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COMPUTATIONAL STUDIES OF GAS PIPELINE JUNCTION IN UNUSUAL OPERATING SCENARIO

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Abstract

This research has been inspired by security concerns due to the recent increase in the terrorist threat to gas and crude oil transportation around the world, especially in regions that are of significant value for the energy supplies. Computational mechanics methods will be used in this research to apply shock wave analysis for possible damage assessment of the affected pipelines.

These methods may be also used for pipelines at power plants, which are usually placed high on the homeland security priority list. The main goal of this research is focused on establishing effective simulation methodology to study the influence of shock waves (caused by explosion) on pipeline infrastructure elements placed on surface to ensure their security.

This study is primarily focused on the behaviour of some type of pipeline junction existing in gas pipeline system which can be subjected to the shock wave produced by the detonation of highly explosive (HE) materials. Outcomes of this research are important in preventing damage progression of pipelines under the blast loading. This data will also be used to develop improved design guidelines for safer and less vulnerable pipelines.

Keywords: *security, numerical simulations, explosive materials, pipeline junction*

1. 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. After the tragedy of terrorist attacks launched upon the United States on September 11, 2001, some of major gas terminals were covered with a special monitoring project. The terminals in question include both sea and land based gas and oil terminals that have been classified among the major targets of potential terrorist attacks. According to the project, harbours and ships have an obligation to maintain defence systems that comprise series of many and various procedural and organisational rules and means as well as requirements for special-purpose equipment. Such a system comprises what follows:

- a system for round-the-clock protection of tankers (LNG tankers and crude oil carriers) from the sea, based on patrol services,
- a system of cameras of industrial closed-circuit TV - the centre for permanent safety monitoring,

- a system of circumferential control of external-access by means of a closed system of passive barriers and an access-control system.

The desired protection-effectiveness level is achieved by means of permanent co-operation and joint training (instruction plus exercise) carried out together with security services (units) and crisis management headquarters. A major problem is the whole infrastructure that remains beyond main points of transmission of energy resources such as oil or natural gas. Exemplary actions in the nature of the theft of these resources prove the lack of inspections and permanent monitoring of transmission networks. Any places where a network crosses various obstacles, e.g. rivers, are typical examples of points exposed to immediate sabotage acts or terrorist attacks; included are also numerous points called block valve stations and regulator stations, and partial/final delivery stations (Figs 1a and 1b), located out in the open, with the only means of protection in the form of metal fencing/railing.

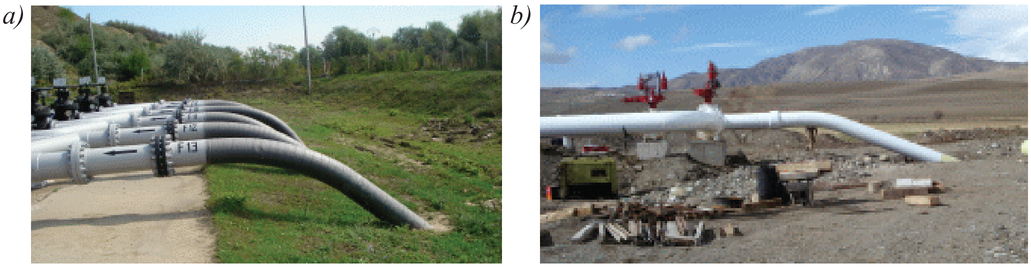

Fig. 1. Exemplary components of power engineering infrastructure under permanent monitoring a) and without constant surveillance system b)

2. Blast wave propagation – short overview

Referring to Wlodarczyk book [7], all explosives produce violent exothermic reactions induced by external effects. 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. 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.

3. Numerical description of analysed structure

Block valve stations are components of gas infrastructure most often found in a landscape (Fig. 2). The only means of protection thereof is the metal fencing/railing. These are components beyond permanent monitoring, usually located above the ground surface. The whole structure consists of two components (Fig. 2): (i) external piping, 235.1 mm in diameter and with walls 8 mm thick, and (ii) internal tube welded on to the external pipe at one end, at $1/3^{rd}$ of its height measured from the base. The diameter of the internal tube is 108 mm, wall thickness – 4 mm.

Fig. 2. The block valve station subjected to numerical analysis

The numerical model of the block valve station has been generated using the MSC.Patran software. To develop the FE model of this assembly eight-node solid elements of the HEX type were used. The whole model consists of 25296 solid elements (Fig. 3b). The mesh of the assembly in question was generated in the Lagrangian domain, i.e. the mesh of a discrete model will suffer deformation in the course of loading the structure in question. The elastic-plastic material model with isotropic hardening was applied to describe the pipe properties including strain rate effect. The implemented Johnson–Cook model provides a satisfactory prediction of flow stress for large strains and high strain rates when its dependence on strain rate is linear in semilogarithmic scale [2]. The possible fracture of the pipe subjected to the wave blast was also taken into consideration using a simple strain criterion. For the sake of numerical analysis of the model of this structure, of the lower part of it, the zero-displacement initial conditions were assumed, since both the pipes had no chance to displace because they were 'embedded' in some hardened foundation.

The numerical model intended to describe the bock valve station's environment covered the domain of 2700 × 2000 × 400 mm (Fig. 3a). This capacity was filled out with 594000 eight-node solid elements. While solving the problem, i.e. while integrating a dynamic equation of motion, there were over 2 mln unknowns to be found in a single integration step. Such an immense size of the problem to be solved resulted from the demand for an accurate solution; therefore, a very dense discrete FE mesh was a necessity. The size of cubic elements applied to describe each material under analysis, i.e. air and TNT charge was 10 × 10 × 10 mm. The detonation process was described with the Johnson-Wilkins-Lee equation [1, 2, 5]. The process of detonation was numerically initiated in the middle of the explosive used. In numerical analyses the mass of the TNT cube was 1600 g, which corresponded to a volume of a cube of 100 × 100 × 100 mm. The analyses covered four locations of the TNT cube: the cube was located on the foundation and then numerically moved by 100, 200, and 300 mm in the direction opposite to the foundation, which made the cube approach the horizontal branching. The analysis was intended to illustrate the effect of the positioning of the charge to be exploded (the distance thereof from the branching) upon this horizontal branching loaded with a detonation wave. In the numerical analyses under discussion the deformation criterion of destruction applied to arrive at the process of destructing the loaded structure of the block valve station.

The rest of the domain, i.e. the ambient air was described with the polynomial equation of state of gas, intended to show the dependence of pressure on specific internal energy [1, 2, 5]. That was the way to show the pressure changes within this space. Furthermore, for the walls of this volume assumed were conditions of reflectionless pressure-wave propagation, i.e. the propagating pressure wave decayed as soon as it reached the boundaries of the model. For the foundation, i.e. the place of fixing the pipes, perfect elastic reflection conditions were assumed.

4. Results of analyses

In the performed calculations the ALE (Arbitrary Lagrangian Eulerian) procedure were implemented [2, 5]. The 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. In the considered cases the second order accurate monotonic advection algorithm was implemented. 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). Generally, the two main steps can be distinguished in the ALE procedure: performing a classical Lagrangian step and performing an advection step, with the several ‘sub-steps’ included. Calculations were performed using the so-called direct-integration procedure, colloquially called the ‘explicit integration’’.

Time-pressure history (Fig. 4) and the permanent deformation of the pipe branching elements are of special interest in this study (Figs. 5 and 6). Preliminary results allowed for analysis of the blast wave propagation and the resulting permanent pipe deformation. The simulation-based test, intended to examine effects of different locations of the TNT charge against the pipe branching wall, proved that the pressure at the front face of the detonation wave considerably decreases against the distance (radius) from the charge (Tab. 1).

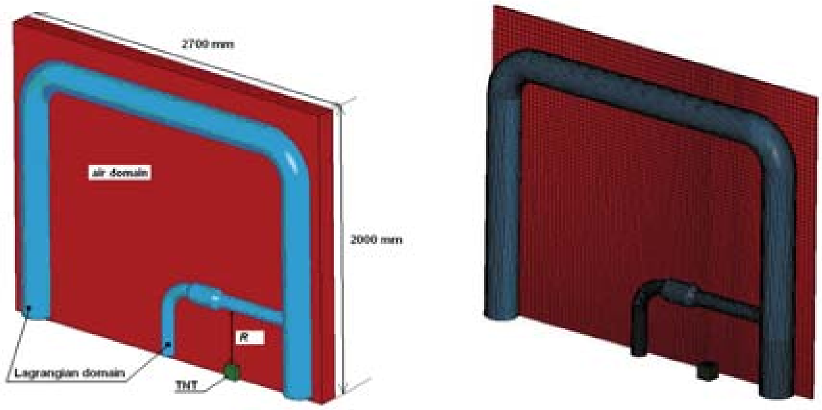

Fig. 3. A geometrical a) / numerical model b) of the block valve station ‘embedded’ in gaseous medium (cross-section of the FE model for air and HE) described in the Eulerian domain

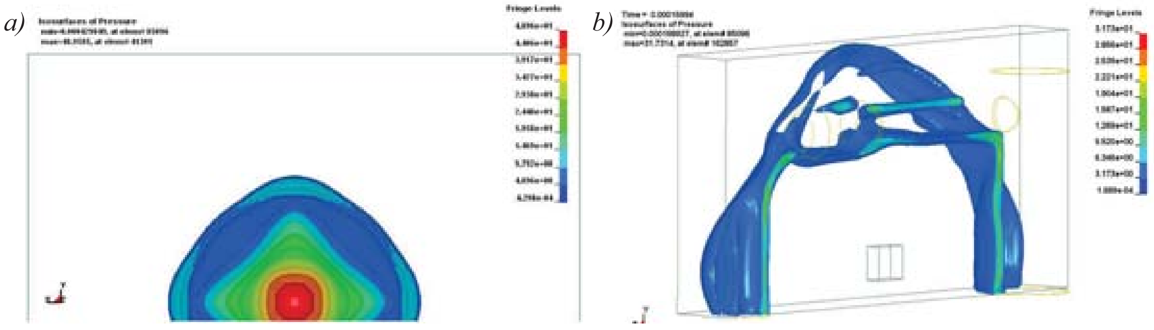

Fig. 4. The fringe of detonation wave pressure – numerical analysis of the detonation process (t = 6.0e-005 s) a) and the fringe of detonation wave pressure – the detonation wave flows around elements of the modelled assembly (t = 0.00016 s) b)

Tab. 1. Illustration of the effect of the positioning of the charge to be exploded (the distance thereof from the branching) upon this horizontal branching loaded with a detonation wave

TNT mass	Pressure value on the boundary between the HE and the air	Estimated numerically value of the pressure wave on the boundary with the horizontal pipe branching			
		Distance between the HE and the horizontal pipe branching: R =410 [mm]	Distance between the HE and the horizontal pipe branching: R = 310 [mm]	Distance between the HE and the horizontal pipe branching: R = 210 [mm]	Distance between the HE and the horizontal pipe branching: R = 110 [mm]
1600 g	~ 2600 MPa	35 MPa	70 MPa	170 MPa	340 MPa

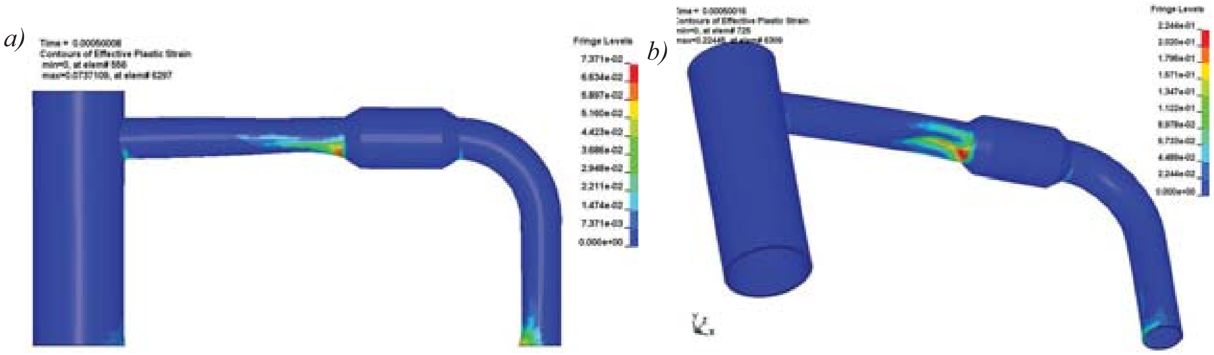

Fig. 5. Permanent deformation generated by the TNT charge located on the foundation; permanent deformation valued at 7.3 % a) and the deformation of the horizontal branching – the TNT at a distance of approx. 310 mm from the horizontal branching; the permanent deformations in the pipe wall valued at approx. 22.5% b)

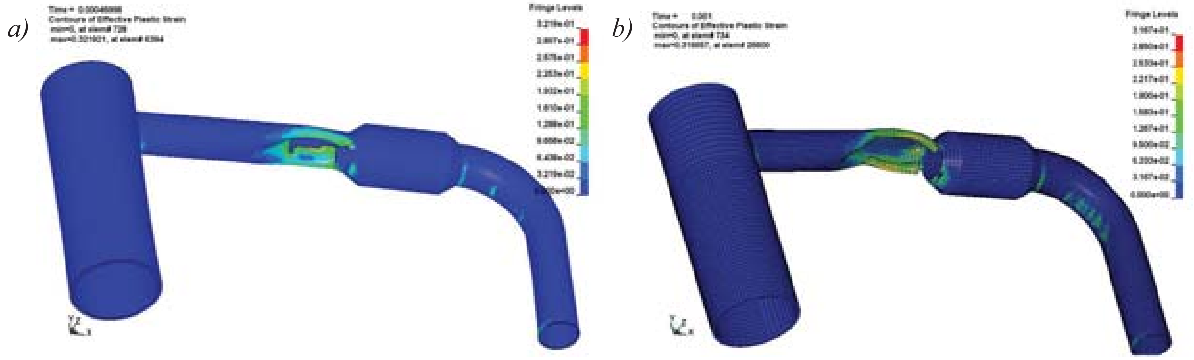

Fig. 6. The deformation of the horizontal branching - evident is the destruction of this element; other components of the assembly did not suffer permanent deformations: the distance between the HE and the pipe branching was respectively 210 mm a) and 110 mm b)

5. Conclusions

The conducted studies prove that terrorist attacks may occur practically any time. The reason is the above-mentioned accessibility of crucial components of gas/liquid fuel transmission pipelines. Daily newspapers keep on informing about terrorist attacks against such facilities. Any interruption in energy-resources supplies results in tremendous losses, sometimes very difficult or even impossible to estimate. Special attention should also be paid to pipeline failures due to the loss of integrity (perforation, ruptures, etc.) that may result in catastrophic and often irreversible damages to the environment, and hence, population, e.g. air and water pollution. General conclusions to be drawn from the conducted numerical analyses can be summarized in the following way:

- numerical analyses have enabled us to develop a modelling and computing method that facilitates numerical modelling of the process of detonation and how the computer-generated wave affects installations/facilities of energy resources transmitting infrastructure,
- the results gained show the infrastructure components are very sensitive to local effects of pressure wave excited with detonation; local damages may result in catastrophic effects,
- numerical studies prove that immediate access to such facilities should be precluded (potential saboteurs including) and a permanent monitoring system should be implemented; these two would probably compose the best solution in the field of safety improvement,
- the present-day development of numerical methods enables us to reduce extremely expensive and dangerous testing work on actual installations down to absolutely indispensible efforts. Thanks to advanced computer-based computational methods we are able to estimate effects of probable damages resulting from, e.g. terrorist attacks.

The greatest advantage of the conducted numerical analyses is that high effectiveness of computer tests in the process of numerical simulation of the TNT charge explosion has been confirmed and capability to reliably predict effects of such actions – shown. Numerical studies involve huge computational capacities that at present can be implemented using cluster solutions only. The most vital idea and conclusion that arise from these analyses is that numerical studies provide a capability to formulate guidelines for designers of new-built items of energy resources transmission infrastructure. These guidelines allow of considerable improvement in the resistance of such structures to damages/failures, and hence, of mitigation in results of such malevolent actions and effects thereof upon local communities.

Research related with blast wave propagation is not only aimed on its effect on structures but also on developing new concepts of protective panels [3, 4, 6]. These panels often manufactured as removable are made from different types of materials with high energy absorption capacity as multifunctional composites, elastomeric materials, metal foams, etc. The first group of materials is characterized by a high relative energy absorption capacity. 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.

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