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Transient Effect of Blast Loads on RCC Building

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Abstract -**The increase in the number of terrorist attacks has shown that the effect of blast loading on structures is a serious matter that should be taken into consideration in the design process. The blast pressure on the structure due to nearby explosion is of very high magnitude and veryshort duration. Such an impulsive loading requires dynamic time-history analysis. This paper describes the nature of explosion of explosive materialsand dynamic pressuredeveloped on the nearby structure in lieu of explosion. Initially, efforts have been made to determine the effect of 1000kg of C4 explosive material as an equivalent weight of TNT on different surfaces of a building model at a stand-off distance of 22.5m. The intensity of blast load on each surface is analytically determined as a record of pressure time history. Further attempts have been made to determine the effect of distance of blast for the same explosive material on building surfaces at stand-off distance of 10m, 18.5m, 22.5m and 27m. The effect of different explosives, i.e., TNT, C4, RDX and PETN on building surfaces at constant stand-off distance of 22.5m has also been determined. From the analysis, it is observed that the effect of blast load on front and rear surface of the building is critical. For close range explosions, deformations on front surface are more but with increase in stand-off distance, maximum deformations occur in roof surface.**
*Keywords:***Blast Loads, Pressure-Time History, TNT, Stand-Off Distance, Heat of Detonation, Surface Bursts**

I. INTRODUCTION

Blast loading is the phenomenon of rapid and abrupt release of energy due to explosions.A bomb explosion within or immediately nearby a building can cause catastrophic damage to the building leading to the collapsing of walls, blowing out of windows and hence dangerous to the inhabitants. The analysis and design of structures subjected to blast loads requires a detailed understanding of blast phenomena. Explosives are 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. Explosives may be in condensed, liquid or solid form and on detonation itdisintegrates emitting the heat and producing gas.The casualties from such a detonation are not only related to instant fatalities as a consequence of direct release of energy, but mainly to structural failures that could result in extensive life loss. Famous examples of such cases are the bombing attacks at the World Trade Centre in 1993 where the structural failure, including glass breakage, resulted in far more victims and injuries than the blast wave itself. Within the Euro codes, these types of loads are not dealt with and the engineers have no guidelines on how to design or evaluate structures for the blast phenomenon for which the detailed understanding of the dynamic response of the structure is required. The blast effects are presented by a wave of high intensity that spreads outward from the source to the surrounding air. As the wave propagates, it decreases in strength and speed. The maximum pressure experienced by the structure subjected to blast load depends on the scaled distance which is the function of distance of the structure from the center of spherical charge and charge mass as a factor of TNT.

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. Blast mitigation may be achieved by structural resistance and physical integrity.Esper [9] studied the behavior of structural components after 4 major bombing incidents took place in Mainland, UK. It is concluded that the ductility and natural period of vibration governs the response to an explosion and ductile elements such as steel and reinforced concrete behave well as they absorb significant amount of strain energy whereas brittle elements fail abruptly.Draganic*et al.*,[1] found that conventional reinforcement provides sufficient ductility for elements exposed to distant explosions while additional reinforcement is required for close explosions.Goyal [8] suggested that it is difficult to numerically predict the exact blast induced pressure field and highly non-linear response due to modeling limitations and uncertainties associated with the blast loads.Priyanka*et al.*,[4] analyzed a series of square RC slabs against blast loads and concluded that slabs require retrofitting on both sides in order to make them resistant to blast loads.Kashif*et al.*,[10] studied the effect of blast on G+4 RCC frame structure and found that variation of displacement along the height of building is non-uniform and different from earthquake and wind loads. He also stated that building does not behave as cantilever structure under blast load.Cheng X.*et al.*,[11] suggested that structural design should pay special attention to the weak parts and strengthen the roof and parapet design since the vibration response of concrete frame structure is maximum at the top under blasting vibration wave.Jamakhandi*et al.*,[12] concluded that regular frame structure is the most optimum model which shows the lowest value of storey drift and good lateral stability against blast loads.

In this paper an attempt has been made to determine the effect of 1000kg of C4 explosive material on the front, rear, side and roof surfaces of the building at a stand-off distance of 22.5m. The dynamic response of the building is evaluated after calculating the loading phenomena on different surfaces of the building as the record of pressure time history. Further attempt has been made to determine the effect of distance of blast for 1000kg of C4 explosive on different surfaces of the building at stand-off distance of 10m, 18.5m, 22.5m and 27m. Moreover, the effect of different explosive materials TNT, C4, RDX and PETN on building surfaces at stand-off distance of 22.5m is also reflected through this paper.

II. EXPLOSION AND BLAST WAVES

A. Nature of Explosion: An explosion is 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 surrounded medium. Along with the produced gases, the air around the blast 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 is released during the detonation and moves faster than the speed of the sound.The idealized profile of the pressure in relation to time for the case of a free air blast wave can be represented by the fig.1

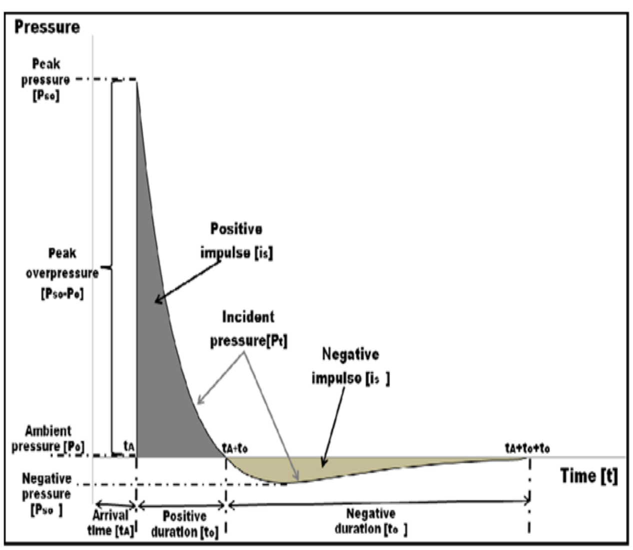

Fig. 1 Ideal blast wave's pressure time history

The pressure surrounding the element is initially equal to the ambient pressureP_0, and it undergoes an instantaneous increase to peak pressure P_{so}at the arrival timet_A, when the shock front reaches that point. The time needed for the pressure to reach its peak value is very small and for design purposes it is assumed to be equal to zero. The peak pressure $P_{so}$is also known as side on overpressure or peak overpressure. The value of the peak overpressure as well as the velocity of propagation of the shock wave decreases with increasing distance from the detonation center. After its peak value, the pressure decreases with an exponential rate until it reaches the ambient pressure at$t_A + t_0$, t_0 being called the positive phase duration. After the positive phase of the pressure-time diagram, the pressure, the pressure becomes smaller than the ambient value, and finally returns to it. The negative phase is longer than the positive one [3], its minimum pressure value is denoted as $P_{so}{}^{-}$ and its duration as$t_0{}^{-}$. During this phase the structures are subjected to suction forces.

The negative phase of the explosion wave is usually not taken into account for design purposes as it has been verified that the main structural damage is connected to the positive phase. Additionally, the pressures that are produced from the negative phase of the blast wave are relatively small compared to those of the positive phase and since these are in the opposite direction, it is usually on the safe side to assume that they do not have a big impact on the structural integrity of buildings under blast loads. However, the pressures that are below the ambient pressure value should be taken into account if the overall structural performance of the building during a blast is assessed and not only its structural integrity.The blast loading pattern can be expressed by the exponential function as:

$$P(t) = P_{so}\left(1 - \frac{t}{t_0}\right)e^{-b\frac{t}{t_0}} \quad (1)$$

Where P_{so} =peak overpressure

t_0 =positive phase duration

b = decay coefficient of waveform

t = time elapsed, measured from the instant of blast arrival

1. Scaled Distance: To obtain the values of peak overpressures and the maximum reflected overpressure, scaled distance is computed which is the function of the maximum distance between the center of spherical charge and the source target and the weight of the explosive expressed as an equivalent mass of TNT.

$$Z = \frac{R}{W^{1/3}} \quad (2)$$

R is the distance from the explosion source to the point of interest (in m)

W is the weight of the explosive (in kg)

2. Explosive Type and Weight: Several types of explosives are available nowadays, which could be used for conducting an attack against a structure. In the majority of the cases, solid explosives are used, because of their transportability, relatively easy manufacturing and the possibility of their placement in the vehicles that could be moved in the vicinity, adjacent or within a building. The wide variety of explosives has led to the adoption of a universal quantity, which is used for all necessary computations of blast parameters. TNT (Trinitrotoluene) is chosen as its blast characteristics resemble those of most solid type explosives. An equivalent TNT weight is computed using the following equation that links the weight of the chosen design explosive to the equivalent weight of TNT by utilizing the ratio of the heat produced during detonation:

$$W_e = W_{\exp} \frac{H_{\exp}^{d}}{H_{TNT}^{d}} \qquad (3)$$

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 I INDICATIVE VALUES OF THE 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
NITROGLYCERIN	6.30
NITROMETHANE	6.40
NITROCELLULOSE	10.60
AMON. /NIT. (AN)	1.59

TABLE II INDICATIVE TNT EQUIVALENT MASS FACTORS

Name of Explosive	TNT equivalent mass factor	
	Peak Pressure	Impulse
TNT	1.00	1.00
C3	1.08	1.01
C4	1.37	1.19
CYCLOTOL	1.14	1.09
OCTOL 75/25	1.06	1.06
TETRYL	1.07	1.05
HMX	1.02	1.03
AMATOL	0.99	0.98
RDX	1.14	1.09
PETN	1.27	1.11

B. Explosion and Blast Loading Types

Unconfined explosions can be distinguished in three basic types depending on the relative position of the explosion source and the structure to be protected, i.e. on the height H above the ground, where the detonation of a charge W occurs, and on the horizontal distance R_G between the projection of the explosive to the ground and the structure. These three explosion types are:

1. *Free Air Bursts:*The explosive charge is detonated in the air; the blast waves propagate spherically outwards and impinge directly onto the structure without prior interaction with other obstacles or the ground.
2. *Air Bursts:*The explosive charge is detonated in the air, the blast waves propagate spherically outwards and impinge onto the structure after having interacted first with the ground; a Mach wave front is created.
3. *Surface Bursts:*The explosive charge is detonated almost at ground surface, the blast waves immediately interact locally with the ground and they next propagate hemi spherically outwards and impinge onto the structure.

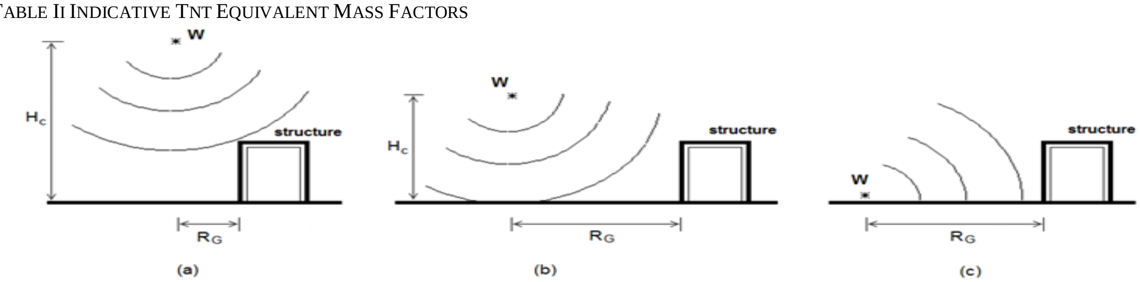

Fig. 2 Types of external explosions and blast loadings a) Free air Bursts, b) Air Bursts, and c) Surface Bursts

C. Blast Pressure andParameters of Blast: There were various proposals for calculation of peak incident overpressure of blast:

Brode [5] presented a formulation for determining the peak overpressure for blasts:

$$P_{so} = \frac{6.7}{Z^3} + 1 \quad \text{, for } P_{so} > 10\ bar \qquad (4a)$$

$$P_{so} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \text{, for } 0.1 < P_{so} < 10 \text{ bar} \quad (4b)$$

where, Z is the scaled distance in m/$kg^{1/3}$

Another formulation, that is widely used for computing peak overpressure values for ground surface blast is proposed by Newmark and Hansen [6]

$$P_{so} = 6784 \frac{W}{R^3} + 93 \sqrt{\frac{W}{R^3}} \qquad (5)$$

where, $P_{so}$is in bars

W is the charge mass expressed in kilograms of TNT and

R is the distance of the surface from the center of a spherical explosion in m.

Mills [7] have also introduced an expression of the peak overpressure in kPa, in which W is expressed in kg of TNT and the scaled distance Z is in m/$kg^{1/3}$

$$P_{so} = \frac{1772}{Z^3} - \frac{114}{Z^2} + \frac{108}{Z} \quad (6)$$

The valuesof peak overpressure may get amplified due to reflections from various surfaces and its effect has to be considered for the blast resistant design of structures. The peak reflected overpressure in case of reflections at zero angle is given as:

$$P_r = 2P_{so}\frac{4P_{so} + 7P_o}{P_{so} + 7P_o} \quad (7)$$

Explosion wave front speed equation, U_s, and the maximum peak dynamic pressure, q_0, is given as:

$$U_s = a_0\sqrt{\frac{6p_{so} + 7p_0}{7p_0}} \quad (8)$$

$$q_0 = \frac{5p_{so}^2}{2(p_{so} + 7p_0)} \quad (9)$$

Where,
p_{so}= peak static wave front overpressure, bar
p_o= ambient air pressure (atmospheric pressure), bar
a_o= speed of sound in air, m/s

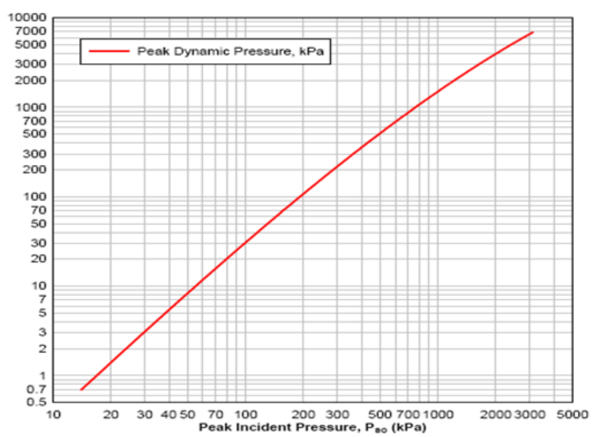

Fig. 3 Variation of peak dynamic pressure q_0 versus peak incident pressure

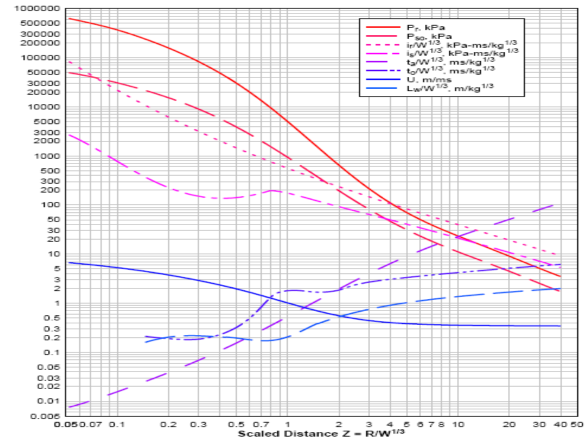

Fig. 4 Parameters of positive phase of shock wave of TNT charges from free air bursts [3]

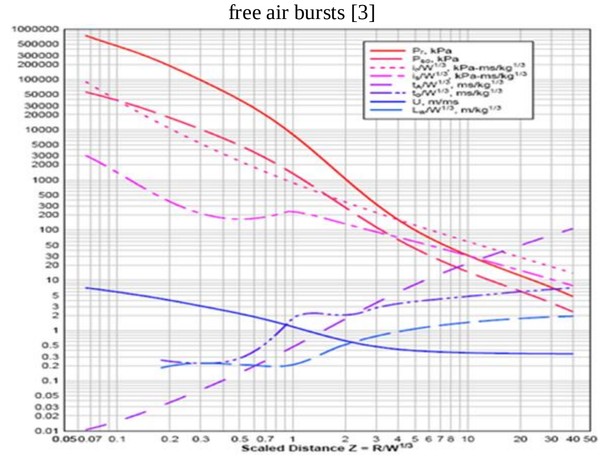

Fig. 5 Parameters of positive phase of shock wave of TNT charges from surface bursts [3]

where,
U = shock wave speed (m/ms)
L_w = blast wavelength (m)
P_{so}= maximum incident overpressure (kPa)
P_r = maximum reflected overpressure (kPa)
i_r = impulse corresponding to maximum reflected overpressure (kPa-ms)
i_s = impulse corresponding to maximum incident overpressure (kPa-ms)
t_a = arrival time of the blast (ms)
t_o = duration of positive phase of the blast (ms)

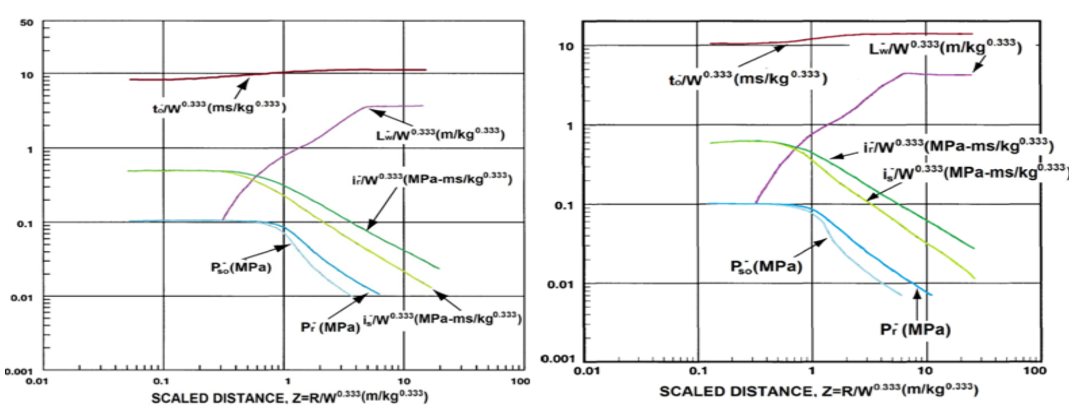

Fig. 6 (a)Parameters of negative phase of shock(b) Parameters of negative phase of shock wave of wave TNT charges from spherical free air burstsTNT charges from semispherical surface bursts

D. Pressure Loads on Building Surfaces

1. Average Pressure on the Front Wall: The variation of the pressure on the front structural façade, for a rectangular structure with sides parallel to the wave front above the ground, is given as:

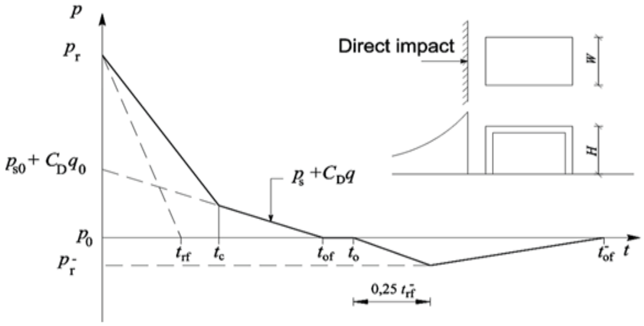

Fig. 7The load on the front surface of the structure

The peak overpressure on the front structural façade in time of the explosion's arrival,t_A, will be the peak refracted overpressure, p_r, which is the function of initial pressure. This pressure then decreases due to the passage of waves above and around the structure, which is less than p_r. 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 initial pressure can be expressed as:

$$t_c = \frac{4S}{(1+R)C_r} \qquad (10)$$

where,
S = length of the clearing, is equal to the height of the structure, H or half-width of the structure,
W/2, whichever is less
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 the sound in refracted area

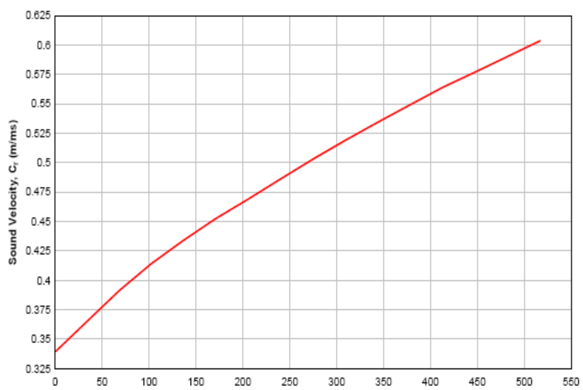

Fig. 8 Sound velocity in reflected overpressure region

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:

$$p = p_{so} + C_D q_0 \qquad (11)$$

where,
p_{so} is the incident pressure.
$C_D$is the drag coefficient, taken equal to 1 for the front wall
$q_0$is the dynamic pressure
The fictitious length of the refracted wave front, t_{rf}, is calculated according to the formula:

$$t_{rf} = \frac{2i_r}{p_r} \qquad (12)$$

The fictitious time t_{of}, for the positive phase of the blast is given as:

$$t_{of} = \frac{2i_s}{p_{so}} \qquad (13)$$

A similar procedure can be applied for the negative phase of the blast wave thus defining a fictitious time t_{of}^- by employing the corresponding impulse and peak pressure values.

2. Average Pressure on the 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. 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.

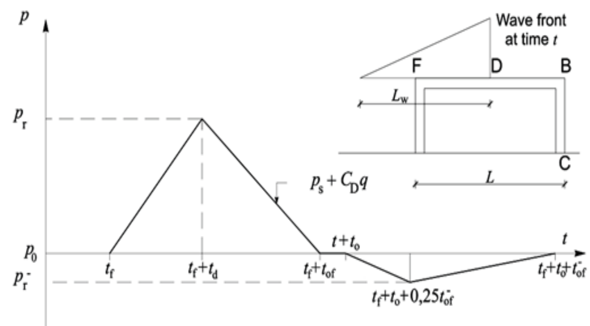

Fig. 9Load on the roof and side surfaces of the structure

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.

$$P_R = C_E P_{sof} + C_D q_{of} \qquad (14)$$

Where,
P_{sof} = the incident pressure at point F of the front edge of the roof
C_E = the equivalent load factor
C_D = the drag coefficient
q_{of} = the dynamic pressure corresponding to $C_E P_{sof}$
The value of the negative pressure that acts on the roof surface, P_R^- ,is equal to $C_E^- P_{sof}$ where C_E^- is the negative value of the equivalent load factor.

TABLE III DRAG COEFFICIENT C_D VALUES FOR ROOF AND SIDE WALLS

Peak dynamic pressure (kPa)	Drag coefficient
0-170	-0.40
170-350	-0.30
350-900	-0.20

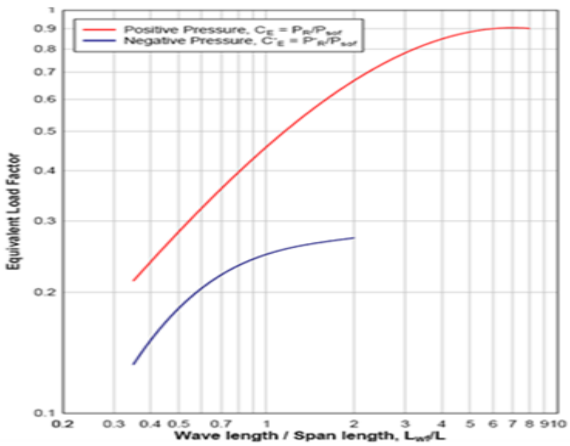

Fig. 10Equivalent load factors for positive and negative phase of blast loading for the roof and side walls of the structure

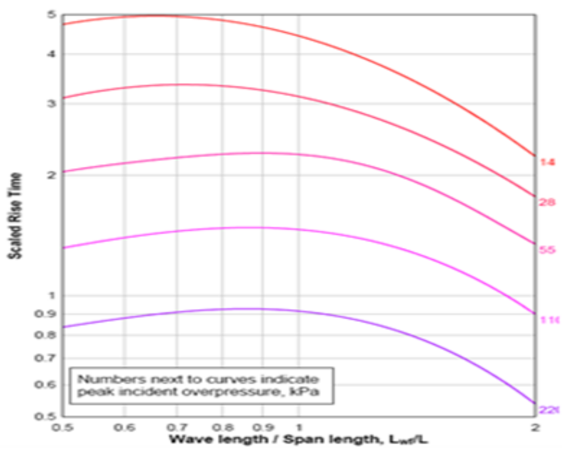

Fig. 11 Scaled rise time t_d of positive and negative phase pressure loading for roof and side walls of structure

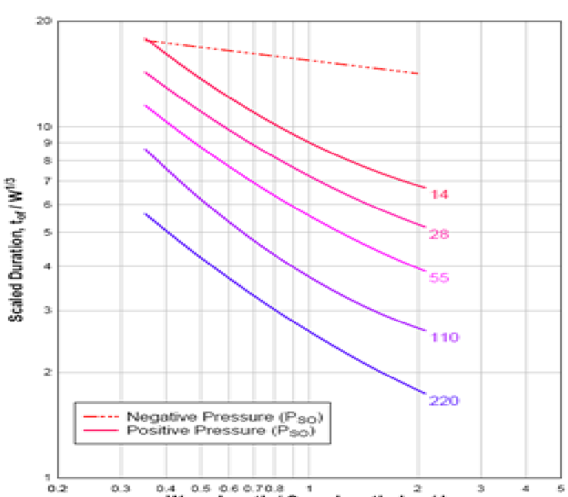

Fig. 12Scaled duration of positive and negative phase pressure loading for roof and side walls of structure

3. Average Pressure on the Rear Surfaces: For the loading analysis the procedure equivalent to the procedure for the loading determination on the roof and side surfaces can be used. The peak pressure and 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 side surfaces.

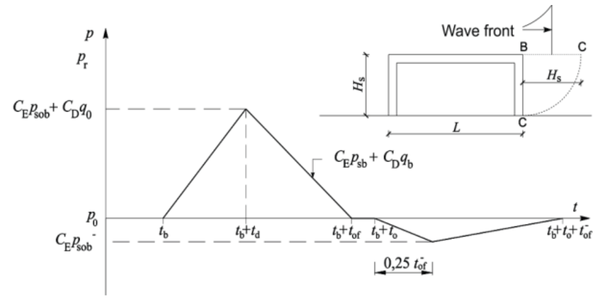

Fig. 13Load on the rear surface of the structure

III. BUILDING MODEL

The structure selected for this study is a small reinforced concrete building. The overall length and width of the building are 6.0m and the height of the building is 3.1m. The beam dimensions used are 300mm x 500mm and the column dimensions used are 500mm x 500mm.

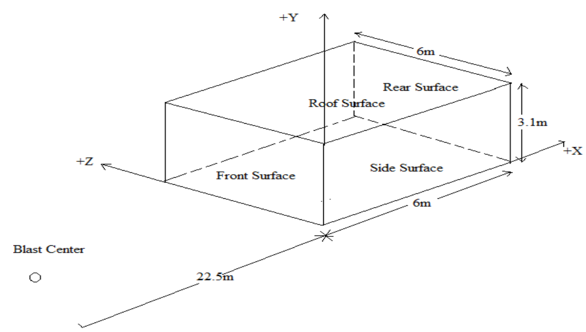

Fig. 14 Geometry of Blast Site

The thickness of the slab is taken as 150mm. The modulus of elasticity of concrete is taken as 21.718 GPa, density of concrete is taken as 24 kN/m^3 and the Poisson's ratio is taken as 0.17. The building is considered as an isolated structure situated at a stand-off distance of 22.5m from a truck, which is assumed to carry a 1000kg of C4 explosive material.The bottom portion of the wall is fixed and the analysis is carried out bySTAAD.Pro software.

A. Blast Loads on the Model: The blast load is evaluated at (the center of) the front surface, which has an area of 18.6 m^2 (6m x 3.1m) and lies normal to the blast wave propagation direction. Except from the reflected pressures at the front face of the building, the pressures at the roof, the side and rear walls are also computed.The explosive is detonated almost at ground level so a hemispherical blast wave will be produced. The distance from the blast point is considered large enough, so as to assume that the blast waveimpinging on the structure is plane and the pressure applied is uniform across the front surface.

The charge weight of W_{exp} = 1000 kg of C4 must be converted to an equivalent charge of TNT as

$$W_e = W_{\exp}\frac{H^d_{\exp}}{H^d_{TNT}} = 1000kg\,\frac{H^d_{C4}}{H^d_{TNT}} = 1000\,\frac{5.86}{4.50} = 1302kg$$

B. Front Wall Pressure: Front surface center height: h = 1.55m,Distance from blast source:

$$R_h = \sqrt{(22.5^2 + 1.55^2)} = 22.55m$$

Scaled distance: $Z = \frac{R_h}{\sqrt[3]{W}} = \frac{22.55}{\sqrt[3]{1302}} = 2.065m/kg^{1/3}$

Angle of incidence: $\alpha = tan^{-1}(\frac{h}{R})$ = 3.93º < 40º

Since, the angle of incidence is lot smaller than 40º so regular reflection environment is expected with conditions not differing from those of the normal reflection. So the use of normal reflected pressure for the building is justified as it will lead to slightly conservative values.

Now obtaining the parameters of the positive phase of the blast from the graphs for TNT charges for surface bursts, i.e. from fig. 5

TABLE IV PARAMETERS OF POSITIVE PHASE OF BLAST FOR SURFACE BURSTS FOR FRONT WALL

Front Face	Incident Pressure P_{so}[kPa]	Positive incident impulse i_s	Reflected Pressure P_r[kPa]	Positive reflected impulse i_r	Arrival time	Positive duration	Shock wave speed U[m/ms]	Wavelength L_w
Diagram read scaled values	275.00	140.00	970.00	355.00	1.88	2.08	0.62	0.55
Absolute values	275.00	1528.73	970.00	3876.43	20.53	22.71	0.62	6.00

Velocity of sound, C_r = 0.504 m/ms (from fig.8)

Clearing time: $t_c = \frac{4S}{(1+R)C_r} = \frac{4 \text{ x } 3}{(1+0.968)0.504}$ = 12.10 ms

Fictitious positive phase duration:

$$t_{of} = \frac{2i_s}{P_{so}} = \frac{2 \text{ x } 1528.73}{275.0} = 11.12 \text{ ms}$$

Fictitious duration of reflected pressure:

$$t_{rf} = \frac{2i_r}{P_{r\alpha}} = \frac{2 \text{ x } 3876.43}{970} = 7.99 \text{ ms}$$

Peak dynamic pressure: q_0= 180kPa (from fig.3)

Drag coefficient for building front wall: C_D = 1.0

Reduced peak pressure:

$P_{so} + C_D q_0$ = 275+ (1.0 x 180.0) = 455kPa

The parameters of the negative phase of the blast from the graphs for TNT charges for surface bursts are obtained as follows from fig. 6

TABLE V PARAMETERS OF NEGATIVE PHASE OF BLAST FOR SURFACE BURSTS FOR FRONT WALL

Front face	Incident negative pressure P_{so^-}[kPa]	Negative incident impulse i_{s^-}	Reflected negative pressure P_{r^-} [kPa]	Negative reflected impulse i_{r^-}	Negative duration t_{0^-}	Negative wavelength L_w
Diagram read scaled values	20.00	0.135	32.00	0.225	16.00	1.50
Absolute values	20.00	1474.13	32.00	2456.89	174.71	16.40

The negative phase curve begins exactly after the end of the positive phase duration t_0 and that its rise-time is equal to 0.25 $t_{of}^{\,-}$ = 0.25 x 174.71 = 43.68ms.

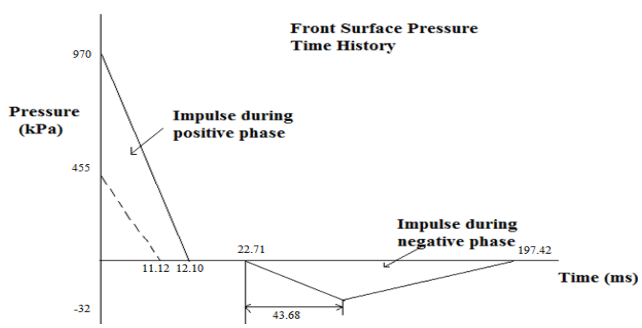

Fig. 15Blast pressure time history at the front wall of the structure

C. Roof and Side Wall Pressure: For the roof of the building the calculations start with reference to its edge nearer to the blast source. The peak incident pressure at this location is equal to that of the front face, i.e.,

$$P_{sof} = 275\text{kPa}$$

Based on that, the wavelength is determined from figure 5 and the ratio L_{wf}/L is calculated,

$$L_{wf} = 6.77 \text{ m}$$

$$L_{wf}/L = 6.77/6.00 = 1.13$$

For the positive phase pressure the equivalent positive phase load factor C_E is found from figure 10:

$$C_E = 0.49$$

And the dynamic pressure q_0, corresponding to incident pressure $C_E P_{sof}$ = 134.75kPa, is determined from figure 3:

$$q_0 = 48\text{kPa}$$

Corresponding to maximum peak dynamic pressure of 48kPa, drag coefficient C_D = -0.4. Therefore, the maximum positive roof pressure is given as:

$$P_R = C_E P_{sof} + C_D q_0 = 134.75 - 0.4 \text{ x } 48 = 115.55\text{kPa}$$

The rise time t_d, and the overall duration of the positive phase t_{of} are also determined from the relevant fig.11 and 12:

$$t_d = 8.74\text{ms}$$

$$t_{of} = 22.93\text{ms}$$

Parameters read from diagrams have been multiplied by $W^{1/3}$ in order to derive their absolute values, where needed

TABLE VI PARAMETERS OF POSITIVE PHASE OF BLAST FOR POSITIVE PHASE FOR ROOF AND SIDE WALL

Roof and Side Wall	Wavelength L_w	Ratio L_w/L	Equivalent positive phase load factor C_E	Duration of rise time t_d	Duration of equivalent uniform pressure t_{of}	P_r=$C_E P_{sof}$ [kPa]	Peak positive pressure [kPa]
Diagram read scaled values	0.62	-	0.49	0.80	2.1	-	-
Absolute values	6.77	1.13	-	8.74	22.93	134.75	115.55

In order to compute the negative phase parameters a similar procedure is followed by reading the diagrams for the negative phase of the blast wave. The negative phase starts at t_0 = 22.71ms. Thus, the equivalent negative phase load factor C_E^- is calculated as: C_E^- = -0.255

And the peak negative roof pressure is calculated as:

$$P_R^- = C_E^- P_{sof} = -0.255 \text{ x } 275 = -70.125\text{kPa}$$

The overall duration of the negative phase t_{of}^- is derived from Fig. 12 as:

$$t_{of}^- = 184.54\text{ms}$$

And the corresponding rise time t_d^- is calculated with the formula:

$$t_d^- = 0.25 t_{of}^- = 0.25 \text{ x } 184.54 = 46.135 \text{ ms}$$

TABLE VII PARAMETERS OF NEGATIVE PHASE OF BLAST FOR SURFACE BURSTS FOR ROOF AND SIDE WALL

Roof and Side Wall	Wavelength L_w	Ratio L_w/L	Equivalent negative phase load factor C_E	Duration of equivalent uniform negative pressure t_{of^-}	Duration of negative phase rise time t_{d^-}	Negative phase reflected pressure P_r=$C_{E^-}P_{sof}$[kPa]
Diagram read scaled values	0.62	-	-0.255	16.9	-	-
Absolute values	6.77	1.13	-	184.54	46.135	-70.125

Based on the parameters defined, the variation of the positive and negative phases of the pressure-time variation is as follows:

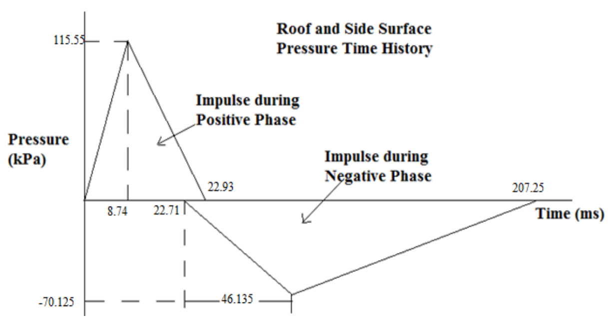

Fig. 16 Blast pressure time history at the roof of the structure

D. Rear Wall Pressure: For the rear wall of the building the calculations start by taking as reference the back edge of the roof. The distance from the explosion source is 22.5 + 6 = 28.5m, thus the scaled distance, arrival time and peak incident pressure there are as follows:

$$Z = 28.5/(1302)^{1/3} = 2.61 m/kg^{1/3}$$

$$t_A = 2.75 \text{ x } (1302)^{1/3} = 30.03ms$$

$$t_0 = 2.5 \text{ x } (1302)^{1/3} = 27.30ms$$

$$P_{sob} = 160kPa$$

The rise time and overall duration of the positive phase are determined from fig. 11 and 12:

$$t_d = 0.62 \text{ x } (1302)^{1/3} = 6.77ms$$

$$t_{of} = 2.10 \text{ x } (1302)^{1/3} = 22.93ms$$

The wavelength at the rear end b is also determined from figure 5 and the ratio L_{wb}/L is calculated as follows:

$$L_{wb} = 0.7 \text{ x } (1302)^{1/3} = 7.644m \longrightarrow L_{wb}/L = 7.644/3.10 = 2.466$$

From Fig. 10, the equivalent load factor is determined as:

$$C_E = 0.73$$

Therefore $C_E P_{sob}$ = 116.8kPa and corresponding peak dynamic pressure is determined from figure 3 as:

$$q_0 = 38.0 \text{ kPa}$$

From table 3, the drag coefficient C_D is determined as:

$$C_D = -0.4$$

The maximum positive rear wall pressure is therefore determined as:

$$P_{rw} = 116.8 - 0.4 \text{ x } 38 = 101.6 \text{ kPa}$$

TABLE VIII PARAMETERS OF POSITIVE PHASE OF BLAST FOR SURFACE BURSTS FOR REAR WALL

Rear Wall	Incident pressure [kPa]	Wavelength L_w	Ratio L_w/L	Equivalent positive phase load factor C_E	Duration of rise time t_d	Duration of equivalent uniform pressure t_{of}	P_r=$C_E P_{sof}$ [kPa]	Peak positive pressure [kPa]
Diagram read scaled values	160.00	0.7	-	0.73	0.62	2.1	-	-
Absolutevalues	160.00	7.644	2.466	-	6.77	22.93	116.8	101.6

A similar approach is used for the derivation of the negative blast phase parameters. In order to compare this curve with those of the front wall, side walls and roof, and for consistency in the timing of load application, the origin has been displaced to the right by 9.5 ms (= 30.03-20.53). This is the delay in the arrival times of the wave to the front (f) and the back (b) face of the building.

TABLE IX PARAMETERS OF NEGATIVE PHASE OF BLAST FOR SURFACE BURSTS FOR REAR WALL

Rear Wall	Wavelength L_w	Ratio L_w/L	Equivalent negative phase load factor C_E	Duration of equivalent uniform negative pressure t_{of^-}	Duration of negative phase rise time t_{d^-}	Negative phase reflected pressure P_r=$C_{E^-}P_{sof}$[kPa]
Diagram read scaled values	0.70	-	-0.275	14.93	-	-
Absolute values	7.644	2.466	-	163.03	40.76	-44.00

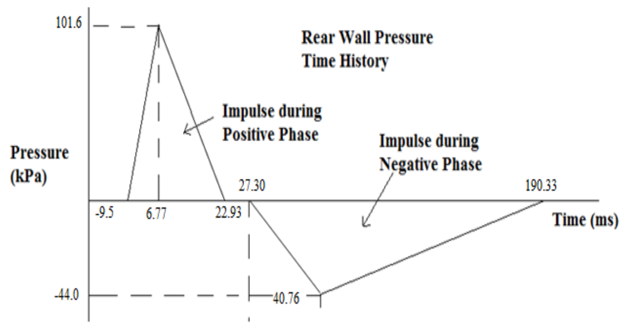

Fig. 17 Blast Pressure time history at the rear wall of the structure

IV. ANALYSIS OF THE BUILDING MODEL

In the model, the coordinate system has been considered as the length of the structure along X- direction, width along Z -direction and height of the structure along Y direction.The building is modeled in STAAD.Pro and analysis is carried out by dividing each surface of the building into 100 equal small elements. The pressure load history multiplied with the area of each element gives the dynamic force acting at the center of each element. Therefore, the 100 time dependent dynamic loads that act on the centre of each element are applied on surface of the building and the analysis is performed.The effect of 1000kg of C4 explosive located at 22.5m from front surface of the building was observed and presented in the following section. The maximum deformation of the front surface occurs at 1.7m from the bottom of the building. Thetime displacement, velocity and acceleration relations are presented in Fig. 18.

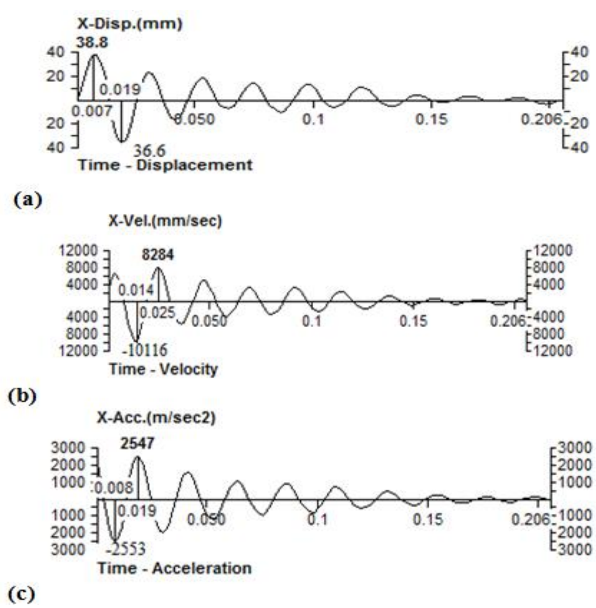

Fig. 18 Variation of (a) critical displacement (b) critical velocity (c) critical acceleration on front surface in X-direction

The variation of deformations at the front surface of the building along the height and width of the structure are shown in Fig.19. It is observed that the maximum displacements occur at the height of 1.7m along the +Y direction (Fig. 19a) and at the centre along the +Z direction (Fig. 19b) of the building.

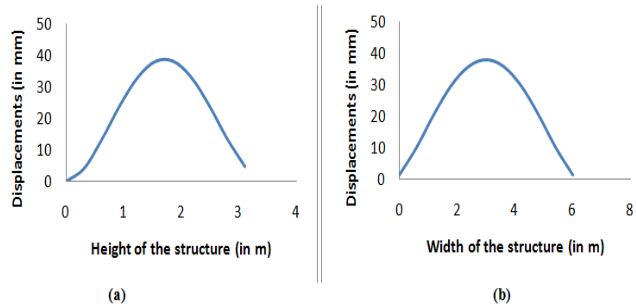

Fig. 19 Variation of displacements along the (a) height of structure (b) width of structure along the centre of front surface of the building

The maximum deformation of the roof surface occurs at 3.9m from the front surface of the building. The time, displacement, velocity and acceleration relations are presented in Fig. 20.

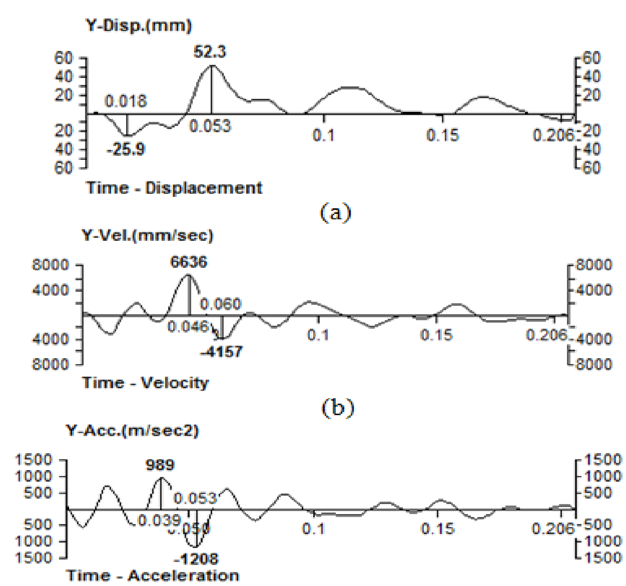

Fig. 20 Variation of (a) critical displacement(b) critical velocity (c) critical acceleration on roof surface in Y-direction

The variation of deformations at the roof surface of the building along the length and width of the structure are shown in Fig. 21. It is observed that the maximum displacements occur at 3.9m from front surface along the +X direction (Fig. 21a) and atcentre along the +Z direction (Fig. 21b) of the building.

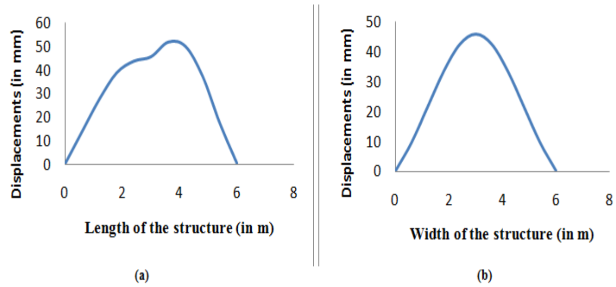

Fig. 21 Variation of displacements along the (a) length of structure (b) width of structure along the centre of roof surface of the building

The maximum deformation of the side surface occurs at 2.7m from the front surface of the building. The time, displacement, velocity and acceleration relations are presented in Fig. 22.

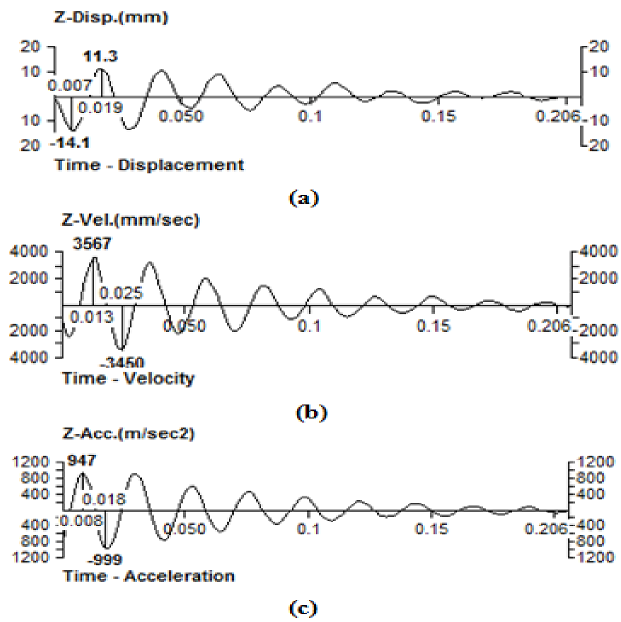

Fig. 22 Variation of (a) critical displacement (b) critical velocity (c) critical acceleration on side surface in Z-direction

The variation of deformations at the side surface of the building along the height and length of the structure are shown in Fig. 23. It is observed that the maximumdisplacements occur at height of 1.7m along the +Y direction (Fig. 23a) and at 2.7m front surface along the +Z direction (Fig. 23b) of the building.

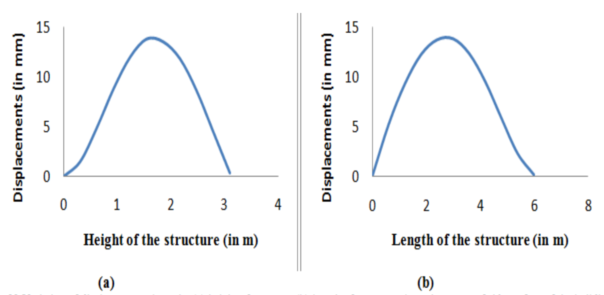

Fig. 23 Variation of displacements along the (a) height of structure (b) length of structure along the centre of side surface of the building

The maximum deformation of the rear surface occurs at height of 1.9m at the centre of rear surface of the building. The time displacement, velocity and acceleration relations are presented in figure 24.

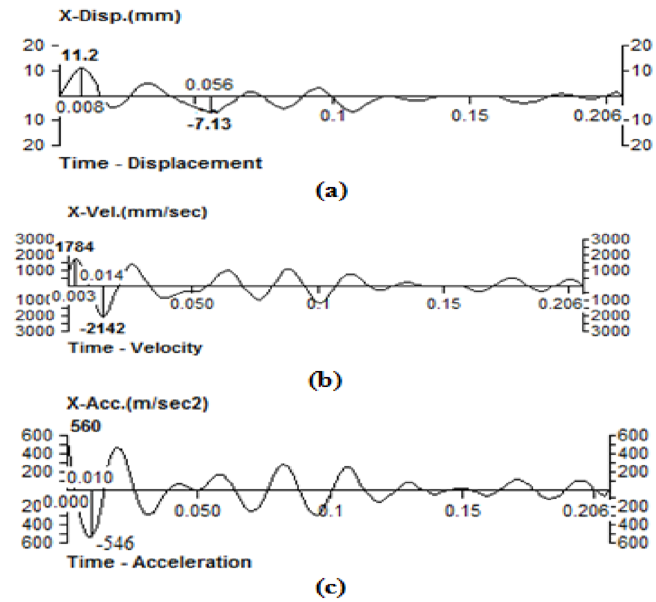

Fig. 24 Variation of (a) critical displacement(b) critical velocity (c) critical acceleration on rearsurfacein X-direction

The variation of deformations at the rear surface of the building along the height and width of the structure are shown in Fig. 25. It is observed that the maximum displacements occur at height of 1.9m along the +Y direction (Fig. 25a) and at centre along the +Z direction (Fig. 19b) of the building.

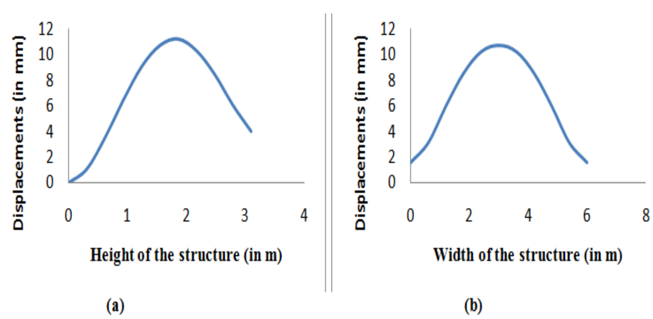

Fig. 25 Variation of displacements along the (a) height of structure (b) width of structure along the centre of rear surface of the building

A. Effect of Distance of Blast on Building Surfaces: To study the effect of stand-off distance between the blast source and target for the same explosive charge the building model is analyzed for 1000 kg of C4 explosive charge and 10m, 18.5m, 22.5m and 27m as the distance between explosive charge and the target and the maximum displacements (in mm) is tabulated as follows:

TABLE X EFFECT OF DISTANCE OF BLAST FOR SAME EXPLOSIVE MATERIAL ON DIFFERENT SURFACES OF THE STRUCTURE

Source Distance	10 m	18.5 m	22.5 m	27 m
Front Surface (mm)	261	71.7	38.8	21.5
Roof Surface (mm)	221	69.3	52.3	37.3
Side Surfaces (mm)	89.1	25.7	14.1	8.59
Rear Surface (mm)	84.2	20.1	11.1	1.77

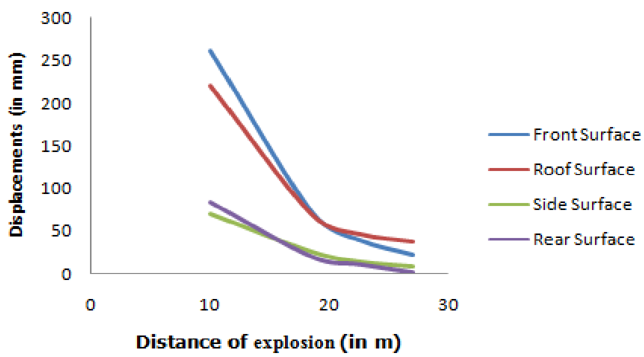

Fig. 26 Effect of distance of blast for same explosive material on different surfaces of the structure

B. Effect of Different Explosives on Building Surfaces: To study the effect of different explosives on building surfaces for the same stand-off distance, the same building configuration is analyzed for 1000kg of TNT, C4, RDX and PETN explosive charges for the stand-off distance of 22.5m. The maximum displacements (in mm) are obtained on different building surfaces are tabulated as follows.

TABLE XI EFFECT OF VARIOUS EXPLOSIVES ON DIFFERENT SURFACES OF THE BUILDING FOR SAME STAND-OFF DISTANCE

Explosive Type	TNT	C4	RDX	PETN
Front Surface (mm)	29.1	38.8	37.2	48.7
Roof Surface (mm)	43.5	52.3	49.3	55.8
Side Surface (mm)	10.9	14.1	13.6	17.7
Rear Surface (mm)	8.22	11.1	9.99	13.3

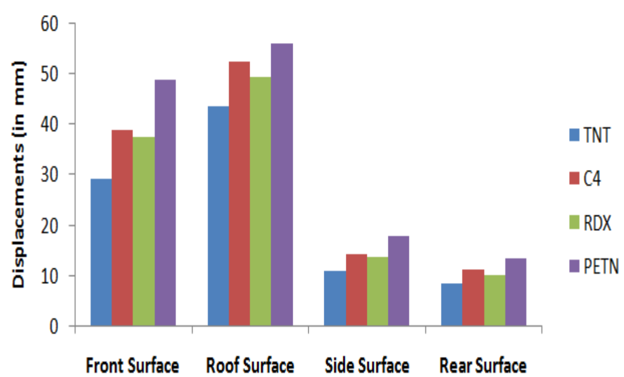

Fig. 27 Effect of various explosives for the same stand-off distance on different surfaces of the building

V. CONCLUSION

The explosion near the structure can cause catastrophic damage to the structure, hence these loads should be considered in design.It is not economical to design all buildings for blast loading. In the present study, extensive work is carried out for blast loads and its effects on RCC building structures. Building model is developed under blast load and analysis is carried out using STAAD.Pro. On the basis of the present study, the following conclusions may be drawn

1. The blast pressure and the corresponding displacements on the structure increases with increase in charge weight and decrease in the stand-off distance.
2. The maximum deformationsare obtained on the front and the roof surface of the structure. For close range explosions displacements on the front surface are critical but as the distance from the structure increases the displacements on the roof surface are critical for the building model.
3. The variation of displacements along the length and width of the front, rear, roof and side surfaces of the structure are approximately sinusoidal in nature with maximum displacements around the center of the surface.
4. It is observed that with increase in distance there is significant decrease in the deformations in the building. Therefore, for close explosions additional reinforcement is needed, while for distant conventional reinforcement provides sufficient ductility.

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