BLAST LOADING ON STRUCTURES FROM THE EXPLOSIONS NEAR THE GROUND SURFACE

ВЗРИВНО НАТОВАРВАНЕ НА КОНСТРУКЦИИ ОТ ЕКСПЛОЗИИ БЛИЗО ДО ЗЕМНАТА ПОВЪРХНОСТ

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Abstract: *The paper describes the process of determining the blast load on structures and provides a numerical example of a fictive structure exposed to this load. The aim was to become familiar with the issue of blast load because of ever growing terrorist threat and the lack of guidelines from national and European regulations on the verification of structures exposed to explosions. The blast load was analytically determined as a pressure-time history.*

Keywords: BLAST LOAD, RC STRUCTURES, PRESSURE TIME HISTORY, EXPLOSION, BLAST WAVE.

1. Introduction

The terrorist activities and threats have become a growing problem all over the world and protection of the citizens against terrorist acts involves prediction, prevention and mitigation of such events. In the case of structures an effective mitigation may also be thought in the terms of structural resistance and physical integrity. If the structures are properly designed for these abnormal loads damage can be contained. Additionally, in order to ensure safety of existing structures against such events, an evaluation procedure for their inspection and eventual retrofit is needed.

Within the Eurocodes these types of loads are not dealt with (EN 1991-1-7) and they need further elaboration as the engineers have no guidelines on how to design or evaluate structures for the blast phenomenon for which a detailed understanding is required as well as that of the dynamic response of various structural elements. There are no guidelines on such topics. On the other hand, this topic is the interesting one in military circles and important data derived from the experience and tests have been restricted to army use. Nevertheless, a number of publications are available in the public domain and published by the US agencies. Analysis of structures under blast load requires a good understanding of the blast phenomenon and a dynamic response of structural elements. The analysis consists of several steps: (a) estimate of the risk; (b) determination of the computational load according to the estimated hazard; (c) analysis of the structural behaviour; (d) selection of the structural system and (e) evaluation of the structural behaviour.

In this paper we have explored the available literature on blast loads, explained special problems in defining these loads and explored the possibility of vulnerability assessment and risk mitigation of structures

2. Materials for Explosions

Explosive is widely used for demolition purposes in: military applications, construction or development works, demolitions, etc. It is, also, a very common terrorist weapon as it is available, easy to produce, compact and with a great power to cause structural damage and injuries. Estimated quantities of explosive in various vehicles are presented in Tab. 1.

Table 1: Estimated quantities of explosives in various vehicles

Vehicle type	Charge mass / kg
Compact car trunk	115
Trunk of a large car	230
Closed van	680
Closed truck	2270
Truck with a trailer	13610
Truck with two trailers	27220

In order to be able to use explosives they have to be inert and stable, which means that the explosion is a triggered, rather than a spontaneous reaction. The explosion is a phenomenon of rapid and abrupt release of energy. Speed of the reaction determines the usefulness of explosive materials that can be condensed, solid or liquid.

When they detonate they disintegrate emitting the heat and producing gas. Most of the explosives detonate by a sufficient excitation and convert into a very hot, dense gas under high pressure that presents a source of strong explosive wave. Only about one third of the total chemical energy is released by detonation. The remaining two thirds are released slowly in the blasts as the explosive products mix with the surrounding air and burn.

The explosion effects are presented in a wave of highintensity that spreads outward from the source to the surrounding air. As the wave propagates, it decreases in strength and speed (Fig. 1).

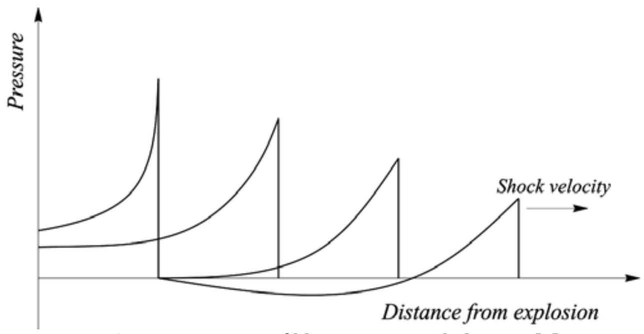

Figure 1 Variation of blast pressure with distance [2]

3. Basic parameters of the explosion

Use of the TNT (Trinitrotoluene) as a reference for determining the scaled distance, *Z*, is universal. The first step in quantifying the explosive wave from a source other than the TNT, is to convert the charge mass into an equivalent mass of the TNT. It is performed so that the charge mass of explosive is multiplied by the conversion factor based on the specific energy of the charge and the TNT. Specific energy of different explosive types and their conversion factors to that of the TNT are given in Tab. 2.

Table 2: Conversion factors for explosives

Explosive	Specific energy	TNT equivalent
	Q_x / kJ/kg	Q_x/Q_{TNT}
60% RDX, 40 % TNT	5190	1,148
RDX	5360	1,185
HMX	5680	1,256
TNT	4520	1,000
Semtex	5660	1,250
C4	6057	1,340

Explosion wave front speed equation, Us, and the maximum dynamic pressure, q_s, are defined as [1]:

(1) $$U_s = a_o.\sqrt{\frac{6p_s + 7p_o}{7p_o}}$$

(2) $$q_s = \frac{5p_s^2}{2.(p_s + 7p_o)}$$

where:
ps – peak static wave front overpressure, bar
p_0 – ambient air pressure (atmospheric pressure), bar
a_0 – speed of sound in the air, m/s.

There are various proposals for the calculation of the main explosion parameters.

Brode [6] gives the following values for the peak static overpressure for near (when the *p*s is greater than 10 bar) and for medium to far away (when the *p*s is between 0,1 and 10 bar):

(3) $$p_s = \frac{6{,}7}{Z^3} + 1, \quad p_s > 10\ bar$$

(4) $$p_s = \frac{0{,}975}{Z} + \frac{1{,}455}{Z^2} + \frac{5{,}85}{Z^3} - 0{,}019, \quad 0{,}1 < p_s < 10\ bar$$

where

Z – scaled distance,

(5) $$Z = \frac{R}{\sqrt[3]{W}},$$

R – distance from the centre of a spherical charge, m
W – charge mass expressed in kilograms of TNT.

Newmark and Hansen [7] proposed the use of the following values:

(6) $$p_s = 6784.\frac{W}{R^3} + 93.\sqrt{\frac{W}{R^3}},$$

Mills [8] proposed the following:

(7) $$p_s = \frac{1772}{Z^3} + \frac{114}{Z^2} + \frac{108}{Z} - 0{,}019, kPa$$

Other important parameters include: t_o = duration of the positive phase during which the pressure is greater than the pressure of the surrounding air and i_s = the specific wave impulse that is equal to the area under the pressure-time curve from the moment of arrival, t_A, to the end of the positive phase and is given by expression:

(8) $$i_s = \int_{t_A}^{t_A+t_o} p_s(t)dt$$

The typical pressure profile of the explosion wave in time for the explosion in the air is given in Fig. 2.

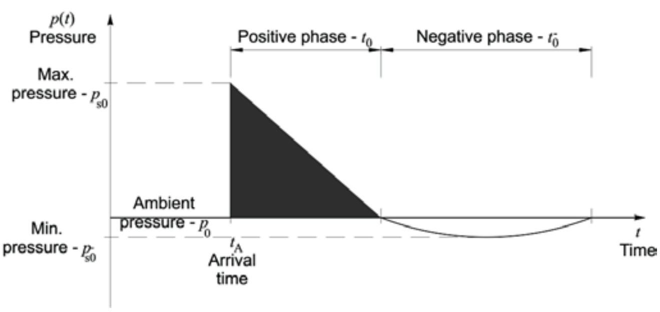

Figure 2 Pressure-time profile of the explosion wave

4. Results and discussions

In most instances simplifications lead to conservative constructions. However, unknown factors may lead to the overestimation of the structural capacity to blast loadings.

Unexpected shock wave refraction, design methods, quality of construction and materials, interaction with ground, are different for each particular structure. In order to overcome these uncertainties it is recommended that the mass of TNT equivalent is increased by 20 %. This increased value of the charge weight is called the "effective charge weight".

4.1. Loading categories

Explosion loadings can be divided into two main groups according to the confinement of an explosive charge: confined and unconfined. Tab. 3 shows an overview of possible loading categories.

Table 3: Explosion load categories

Charge confinement	Categories
Unconfined	The explosion in the free air
	The explosion in the air
	The explosion near the ground
Confined	Full ventilation
	Partially confined
	Fully confined

4.2. Structure – explosion interaction

As the wave propagates through the air, the wave front encircles the structure and all its surfaces so that the whole structure is exposed to the blast pressure. The magnitude and distribution of the structural loading depends on the following factors:

a) the characteristics of explosives that depend on the type of explosive material, released energy (size of detonation) and weight of explosive,
b) the detonation location relative to the structure,
c) intensity and magnification of pressure in the interaction with the ground or the structure itself.

Time record of the explosion pressure wave is usually described as an exponential function in the form of Friendlander's equation [1], in which the *b* is the parameter of the waveform:

(9) $$p(t) = p_s.\left(1 - \frac{t}{t_0}\right)\exp\left(-\frac{b_t}{t_0}\right)$$

For the various purposes approximations are satisfactory. This change in pressure over time is shown in Fig. 2.

Rankine and Huguenot [1] derived an equation for refracted overpressure p_r:

(10) $$p_r = 2\,p_s + (\gamma+1).q_s$$

Substituting (2) into the equation (10):

(11) $$p_r = 2p_s.\left(\frac{7p_0 + 4p_0}{7p_0 + p_0}\right)$$

If the rectangular structure is exposed to an explosion, it will be exposed to pressures on all its surfaces. Each surface suffers two concurrent components of the load. Diffraction of explosion around the structure will enclose a target and cause a normal force to any exposed surfaces (Fig. 3). Structure is pushed to the right if the left side is loaded while simultaneously pushed slightly to the left as the diffraction ends. Drag force pushes the structure from the left side and that is followed by the suction force on the right when the dynamic pressure crosses (blast wind) over and around the structure.

As the shock front expands in surrounding volume of the air, the peak initial pressure is reduced and the duration of the pressure increases.

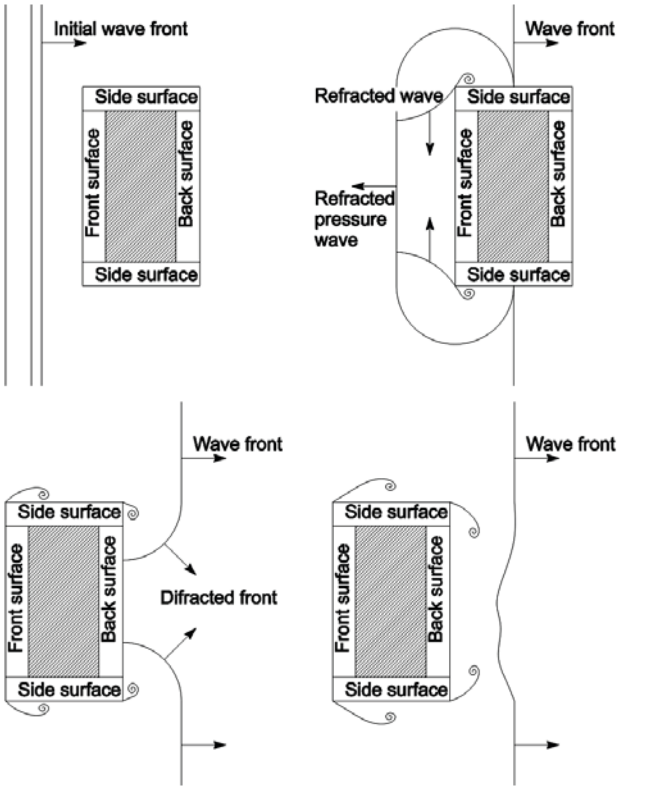

Figure 3 Behaviour of the wave during its pass around the structure

Wave front comes to a particular location at the time t_A, and after the increase to a maximum value of p_{s0}, the peak pressure decreases to the value of atmospheric pressure at the time t_0 what represents a positive phase.

This is followed by a negative phase with duration t_0 which is usually much longer than the positive phase and it is characterized by a negative pressure (below atmospheric) with a maximum value of p_{s0} and reverse flow of particles. Impulse associated with the shock wave is the surface below pressure-time curve and is indicated with *i*s for the positive phase and i_s for a negative phase (Fig. 2).

4.3. The explosion near the ground

If the charge is located very close to the ground or on the ground the explosion is termed near the ground. Refracted wave arises as the initial blast wave is refracted and increased by reflection of the ground. Unlike an explosion in the air, the refracted wave is merged with the initial wave in the detonation point, and they form a single wave (Fig. 4).

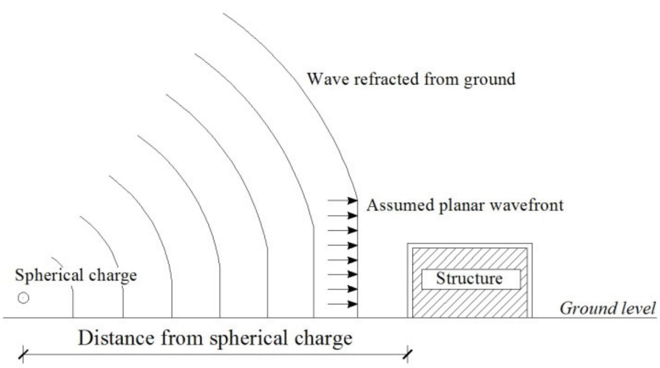

Figure 4 Refracted wave of the explosion near the ground

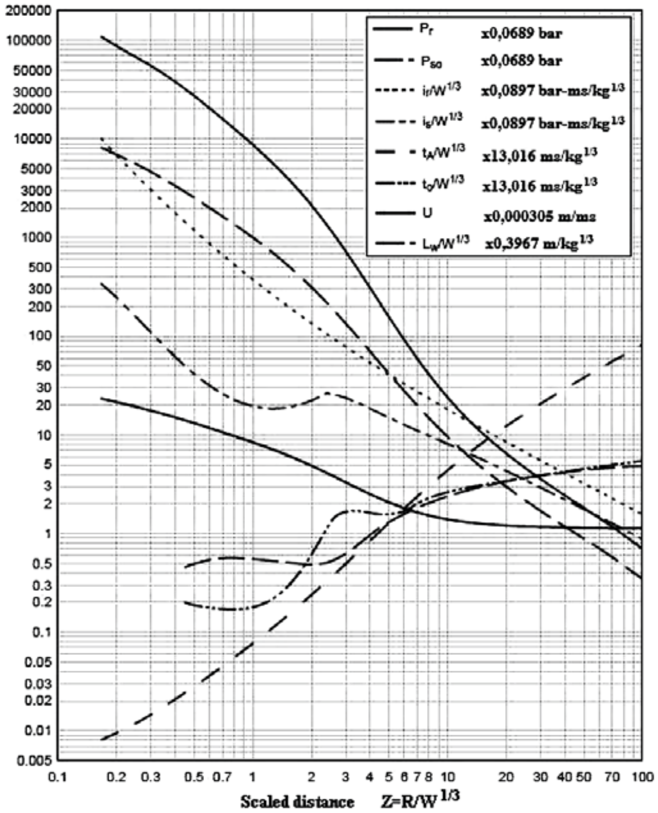

Figure 5 Parameters of the positive phase blast wave near the ground [5]

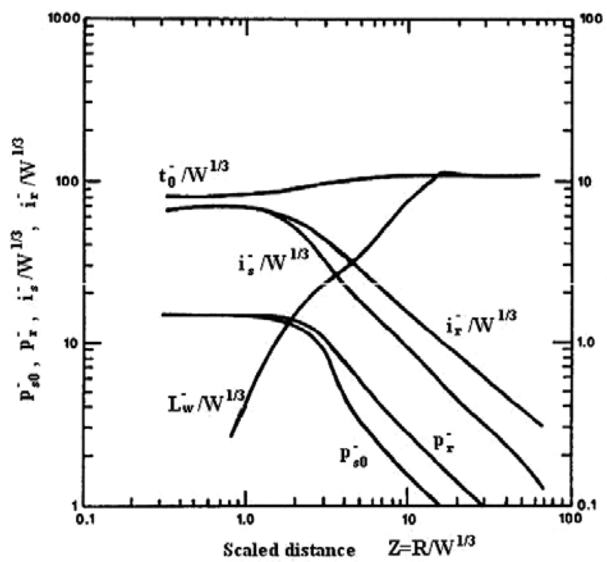

Figure 6 Parameters of the negative phase blast wave near the ground [5]

For an explosion near the ground, the load acting on the structure is calculated as for the explosion in the air, except that the initial pressure and other parameters for the positive phase are determined as explained in Fig. 5 and the theoretical parameters of the negative phase as in Fig. 6.

4.4. Pressures on the structural surfaces

In order to analyze the blast loadings it is necessary to determine the initial reduction of the dynamic pressure in the time as the effects on the structure depend on the pressure-time history as well as on the peak value. The explosion wave form (Fig. 7) is characterized by a sudden increase in pressure to peak, decrease to an atmospheric pressure (positive phase) and the period in which the pressure falls below the atmospheric pressure (negative phase).

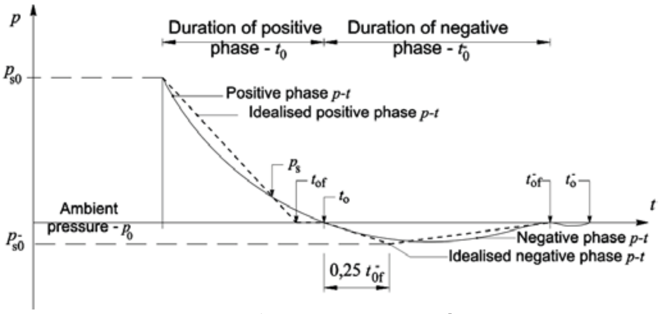

Figure 7 Pressure time history

The reduction speed of the initial and dynamic pressure, after the passing of the wave front, is a function of the peak pressure and the magnitude of detonation. For the analysis purposes, the actual reduction of the initial pressure can be assumed as a triangular pressure impulse.

The actual duration of the positive phase is replaced by a fictitious duration and is expressed as a function of the total positive impulse and the peak pressure:

This expression can be used for the initial and for the refracted pressure by taking the values of refracted impulse pressure and peak refracted pressure, respectively.

As the fictitious duration of the positive phase is shorter than the actual duration, a difference between the fictitious phase and the beginning of the negative phase is created. This difference, shown in Fig. 7, should be retained in the analysis because of the retention order of the different stages of loading.

4.5. The average pressure on the front facade

The variation of the pressure on the front structural facade, for a rectangular structure with sides parallel to the wave front above the ground, in the area of low pressure is shown in Fig. 8.

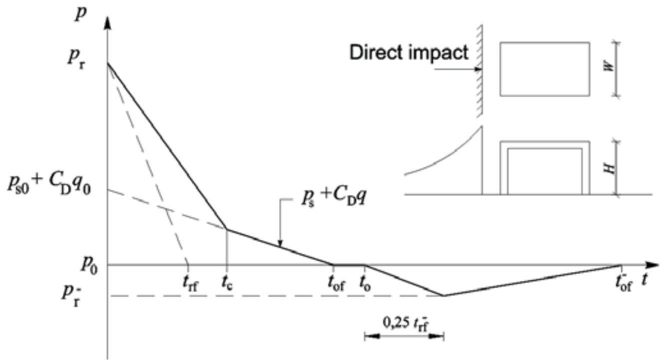

Figure 8 The load on the front surface of the structure

The peak pressure on the front structural facade in time of the explosion's arrival, t_A, will be the peak refracted overpressure *p*r, which is a function of the initial pressure (Fig. 5). This pressure then decreases in time interval [t', t_A] due to the passage of waves above and around the structure, which is less than p_r (peak overpressure over and around the structure will be p_s).

The overpressure on the front surface of the structure continues to decrease until the pressure is equalized with the pressure of the surrounding air. Clearing time (passing time), t_c, needed that the refracted pressure drops to the level of the initial pressure can be expressed as:

(12) $$t_c = \frac{4S}{(1+R).C_r}$$

S – length of the "clearing", is equal to the height of the structure,
H or a half-width of the structure, *W*/2, whichever is less (Fig. 8),
R – ratio *S*/*G*, where *G* is the height of the structure,
H or half-width of the structure, *W*/2, whichever is less,
*C*r – speed of sound in refracted area (Figs. 2 ÷ 192, [5]).

Pressure that acts on the front surface after the time t_c is the algebraic sum of the initial pressure p_s and drag dependent pressure, $C_D \cdot q$:

(13) $$p = p_s + C_D.q,$$

Drag coefficient C_D connects the dynamic pressure and total translational pressure in the direction of the wind-induced dynamic pressure and varies with Mach number (or Reynolds number in the area of low pressure), and depends on the geometry of the structure. It can be taken as ≥ 1,0 for the front facade, while for the side, rear and roof surfaces it can be taken < 1,0 (Tab. 4).

The fictitious length of the refracted wave front, t_{rf}, is calculated according to the formula:

(14) $$i_{rf} = \frac{2i_r}{p_r},$$

where *p*r is the refracted peak pressure.

Table 4: Drag coefficients

Loaded surface	C_D
Front	0,8 ÷ 1,6
Rear	0,25 ÷ 0,5
Side and roof	
0 ÷ 172	- 0,4
172 ÷ 345	- 0,3
345 ÷ 896	- 0,2

5. Conclusion

The explosion in or near the structure can cause catastrophic damage to the structure, formation of fragments, destruction of life-support systems (air conditioning, sprinklers). Injuries and deaths can be caused by exposure to explosion wave front, collapse of the structure, impact of parts, fire and smoke. Secondary effects of the explosion can hinder or even prevent the evacuation of people from the structure causing additional injuries and deaths.

The Bulgarian national legislation and also Euronorms have no guidelines for design of buildings to blast loads.

It is shown that the effects of blast loading can be taken into account for structural design by the use of available literature. Available commercial software for structural analysis can be used for design purposes, while further analysis should be directed towards familiarizing the phenomenon of the internal explosion. Thus a complete picture of the explosion effects on the structure can be obtained.

6. Literature

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