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BLAST LOADING OF STRUCTURES - A REVIEW

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ABSTRACT

The use of explosives in vehicles to attack city centers has become a common technique by terrorist organizations around the world. A bomb explosion within or in the vicinity of a building can cause significant damage on the building's internal and external structural frames, collapsing of walls and structural walls, blowing out of large expanses of window and closing down of critical safety systems. Injuries and loss of life of occupants can result from many causes such as direct explosion-effects, collapse of structure, impact of debris, fire and smoke. Blast loads results in large dynamic loads larger than the original design loads of many structures. Due to the threat from such extreme loading conditions, continuous efforts have been made during the last few decades to generate methods of structural analysis and design which helps the structure to resist blast loads. The analysis and design of Civil Engineering structures subjected to blast loading requires a thorough understanding of blast phenomenon and the dynamic response of various structural elements. This paper presents a brief overview of the effects of explosion on structures and modeling of blast loading.

KEYWORDS: Overpressure, Dynamic, Blast loading.

INTRODUCTION

Blast may be defined as a rapid release of large amount of energy within a limited space. Blast can be classified based on its nature as physical, nuclear and chemical events. In physical explosion energy is released from the catastrophic failure of a cylinder of compressed gas, volcanic eruption or even mixing of two liquids at different temperature. During nuclear explosion energy is released from the formation of different atomic nuclei by the redistribution of the neutrons and protons within the inner acting nuclei. In chemical explosion energy is released by rapid oxidation of the fuel elements (carbon and hydrogen atoms). Blast can be classified based on its type as Air Blast, Surface Blast, High Altitude Blast, Underwater Blast and Underground Blast. Here the discussion is limited to surface blast.

EXPLOSIVES USED

Explosive materials can be classified based on their physical state such as solids, liquids and gases. Solid explosives are basically high explosives due to which major blast effects are well known. Explosive materials can also be classified based on their sensitivity to ignition as primary and secondary explosives. Materials such as Mercury Fulminate and Lead Azide are primary explosives and can be easily detonated by simple ignition from a spark, flame or impact. Explosives such as Trinitrotoluene (TNT) and ANFO are termed as secondary explosives which when detonated create blast (shock) waves which can result in widespread damage to the surroundings.

EXPLOSION MECHANISM AND BLAST PROPAGATION

The blast of a condensed high explosive generates hot gases having pressure upto 300 kilobar and a temperature of about 3000-4000˚c. The hot gas expands and forces out the volume it occupies. As a result a layer of compressed air or blast wave forms in front of this gas volume which contains most of the energy released by the explosion. The blast wave continuously increases to a pressure which is above the ambient atmospheric pressure. This is referred to as the side-on overpressure that dissipates as the shock wave expands away from the explosion source. After a short period, the pressure behind the wave front drops below the ambient atmospheric pressure (Figure 1) such a phase is known as negative-phase or suction. During this negative phase a partial vacuum is created and as such air is sucked in, this is also followed by high suction winds which carry the debris from long distances away from the detonation source.

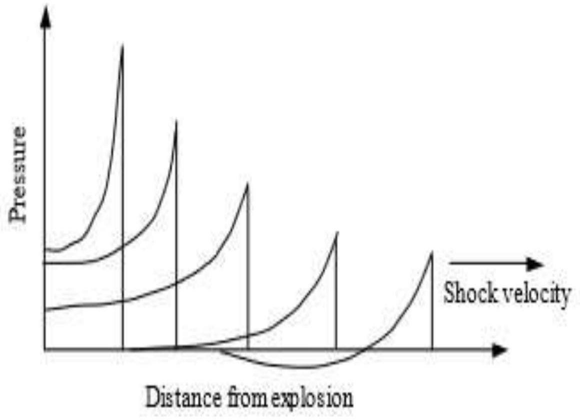

Figure 1: Blast Wave Propagation [Ref.3]

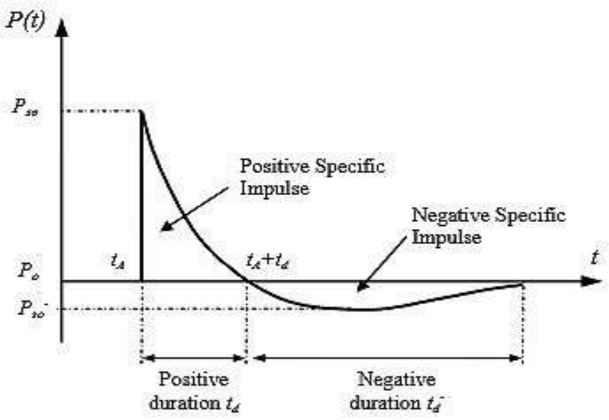

Figure 2: Blast Wave Pressure-Time History [Ref.3]

BASIC PARAMETERS OF EXPLOSION AND EXPLOSIVES USED

Basic explosive TNT (Trinitrotoluene) has been used as a reference for determining the scaled distance Z. If the explosive used is other than TNT, then the charge mass is converted as an equivalent mass of TNT. This is done, so that the charge mass of explosive gets multiplied by the conversion factor based on the specific energy of the charge and the TNT equivalent. Specific energy of various types of explosives and their conversion factors to that of TNT are given below in Table 1:

Table 1: *Conversion factors for explosives* [Ref.2]

Explosive	Specific Energy	TNT Equivalent
	Q_x /kJ/kg	Q_x/ Q_{TNT}
Compound B (60% RDX, 40% TNT)	5190	1148
RDX (Ciklonit)	5360	1185
HMX	5680	1256
Nitroglycerin (liquid)	6700	1481
TNT	4520	1000
Explosive Gelatin (91% Nitroglycerin, 7.9% Nitrocellulose, 0.9% Antracid, 0.2% Water	4520	1000
60% Nitroglycerin Dynamite	2710	600
Semtex	5660	1250
C4	6057	1340

EXPLOSION LOADING

In many circumstances simplified approach leads to conservative constructions. However, unknown factors may lead to over-estimation of the structural capacity to blast loadings. Different structures have different design methods, shock wave refraction and interaction with ground. In order to overcome these uncertainties it is advisable that the mass of equivalent TNT is increased by 20%. This increased value of the charge weight is known as *effective charge weight*.

Categories of Loading:

Explosion loadings can be categorised into two main groups according to the confinement of an explosive charge:

a) *Unconfined*
b) *Confined*

Table 2: *Explosion Load Categories* [Ref.2]

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

a) Unconfined Explosions:

The explosion in an open air causes a wave that spreads from the source of detonation to the structure without any amplification. These explosions are located at a given distance and altitude away from the structure and there is an increase in wave due to the reflection of the ground before it contacts the structure. The limitation of height of these kind of explosions are two to three times of the height of a single-storey or double-storey structure. The explosion near the ground is an explosion which takes place near or on the ground and the initial pressure is increased immediately as a result of refraction on the ground.

b) Confined Explosions:

When an explosion occurs inside the structure, the peak pressures associated with the initial wave fronts are considered to be extremely high. Enhancement of pressure occurs by refraction within the structure. Depending upon the degree of confinement high temperature and accumulation of gaseous products of chemical reactions in the blast would generate more pressure thereby increasing the load duration within the structure. The combined effects of these pressures may lead to collapse of the structure, if structure is not designed to resist internal pressure. Proper ventilation reduces the strength and duration of blast pressure, hence effect of pressure on structures with openings are different from structures without openings.

Interaction between Structure and Explosion:

As the blast wave propagates through the air, the wave front covers the structure and all its surfaces such that the whole structure is subjected to blast pressure. Following are the factors in which magnitude and distribution of the structural loading depends:

a) The characteristics of explosives that depends on the type of explosive material, released energy and weight of explosive.
b) The detonation location relative to the structure.
c) Intensity and Magnification of pressure and the interaction with the ground or the structure itself.

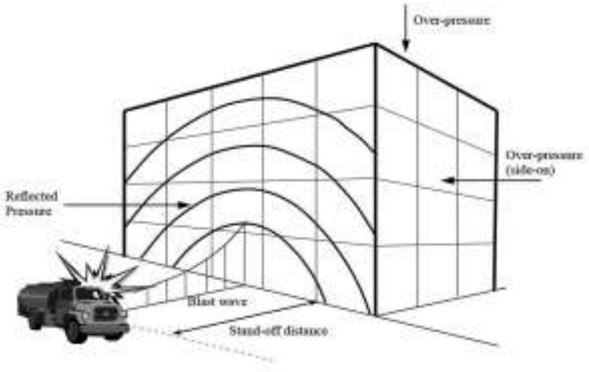

Figure 3: Blast loads on a Building [Ref.4]

BLAST WAVE SCALING LAWS

Blast parameters are basically dependent on the amount of energy released by a detonation in the form of blast wave and its distance from the explosion. A universal normalized description of the blast effects can be given by scaling distance which is a measure of similar blast effects from various explosive weights at various distances. Thus as per scaling laws:

$$\text{Scaled Distance } (Z) = \frac{R}{W^{0.33}}$$

Where,

R = Actual effective distance from the explosion.
W = Charge weight in kg.

Prediction of Blast Pressure [Ref.3]**:**

Peak Overpressure (Pso) as per various researchers	
Brode (1955)	$\mathrm{Pso} = \frac{6.7}{Z^3} + 1\ bar\ (\mathrm{Pso}>10bar)$ $\mathrm{Pso} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019\ bar\ (0.1<\mathrm{Pso}<10\ \mathrm{bar})$
Newmark and Hansen (1961)	$\mathrm{Pso} = 6784\frac{W}{R^3} + 93\sqrt{\frac{W}{R^3}}\ bar$
Mills (1987)	$\mathrm{Pso} = \frac{1772}{Z^3} + \frac{114}{Z^2} + \frac{108}{Z} - 0.019\ kPa$

If the blast wave faces an obstacle perpendicular to the direction of propagation, reflection increases the overpressure to maximum reflected pressure *Pr* as:

$$Pr = 2\,Pso\,\{(7Po+4Pso) + (7Po+Pso)\}$$

Table 3: *Peak reflected overpressures Pr (in MPa) with different W-R combinations (May and Smith, 1995* [Ref.4]

W	100 kg TNT	500 kg TNT	1000 kg TNT	2000 kg TNT
R				
1m	**165.8**	**354.5**	**464.5**	**602.9**
5m	**6.65**	**24.8**	**39.5**	**60.19**
10m	**0.85**	**4.25**	**8.15**	**14.7**
15m	**0.27**	**1.25**	**2.53**	**5.01**
20m	**0.14**	**0.54**	**1.06**	**2.13**
25m	**0.09**	**0.29**	**0.55**	**1.08**
30m	**0.06**	**0.19**	**0.33**	**0.63**

Other essential parameters involve: t_d = duration of the positive phase during which the blast pressure is greater than the atmospheric pressure and i_s = specific wave impulse which is equal to the area under the pressure-time curve from the moment of arrival, t_A to the end of positive phase and is given by the expression as:

$$i_s = \int_{tA}^{tA+tp} Ps(t)\,dt$$

The typical pressure-profile can be seen in **Figure 2**. Brode proposed the following relationship for negative pressure (i.e. pressure below ambient pressure) p^-:

$$p^- = -\frac{0.35}{Z}\ bar\ (Z > 1.6)$$

And the corresponding specific impulse at this stage i_s^- is given by:

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

The explosion wavefront speed *Us* is given by:

$$Us = a_o\sqrt{\frac{6Ps+7Po}{7Po}}$$

And Maximum dynamic pressure q_s is given by:

$$q_s = \frac{5Ps^2}{2(Ps+7Po)}$$

Where,

Ps = peak static wavefront overpressure, bar
Po = ambient air pressure (atmospheric pressure), bar
a_o = speed of sound in the air, m/s

PARAMETERS OF POSITIVE AND NEGATIVE PHASE BLAST WAVE NEAR THE GROUND

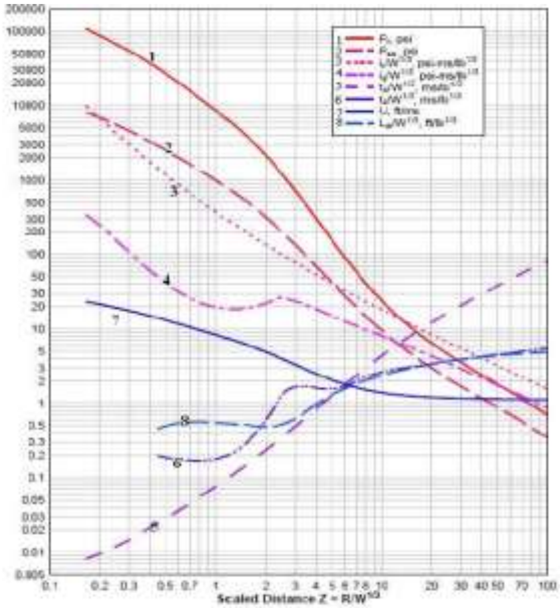

Figure 4: Parameters of positive phase blast wave near the ground [Ref.5]

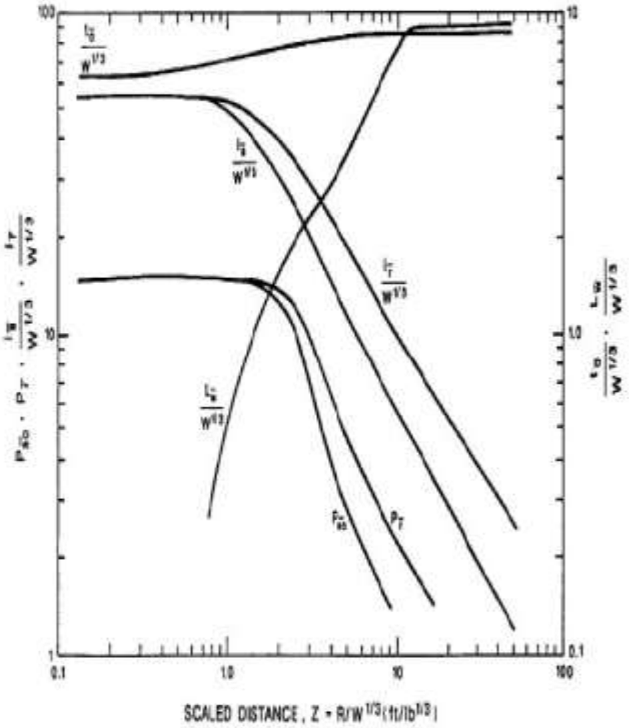

Figure 5: Parameters of negative phase blast wave near the ground [Ref.2]

BLAST PRESSURES ON STRUCTURAL SURFACES

For the purpose of analyzing blast loads it is essential to determine the initial reduction of the dynamic pressure in the time, as the blast effects on the structure depends on the pressure-time history as well as on the peak value.

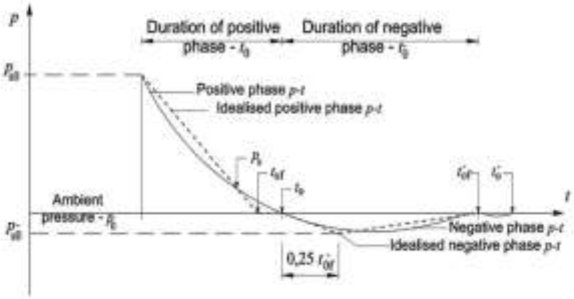

Figure 6: Pressure-Time History [Ref.2]

For analysis purpose, the actual reduction of the initial pressure can be idealized as a triangular pressure impulse. The actual duration of the positive phase is being replaced by an artificial or fictitious duration and is expressed as:

$$t_{of} = \frac{2i}{p}$$

Where,

i = total positive impulse
p = peak pressure.

Again, in case of negative phase:

$$t_{of}^{-} = \frac{2i-}{p-}$$

Since the fictitious duration of the positive phase varies from the actual duration i.e. the fictitious duration of the positive phase is lesser than the actual duration, a difference between the fictitious phase and the beginning of the negative phase is generated.

Average pressure on front face:

Figure 7 shows the variation of the pressure on the front face of a rectangular structure with sides parallel to the wavefront above the ground in an area of low pressure.

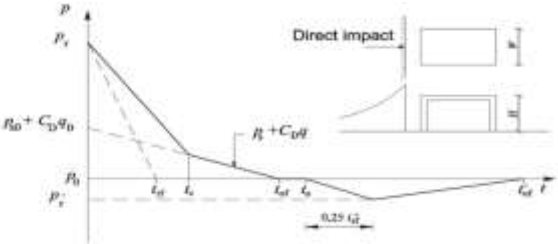

Figure 7: Blast Pressure on the Front face of the structure [Ref.2]

The peak pressure on the front face of the structure at the time of explosion arrival t_A will be the peak refracted overpressure p_r. This pressure decreases at a certain time interval due to passage of blast waves above and around the structure, which is less than peak refracted overpressure p_r. The blast overpressure on the front face of the structure decreases continuously until the pressure equalizes with the pressure of the surrounding air. The clearing time t_c which is needed for the refracted pressure to drop to the level of initial pressure can be expressed as:

$$t_c = \frac{4S}{(1+R)Cr}$$

Where, S = length of the clearing which is equal to height of the structure H or half-width of the structure $W/2$, whichever is less.
R = ratio S/G, G is lesser of H or $W/2$.

Cr = speed of sound in the refracted area.

Pressure acting on the front face of the structure after the time t_c is:

$$p = p_s + C_D . q$$

Where,

C_D = Drag Coefficient
p_s = initial pressure.

The fictitious duration of the refracted wavefront, t_{rf} is given by:

$$t_{rf} = \frac{2ir}{pr}$$

Table 4: *Drag Coefficients* [Ref.2]

Loaded Surface	C_D
Front	0.8-1.6
Rear	0.25-.5
Side and Roof (depending pressure, kN/m^2)	
0-172	-0.4
172-345	-0.3
345-896	-0.2

Average pressure on Roof and Side surfaces:

When the blast wave encloses the structure the pressure on the top and sides of the structure is equal to the initial pressure which gradually decreases to negative pressure due to drag.

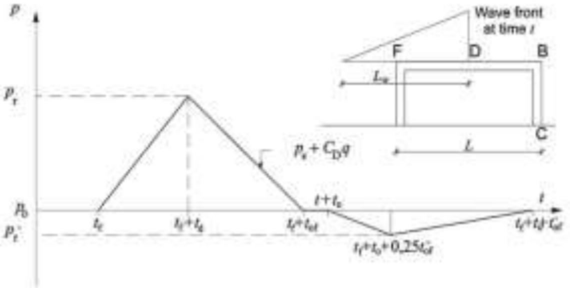

Figure 8: Blast Pressure on the Roof and Side of the structure [Ref.2]

On the roof surface the initial peak pressure is reduced as the wavelength increases when the blast wave encloses the structure. The equivalent uniform pressure increase linearly from the wave-arrival time t_f at point *F* to the time t_d when the wave reaches its peak value at point *D*. At point *B* the equivalent uniform pressure is minimized to zero.

The peak roof pressure is given by:

$$p_R = C_E.p_{sof} + C_D.q_0$$

Where,

p_{sof} = initial pressure at point F

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

The coefficient of load C_E, increase time and duration of equivalent uniform pressure is determined from from Figure 2-196 and 2-197 of [Ref.5]. It is a ratio of L_{wf}/L.

The peak negative roof pressure is given by:

$$p_R^- = C_E^-.p_{sof}$$

Where, C_E^- is the negative and the scaled duration of equivalent negative pressure t_{of} is determined from Figure 2-198 [Ref.5]. The increase in time of negative phase is equal to 0.25 t_{of}.

Average pressure on Rear surfaces:

When blast wave passes over the ends of the roof and side surfaces, spreading of pressures take place thereby creating a secondary wave which continues to spread across the rear surfaces of the structure. For loading analysis the procedure similar to the procedure for load determination on the roof and side surfaces can be used. The peak pressure is determined using the peak pressure at the extreme edge of the roof surface p_{sob}. The dynamic drag pressure corresponds to the pressure $C_E.p_{sob}$, whereas the preferred drag coefficients are equal to those of roof and side surfaces.

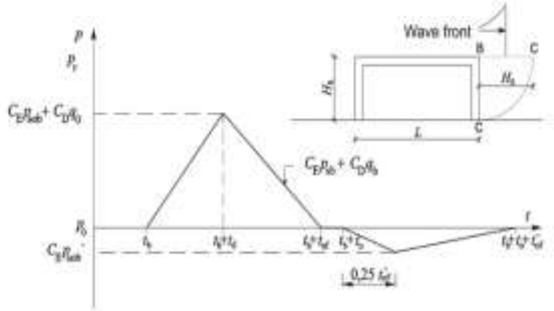

Figure 9: Blast Pressure on the Rear face of the structure [Ref.1]

BEHAVIOUR OF MATERIAL AT HIGH STRAIN RATE

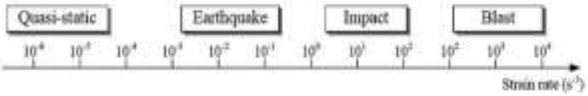

Figure 10: Strain rates associated with different types of loading [Ref.4]

Dynamic properties of concrete at High-Strain rate:

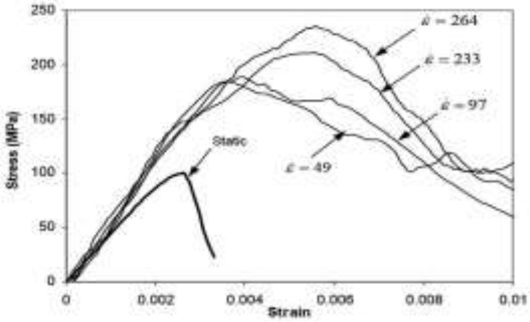

Figure 11: Stress-Strain curves of concrete at different strain rates [Ref.4]

Following are the properties of concrete under dynamic loading of Blast:

a) The mechanical properties of concrete under dynamic loading conditions are different from that under static loading condition.
b) The stresses that are sustained for a particular period of time under dynamic conditions may gain values that are remarkably higher than the static compressive strength.
c) Strength magnification factor as high as 4 in compression and up to 6 in tension for strain rates in the range 100- 1000s^{-1} have been reported by **Grote et al., 2001.**

For the increase in peak compressive stress *fc'*, a dynamic increase factor (DIF) is introduced in the CEB-FIP (1990) model for strain-rate enhancement of concrete:

$$DIF = \{\dot{\varepsilon}/\dot{\varepsilon}_s\}^{1.026\alpha} \qquad for\ \dot{\varepsilon} \leq 30s^{-1}$$
$$DIF = \gamma\{\dot{\varepsilon}/\dot{\varepsilon}_s\}^{1/3} \qquad for\ \dot{\varepsilon} > 30s^{-1}$$

Where, $\dot{\varepsilon}$ = Strain Rate, $\dot{\varepsilon}_s = 30\text{x}10^{-6}\ s^{-1}$, $\log\gamma = 6.156\alpha - 2$, $\alpha = 1/\{5+9f'c/fco\}$, fco = 10MPa = 1450psi

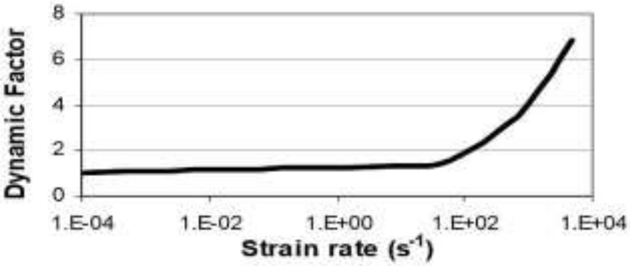

Figure 12: Dynamic Increase Factor (DIF) for peak stress of concrete [Ref.4]

Dynamic properties of Reinforcing steel at High-Strain rate:

Following are the properties of reinforcing steel under dynamic loading of Blast:

a) **Norris et al. (1959)** tested steel with two different static yield strength of 330 MPa and 278 MPa under tension at strain rates ranging from 10^{-5} to 0.1 s^{-1}, it has been observed that there is an increase in strength of 9-21% and 10-23% for two types of steel.

b) **Dowling and Harding (1967)** conducted tensile experiments using Split Hopkinton's Pressure Bar (SHPB) at strain rates ranging from 10^{-3} to 2000 s^{-1} and concluded that there is an increase in strength of upto 50%.

c) **Malvar (1998)** also studied the strength enhancement of steel reinforcing bars under the effect of high strain rates, which was described in terms of dynamic increase factor (DIF), which can be evaluated for different steel grades and for yield stresses, fy ranging from 290 to 710 MPa as:

$$DIF = \{\dot{\varepsilon}/10\text{^-}4\}^{\alpha}$$

Where for calculating yield stress:

$$\alpha = \alpha_{fy};\ \alpha_{fy} = 0.074 - 0.04(f_y/414)$$

For ultimate stress calculation:

$$\alpha = \alpha_{fy};\ \alpha_{fy} = 0.019 - 0.009(f_y/414)$$

BLAST LOADING CALCULATION

For blast loading calculation on structural surfaces, following are the steps involved [Ref.2]:

Step 1: Determine the charge weight, *W*, charge distance, R_G, charge height, H_c (for air blast) and structural dimensions.

Step 2: Apply factor of safety of 20 %

Step 3: Select several surfaces of the structure (front face, roof, side and rear surface) and determine the explosion parameters for each selected surface.

For explosion at surface:

a) Determine the scaled distance:

$$Scaled\ Distance\ (Z) = \frac{R}{W^{0.33}}$$

b) Determine the blast parameters using Fig. 4 for the obtained scaled distance *Z* and read:
   - peak initial positive overpressure p_{so}
   - wave front speed *U*
   - scaled initial positive impulse $i_s/W^{1/3}$
   - scaled length of positive phase $t_0/W^{1/3}$
   - scaled value of wave arrival $t_A/W^{1/3}$. Multiply the scaled value with the value of $W^{1/3}$ so as to obtain the absolute values.

Step 4: For the front face:

a) Calculate the peak positive refracted pressure $p_{r\alpha} = C_{r\alpha} \cdot p_{so}$ and read the coefficient $C_{r\alpha}$ for p_{so} from Figure 2 - 193, of [Ref.5].

b) Now read the value of scaled positive refracted impulse $i_{r\alpha}/W^{1/3}$ from Figure. 2 - 194 (b), of [Ref.5] for p_{so} and α. Multiply the scaled value with the value of $W^{1/3}$ so as to obtain the absolute value.

Step 5: Determine positive phase of the load on the front face:

a) Determine the speed of sound in the area of refracted overpressure C_r from Figure. 2 - 192, from [Ref.5] for the peak overpressure p_{so}.

b) Calculate the "clearing" time t_c:

$$t_c = \frac{4S}{(1+R)Cr}$$

c) Calculate the fictitious length of the positive phase t_{of}:

$$t_{of} = \frac{2i}{p}$$

d) Determine the peak dynamic pressure q_o from Figure 2 - 3, of [Ref.5] for p_{so}

e) Determine $p_{so} + C_D \cdot q_o$, C_D from Table 4

f) Calculate the fictitious duration t_{rf} of the refracted pressure:

$$t_{rf} = \frac{2ira}{pra}$$

g) Define the pressure-time history curve for positive phase.

Step 6: Determine the negative phase of the load on the front face. Read the value of Z from Figure 4 for $p_{r\alpha}$ according to Step 4a) and $i_{r\alpha}/W^{1/3}$ according to Step 4b).

a) Determine $p_{r\alpha}^{-}$ and $i_{r\alpha}^{-}/W^{1/3}$ from Figure 4 for the value of Z. Multiply the scaled value of the negative impulse with $W^{1/3}$ in order to obtain an absolute value.

b) Calculate the fictitious duration t_{rf}^{-} of the negative refracted pressure:

$$t_{rf}^{-} = \frac{2ira-}{pra-}$$

c) Calculate the increase in time of negative phase which is equal to 0.25 t_{rf}^{-}.

d) Define the pressure-time history curve for negative phase.

Step 7: Determine the positive phase of the load on the side surfaces:

a) Determine the wavelength ratio and the range of L_{wf}/L.

b) Read the values of C_E, $t_d/W^{1/3}$, $t_{of}/W^{1/3}$ from Figures. 2 - 196, 2 - 193 and 2 - 194(b), of [Ref.5] (peak incident overpressure × 0.0689 bar).

c) Read p_R, t_r, t_o.

d) Determine the dynamic pressure q_o from Figure. 2 - 3 of [Ref.5] using p_{so}.

e) Calculate $p_R = C_E.p_{sof} + C_D.q_0$ and obtain the coefficient C_D as per Table 4.

f) Define the pressure-time history curve for positive phase.

Step 8: Determine the negative phase of the load on the side surfaces:

a) Determine the values of C_E^{-} and $t_{of}^{-}/W^{1/3}$ for the value of L_{wf}/L as per Step 7a) from Figures 2 - 196 and 2 - 198, of [Ref.5].

b) Calculate $p_R = C_E{\cdot}p_{sof}\ i\ t_{of}$.

c) Calculate the increase in time of negative phase which is equal to 0.25 t_{of}^{-}.

d) Define the pressure-time history curve for negative phase.

Step 9: Determine roof surface loading by applying the steps for the side surfaces.

Step 10: Determine the rear surface loading by applying the steps for the side surfaces and by assuming that the rear surface is rotated to a horizontal position.

EFFECT OF COMPRESSIVE STRENGTH AND SHEAR REINFORCEMENT

The Compressive strength of concrete and Shear reinforcement plays an important role in the blast behavior of a structure. It has been found that RC column with larger cross-section and lower compressive strength offers less lateral deflection against blast loading then RC column with smaller cross-section and larger compressive strength.

Stirrup spacing also plays a vital role in blast resistance. It has been observed that columns with lesser stirrup spacing offers better resistance against blast loading.

CONCLUSION

The surface of the structure subjected to direct blast pressure cannot be protected; it can however be designed to resist the blast pressure by increasing the stand-off distance from the point of explosion. For high-risk structures such as public and commercial tall buildings, design consideration against extreme loading (bomb blast, high velocity impact) are very necessary. Use of special moment resistant frames are recommended for blast resistance design.

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