delta\varepsilon_{kl}^{n+1/2} \qquad (11)$$
$$\Delta\varepsilon_{ij}^{\nabla n+1/2}=\dot{\varepsilon}_{ij}^{n+1/2}\Delta t^{n+1/2}$$

where C_{ijkl} is the stress dependent constitutive matrix and r_{ij}^{n} gives the rotation of the stress at time t^n to the configuration t^{n+1}.

Fracture of the pipe subjected to the wave blast was taken into consideration using a simple strain criterion [5,8]. All required material properties for this pipe were obtained from experimental tests [1]. The steel pipe model was developed solid elements in Lagrangian formulation. The total number of solid elements used for the entire Lagrange domain with the pipeline consisted of 156,000 solid elements (Fig. 4).

This tube model was submerged within the air domain model. The air has been modeled by the polynominal equation of state [5,10]:

$$p=C_0+C_1\mu+C_2\mu^2+C_3\mu^3+(C_4+C_5\mu+C_6\mu^2)e \qquad (11)$$

in which C_0, C_1, C_2, C_3, C_4, C_5 and C_6 are users' constants, e is the specific internal energy (internal energy per unit of mass) and $\mu=1/V-1$, where V is the relative volume. The air surrounding the HE and the pipe was assumed as an ideal gas with polynomial equation of state. Non-reflecting boundary conditions were applied on all surfaces of the Eulerian mesh, which surrounded the air space model. The total number of solid elements used for the entire Euler domain with the air and HE consisted of 158,400 brick elements (Fig. 4).

C. *Results from simulation*

Preliminary simulation results of this study allowed for analysis of the blast wave propagation and the resulting damage inflicted by the tube element (Figs 5-9). The blast wave propagation (pressure and velocity) and acceleration of chosen points located on the pipe wall were of special interest in this study as well as the damage of the structure [8,10]. The numerical results of this study clearly showed that at the initial stage of detonation process the rectangular piece of metal sheet is cut out from the pipe wall. The rapture process of the pipe first starts on the edges and mainly is caused by shear and tension stresses. This kind of behavior found the exact confirmation in our experimental studies described below.

D. *Results from field tests*

Results of experimental work have shown very low resistance of gas-pipe components to explosive-charge-effected loads. Photos (Fig. 3a,b and c) show characteristic damages in the form of pieces of metal cut out from the pipe's structure. These pieces of metal represent geometric shapes of cubes of the detonation material. In practice, every instance given consideration (after having analysed results of measuring the deformations) confirms that putting any explosive directly on the pipe wall results in plastic strain (permanent deformation) of local range which means cutting some element out of the pipe wall. Visual inspection proves that pieces cut out of the pipe walls behaved like elements of a fragment, i.e. they were deforming the opposite internal wall of the pipe.

a)

b)

c)

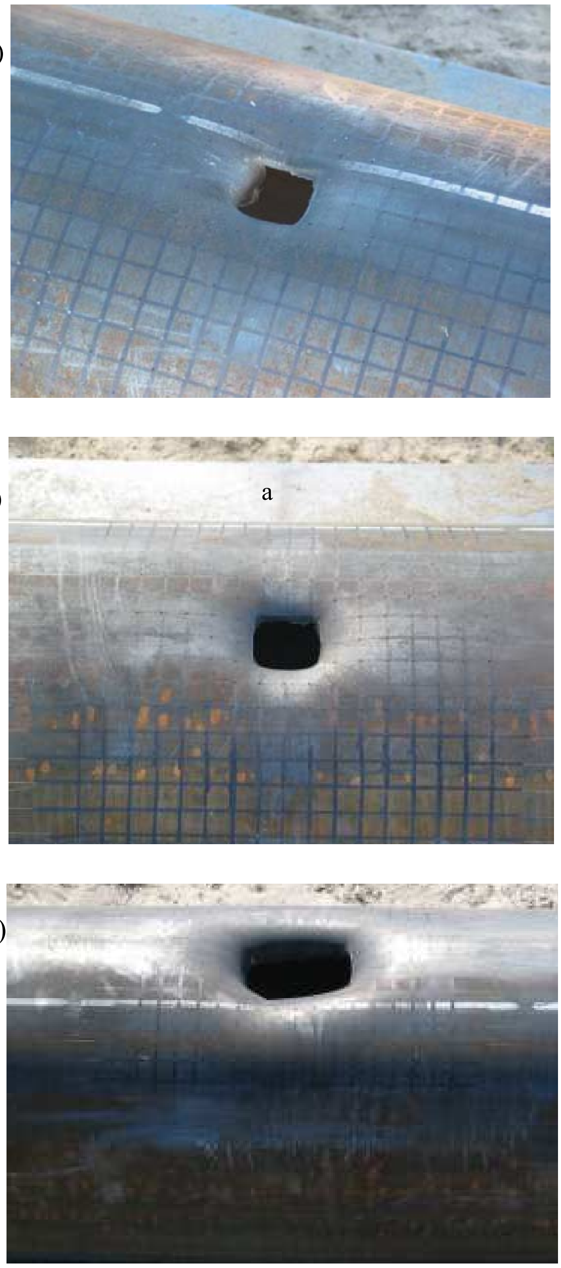

Fig. 3 Exemplary photos from experimental tests depicting the effects of interaction between blast wave and pipe wall

IV. Summary of Numerical Studies

The presented results and capabilities to numerically analyse/represent the process of the pipeline component interacting with the detonation wave have proved very low resistance of it to strong short-lasting pressure pulse generated in effect of burning the explosive charge. Results of our own work on the one hand, and on the other hand, nearly every day news on terrorist attacks aimed at cutting off local communities from the sources of energy (e.g. gas or oil/petroleum) to skillfully affect decision-making processes confirm the above-formulated statement. Additionally coupled Euler-Lagrange formulation which was used in the FE analysis accurately represents the detonation phenomenon. Analysis of the several numerical cases showed that complex meshes for Euler and Lagrange formulations are required. Thanks to applied very complicated materials models and additional, an option allowing for interaction between different materials, the very good and reasonable results which match experimental results were achieved [9].

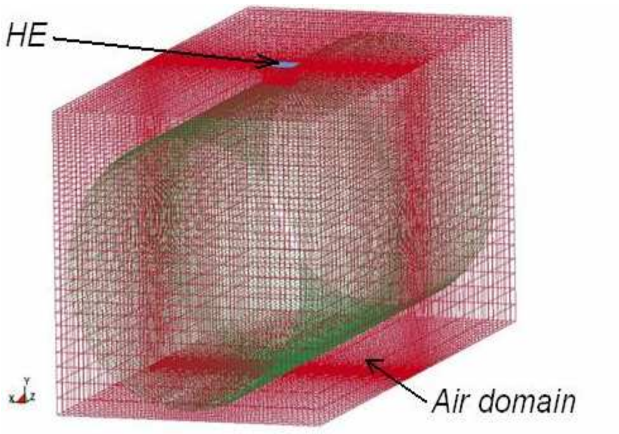

Fig. 4 FE model for the tube described in Lagrange domain and submerged in the Euler's domain

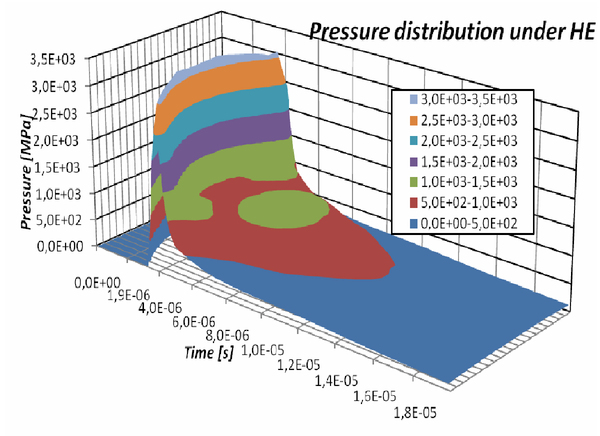

Fig. 5 Blast wave pressure history recorded in the Euler domain (below HE) from numerical simulation

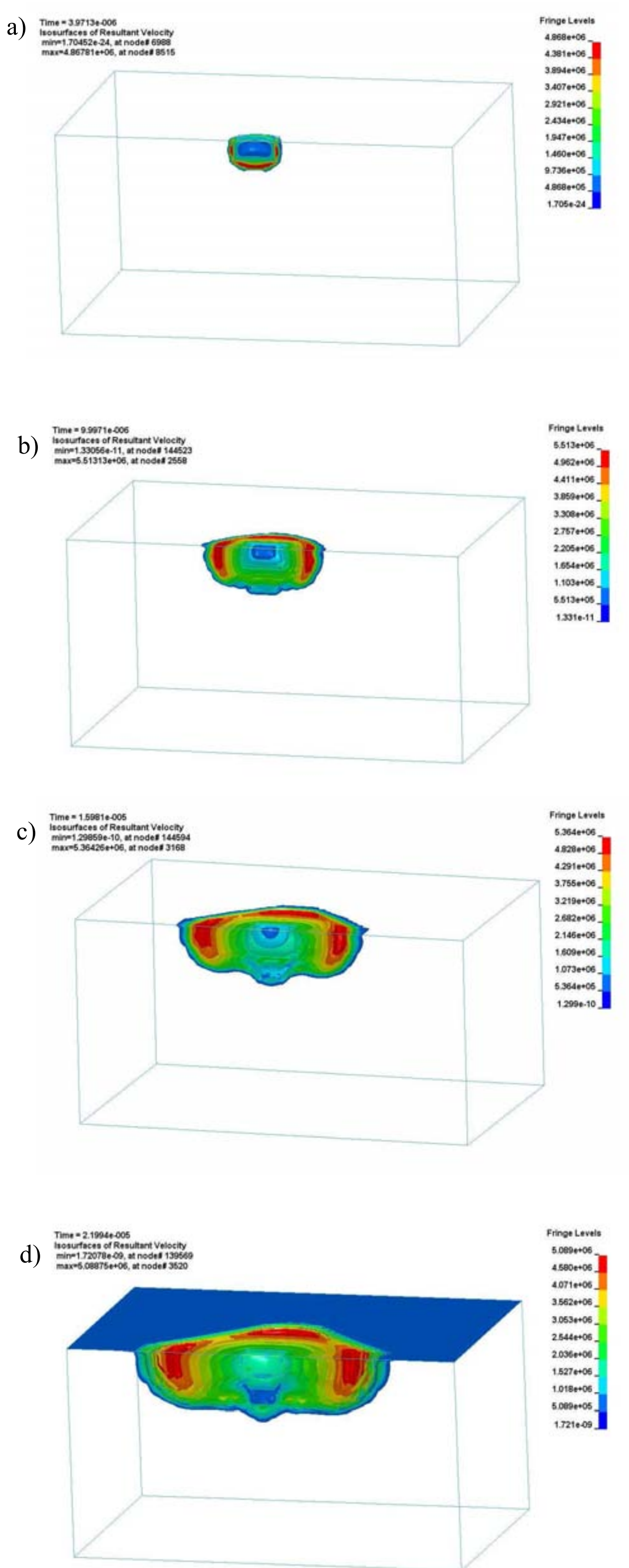

Fig. 6 Blast wave velocity recorded in the Euler domain

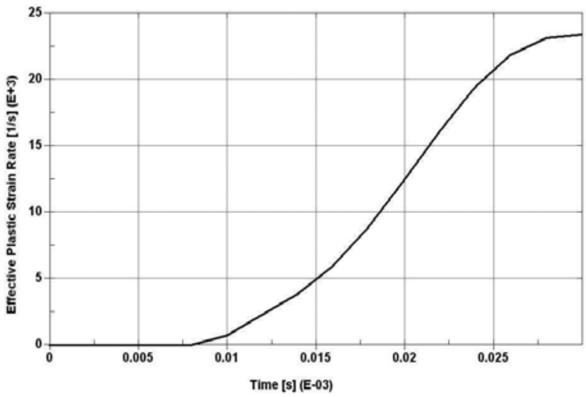

Fig. 7 Blast wave pressure history recorded in the Euler domain (below HE) from numerical simulation

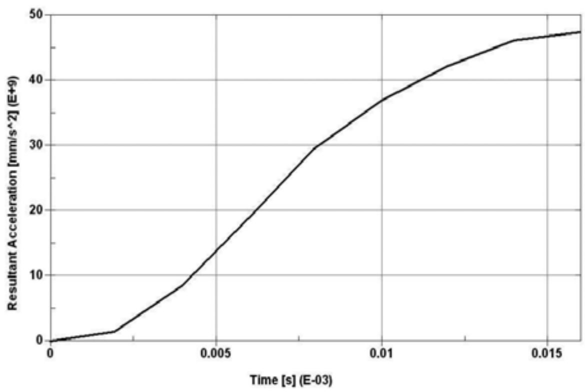

Fig. 8 Resultant acceleration history for chosen node in the pipe located directly under the HE

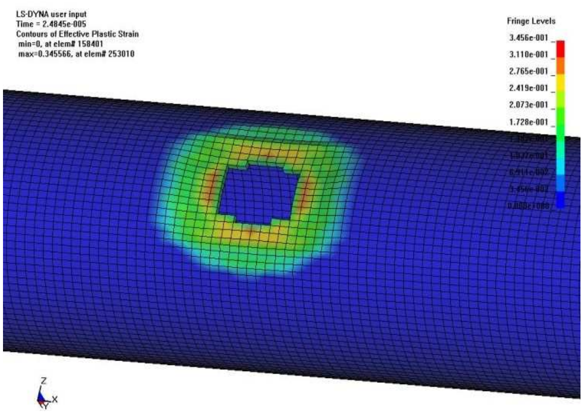

Fig. 9 The perforation process of the tube element subjected to HE charge

V. Conclusion

Research related with blast wave propagation is not only aimed on its effect on structures but also on developing new concepts of protective panels [4,6,7,9,11]. These panels often manufactured as removable are made from different types of materials with high energy absorption capacity as multi-functional composites, elastomeric materials, metal foams, etc. The first group of materials is characterized by a high relative energy absorption capacity. Advanced protection ability of the panels made from the multi-functional elastomeric composites is improved continuously, therefore they can be used to protect against existing threats as well as future ones. These new advanced materials can be often easily combined resulting in reduced production, maintenance and operating costs. All these features make multi-functional composites popular and inexpensive with increased resistance to destructive action of blast wave.

One of the possible options as a material for protective layers are aluminum foams which become also very popular due to their lightweight and excellent plastic energy absorbing properties [6,7]. Such characteristics have been appreciated by the automotive industry with continued research to further understand foam properties. Compressed foaming materials exhibit extensive plastic response, while the initial elastic region is limited in tension by a tensile brittle-failure stress. Aluminum foams have become an attractive material as blast protective layers due to their desirable compressive properties. With different material engineering techniques (as, for example double-layer foam cladding) they can be customized to achieve the most desirable properties. Energy absorption capacity of foams under blast load was analytically confirmed based on a rigid-perfectly plastic-locking foam model. Initial research indicates that energy absorbed by the cladding is much larger than that under quasi-static conditions due to shock wave effect. This unique property of the double-layer foam cladding makes it very useful for protective panels.

For last few years, the research team from the Department of Mechanics and Applied Computer Science at the Military University of Technology (MUT) has been involved in numerical and experimental studies on the capabilities of different energy absorbing materials. Moreover, the team has conducted research on various structures (such as multi-layer panels) to find out the most efficient protection against detonation wave. Other MUT research projects were also helpful to design structures protecting against firing or detonating other battlefield-dedicated warfare agents, such as mines. As expected, results of static tests conducted under laboratory conditions for designed energy-absorbing elements have encouraged the team to undertake further research. It included the effects of impact loads from explosion-induced shock wave on multi-layer energy-absorbing items.

Experimental tests of the ability of multi-layer protective panels to absorb the explosion energy were also conducted under field conditions [9]. Results of these tests are promising to further study resistance of structures to the terrorist attacks. The steel pipes were subjected to the blast wave during this research. Tests conducted on the pipes without the protective layers produced a perforation of the pipe wall, while application of the protective panels caused only a local, permanent deformation of the pipe wall. The first outcomes encouraged our team to conduct further work which can be aimed at finding optimum (dimensions, combination of layers with different fillings, etc.) solution of the protective panel from the standpoint of both the resistance to detonation-wave effects and energy-absorbing capability. The second criterion, also of great importance and taken into account throughout the testing program, is the cost of manufacturing such a panel, which is closely related to developing a suitable manufacturing and mounting processes.

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