BLAST LOAD ANALYSIS AND EFFECT ON BUILDING STRUCTURES

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ABSTRACT. The increase in the number of terrorist attacks especially in the last few years has shown that the effect of blast loads on buildings is a serious matter that should be taken into consideration in the design process. The analysis and design of structures subjected to blast loads require a detailed understanding of blast phenomena and the dynamic response of various structural elements. This paper presents a comprehensive overview of the effects of explosion on structures. An explanation of the nature of explosions and the mechanism of blast waves in free air is given. Designing the structures to be fully blast resistant is not a realistic and economically viable option, however better understanding of the mechanism of blast load will enable us to make blast resistant building design much more efficient.

Keywords: *explosion, blast wave, terrorist attacks, shock wave, blast load*

АНАЛИЗ НА ВЗРИВНОТО ВЪЗДЕЙСТВИЕ ВЪРХУ СТРОИТЕЛНИТЕ КОНСТРУКЦИИ

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РЕЗЮМЕ. Увеличаването на броя на терористичните атаки, особено през последните няколко години, показа, че ефектът от взривното въздействие върху сградите е сериозен проблем, който трябва да се вземе под внимание в процеса на проектиране. Анализът при проектирането на конструкции, подложени на взривни натоварвания, изискват обстойно разбиране на взривните явления и динамичната реакция на различните структурни елементи. Тази статия представя преглед на ефектите от взрива върху конструкциите. Дава се обяснение за зависимостта на основните параметри на взрива и механизмите на ударната въздушна вълна. Проектирането на конструкции напълно устойчиви на взрив не е реалистичен и икономически оправдан вариант, но по-доброто познаване на механизма взривното въздействие ще позволи да направим устойчивостта на сградите при взрив много по- ефективна.

Ключови думи: експлозия, взривна вълна, терористични атаки, ударна вълна, взривно въздействие

Introduction

The use of explosives by terrorist groups around the world that target civilian buildings and other structures is becoming a growing problem in modern societies. Bomb explosion near the building can cause such amount of pressure and produces a large amount of heat resulting in a high strain loading on a building and its elements. Such a high strain loading can cause catastrophic damage on building's external and internal structural frame, collapsing of walls, blowing out large expense of windows and shutting down of critical life safety systems.

Due to the threat from such extreme loading conditions, during the past three decades efforts have been made to develop methods of structural analysis and design to resist blast loads. The analysis and design of structures subjected to blast loads require a detailed understanding of blast phenomena and the dynamic response of various structural elements. The aim of this study is to review the work carried out in past few years on blast effects on structures. This article includes introduction and detailed explanation on blast wave phenomenon.

Explosions and Blast Waves

An explosion can be defined as a very fast chemical reaction involving a solid, dust or gas, during which a rapid release of hot gases and energy takes place. The phenomenon lasts only some milliseconds and it results in the production of very high temperatures and pressures. During detonation the hot gases that are produced expand in order to occupy the available space, leading to wave type propagation through space that is transmitted spherically through an unbounded surrounding medium. Along with the produced gases, the air around the blast (for air blasts) also expands and its molecules pile-up, resulting in what is known as a blast wave and shock front. The blast wave contains a large part of the energy that was released during detonation and moves faster than the speed of sound.

Blast wavefront parameters

Of particular importance are the blast wavefront parameters. Analytical solutions for these quantities are first given Ьy Rankine aпd Hugoniot in 1870 (Rankine, 1870) to describe normal shocks in ideal gases and are available in a number of references such as Liepmann and Roshko (Liepmann & Roshko, 1957). The equations for blast wavefront velocity and maximum dynamic pressure are given below:

$$U_S = \sqrt{\frac{6p_s+7p_0}{7p_0}}.a_0 \quad (1)$$

$$q_s = \frac{5p_s^2}{2(p_s+7p_0)} \quad (2)$$

where:

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

The analysis due to Brode (Brode, 1955) leads to the following results for the peak static overpressure in the near field (when the p_s is greater than 10 bar) and for medium to far field (when the p_s is between 0.1 and 10 bar):

$$p_s = \frac{6.7}{Z^3} + 1, \text{bar}; \quad (p_s > 10 \text{ bar}) \quad (3)$$

$$p_s = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \text{ bar} \quad (4)$$

$$(0.1 < p_s < 10 \text{ bar})$$

where Z is scaled distance,

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

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

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. The simplest way of achieving this is to multiply the mass of explosive by a conversion factor based on its specific energy and that of TNT. Conversion factors for a number of explosives are shown in Table 1 adapted from Baker (Baker et al., 1983).

Table 1**.** *Conversion factors for explosives*

Explosive	Specific energy Q_x / kJ/kg	TNT equivalent Q_x/Q_{TNT}
Compound B (60% RDX, 40% TNT)	5190	1.148
RDX (Cyclonite)	5360	1.185
HMX	5680	1.256
Nitroglycerin (liquid)	6700	1.481
TNT	4520	1.000
Blasting Gelatin (91% nitroglycerin, 7.9% nitrocellulose, 0.9% antracid, 0.2% water)	4520	1.000
60% Nitroglycerin dynamite	2710	0.600
Semtex	5660	1.250

An equivalent TNT weight is computed according to Equation (6) that links the weight of the chosen design explosive to the equivalent weight of TNT by utilising the ratio of the heat produced during detonation (Karlos, Solomos, 2013):

$$W_e = W_{exp} \frac{H_{exp}^d}{H_{TNT}^d} \quad (6)$$

where, W_e is the TNT equivalent weight (kg),
W_{exp} is the weight of the actual explosive (kg),
H_{exp}^d is the heat of detonation of the actual explosive (MJ/kg),
H_{TNT}^d is the heat of detonation of the TNT (MJ/kg).

Table 2 provides estimates of the produced heat of detonation of some common explosives as defined in (TM5-1300). These values can be used for the calculation of the equivalent TNT weight with the use of Equation (6).

Table 2. *Indicative values of heat of detonation of common explosives*

Name of explosive	Heat of detonation (MJ/Kg)
TNT	4.10-4.55
C4	5.86
RDX	5.13-6.19
PETN	6.69
PENTOLITE 50/50	5.86
NITROGLYSRIN	6.30
NITROMETHANE	6.40
NITROCELLULOSE	10.60
AMON./NIT.(AN)	1.59

Other important blast wave parameters

Other significant parameters include t_0, duration of the positive phase (the time when the pressure exceeds the ambient pressure) and i_s the specific impulse of the wave which is the area beneath the pressure-time curve from the moment of arrival, t_A, to the end of the positive phase and is given by expression (Mays, Smith,1995):

$$i_s = \int_{t_A}^{t_A+t_0} p_S(t)dt \quad (7)$$

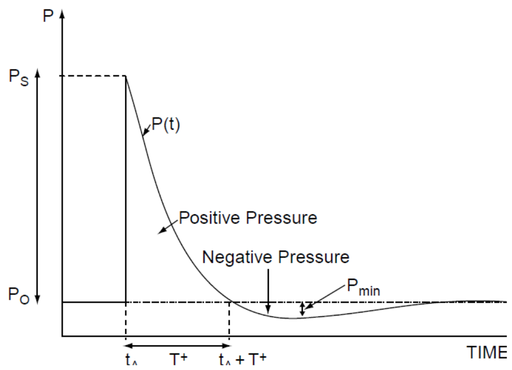

Fig. 1. Pressure-time profile for blast wave in free air

A typical pressure- time profile for a blast wave in free air is shown in Figure 1 were p^- is the greatest value of underpressure (pressure below ambient) in the negative phase of the blast. This is the rarefaction or underpressure component of the blast wave. Brode's solution for p^- (bar) is:

$$p^- = \frac{0,35}{Z}, \text{bar}; Z > 1,6 \quad (8)$$

and the associated specific impulse in this phase i_s^- is given by:

$$i_s^- \approx i_s.\left(1-\frac{1}{2Z}\right) \quad (9)$$

Blast wave scaling laws

The most commonly used blast wave scaling is the cube root scaling law, otherwise known as Hopkinson's Law (Baker, 1973). This law states that any pressure generated at a distance R_1 from a reference explosion with weight W_1 will generate the same pressure at a distance R_2 from the same explosive with weight W_2 provided the charges are of similar geometry and in the same atmosphere.

$$\frac{R_2}{R_1}=\left(\frac{W_2}{W_1}\right)^{\frac{1}{3}}=\lambda \quad (10)$$

The parameter λ is referred to as the explosive yield factor. Hopkinson's Law approach leads readily to the specification of the scaled distance Z (m/kg$^{1/3}$), introduced above.

Hemispherical surface bursts

The foregoing calculations refer to free- air bursts remote from any reflecting surface and are usually categorised as spherical airbursts. When attempting to quantify overpressures generated by the detonating of high explosives sources in contact with the ground, modification must be made to charge weight. Surface bursts produced blast waves that appear to come from free air bursts are 1-8 times the actual source energy. It should be noted that if the ground was a perfect reflector and no energy was dissipated (in producing a crater and groundshock) the reflection factor would be 2 (Mays, Smith, 1995).

Blast wave pressure profiles

The pressure-time history of a blast wave is often described by exponential function such as the Freelander equation (in which the b is the parameter of the waveform):

$$p(t)=p_s\left(1-\frac{t}{t_0}\right)\exp\left(-\frac{bt}{t_0}\right) \quad (11)$$

where, p_s is the peak overpressure,
t_0 is the positive phase duration,
b is a decay coefficient of the waveform and
t is the time elapsed, measured from the instant of blast arrival.

For many purposes however, approximations are quite satisfactory. Thus, linear decay is often used in design where the conservative approach would be to present the pressure-time history by a line (Fig. 1).

Blast wave interactions

When blast waves encounter a solid surface or an object made of a medium denser than air, they will reflect from it and, depending on its geometry and size, diffract around it. The simplest case is that of an infinitely large rigid wall on which the blast wave impinges at zero angle of incidence. In this case the incident blast wave front travelling at velocity U_S, undergoes reflection when the forward moving air molecules are brought to rest and further compressed upon meeting an obstacle. Rankine and Huguenot (Mays & Smith, 1995) derived an equation for refracted overpressure p_r:

$$p_r = 2p_s + (\gamma+1).q_s \quad (12)$$

Substituting (2) into the equation (12):

$$p_r = 2p_s\left(\frac{7p_0+4p_s}{7p_0+p_s}\right) \quad (13)$$

If the rectangular structure is exposed to an explosion, it will be exposed to pressures on all of 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. 2). The 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 the surrounding volume of the air, the peak initial pressure is reduced and the duration of the pressure increases.

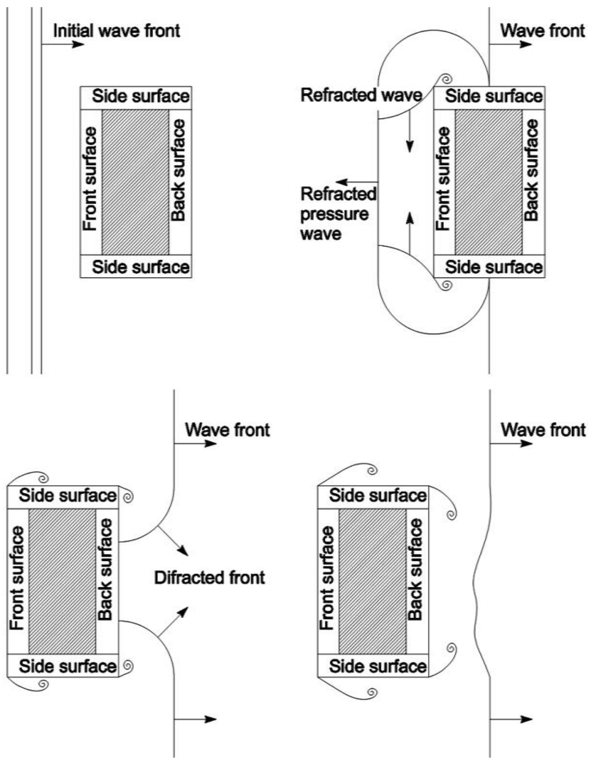

Fig. 2. Behaviour of the wave during its pass around the structure

Explosion and blast-loading types

Air blasts phenomena can be separated into three categories: free air burst, ground reflection effects and surface air burst. (Blanc et al., 2005)

Free Air Burst

Free air burst occurs when the incident wave reaches the structure before being reinforced. The main wave reinforcement takes place during ground impact.

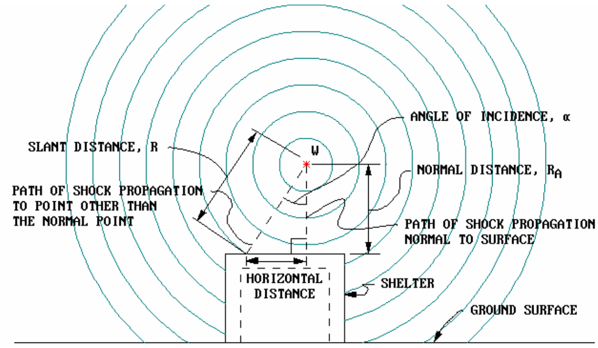

Fig. 3. Free air burst configuration (TM5-1300)

Ground reflection

It is necessary to take in account the ground effect when the incident wave is reinforced by it. Two phenomena can occur: either a classical reflection (Fig. 4) or a reinforcement reflection (Mach Front, Fig. 5).

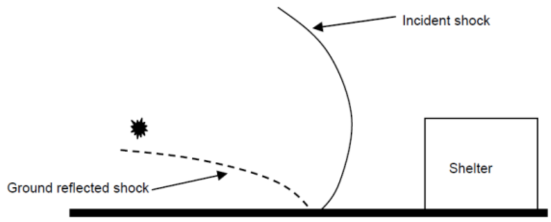

Fig. 4. Ground reflection configuration – classical

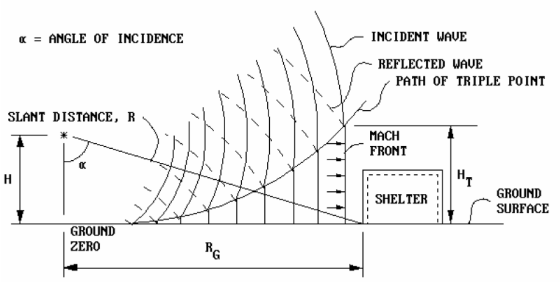

Fig. 5. Ground reflection configuration – Mach Front (TM5-1300)

The Mach front is formed by the interaction between incident and reflected pressure waves. This interaction depends on the angle of incidence between ground and incident wave. The critical angle is around 40°. The pressure-time variation of the Mach front is similar to that of the incident wave except that the magnitude is somewhat larger.

Surface burst

Surface air burst occurs when the charge detonation takes place close to or on the ground. Unlike what happens in an air burst, the incident and reflected wave are merged near the detonation point to form a single reinforced wave. The created wave is hemispherical.

This wave merging can also take place very far from the detonation point when the height of burst is important (Kinney, Graham, 1985).

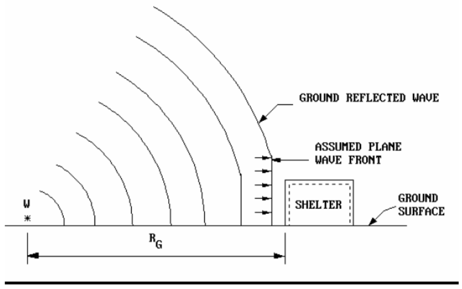

Fig. 6. Surface burst configuration (TM5-1300)

Structural Loading

The forces acting on a structure associated with a plane shock wave are dependent upon both the peak pressure and the impulse of the incident and dynamic pressures acting in the free-field.

For each pressure range there is a particle or wind velocity associated with the blast wave that causes a dynamic pressure on objects in the path of the wave. In the free field, these dynamic pressures are essentially functions of the air density and particle velocity. For typical conditions, standard relationships have been established between the peak incident pressure, the peak dynamic pressure, the particle velocity, and the air density behind the shock front. The magnitude of the dynamic pressures, particle velocity and air density are solely functions of the peak incident pressure, and, therefore, independent of the explosion size. Of the three parameters, the dynamic pressure is the most important for determining the loads on structures.

For design purposes, it is necessary to establish the variation or decay of both the incident and dynamic pressures with time since the effects on the structure subjected to a blast loading depend upon the intensity-time, history of the loading as well as on the peak intensity. The form of the incident blast wave is characterised by an abrupt rise in pressure to a peak value, a period of decay to ambient pressure and a period in which the pressure drops below, ambient (negative pressure phase).

The rate of decay of the incident and dynamic pressures, after the passage of the shock front, is a function of the peak pressure (both positive and negative phases) and the size of the detonation. For design purposes, the actual decay of the incidental pressure may be approximated by the rise of an equivalent triangular pressure pulse. The actual positive duration is replaced by a fictitious duration which is expressed as a function of the total positive impulse and peak pressure:

$$t_{of} = 2i/p \, .$$

The above relationship for the equivalent triangular pulse is applicable to the incident as well as the reflected pressures; however, in the case of the latter, the value of the pressure and impulse used with Equation 2-6 is equivalent to that associated with the reflected wave. The fictitious duration of the dynamic pressure may be assumed to be equal to that of the incident pressure.

For determining the pressure-time data for the negative phase, a similar procedure as the one used in the evaluation of the idealised positive phase may be utilised. The equivalent negative pressure-time curve will have a time of rise equal to 0.25, whereas the fictitious duration t_{of}^{-} is given by the triangular equivalent pulse equation:

$$t_{of}^{-} = 2i^{-}/p^{-}$$

where i^{-} and p^{-} are the total impulse and peak pressure of the negative pulse of either the incident or reflected waves. The effects of the dynamic pressure in the magazine phase region may usually be neglected.

For any given set of free-field incident and dynamic pressure pulses, the forces imparted on an above the ground structure can be divided into four general components:

- the force resulting from the incident pressure,
- the force associated with the dynamic pressures,
- the force resulting from the reflection of the incident-pressure impinging upon an interfering surface, and
- the pressures associated with the negative phase of the shock wave. The relative significance of each of these components is dependent upon the geometrical configuration and size of the structure, the orientation of the structure relative to the shock front, and the design purpose of the blast loads (TM5-1300).

Front Wall Loads

The blast face (or faces) is described as the area or face on a structure which is directly loaded by the incoming blast wave either from an incident wave or from a wave hitting the structure after undergoing reflection off the ground surface.

A point on the blast face loaded by the incoming blast wave will experience a sudden rise in pressure to the reflected overpressure followed by decay. The time required to relieve the reflected pressure, known as the clearing time can be expressed as:

$$t_c = \frac{4S}{(1+R).\,C_r} \qquad (14)$$

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. 7),
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

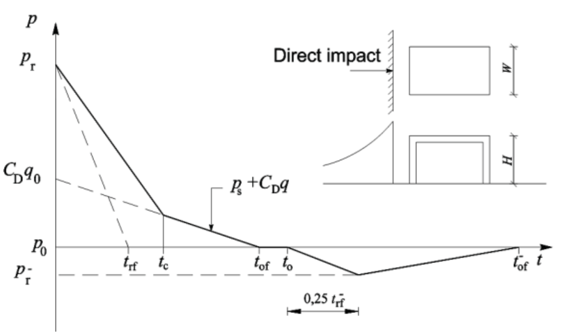

Fig. 7. The load on the front surface of the structure

The 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, $C_D.q$:

$$p = p_s + C_D.q \qquad (15)$$

The drag coefficient C_D connects the dynamic pressure and the 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 (Table 3).

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

$$t_{rf} = \frac{2i_r}{p_r} \qquad (16)$$

where p_r is the refracted peak pressure.

Table 3. *Drag coefficients*

Loaded surface	C_D
Front	0.8 ÷ 1.6
Rear	0.25 ÷ 0.5
Side and roof (depending pressure, kN/m²)	
0 ÷ 172	–0.4
172 ÷ 345	–0.3
345 ÷ 896	–0.2

Roof and side walls

As the wave encloses the structure, the pressure on the top and sides of the structure is equal to the initial pressure and then decreases to a negative pressure due to the drag (Fig. 8). The structural part that is loaded depends on the magnitude of the initial pressure wave front, the location of the wave front and the wavelength of the positive and negative phases.

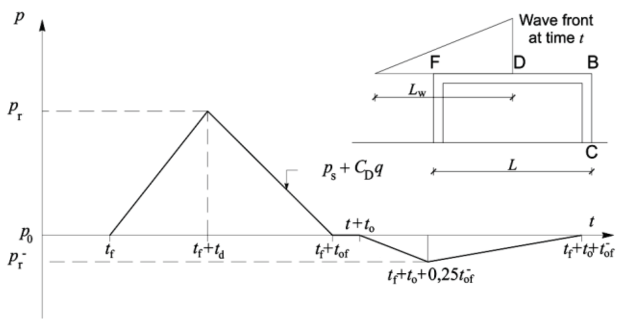

Fig. 8. The load on the roof and side surfaces of the structure

The initial peak pressure on the roof surface is reduced and the wavelength increases when the wave encloses the structure. The equivalent uniform pressure increases linearly from the wave-arrival time t_f (point F on the element) to the time t_d when the wave reaches the peak value and gets to the point D. At the point B the equivalent uniform pressure is reduced to zero.

The load coefficient C_E, increases time and duration of an equivalent uniform. It is a ratio of the wavelength and range, Lwf/L. The peak pressure that acts on the roof, p_R, is the sum of the equivalent uniform pressure and the drag pressure:

$$p_R = C_E.p_{sof} + C_D.q_0 \quad (17)$$

where are:

p_{sof} – the initial pressure at the point F,

q_0 – a dynamic pressure corresponding to $C_E.p_{sof}$

Rear wall

As the wave passes over the ends of the roof and the side surfaces, pressures are spreading, thus creating a secondary wave that continues to spread across the rear surfaces of the structure. The secondary waves that enclose the rear surface, in the case of long structures, are the result of a wave "overflow" from the roof and side surfaces. They are amplified due to the refraction of the structural surfaces. The increase of the waves from the roof is caused by the refraction of the ground at the bottom of the rear surface, and the increase of the waves "overflowed" from the side surface is caused by their mutual collisions in half the length of the surface, or collision with a wave "overflowed" from the roof.

For the loading analysis the procedure equivalent to the procedure for the loading determination on the roof and side surfaces (Fig. 9) can be used. The peak pressure for pressure-time history is determined using the peak pressure on the extreme edge of the roof surface, p_{sob}. Dynamic drag pressure corresponds to the pressure $C_E.p_{sob}$, while the preferred drag coefficients are equal to those for the roof and the side surfaces.

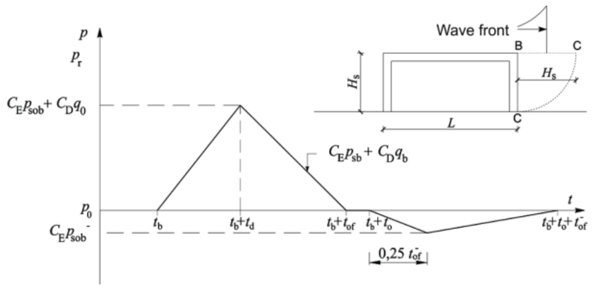

Fig. 9. The load on the rear surface of the structure

Conclusions

Blast resistant design is an important topic of study and therefore requires careful understanding of the blast phenomena and its effect and impact on various structural elements. Technical information has been collected, adapted and presented in this article for the calculation of the external explosion loads to be considered in the blast protection design of a structure. Empirical methods for the prediction of blast loads have been chosen as this is closer to the traditional engineering design approach. Simple expressions are presented for the calculation of the blast load on building structures. Of course, more complicated cases of blast loading, where obstacles are involved and wave shadowing and channeling phenomena take place, cannot be handled through this approach. The material presented can be used to introduce the subject, and in most cases, it can form a basis for initiating a reliable blast assessment of a structure.

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