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Dynamic analysis of a blast loaded steel structure

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Abstract

With the increase in terrorist attacks in recent years, the effects of explosions on building become highly topical. In this regard, the paper deals with the analysis of blast loaded steel structures. When a blast loaded structure is analysed, as known, two major design issues and scientific challenges have to be approached and solved. The first issue derives from the analysis and description of the input dynamic load (time-pressure wave), being dependent on the type of explosion and explosive, while the second issue is related to the analysis of the actual dynamic response of the structure under impact. As such, real field blast tests using the so called ANFO explosives are first presented. The examined constructional system consists of steel rolled beams with two different type of cross sections (HEB100 and IPE120). The actual experimental observations are then assessed and compared with both SDOF and FE models carried out in ABAQUS. In doing so, the actual shape (i.e. decaying path for the pressure load) of the experimental blast wave is used, together with two further approximations for its description. The comparative calculations are then proposed for selected control points, in terms of mechanical and kinematic quantities (i.e. displacements, accelerations and strains). A critical discussion of the so collected comparative results is hence proposed.

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Keywords: blast load; dynamic analysis; SDOF model; FEM model; critical infrastructure protection

1. Introduction

With the growing of number of terrorist attacks recently it is essential to protect objects and human lives [1]. This kind of extreme loading condition, as in the case of blast waves generated by explosions, is usually considered as an

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exceptional configuration for buildings, with appropriate design verifications in the case of few structural typologies only [2,3]. The design of blast-resistant structures is in fact implicitly related to the protection of critical infrastructures, as government strategical buildings or structures in which huge concentration of people is expected. On the other hand, several other aspects should be implicitly considered when designing a blast-resistance system. In terms of design, blast resistance of structural systems is hence a currently open issue, aimed to be solved by exploiting protection of people and optimizing the structural efficiency of buildings or infrastructures in general [4, 5, 6]. The first challenge arises from the description of the blast load, whose decaying path over time depends on the type of explosion and type of explosives, including stand-off distance. The second issue is given by the accurate description of blast related effects on a given structural systems, including both analytical or FE numerical methods. In this paper, an experimental investigation carried out in 2014 on steel beams under blast loads is first presented. Analytical calculations derived from a SDOF method are then proposed for some selected specimens [7], aiming to capture the potential or criticisms of such simplified mathematical approach. A FE investigation is then also proposed, based on full 3D models implemented in the ABAQUS/Explicit software [8].

Nomenclature

ANFO	ammonium nitrate and fuel oil
FE	Finite Element
SDOF	Single Degree of Freedom

2. Analysis of a blast loaded steel structure

2.1. Available field test

The reference experimental results accounted for the actual comparative investigation were obtained from an earlier program of field tests. The experiments took place in January 2014, at the Military Technical and Testing Institute Zahorie (Slovakia). Blast tests were carried out on steel beam specimens consisting of HEB100 and IPE120 profiles, aiming to investigate their actual response under impulsive loads. As detonating charge, an ANFO explosive (being provided as ‘POLONIT’ from the Slovak company Istrochem Explosives a.s., Bratislava) was used, as also compared with a reference sample of TNT (field tests for further input features). The explosive charges were placed on a wooden base at a height of 1.0m from ground (i.e. approximately at the beams mid-span section, see Fig. 1). Three weights of charge were then preliminary selected for the explosive loading scenarios, corresponding to 2.3kg (pipe bomb), 4.5kg (bomb belt) and 9kg (bomb vest) respectively. The latter one was not detonated, however, due to damage in the steel specimens after the 4.5kg explosive charge. After the bomb belt explosion, the steel frame supporting beam specimens was in fact disrupted, with severe cracks in the lateral wall enclosing the test specimens and severe damage in part of the instrumentation (i.e. connection of cables and surface strain sensors). All the explosives charges were used together with 25g of ignition explosive (PLNp10 type).

Table 1. Main features of used explosives and loading conditions for the reference field tests.

Explosive	Type of explosive	Explosive velocity [m/s]	Heat of combustion [kJ/kg]	Density [g/cm^3]	Explosive pressure [GPa]
Polonit	AN+oil+TNT	4000	5138	0.90	6.93
TNT	Reference sample	6800	4200	1.58	18.4

The overall structural system (i.e. beam specimens and structural background) basically consisted of a steel frame, plus 4 steel beams type HEB100, and 12 steel beams, type IPE120. All the specimens were composed of S235 steel resistance class. The mechanical features of such members, i.e. the experimentally derived yield and ultimate strength values under static loads were 313MPa and 441MPa for the HEB100 profiles, and 330MPa and 452MPa for IPE120 profiles respectively. The span length was set to 1770 mm, and all the beams were pinned at the top with roller support at the base. For convenience, the beams were tested in vertical position (see Fig. 1(a)). The actual setup hence resulted representative of the dynamic bending performance of simply supported beams, being the specimens mainly affected to orthogonal blast pressures with axial stresses due to self-weight almost negligible.

Two main tasks were investigated through the experimental program, namely the blast wave propagation and the structural behavior of beam specimens. In the first case, blast wave pressures were measured according to ITOP 4-2-822 standard [9]. To this aim, 3 pressure sensors (137A23 type) were placed at an height of 1.6m from ground, with an angle of 45° from the surface of specimens exposed to blast, at the distances of 2m, 5m and 10m respectively from the source of the explosion (see Figs. 1(c) and (e)). One additional sensor was also used, and orientated so that could be parallel to the steel beams flanges. The latter one was positioned at a distance of 5.5 m from the gabion wall and 3m from the source of explosion (see Fig. 1(e)), so that the reflected blast wave could be properly recorded. For the analysis and description of the structural response of steel beams under impact, finally, strain time histories were continuously measured at the mid-span section of few selected beams only (i.e. beams labelled as n.2, 5, 12 and 15 in Fig. 1(a)), by means of surface strain sensors. The corresponding accelerations were also monitored with surface accelerometers, in the same control points.

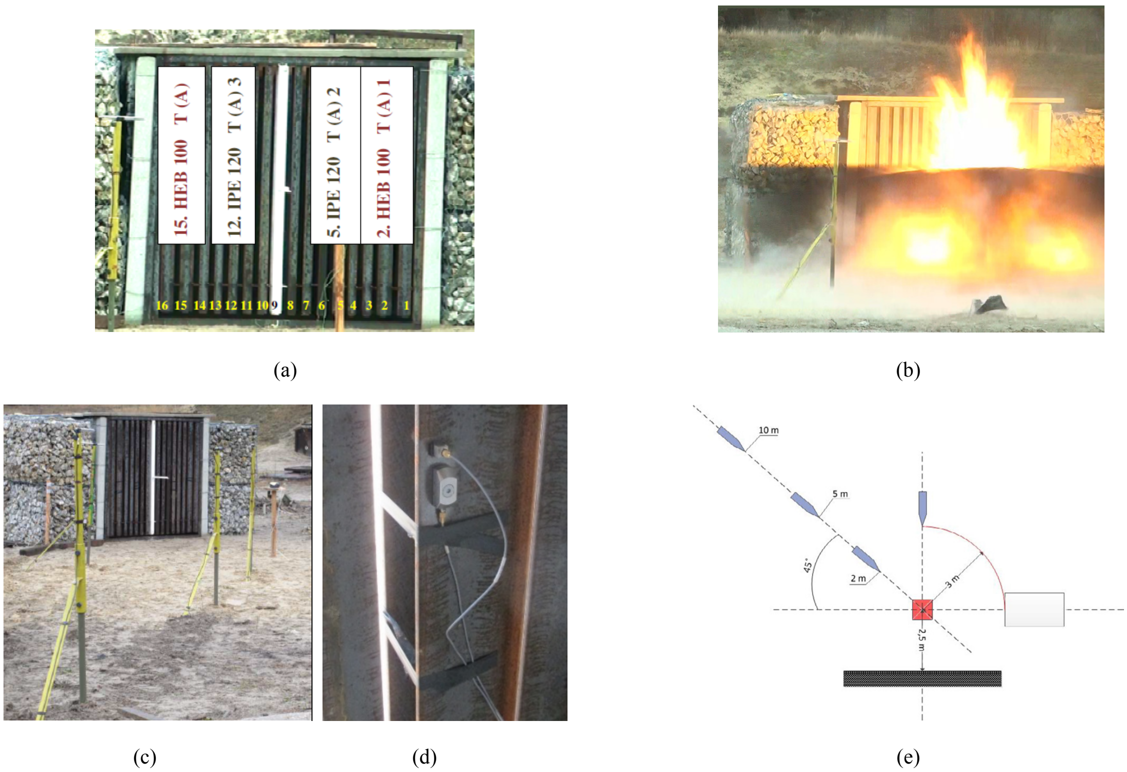
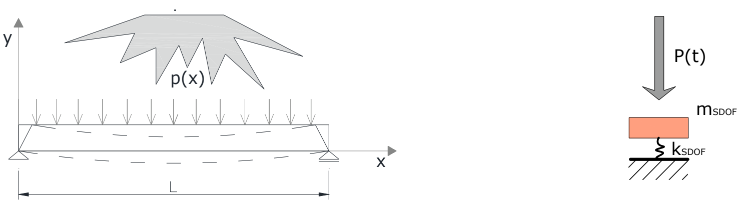


Fig. 1. Field tests on steel beams. (a) Labelling of the specimens, with (b) overview of the typical charge explosion, with blast pressure sensors (c), strain sensors and accelerometer (d) for measurements and (e) their position (top view)

2.2. SDOF analytical model

As known, an explosive event represents, for a given structural system, a typical source of impulsive, non-periodic loading condition. As such, the analysis of the dynamic response induced to blast loads on structures is generally very complex. Various literature approaches can be used to this aim, see for example [10,11]. To simplify the analysis and obtain reliable estimations of the expected performances, however, a given structure can be conventionally idealized as a SDOF system, in which a concentrated mass m_{SDOF} and a spring stiffness k_{SDOF} are used to represent the actual capacity of the structure to contrast the incoming blast wave.

In this research contribution, see Fig. 2, an undamped SDOF system was taken into account for the estimation of the impulsive response of the tested steel beams, since maximum dynamic effects on blast loaded structures usually occur during within few instants or at least in the first vibration cycle, hence when damping has minimum contribution to the overall response. In addition, for the structural beams object of investigation, null damping contribution was further justified since the higher energy dissipation was expected to take the form of plastic deformations, hence resulting in a conservative analytical estimation of maximum effects.



(a) (b)

Fig. 2. Equivalent SDOF system, with evidence of (a) real beam and (b) equivalent system

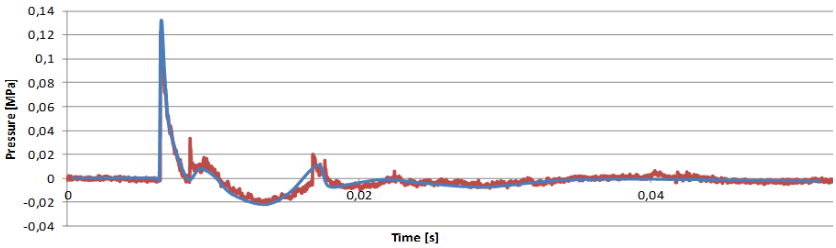


Fig. 3 Experimental blast wave time-history derive from the field tests (red) and approximated wave for SDOF and FE simulations (blue)

Simple dynamic systems can be analysed using rigorous analytical methods. The solution will take the form of time-displacement function, hence is possible for system subjected to mathematically simple time variations of load. For this reason, the experimentally measured blast waves were first idealized as a triangular pulse with peak force P_+ positive duration t_d and linear decay:

$$P(t) = P_+\left(1 - \frac{t}{t_d}\right) \quad (1)$$

Eq.(1) only roughly describes the actual decaying path for a typical blast wave, which is conventionally idealised by Eq.(2), where b is a shape parameter having major effects especially for the shape of negative phase:

$$P(t) = P_+\left(1 - \frac{t}{t_d}\right) e^{-b\frac{t}{t_d}} \quad (2)$$

Following Fig. 3, a shape parameter equal to b= 1.1 was found to best fit the experimentally derived pressure time history. The equation of motion of the SDOF system subjected to an impulsive pressure P_+ varying in time with (Eq.(2)) is hence given by [7]:

$$m\ddot{y}(t) + ky(t) = P_s\left(1 - \frac{t}{t_d}\right) e^{-bt/t_d}, \quad (3)$$

where m and k denote the SDOF mass and stiffness, with being $\ddot{y}$ the acceleration, $\dot{y}$ the velocity and y the corresponding displacement. Solving the differential Eq.(3), the displacement y of the blast loaded steel beam is obtained according to Gantes [4], see Eq.(4), where for a given time instant t, T is time period, t_{el} represents the time at the end of the elastic stage, t_d is the time of reversal of pressure direction and a denotes the ratio between the maximum system resistance and the external load peak (see also [10] for further details).

$$y_{(t)} = \frac{1}{6a\pi T^2 t_d}\{-2\pi(2\pi^2 t^3 + 3tT^2 - 6\pi^2 t^2 t_d + 6a\pi^2 t^2 t_d - 3T^2 t_d + 12t\pi^2 t_d t_{el} - 6t\pi^2 t_{el}^2 - 6\pi^2 t_d t_{el}^2 + 6a\pi^2 t_d t_{el}^2 + 4\pi^2 t_{el}^3) + 6\pi T^2 (t - t_d - t_{el}) \cos\frac{2\pi t_{el}}{T} + 3T (T^2 + 4t\pi^2 t_d - 4\pi^2 t_d t_{el}) \sin\frac{2\pi t_{el}}{T} \quad (4)$$

As far as *y(t)* is known, velocity and acceleration of the system can be also derived. Following Eq.(4), the velocity is given by:

$$\dot{y}_t = \frac{2\pi td}{a\,(b^2T^2+4\pi^2t_d^2)^2}\left\{2e^{-bt/bd}\frac{b\pi}{td} + (b^2(t-td)T^2 + 2btdT^2 + 4\pi^2(t-td)t_d^2) - 2e^{-bt/td}\pi(b^2T^2 + 4\pi^2t^2a) + \frac{4\pi^2 td}{T}\big((b-2)bT^2 + 4\pi^2b^2d\big)\sin\frac{2\pi t}{T} + 2\pi\big((b-1)b^2T^2 + 4(b+1)\pi^2t^2d\big)\cos\left(\frac{2\pi t}{T}\right)\right\} \quad (5)$$

while the corresponding acceleration takes the form:

$$\ddot{y}_{(t)} = \frac{2\pi td}{a\,(b^2T^2+4\pi^2t_d^2)^2}\left\{2e^{-bt/bd}\left(\frac{b\pi}{td}\right)\left[\left(\frac{-b}{td}\right)(b^2(t-td)T^2) + (2btdT^2) + (4\pi^2(t-td)t^2d) + 2(b^2T^2 + 4\pi^2t^2d)\right] + \left(\frac{8\pi^3 td}{T^2}\big((b-2)\,bT^2 + 4\pi^2t^2d\big)\cos\left(\frac{2\pi t}{T}\right)\right) - \left(\frac{4\pi^2}{T}\big((b-1)\,b^2T^2 + 4\,(b+1)\pi^2t^2d\big)\sin\frac{2\pi t}{T}\right)\right\}$$
(6)

Comparative results are proposed for some selected specimens in Table 2, where test measurements are compared with the analytical estimations given by the SDOF approach summarized above.

Analytical results are distinguished by calculations carried out with the linear or exponential decay assumption. As shown, rather interesting correlation was found in terms of maximum strains for the selected specimens. Close fitting with the experiments was observed especially when assuming an exponential decaying path for the assigned blast wave pressure, compared to the linear slope condition.

Major scatter was indeed observed in terms of maximum acceleration of the same specimens, both with the linear or the exponential path for the blast wave description, being the SDOF approach often underestimating the actual acceleration values experimentally recorded. In some cases, see also [10], the SDOF estimations resulted in the order of -50% the test predictions, while in some other circumstances, an almost exact match was found.

2.3. Finite Element numerical modelling

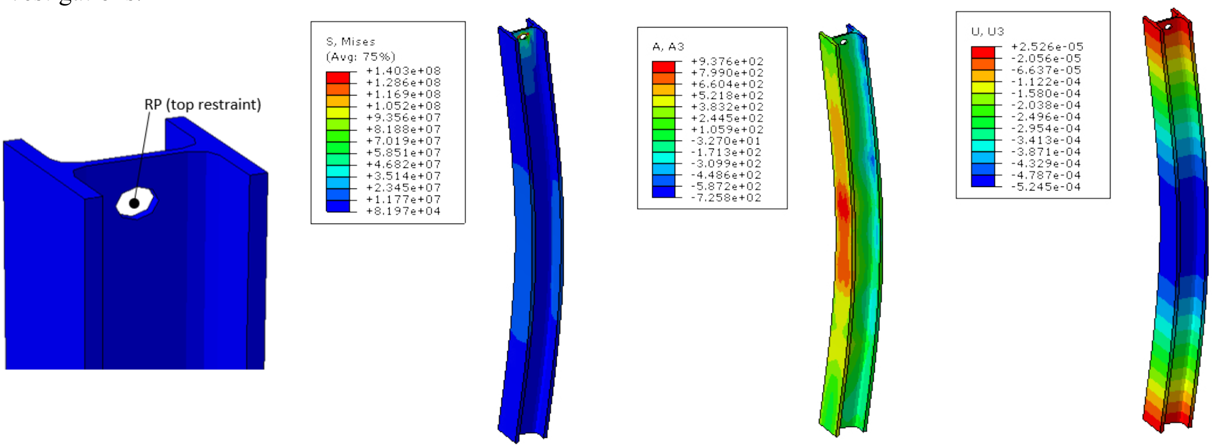
As a further attempt to investigate the impulsive response of the same steel beams, a FE study was carried out in ABAQUS/Explicit [8]. To this aim, both a simplified FE model composed of 1D beam elements and a refined 3D model consisting of solid brick elements were considered for the same beams. In both the cases, two assemblies representative of a HEB100 and a IPE120 beam types respectively were then described. For the 1D models, wire elements with I-shaped beam section properties were considered, with 2-node B31 type the chosen elements. The nominal geometry was accounted in them, for the section features and in terms of ideal boundaries. A key role was given to the computational efficiency of these models, with 25 elements and 150 DOFs. The blast wave pressure was described in accordance with Fig. 3, in the form of an equivalent time-varying line load acting on the full beam assembly, by taking into account the experimental measurements.

Regarding the geometrically refined FE models, full 3D assemblies consisting of 8-node, C3D8R type brick elements were also carried out. The blast wave was described as a time-varying pressure uniformly distributed on the external flange of each beam (Fig. 3), careful consideration was paid for the beam restraints, based on technical drawings (see Fig. 4(a)). At the top end of each FE assembly, the pinned restraint was in fact described via a reference (RP) node and a rigid kinematic *coupling*, being well representative of the actual restraint for the experimental specimens. To this aim, a hole (24mm its diameter) with centre positioned at a distance of 32mm from the top edge of the steel member was also accounted. A reference node on the beam flange was simply supported and restrained towards possible translations in the direction of the incoming blast wave, with free rotations. A regular mesh pattern was then used for the so described solid elements, aiming to maximize the accuracy of FE predictions. Each FE model hence consisted of 5,000 solid elements and 18,000 DOFs. For both 1D and 3D models, Von Mises elasto-plastic mechanical laws were defined for steel. Quasi-static yielding and ultimate stress values given in Section 2.1 were preliminary taken into account, with 210GPa the modulus of elasticity and 0.3 the Poisson' ratio.

Table 2. Comparison of experimental, analytical (SDOF) and FE numerical (ABAQUS) maximum effects due to blast, as obtained for selected HEB100 type beams only

Charge	Spec.	Strain [με]						Acceleration [m/s^2]					
		Test		SDOF		FE		Test		SDOF		FE	
		Min	Max	Lin.	Exp.	1D	3D	Min	Max	Lin.	Exp.	1D	3D
Polonit	T1	-98.28	96.81	165.03	143.64	31.05	93.55	-1005.20	1044.63	435.57	391.14	1328.15	1112.15
2.3kg	T4	-70.46	95.33					-205.07	352.33				

In Table 2, comparative results are proposed for the HEB type specimens, as obtained from the experiments with 2.3kg of charge and from the corresponding FE models (ABAQUS results given in absolute value). While the 1D model proved to offer only rough estimations for the reference experiments, the 3D simulation offered more accurate and reliable predictions. A key effect was also given by the end restraints, being maximum stresses numerically measured close to the top restraint rather than at the mid-span section (see Fig. 4(b)). Current FE studies however still require to be further extended. Worth of interest is for example the high scatter in Table 2 between experimental measurements of accelerations for the T1 and T4 beams, hence requiring further analysis and investigations.



(a) (b) (c) (d)

Fig. 4 FE modelling of HEB100 beams (ABAQUS). (a) Restraint detail, with (b) stresses ([Pa]), (c) accelerations ([m/s^2]) and (d) deflections (values in [m]). Blast effects proposed in plots (b)-(c)-(d) after 0.01s of impact exposure.

3. Conclusions

In this paper, past experimental investigations have been presented for the assessment of the overall performance of structural steel beams subjected to blast loads, including both HEB100 and IPE120 type specimens. Analytical SDOF calculations and FE numerical predictions have been then proposed for some selected test specimens, aiming to compare maximum experimentally observed strains and accelerations. As shown, careful considerations should be given in design of blast loaded structures to a multitude of aspects, including the description of the actual blast wave, as well as the refinement in geometrical and mechanical characterization of the actual specimens features.

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