Abstract: To determine the effects of a vehicle bomb explosion on a building involves the computing of blast loadings. In engineering calculations, this blast loading has the form of pressure-time variation, and in order to determine this function, it is necessary to compute the parameters of the shock wave. Then the pressure-time variation should be simplified to have a simple shape as to be easily integrated into various schemes for calculation.

This paper presents a comprehensive overview of different equations to estimate blast parameters and to model the blast wave as a triangular pulse. Empirical relations and numerical simulations are presented, and the results obtained are discussed and compared.

1. Introduction

In recent years, there has been a more prominent idea of protecting buildings (especially public ones) against vehicle bomb attacks. The main point of such protection is to increase the stand-off distance.

Even in these circumstances, the necessity of determining the blast loadings and effects on buildings [1], [2], [3] in order to estimate the damage or to design the structure to withstand the detonation of a certain explosive charge.

In determining the loads and the effects of an explosion on a building should be considered explosive charge-building configuration. Thus, it is possible to have the following cases: i) contact detonation; ii) near detonation and iii) burst away from the structure, Fig. 1.

The contact detonation appears when the explosive charge is in contact with the element or at a distance less than the distance of detonation products action (approximately ten radius of explosive charge). The main effect produced on a building by this type of explosion is a local effect against construction elements. A global effect in this case can be obtained if the explosive charge is large enough to initiate the collapse of the structure. Near detonation case is right near the contact detonation, beyond the limit of the detonation products limits of
action, but the main effect produced on structure is still a local one.

This latter case can in turn be divided in three cases depending on the configuration of the explosive charge-structure-ground surface: free-air burst, air burst and surface burst [4].

A. Free Air Burst Explosion

An explosion, which occurs in free air, produces an initial output whose shock wave propagates away from the center of the detonation, striking the structure without intermediate amplification of its wave.

As the incident wave moves radially away from the center of the explosion, it will impact with the structure, and, upon impact, the initial wave (pressure and impulse) is reinforced and reflected. The reflected pressure pulse of figure is typical for infinite plane reflectors. When the shock wave impinges on a surface oriented so that line which describes the path of travel of the wave is normal to the surface, then the point of initial contact is said to sustain the maximum (normal reflected) pressure and impulse.

B. Air Burst Explosion

The air burst environment is produced by detonations which occur above the ground surface and at a distance away from the protective structure so that the initial shock wave, propagating away from the explosion, impinges on the ground surface prior to arrival at the structure. An air burst is limited to an explosion which occurs at two to three times the height of a one or two-story building.
As the shock wave continues to propagate outward along the ground surface, a front known as the Mach front is formed by the interaction of the initial wave (incident wave) and the reflected wave. This reflected wave is the result of the reinforcement of the incident wave by the ground surface, fig. 3. The pressure-time variation of the Mach front is similar to that of the incident wave except that the magnitude of the blast parameters are somewhat larger. The height of the Mach front increases as the wave propagates away from the center of the detonation. This increase in height is referred to as the path of the triple point and is formed by the intersection of the initial, reflected, and Mach waves. A protected structure is considered to be subjected to a plane wave (uniform pressure) when the height of the triple point exceeds the height of the structure. If the height of the triple point does not extend above the height of the structure, then the magnitude of the applied loads will vary with the height of the point being considered. Above the triple point, the pressure-time variation consists of an interaction of the incident and reflected incident wave pressures resulting in a pressure-time variation different from that of the Mach incident wave pressures. The magnitude of pressures above the triple point is smaller than that of the Mach front. In most practical design situations, the location of the detonation will be far enough away from the structure so as not to produce this pressure variation. An exception may exist for multistory buildings even though these buildings are usually located at very low-pressure ranges where the triple point is high.

C. Surface Burst Explosion

A surface burst explosion will occur when the detonation is located close to or on the ground so that the initial shock is amplified at the point of detonation due to the ground reflections.

A charge located on or very near the ground surface is considered to be a surface burst. The initial wave of the explosion is reflected and reinforced by the ground surface to produce a reflected wave. Unlike the air burst, the reflected wave merges with the incident wave at the point of detonation to form a single wave, similar in nature to the Mach wave of the air burst but essentially hemispherical in shape (Fig. 4). A comparison of the parameters of surface burst with those of free-air indicate that, at a given distance from a detonation of the same weight of explosive, all of the parameters of the surface burst environment are larger than those for the free-air environment. As for the case of air bursts, protected structures subjected to the explosive output of a surface burst will usually be located in the pressure range where the plane wave (Fig. 4) concept can be applied.
This paper discusses how to determine the loads produced on a building by a vehicle bomb explosion (the third situation of the third case: explosion near the ground). After completing the empirical equations which can be used to determine the variation in time of the incident and reflected overpressure, a case study was used to exemplify the determining of the equivalent load produced in a specific situation (detonation of 450 kg TNT at 10 m stand-off distance to building).

2. Relations to determine pressure time history and impulse

In engineering calculations, the blast loadings on a building are simulated using pressure-time variation. This pressure time history, figure 5 is further simplified by modeling this function as a triangular pulse characterized by peak reflected overpressure and the reflected impulse. To define peak reflected overpressure and impulse it has to determine first the parameters of incident shock wave.

Parameters needed to fully define the shock wave are: peak positive overpressure, $\Delta p_f$; impulse for positive phase $I_p$ and positive phase duration, $t_p$; arrival time, $t_a$ [ms] and wave form parameter, $b$.

In this paper the effect of negative pressure phase of the blast wave was negligible. The most commonly used relation to describe pressure–time variation is modified Friedlander equation:

$$P(t) = P_o + \Delta p_f \left(1 - \frac{t}{t_p}\right) e^{-b \frac{t}{t_p}}$$

where: $P_o$ is the atmospheric pressure.

2.1 Peak overpressure

Henrych [5] determined the following equations for peak overpressure computing:

$$\Delta p_f = \frac{14.0717}{Z} + \frac{5.5397}{Z^2} - \frac{0.3572}{Z^3} + \frac{0.00625}{Z^4}, \text{[bar]} \text{ for } 0.05 \leq Z \leq 0.3 \ . \ (2)$$

$$\Delta p_f = \frac{6.1938}{Z} - \frac{0.3262}{Z^2} + \frac{2.1324}{Z^3} \text{ [bar]} \text{ for } 0.3 \leq Z \leq 1 . \ (3)$$

$$\Delta p_f = \frac{0.662}{Z} + \frac{4.05}{Z^2} + \frac{3.288}{Z^3} \text{ [bar]} \text{ for } 0.1 \leq Z \leq 10 \ . \ (4)$$

Kinney and Graham [6], based on the analysis of large experimental data, presented the following equation to determine the peak positive overpressure:
Sadovskiy [7] used the following equation:

\[
\Delta p_f = \frac{0.085}{Z} \left( \frac{0.3}{Z^2} + \frac{0.8}{Z^3} \right) \text{ [MPa].} \tag{6}
\]

Kingery and Bulmash [8] proposed for computing the peak overpressure the following polynomial equation:

\[
\Delta p_f = \exp(A + B \cdot \ln Z + C \cdot (\ln Z)^2 + D \cdot (\ln Z)^3 + E \cdot (\ln Z)^4) \text{ [kPa]}, \tag{7}
\]

where constants A, B, C, D and E are presented in Table 1.

In all the above equations, Z is the scaled distance:

\[
Z = \frac{R}{W^{1/3}}, \text{ [m/kg}^{1/3}]\tag{8},
\]

where \(R\) is the stand-off distance in m and \(W\) is the charge weight in kg.

### Table 1

<table>
<thead>
<tr>
<th>Range, Z (m/kg(^{1/3}))</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2-2.9</td>
<td>7.1206</td>
<td>-2,1069</td>
<td>-0.3229</td>
<td>0.1117</td>
<td>0.0685</td>
</tr>
<tr>
<td>2.9-23.8</td>
<td>7.5938</td>
<td>-3.0523</td>
<td>0.40977</td>
<td>0.0261</td>
<td>-0.01267</td>
</tr>
<tr>
<td>23.8-198.5</td>
<td>6.0536</td>
<td>-1.4066</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

A comparison of the all above mentioned equations is presented in Fig. 6. It can be seen that the curves obtained using equations proposed by Kinney and Kingery are almost identical for small scaled distances, but the differences between the peak overpressures are increased as the scaled distance is increased (almost 50% for \(Z = 10\)).

#### 2.2 Positive phase duration

The positive phase duration is the time between the time of the passing shock front and the end of the positive pressure phase.
According Henrych [5] positive phase duration can be computed using this equation:
\[
t_p = W^{1/3} \cdot (0.107 + 0.444 \cdot Z + 0.264 \cdot Z^2 + 0.129 \cdot Z^3 + 0.0335 \cdot Z^4) \text{[ms]} \text{ for } 0.05 \leq Z \leq 3.9
\]

Also, Sadovskiy [7] proposed the following relation:
\[
t_p = B \cdot \sqrt{W} \cdot \sqrt{R} \text{ [ms]}
\]
where \( B \) is between 1.0 and 1.5.

Kinney and Grahm [6] presented the following equation to compute positive phase duration:
\[
t_p = W^{1/3} \left( 980 \left( \frac{Z}{0.54} \right)^{10} \left( \frac{Z}{0.02} \right)^3 \left( \frac{Z}{0.74} \right)^{10} \left( \frac{Z}{6.9} \right)^2 \right)^{1/3} \text{ [ms]}
\]

Kingery and Bulmash [8] polynomial equation can also be used to compute the positive phase duration function of scaled distance. Graphical representation of relations describing the positive phase duration is shown in Fig. 7.

Note that the graphical representation of equations (9), (10) and (11), shown in Fig. 7, was made without taking into account the amount of explosives.

### 2.3 Impulse

For a blast wave the positive impulse represent the area under the positive phase of pressure-time curve.

An empirical equation is presented by Kinney and Grahm [6]:
\[
I = 0.067 \sqrt{1 + \left( \frac{Z}{0.23} \right)^4 Z^2 \left( 1 + \left( \frac{Z}{1.55} \right)^3 \right)} \text{ (bar*ms)} \quad (12)
\]

To compute positive impulse Sadovkiy [7] proposed the following relation:
\[
I = 200 \frac{W^{1/3}}{R} \text{ (Pa*s)} \quad (13)
\]

Equation proposed by Held [9] is similar to the Sadovski relation and has the form:
\[
I = 300 \frac{W^{1/3}}{R} \text{ (Pa*s)} \quad (14)
\]

Another possibility for determining the impulse is to use the polynomial equation of Kingery and Bulmash [8].

### 2.4 Wave form parameter

**Table 2** Parameters for incident and normal reflected waves (\( W = 450 \text{ kg TNT, R} = 10\text{m} \))

<table>
<thead>
<tr>
<th>Method</th>
<th>( Z_i ) (m/kg(^{1/3} ))</th>
<th>( t_s ) (ms)</th>
<th>( t_p ) (ms)</th>
<th>( \Delta p_i ) (kPa)</th>
<th>( \Delta p_r ) (kPa)</th>
<th>( I_i ) (kPa*ms)</th>
<th>( I_r ) (kPa*ms)</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinney</td>
<td>1.305</td>
<td>6,391</td>
<td>13.969</td>
<td>558.66</td>
<td>2692</td>
<td>1084.1</td>
<td>-</td>
<td>2.530</td>
</tr>
<tr>
<td>Kingery</td>
<td>5,845</td>
<td>5,845</td>
<td>16.990</td>
<td>756.80</td>
<td>3834</td>
<td>1517.0</td>
<td>4771</td>
<td>2.332</td>
</tr>
</tbody>
</table>
This parameter describes the way of how decay pressure-time function and also is an adjustable factor so overpressure-time relation provide suitable values of blast impulse.

The relation between blast impulse and the wave form parameter can be obtained by integration of the following equation [6]:

\[
\frac{I}{A} = \int_{t_i}^{t_f} \Delta P \cdot t_p \cdot \left[ \frac{1}{b} - \frac{1}{b^2} \cdot \left(1 - e^{-b} \right) \right] dt
\]

(15)

where \( t_i \) and \( t_f \) are above defined.

2.4 Reflected overpressure

In order to determine the reflected overpressure it can be used the following equations:

- for normal reflection:

\[
P_y = \frac{3 \cdot (k - 1) \cdot \left( \frac{P_y}{P_x} \right) - (k - 1)}{(k - 1) \cdot \left( \frac{P_y}{P_x} \right) + (k + 1)}
\]

(16)

- for oblique reflection:

\[
P_y = P_x \cdot \frac{2k \cdot M_r^2 - (k - 1)}{k + 1}
\]

(17)

where, \( P_y \) is the pressure in disturbed medium after passage of the incident shock, \( P_x \) is the atmospheric pressure, \( M_r \) is Mach number for reflected shock and \( k \) is the ratio between heat capacities. Parameters for disturbed medium after passage of incident and reflected shock waves can be computed using steady flow counterpart of normal or oblique reflection [6].

3. Case study

To compare the parameters of shock wave computed using all above empirical equation an explosive charge of 450 kg TNT at a stand-off distance of 10 m was considered. The amount of explosive charge corresponds to a vehicle bomb attack (sedan vehicle) and the stand-off distance of 10 m was chosen in accordance with minimum defended stand-off distances in order to respect the medium ISC level of protection for reinforced concrete construction [6].

Because only Kinney and Kinengery methods include equations necessary to determine all parameters for incident and reflected shock wave, it was compared pressure-time variations obtained by these two methods.

Parameters for incident and normal reflected waves are presented in Table 2 and pressure-time variations are shown in Fig. 8. Note that the zero pressure, in Fig. 8 and 9, corresponds to the atmospheric pressure.

It can be seen that both the peak overpressure and impulse calculated with the Kingery’s method are higher than those calculated with the Kinney’s method for the surface burst. The difference is about 35% for pressure and 40% for impulse.
In these conditions it will be used the Kingery’s equations to determine pressure-time variation. A comparison between incident and reflected overpressures and impulses, for surface burst, is presented in Fig. 9. To establish equivalent triangular pulse it can be used the following relation:

\[
\int_{t_s}^{t_p} \Delta p \left( \frac{t_{p,\text{echiv}} - t}{t_{p,\text{echiv}} - t_s} \right) dt = \int_{t_s}^{t_p} \Delta p \left( 1 - \frac{t}{t_p} \right) e^{-\frac{t^2}{t_p^2}} dt
\]

where left term represents area under equivalent triangular line passing through points \((\Delta p_f, t_s)\) and \((0, t_{p,\text{echiv}})\), and right term represents area under pressure-time curve, which is actually the blast impulse. The parameter \(t_{p,\text{echiv}}\) is the triangular phase duration for equivalent load and it can be iterative computed. The initial value of \(t_{p,\text{echiv}}\) is equal with \(t_p\) and then it will be decreased until the value of left term of equation (18) will be equal with the value of blast impulse (the right term of the same equation). The equivalent triangular pulse can be seen in Fig. 10. This equivalent load was determined by using the peak overpressure and the value of impulse, but modifying the positive phase duration.
4. Numerical simulations

The goal of the simulations is to analyze the blast effects on a building associated with the detonation of a bare 450 kg, spherical charge of TNT, 1.5 m above a rigid surface (the same conditions like in case study). For this it was used the Autodyn software. The Autodyn is a computer code used to simulate the response of solids, fluids and gases to high speed and extreme loadings. The dimensions of the building (2m x 6m x 10 m) were chosen arbitrarily only to see the effects of the blast and to compare the analytical and numerical results.

The comparison between Kingery and Autodyn values for normal reflected pressure when the explosive charge is detonated at 1.5m from rigid surface (hemispherical surface burst) is presented in Fig 11. The same comparison is done for the case when explosive charge is detonated at 3.0 m from the ground (air burst), Fig. 12.

As it can be seen in Fig. 11, the peak pressures from Kingery and Autodyn are approximately the same (3.5% difference), but the impulse is different. To avoid the Mach stem and obtain the normal reflected pressure at the direct distance, the explosive charge was detonation at a 3m to ground surface, Fig. 14. In this case the incident shock wave impinges on the surface of the building before the wave reflected by the ground hits the building. The pressure-time curve traced based on Kinney parameters for incident and normal reflected wave was added in Fig. 11 and 12 to compare with Kingery and Autodyn results.

5. Conclusions

To calculate blast loads on a building it has to determine the reflected pressure-time variation and the value of reflected blast impulse. In this respect the incident shock wave parameters need to be computed first. Thus, empirical equations by various authors have been examined to calculate the parameters of the shock wave. The results showed that only Kinney and Grahm method and respectively Kingery și Bulmash method provide equations to compute all blast wave parameters. There are differences between peak values of incident overpressure computed with Kinney and Kingery equations: 20% for scaled distances less than 1.2 m/kg$^{1/3}$ and up to 50% for scaled distances of 10 m/kg$^{1/3}$. Note that Kinney method uses only an equation to compute peak overpressure no matter of height of burst. According with case study, it was showed that for Z greater than 1 m/kg$^{1/3}$ the peak and decay of reflected overpressure in time computed with Kinney method are much closer to Kingery results for air burst (24% difference) than Kingery results for surface burst (49%).
Based on the pressure-time variation (incident or reflected) it was computed and drawn the equivalent triangular pulse, keeping the maximum overpressure and impulse value, but
modifying the positive phase duration. This equivalent blast load can be further used to compute the structural response under blast loadings.

References


