# NUMERICAL ANALYSIS OF I-BEAM SUPPORTING STRUCTURE WITH MULTIMATERIAL PROTECTIVE PANEL – PARAMETRIC STUDY

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***Abstract***

*Dynamic response of an I-beam supporting structure subjected to shock wave produced by the detonation of high explosive materials is presented in this paper. Dynamic response of structural components in different load cases – with multimaterial panel protection and without protection, subjected to blast wave from various charge weight and various distance stand-off was determined. LS-DYNA, a 3-D explicit, finite element computer code with Lagrangian-Eulerian coupling was used to study this behaviour. Also initial static load was taken into account as pre-stress field present in the column obtained using dynamic relaxation procedure. The protective panel is composed of fibreglass composite and aluminium foam. The composite orthotropic properties and the failure criteria for fibre and matrix damage as well as the stress-volumetric strain curve for metallic foam were taken into account. The previous study shows that critical to the structure durability are the plastic strains and the structure failure caused by high deformation. Results of the analyses indicate that application of the blast panel around the supporting structure increase the resistance and significantly reduce the plastic deformation of the structure. The pillar without protection can be destroyed by 2 kg TNT placed close to the structure. Analysed beam covered by the blast panel can resist over three times bigger charge without significant deformation of the structure.*

***Keywords:*** *ALE formulation, blast wave, dynamic response, protective panel*

## 1. Introduction

The motivation to undertake the work aimed to develop protective panels was described in [1], where it was pointed out that majority of terrorist attacks are bombing attacks. Fragment of research presented in this paper shows dynamic analysis procedure of determination of dynamic behaviour and resistance of a structure pillar subjected to the blast wave. 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.

The problem of blast wave interaction with structure and its destructive effect was already described in many papers [2-6]. In the present work this procedure will be used in analyses of I-beam steel supporting structure protected by the multimaterial blast panel. The main aim of this study is to assess the protective panel effectiveness and the safety of structure after the explosion.

The previous research clearly shows that the load carrying capacity of presented supporting structure is not decreasing significantly after the blast wave interaction, even with high plastic deformation close to the failure limit. It means that the critical to the structure resistance is not a stability problem, but maximum plastic strains and in effect the failure occurrence.

The authors expect that the application of the protective panel significantly reduce the plastic strains occurring in the pillar and prevent structure from the loss of stability.

## 2. Simulated problem

Geometry of analysed structure is shown on Fig. 1. Support pillar is made of I beam and is loaded by weight of surrounding roof structure, represented by force P and lumped mass M. Multilayer protective panel consists of steel, fibre reinforced composite and metallic foam. It is assumed, that two different phenomena will be responsible for minimization of shock wave effects: flow around cylindrical panel and energy absorption by panel structure. Additionally, application of the panel increases the charge stand-off distance. Therefore to assess the panel energy absorption capacity and the improvement of structure blast resistance due to panel application load cases with two different charge stand-off distances were analysed (Fig. 1a and b). Mass of the charge was evaluated based on “abandoned briefcase” scenario, where briefcase filled with TNT lies just by the pillar.

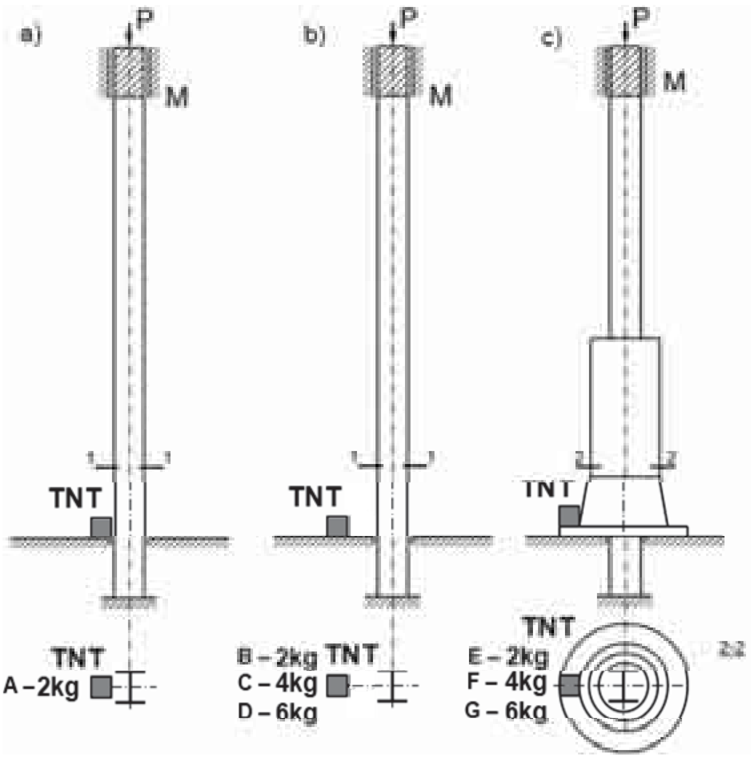


*Fig. 1. Studied cases A-G*

From the analytical point of view, such scenario means that blast wave is acting on preloaded I-beam. Thus the pre-stress in the pillar will be also taken in to consideration.

## 3. Numerical model

FE models of the column and each part of protective panel were developed using HyperMesh software. Part of the panel made from metallic foam was modelled using 8-node hex elements. Other parts of panel assembly, as well as column were discretized using 4-node Belytschko-Lin-Tsay shell elements (Fig. 2).

Both column and panel mount to a concrete foundation has been modelled by fixing translational degrees of freedom in appropriate nodes. Additional rigid walls were also introduced in order to describe contact conditions between a concrete base and the steel structure. In order to save computer resources, fluid domain, required to model blast wave propagation, covered only lower part of the panel and the post. Ready to run FE model consisted of 1.078 mln Euler (fluid) elements and over 78K. Lagrange (structural) elements. The whole model is shown on Fig. 2.

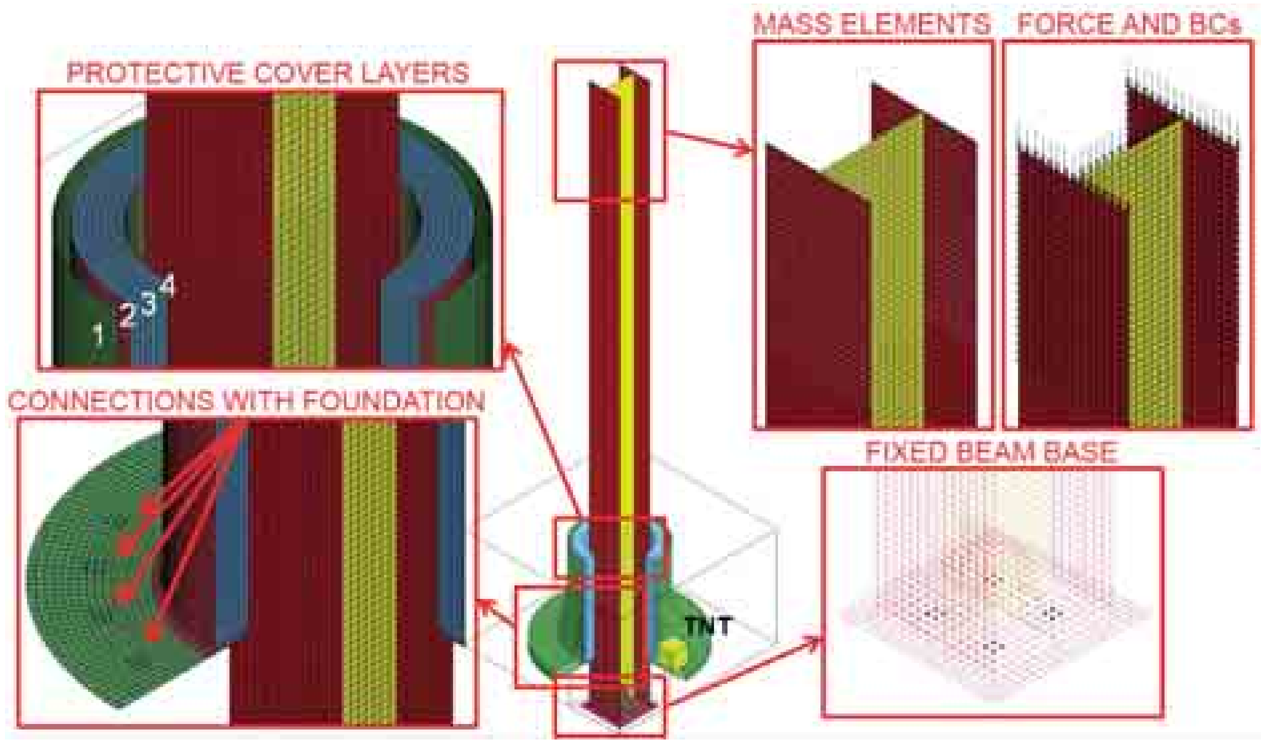


*Fig. 2. Discrete model of pillar with*

The elastic-plastic material model with isotropic hardening was applied to describe the steel structural components properties including strain rate effect. The Johnson–Cook model provides a satisfactory prediction of flow stress $\sigma_{flow}$ 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.

From the number of composite materials models available in the LS-Dyna software, MAT_54 was chosen to describe the layered composite component of the panel. This material model is specially designated to model failure mechanisms observed in composite materials. Besides usual static orthotropic properties, the various types of failure can be specified [7]:

– for the tensile fibre mode:

$$\sigma_{aa} > 0 \ \ then \ \ e_f^2 = \left(\frac{\sigma_{aa}}{X_t}\right)^2 + \beta\left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \begin{cases} \geq 0 \ \ failed, \\ < 0 \ \ elastic, \end{cases}$$
$$E_a = E_b = G_{ab} = \nu_{ba} = \nu_{ab} = 0 \tag{2}$$

– for the compressive fibre mode:

$$\sigma_{aa} < 0 \ \ then \ \ e_c^2 = \left(\frac{\sigma_{aa}}{X_c}\right)^2 - 1 \begin{cases} \geq 0 \ \ failed, \\ < 0 \ \ elastic, \end{cases}$$
$$E_a = \nu_{ba} = \nu_{ab} = 0 \tag{3}$$

– for the tensile matrix mode:

$$\sigma_{bb} > 0 \ \ then \ \ e_m^2 = \left(\frac{\sigma_{bb}}{Y_t}\right)^2 + \left(\frac{\sigma_{ab}}{S_c}\right) - 1 \begin{cases} \geq 0 \ \ failed, \\ < 0 \ \ elastic, \end{cases}$$
$$E_b = \nu_{ba} = 0 \rightarrow G_{ab} = 0 \tag{4}$$

– for the compressive matrix mode:

$$\sigma_{bb} < 0 \;\; then \;\; e_d^2 = \left(\frac{\sigma_{bb}}{2S_c}\right)^2 + \left[\left(\frac{Y_c}{2S_c}\right)^2 - 1\right]\frac{\sigma_{bb}}{Y_c} - 1 \begin{cases} \geq 0 \;\; failed, \\ < 0 \;\; elastic, \end{cases}$$
$$E_b = \nu_{ba} = \nu_{ab} = 0 \rightarrow G_{ab} = 0, \qquad . \tag{5}$$
$$X_c = 2Y_c \;\; for\; 50\%\; fiber\; volume.$$

In the material model also erosion can occurs when:

– the tensile fibre strain is greater than $\varepsilon_{max}^{+}$ or smaller than $\varepsilon_{max}$,
– the effective strain is greater than $\varepsilon_{fs}$.

When failure has occurred in all of the composite layers (through-thickness integration points), the element is deleted.

Another important component of the panel is metallic foam applied to consume the blast wave energy by the plastic deformation. The behaviour of that material was described by the honeycomb material model. In this model the elastic moduli vary, from their initial values to the fully compacted values at $V_f$, linearly with the relative volume $V$. The relative volume, $V$, is defined as the ratio of the current volume to the initial volume. Typically, $V=1$ at the beginning of a calculation. For the uncompacted material, the trial stress components are updated using the elastic interpolated moduli [7]:

$$\sigma_{ij}^{n+1\,trial} = \sigma_{ij}^{n} + E_{ij}\Delta\varepsilon_{ij} \,. \tag{6}$$

If the stress values exceed the permissible values determined from the material curves than:

$$\sigma_{ij}^{n+1} = \sigma_{ij}\left(V\right)\frac{\lambda\sigma_{ij}^{n+1\,trial}}{\left|\lambda\sigma_{ij}^{n+1\,trial}\right|}, \tag{7}$$

where λ is a parameter in function of strain-rate defined by curve.

For fully compacted material it is assumed that the material behaviour is elastic-perfectly plastic and the stress components updated according to:

$$\sigma_{ij}^{trial} = \sigma_{ij}^{n} + 2G\Delta\varepsilon_{ij}^{dev\,n+1/2}, \tag{8}$$

where $\Delta\varepsilon_{ij}^{dev\,n+1/2}$ is deviatoric strain increment.

In the performed numerical tests the detonation process of *TNT* high explosive material was implemented through the automatically 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. Hence Jones-Wilkins-Lee (*JWL*) equation of state was implemented in the applied explosive burn model with the following form [7, 8]:

$$p = A\left(1 - \frac{\omega}{R_1\overline{\rho}}\right)exp\left(-R_1\overline{\rho}\right) + B\left(1 - \frac{\omega}{R_2\overline{\rho}}\right)exp\left(-R_2\overline{\rho}\right) + \frac{\omega\overline{e}}{\overline{\rho}}, \tag{9}$$

where:

$\overline{\rho} = \rho_{HE}/\rho$, $\overline{e} = \rho_{HE}\, e$, $\rho_{HE}$ – density of the high explosive,

$p$ – pressure of *PD*,

$e$ – specific internal energy of *PD*,

$\rho$ – density of *PD*. $A$, $B$, $R_1$, $R_2$, $\omega$ are empirical constants determined for specific type of a high explosive. All constants required are taken from literature [5].

Since, the blast wave propagates in air medium the pillar 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 [7]:

$$p = \left(C_4 + C_5\mu\right)E\ , \tag{10}$$

where:
$\mu=\rho/\rho_0$, $C_4$ and $C_5$ – polynomial equation coefficients,
$\rho$ – density,
$\rho_0$ – initial density,
$E$ – internal energy.

## 4. Numerical analysis

In the first stage I-beam structure was subjected to nominal load $P_n$, which was equal to the load carried by the pillar during its normal service. Incremental static analysis was performed using full Newton-Rapshon algorithm. Equation solved in this stage had the following form [7]:

$$K_i \Delta x_{i-1} = \Delta Q_i\ , \tag{11}$$

where:
$K_i$ – stiffness matrix,
$\Delta x_{i-1}$ – displacement vector,
$\Delta Q_i$ – external force vector.

Convergence of the problem was controlled by two criteria: displacement relative convergence tolerance and energy relative convergence tolerance.

In the second stage results from the previous stage were taken into account as pre-stress field present in the column. It was obtained using dynamic relaxation procedure. Dynamic relaxation allows to quickly reaching preloaded state by linear ramping nodal displacement field to prescribed values over 100 time steps. It should be noted that the comparison of stress field taken from static analysis and stress field generated by dynamic relaxation procedure showed small differences introduced by the latter. On the other hand, the procedure allows for application of predefined stress filed on selected part of FE model in a very effective manner.

The blast loading in this stage require applying transient dynamics procedure with explicit central difference time integration. Equation solved had the following form [7]:

$$M\ddot{x}_n = F_n^{ext} - F_n^{int} - C\dot{x}_n\ , \tag{12}$$

where:
$M$ – the diagonal mass matrix,
$F_n^{ext}$ – external and body force loads,
$F_n^{int}$ – the stress divergence vector,
C – dumping matrix.

In this stage gas domain, consisted of air and detonation products, was modelled using finite volume technique (so called Euler formulation). The coupling between Lagrangian formulation (solid material) and Eulerian formulation (gas medium) was taken into account during calculations. Generally *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).

## 5. Results

The protective panel does not provide full protection of the structure. The panel elements erode due to high strains during the analysis (Fig. 3) and the blast wave is reaching the structure. On the other hand the area of interaction, as well as, the pressure values are much lower than in case without protection.

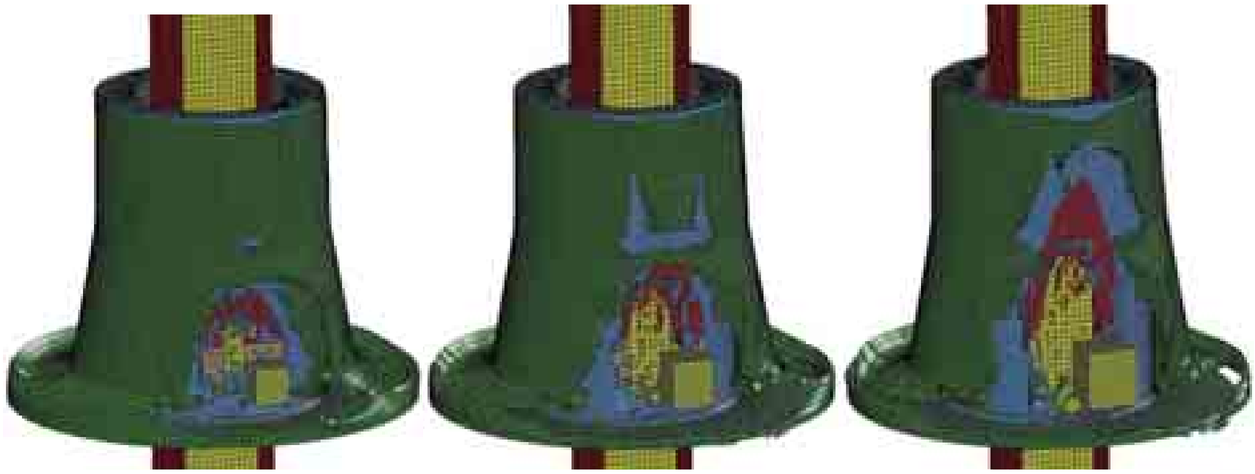

*Fig. 3. Protective panel destruction after the explosion – respectively with 2kg, 4kg and 6kg of TNT*

The resultant velocity vectors were presented to illustrate the characteristic of blast wave propagation (Fig. 4). At the early stage of deformation the blast wave propagation character is very different in cases with and without protection. It is clearly noticeable that the protective panel consumes the major part of the blast wave and keeps it away from the pillar.

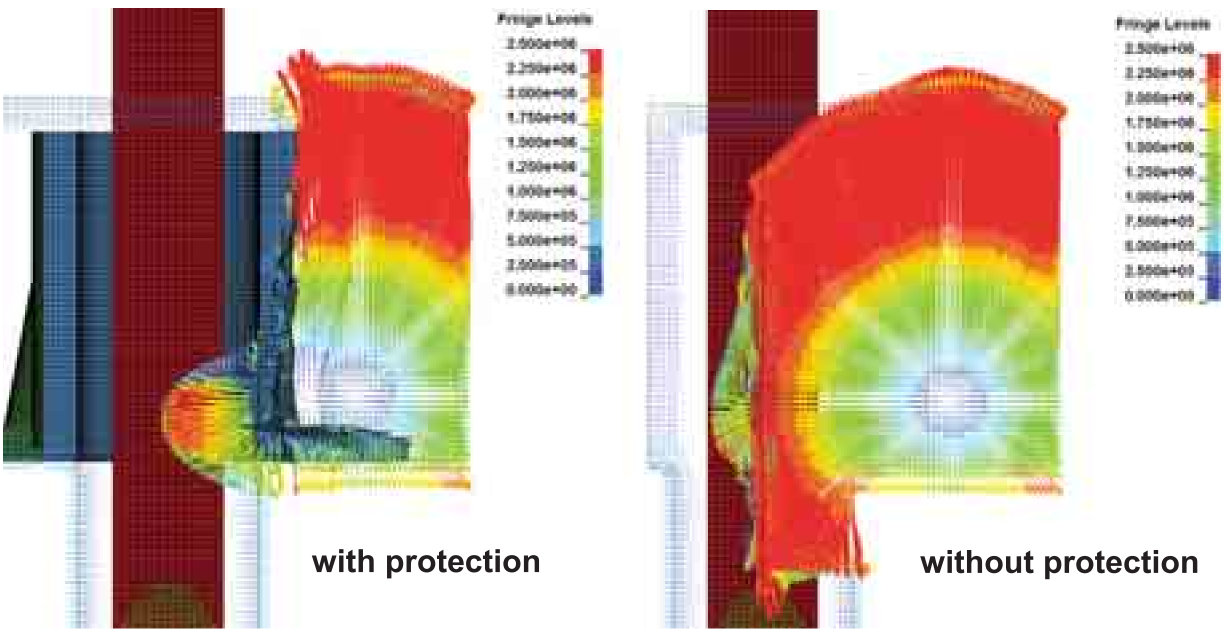


*Fig. 4. Resultant velocity vectors [mm/s] for Eulerian domain at t=0.002s – cases 6kg with and without protection*

The blast panel effectiveness is represented by the beam deflection (Fig. 6) and the plastic strains which occurs in the structure (Fig. 5). We can observe that the pillar deformation after the explosion were very significant for structure without protection. Additionally, the worst scenario occurs when the charge is placed close to the structure. The relatively small charge caused structure failure – the web was deboned form the flanges.

Figure 5 shows the plastic strains of the structural component. It is clearly visible that application of the protective panel reduces the plastic strains caused by explosion, for cases A and B they were reduced to zero, and for case C reached to 1.5%.

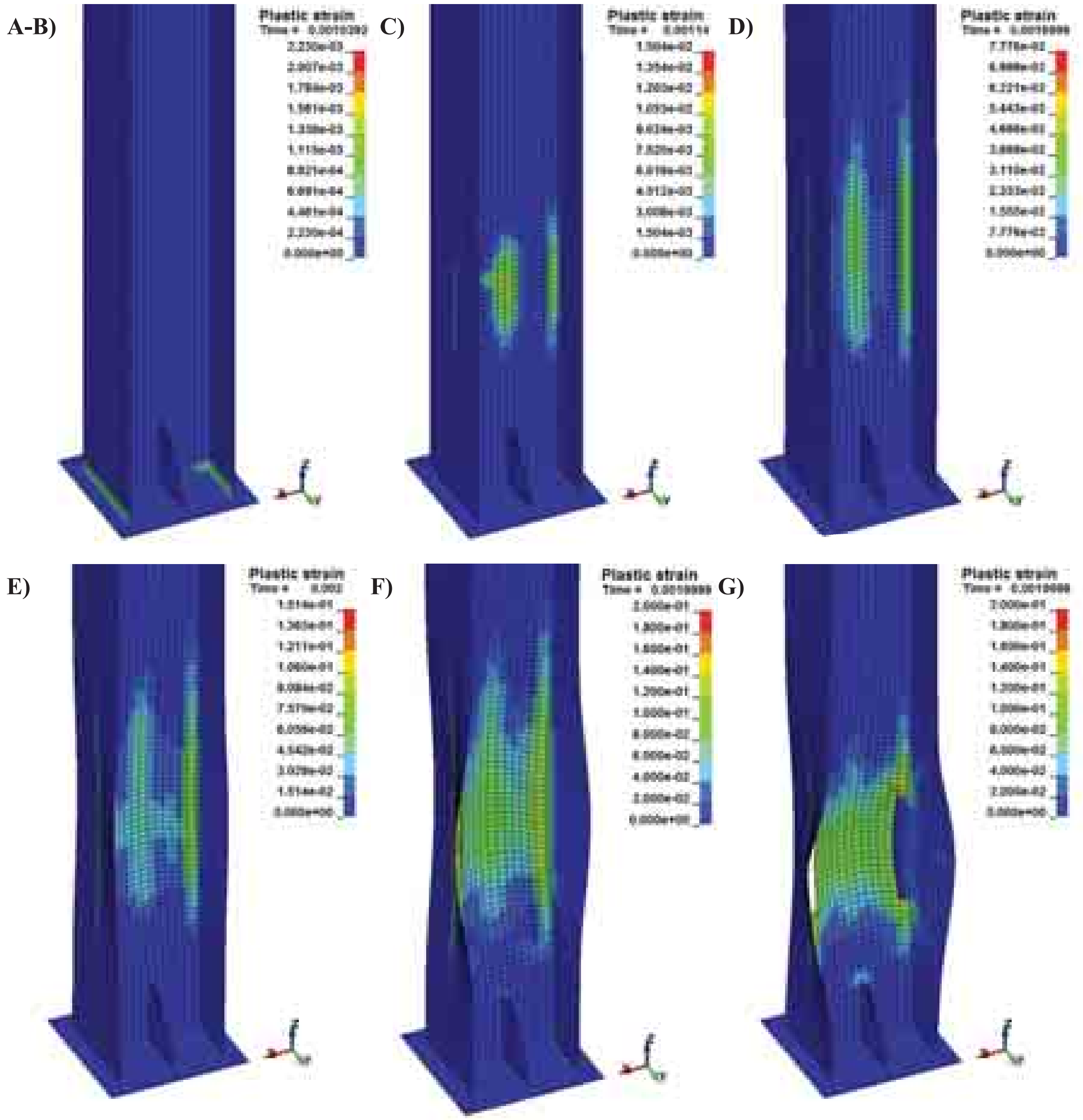


*Fig. 5. Plastic strain map at maximum deflection [mm] for all cases*

In the Fig. 6 the deflection curves of the beam axes are shown. Again big differences in the behaviour of the protected and unprotected can be seen. In case of unprotected panel local deflection caused by blast wave predominates.

The destructive effects of the blast wave can be also observed in Fig. 7, where the amount of energy consumed by the pillar is presented. The biggest amount of energy was absorbed by the pillar in case F, due to smaller area of blast wave interaction deformation in case G is more local and less energy was absorbed by the structure.

The panel component energy consumption was presented in the Fig. 8. It can be noticed that the composite consumed major part of the blast wave energy. Thanks to the streamline shape of the panel the sum of the internal energy for all structural elements was also significantly lower comparing to the internal energy of pillar without protection.

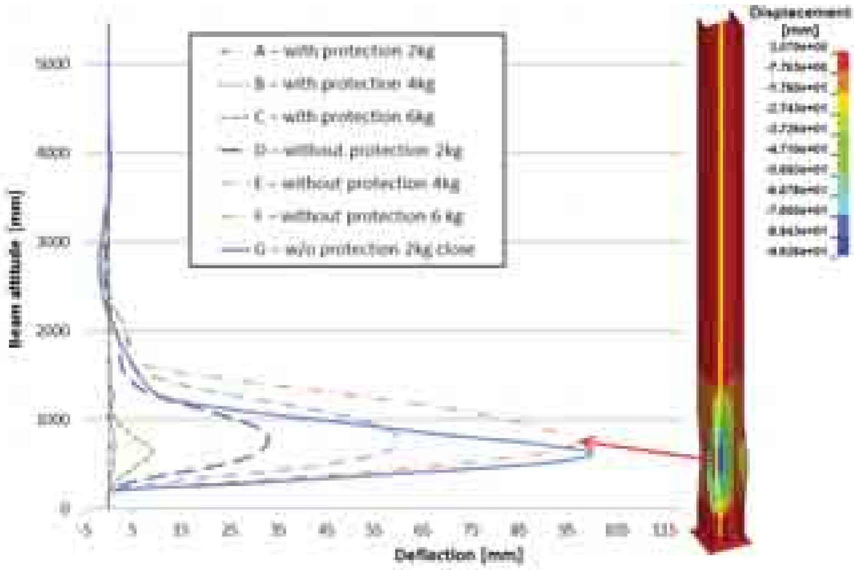


Fig. 6. Deflection profile and displacement of pillar at maximum deflection

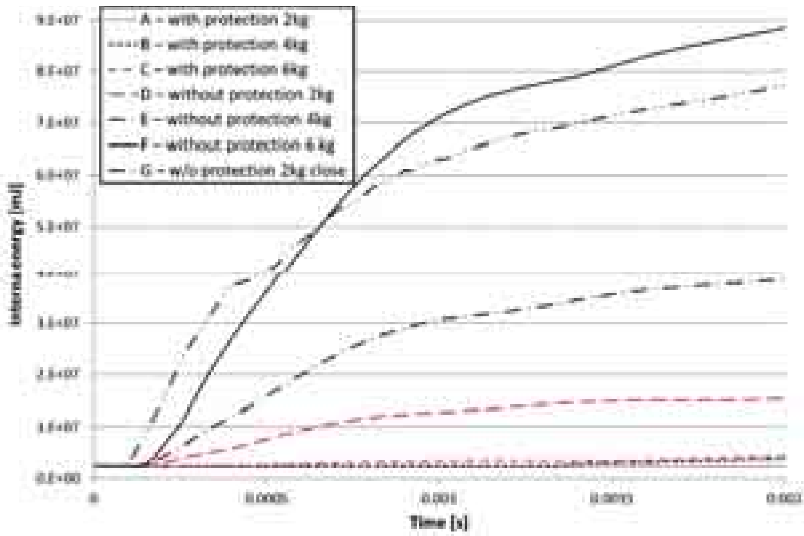


Fig. 7. Internal energy of the pillar for all cases

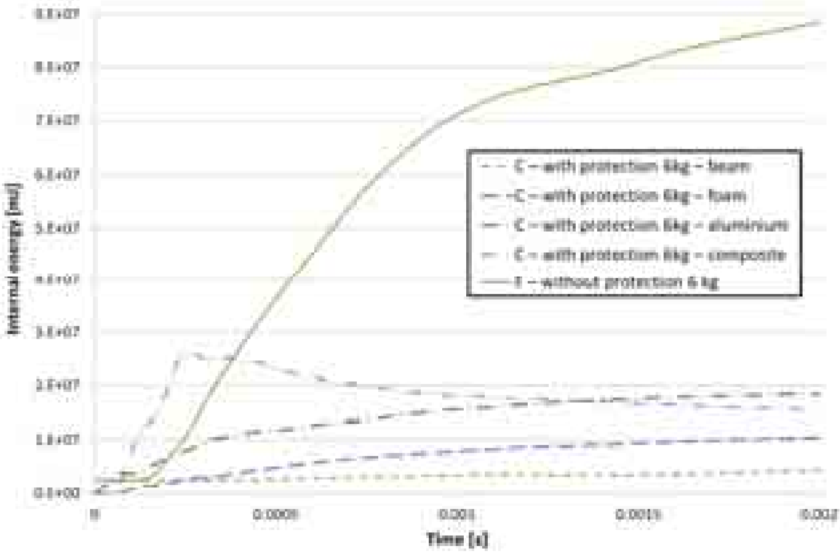


Fig. 8. Internal energy of the pillar and panel components

Deflection for the most affected point of I-beam web is presented in the Fig. 9. Deflections of the beams protected by panel are by order smaller than beams without protection. From the shape of curves it can be seen that displacement in protected panels is dominant by elastic part of strain with tendency to vibrate after the outbreak. In the unprotected beams displacements immediately reach the elastic limit and stay at the high level without any oscillations.

## 6. Summary

The main aim of this work was to determine the dynamic response of structural components in different load cases – with and without protection, subjected to blast wave from various charge weight and various distance stand-off and also assess the structure safety after the explosion.

The previous study shows that critical to the structure durability are the plastic strains and the structure failure caused by high deformation. As authors expected the application of the protective panel significantly reduced the plastic strains occurring in the pillar and prevented from structure failure. The research results shows that pillar without protection can be destroyed by 2 kg high explosives (TNT) placed close to the structure. Analysed beam covered by the blast panel can resist over three times bigger charge without significant deformation of the structure. All above proves that the developed multimaterial protective panel is efficient way to prevent structure from the collapse.

Future work will be aimed to assess the influence of the charge location. Also the dynamic relaxation procedure will be changed to the "full restart" in order to eliminate differences between the actual strains and the one obtained by linear ramping nodal displacement.

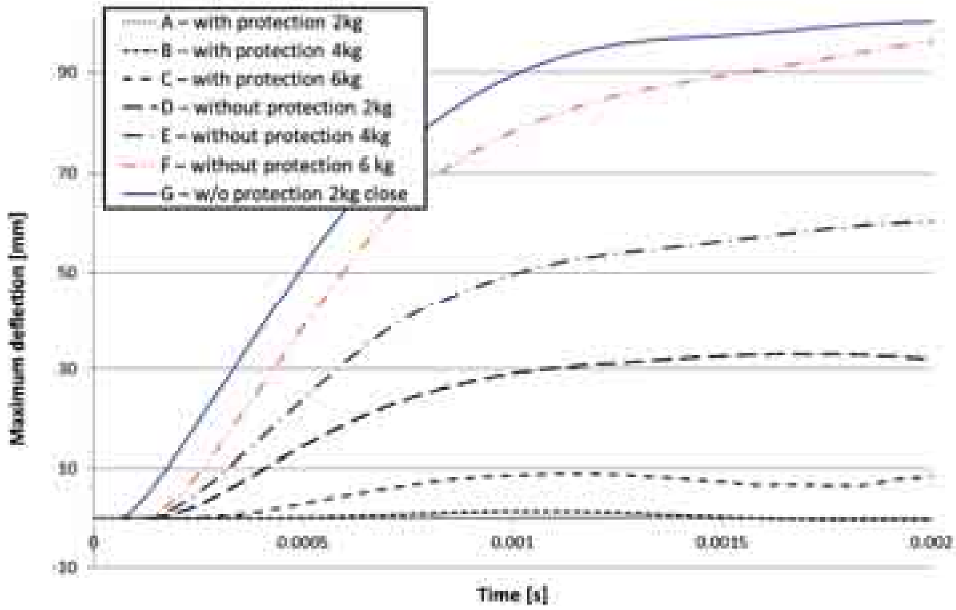


*Fig. 9. Deflection vs. time for the most affected point of I-beam web*

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