Modelling and Testing of Blast Effect On the Structures

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Abstract. As a blasting agent in the blasting and mining engineering, has been using one of so called new generation of explosives which offer greater flexibility in their range and application, and such explosive is ANFO. It is type of explosive consists of an oxidiser and a fuel (ammonium nitrate and fuel oil). One of such ANFO explosives which are industrially made in Slovakia is POLONIT. The explosive is a mixture of ammonium nitrate, methyl esters of higher fatty acids, vegetable oil and red dye. The paper deals with the analysis of structure subjected to the blast load created by the explosion of POLONIT charge. First part of paper is describing behaviour and characteristic of blast wave generated from the blast (detonation characteristics, physical characteristics, time-history diagram etc.) and the second part presents the behaviour of such loaded structures, because of the analysis of such dynamical loaded structure is required knowing the parameters of blast wave, its effect on structure and the tools for the solution of dynamic analysis. The real field tests of three different weight of charges and two different structures were done. The explosive POLONIT was used together with 25 g of ignition explosive PLNp10. Analytical and numerical model of blast loaded structure is compared with the results obtained from the field tests (is compared with the corresponding experimental accelerations). For the modelling structures were approximated as a one-degree system of freedom (SDOF), where the blast wave was estimated with linear decay and exponential decay using positive and negative phase of blast wave. Numerical solution of the steel beam dynamic response was performed via FEM (Finite Element Method) using standard software Visual FEA.

1. Introduction
In the engineering blasting operation, a wide range of explosive products are used. It is very important to identify each explosive characteristics in order to select and use the explosive efficiently and safely. For the describing of blast effect on the structure, there are two steps essential: The first one is an analysis of the dynamic load - blast wave generated in the detonation of explosives and the second area is an analysis of the structure response. The parameter of blast wave is dependent of the type of used explosives. Research on the blast loaded structures has been coming to the fore in the last years. It is evidence from the research made by Hajek et al [1], where the research builds on the long-time ongoing research and informs about new results of an experimental program focused on the study of blast resistance of concrete based materials and from the research made by Stoller, Zezulová, [2], where the research is focused on the use of ultrasound method for the diagnostics of protective structures under blast load.
2. Types of explosives

2.1 Explosive classifications

The explosives can be classified into the following types (according to [3]):

- Low (or deflagrating) explosives;
- High explosives

The first developed explosives were low ones. The explosion is really a rapid form of combustion in which the particles burn at their surfaces and expose more and more of the bulk until all has been consumed. Such an explosion is called deflagration and the reaction in this case moves slower than the speed of sound [3]. Such low explosives are: blasting and gun powder, propellants (rocket and in ammunition) and pyrotechnics. High explosives produce large volumes of gases at considerable heat at extremely high pressures. They could be subdivided into primary and secondary explosives. Primary explosives are characterised by their sensitiveness to stimuli, due to they are used as ignitiating charges in the ignition devices such as detonators. Examples of these explosives are Mercury Fulminate, Lead Azide, Lead Styphane etc. Secondary explosives are capable of detonation under the influence of shockwave generated by the detonation of primary explosives. Example of these explosives are military explosives like TNT, RDX, PETN and other.

2.2 ANFO type explosives

Mixtures of ammonium nitrate and fuel oil is known as ANFO. It has been using for blasting operations in mid 1950s. From the chemical-technological point of view it is possible to differentiate three different versions of ANFO explosives: ammonium nitrate + fuel, ammonium nitrate + fuel + powder metal (usually aluminium or magnesium) and ammonium nitrate + fuel + wooden powder - delaborated TNT. Affordability of the raw materials and ease of manufacture allows for its production using only simple devices. Availability of nitrate as agricultural fertilizer is almost unlimited and so is fuel (oil, diesel, petrol).

In the field test described later, there was used industrially made ANFO explosives called POLONIT of the Slovak company called Istrochem Explosives a.s. Bratislava. It is the explosive mixture of ammonium nitrate, kerosene, charcoal, ground TNT with water-resistant additives. The explosive is of loose consistency, white to yellowish in colour and it can be used in blasting works on the surface as well as in the underground in an environment without the danger of gas, vapour and dust explosions.

| Table 1. Characteristics of used explosives in the field test |
|---------------------------------------------------------------|
| Explosive | Type of represented ANFO explosive | Explosive velocity [m/s] | Heat of combustion [kJ/kg] | Density [g/cm³] | Explosive pressure [GPa] |
| Polonit - V | AN+oil+TNT | 4000 | 5138 | 0.9 | 6.93 |
| TNT | Reference sample | 6800 | 4200 | 1.58 | 18.4 |

3. Field tests – blast loaded structures

The field tests were focusing on the measurement of overpressure and its influence on steel beams. POLONIT was used as the explosive. The field tests took place at Military Technical and Testing Institute Zahorie. The weight of charges was selected: 2.3 kg, 4.5 kg and 9 kg (it was not detonated because of a high overpressure of 4.5 kg explosive which caused a damage of construction with steel beams). The explosives were used together with 25 g of ignition explosive PLNp10. The sensors were placed in the height of 1.6 m in the angle of 45° from the normal line in the distances 2 m, 5 m and 10 m from the source of the explosion. One of the sensors was orientated in parallel with steel beams in the distance of 5.5 m opposite of gabion wall and in the distance of 3 m from the source of explosion (we
wanted to record the reflected blast wave). The explosive charges were placed at a wooden base in the height of 10 m. The structure consists of steel frame and four wide flange steel beams HEB 100 and 12 steel beams IPE 120 with span length of 1770 mm. For convenience the beams were tested in the vertical positions and simply supported. They were loaded mainly to bending caused by the blast pressure as the axial stress due to self-weight was practically negligible. All the beams were pinned at the top and roller supported at the bottom, Figure 1.

![Figure 1. Field tests: a) blast pressure sensors b) steel beams](image)

During the blast test pressure, strain and acceleration were measured. Maximum overpressure was measured using blast pressure sensors type 137A23 and 137A24 PCB Piezotronics. The sensors were placed in the height of 1.6 m in the angle of 45° from the normal line in the distances 2 m, 5 m and 10 m from the source of the explosion. One of the sensors was orientated in parallel with steel beams in the distance of 5.5 m opposite of gabion wall and in the distance of 3 m from the source of explosion (we wanted to record the reflected blast wave). The strain time histories were measured at the middle of beams number 2, 5, 12, 15 by surface strain sensors and accelerations by the accelerometers. In our field test we have succeeded measured only two explosions. In explosion n. 1 (1 kg) and No. 2 (2.3 kg), the maximum pressure has been not documented. In explosion No. 5 strains and accelerations have been not recorded. Hence we can compare only two set of results.

4. Simulation of blast loaded beams

4.1. Blast loading

Structure is subjected to the blast wave created when the detonation of explosive occur. The blast wave, which can be characterized with instantaneous increase of ambient atmospheric pressure with peak characteristic. When the initial part of blast wave reaches its maximum value, it drops to the level of the ambient pressure and it is followed by negative phase, which has longer duration as a precedent phase. The real measured blast wave profile can be seen in Figure 2. Analysing of blast loaded stricter many approximations are used. Time history of blast wave is generally approximated, emphasizing only the positive phase. The simplest form assumes a linear decay. The negative phase is commonly neglected in design of structures. More complicated approximation (and the most realistic idealized pressure time history of blast wave) can be described with exponential function emphasizing both positive and negative phase too.

All parameters, which are connected with explosions, primarily depend on the size of the explosion energy in the form of blast wave, the location of the object and its parameters and distance from the
explosion [4]. The most important characteristics for blast load estimation is to know the maximum pressure. The estimation of the maximum pressure could be done using formulas described by Stoller and Rejmont, [4].

4.2. Analytical approach
4.2.1 SDOF system
The analysis of dynamic response of blast-loaded structures is very complex. To simplify the analysis, the structure is idealized as a single degree of freedom (SDOF) system. Therefore, so called single degree of freedom system is a springmass-damper system where the mass is allowed to move in only one direction. For structures under the impulsive loads (blast loads) damping has much less importance because the maximum response will be reached in a very short time, before the damping forces can absorb much energy from the structure.

4.2.2 Mechanical properties
Mechanical properties are very important in determining the resistance of a structure subjected to blast loads. The mechanical properties, especially yield stress, of steel under dynamic loading condition are quite different from that under static loading. The stresses that are sustained under dynamic conditions gain values that are remarkably higher than the static compressive strength. It could be seen from the research [5], where the strengthening of the material S 355 during rapid deformation were taken into account. The values of static and dynamic strengths of the steel beams are in the next table.

| Beam  | Static characteristics | Dynamic characteristics |
|-------|------------------------|-------------------------|
|       | nominal yield          | ultimate strength       | nominal yield | ultimate strength |
| HEB 100 | 313 MPa           | 441 MPa                  | 444 MPa       | 625 MPa           |
| IPE 100 | 330 MPa           | 452 MPa                  | 468 MPa       | 641 MPa           |

4.2.3 Blast load
As from our previous work is known [6] a pressure time history of blast wave can be is idealized as a triangular pulse having a peak force $P^+$ and positive duration $t_d$. The simplest form assumes a linear decay

$$P(t) = P_0 \left( 1 - \frac{t}{t_d} \right).$$

The most realistic idealised pressure time history of blast wave can be described with mathematical function (Eq. 2), where $b$ is a shape parameter important for the shape of negative phase. Our research concludes that the shape parameter $b = 1.1$ describes the pressure time history the most satisfactory way,

$$P(t) = P_0 \left( 1 - \frac{t}{t_d} \right) e^{-b\frac{t}{t_d}}.$$
4.3 Numerical simulation

2.3 kg ANFO + 25 g PINp10

![Graph of real blast wave time–history from field tests and approximation in numerical simulation](image)

**Figure 2.** Real blast wave time–history from the field tests (red) and approximation of time–history in numerical simulation (blue)

4.3.1 FEM model

For the numerical simulation programme VisualFEA was used. VisualFEA is finite analyse software which allow to make the dynamic analysis. As a first approximation of model, a FEM beam model was selected. Beam was supported as the real structure, on the one fixed in both direction and on the other end pinned allowing movement in the direction x (local system of beam). Material and section characteristics were downloaded from VisualFEA database. Numerical solution leads to 200-time iteration of system with 32 equations.

4.3.2 Blast loading

Numerical model was loaded by approximated time history diagram obtained by close approximation of real blast wave time history from the field tests (Figure 3). The approximation was done in such way, that all characteristics points were considered. Values of pressures are in discrete form. The time step 0.001 s was chosen.

![Graph of acceleration time–history of numerical model](image)

**Figure 3.** Acceleration time–history of numerical model
5. Results and Discussions

Experimental data and results of SDOF model has been just compared in details in [7]. The dynamic analysis of the beam was done where accelerations were compared with the experimental results from field tests. Figure 4 shows the measured mid-span acceleration – time histories of the test beams and their corresponding values using the MDOF model. Generally, as can be seen model predict reasonably well both the peak and overall acceleration response of the beams.

The results from the numerical simulations could be compared with only small amount of the results measured in experiments. It can be noticed that the blast pressure sensors used for measuring the blast pressure time-history in shots No 1 and 2, were failed to capture any data because it was destroyed by the blast and falling debris. The same thing was for the shot No 5 where the sensors for acceleration and strains were hit.

![Figure 4. Comparison of acceleration time–history of numerical model (blue) and real beam (red)](image)

6. Conclusions

The paper presents a comparison between experiments – field tests and numerical simulations for air blast loaded steel beams. It contains analysis of the dynamic response of a number of rolled I and H beams tested under the blast loads. The measured blast wave parameters were compared with the model for blast load prediction. The test beam was analysed by using MDOF model based on beam finite elements. The results of models were compared with the corresponding experimental acceleration time-histories (Figure 4). Based on the analysis of the results and their comparison with the experimental data we could conclude that the MDOF model could predict reasonably well the blast loaded beam behaviour. It is about one dimensional beam model, and it can give very compliant results with the experimental measured ones. Advantage of such model is that it not requires a large computation power and is easy to done. Analysis and publication of the new detailed numerical models are also foreseen.
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