COMPUTATION OF BLAST LOADING FOR A MULTI STOREYED FRAMED BUILDING

Sarita Singla[1], Pankaj Singla[2], Anmol Singla[3]

[1]Associate Professor, Civil Engineering Department, PEC University of Technology, Chandigarh, India
[2]Serving as Engineer in Public Works Department (Building & Roads), Punjab, India
[3]B.E. Student, Civil Engineering Department, PEC University of Technology, Chandigarh, India

Abstract
The number and intensity of domestic and international terrorist activities have heightened our concerns towards the safety of our infrastructure systems. Due to different accidental or intentional events, related to important structures all over the world, explosive loads or blast loads have received considerable attention in recent years. The development in this field is made mostly through publication of the U.S. Army Corps of Engineers, Naval Facilities Engineering Command (NAVFAC), and Air Force Civil Engineer Support Agency. In India also, the guidelines for the blast loading are published in IS 4991. In the present study, blast pressures for different weights of surface blast or TNT and varying stand-off distances are computed for a multi-storeyed framed building adopting wave scaling laws given by U.S Army technical manual (UFC3-340-02). Blast pressures for different cases are computed using correlation between blast pressure and blast scaled distance based on charts given in U.S manual. Time history loading is also obtained with parameters of reflected total over pressure and duration of positive phase of blast.

Keywords: blast loading, blast wave, scaled distance, blast pressure.

---***---

1. INTRODUCTION

The term blast is commonly used to describe any situation in which the rapid release of energy occurs from a chemical, mechanical or nuclear source. However, from the point of view of the effects of explosions upon structural systems, there exists a set of fundamental characteristics which must be defined and considered, irrespective of the source. Explosions occurring in urban areas or close to facilities such as buildings and protective structures may cause tremendous damage and loss of life. The immediate effects of such explosions are blast overpressures propagating through the atmosphere, fragments generated by the explosion and ground shock loads resulting from the energy imparted to the ground. Conventional buildings are constructed quite differently than hardened military structures and as such are generally quite vulnerable to blast and ballistic threats. In order to design structures which are able to withstand explosions it is necessary to first quantify the effects of such explosions. Typically, it takes a combination of specialist expertise, experimental tests, and analysis tools to properly quantify the effects. With this in mind, developers, architects and engineers increasingly are seeking solutions for potential blast situations, to protect building occupants and the structures.

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 to be considered. It is performed so that the charge mass of explosive is multiplied by the conversion factor based on the specific energy of the charge and the TNT. Specific energy of different explosive types and their conversion factors to that of the TNT are given in Table 1. [1]

Table-1: Conversion factors for various explosives

Explosive	Specific Energy Q_x kJ/kg	TNT equivalent Q_x/Q_{TNT}
Compound B (60% RDX, 40% TNT)	5190	1.148
RDX(Ciklonit)	5360	1.185
HMX	5680	1.256
Nitro-glycerine (liquid)	6700	1.481
TNT	4520	1.000
Explosive gelatine	4520	1.000
60% Nitro-glycerine dynamite	2710	0.600
Semtex	5660	1.250
C4	6057	1.340

The threat for a conventional bomb is defined by two equally important elements, the bomb size, or charge weight W, and the stand-off distance R between the blast source and the target. The incident peak over pressures P_{so} are amplified by a reflection factor as the shock wave encounters an object or structure in its path. Except for specific focusing of high intensity shock waves at near 45° incidence, these reflection factors are typically greatest for normal incidence (a surface adjacent and perpendicular to the source) and diminish with the angle of obliquity or angular position relative to the source.

Reflection factors depend on the intensity of the shock wave, and for large explosives at normal incidence these reflection factors may enhance the incident pressures by as much as an order of magnitude.

The blast characteristics define a transient pulse of pressure which rapidly radiates out from the source of the explosion. In general terms the transient pulse will consist of a positive phase, during which the incident pressure in the medium significantly exceeds the ambient pressure, often followed by a negative phase during which the incident pressure falls below ambient. It is the interaction between this transient pulse and an affected structure which governs the dynamic response of that particular structure.

Throughout the pressure-time profile, two main phases can be observed; portion above ambient is called positive phase of duration *to*, while that below ambient is called negative phase of duration, *to-*. The negative phase is of a longer duration and a lower intensity than the positive duration. As the stand-off distance increases, the duration of the positive-phase blast wave increases resulting in a lower-amplitude, longer-duration shock pulse.
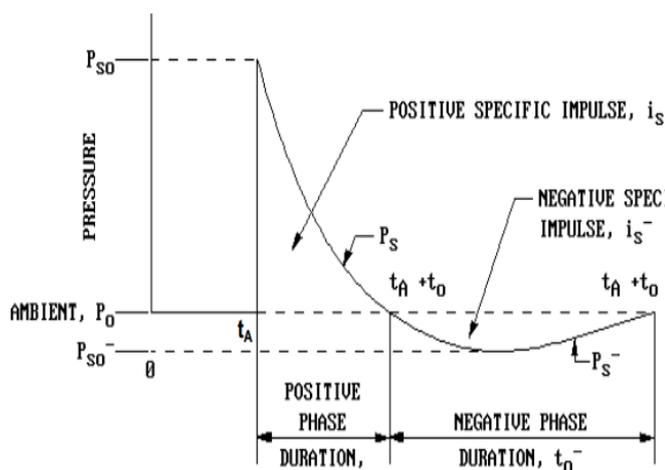

Fig-1: Typical blast pressures with time [2]

Charges situated extremely close to a target structure impose a highly impulsive, high intensity pressure load over a localized region of the structure; charges situated further away produce a lower-intensity, longer-duration uniform pressure distribution over the entire structure. Eventually, the entire structure is engulfed in the shock wave, with reflection and diffraction effects creating focusing and shadow zones in a complex pattern around the structure.

During the negative phase, the weakened structure may be subjected to impact by debris that may cause additional damage. If the exterior building walls are capable of resisting the blast load, the shock front penetrates through window and door openings, subjecting the floors, ceilings, walls, contents, and people to sudden pressures and fragments from shattered windows, doors, etc. Building components not capable of resisting the blast wave will fracture and be further fragmented and moved by the dynamic pressure that immediately follows the shock front.

Building contents and people will be displaced and tumbled in the direction of blast wave propagation. In this manner the blast will propagate through the building.
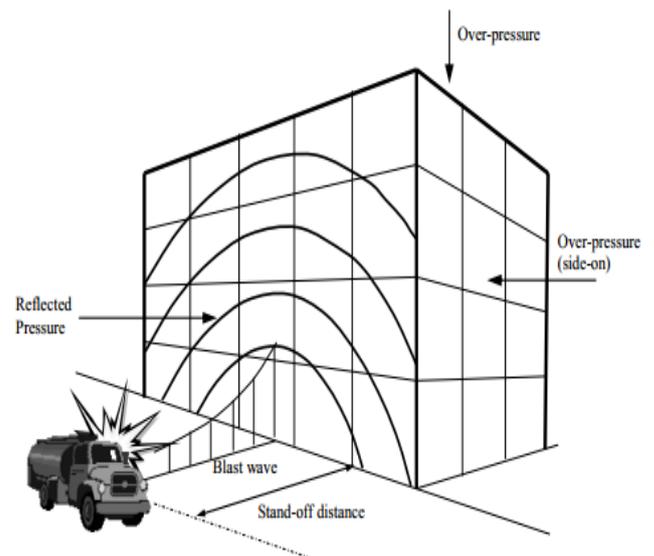

Fig-2: Blast Loads on a Building

If the exterior building walls are capable of resisting the blast load, the shock front penetrates through window and door openings, subjecting the floors, ceilings, walls, contents, and people to sudden pressures and fragments from shattered windows, doors, etc. Building components not capable of resisting the blast wave will fracture and be further fragmented and moved by the dynamic pressure that immediately follows the shock front. Building contents and people will be displaced and tumbled in the direction of blast wave propagation. In this manner the blast will propagate through the building.

1.1 Blast Wave Scaling Laws

All blast parameters are primarily dependent on the amount of energy released by a detonation in the form of a blast wave and the distance from the explosion. A universal normalized description of the blast effects can be given by scaling distance relative to $(E/Po)^{1/3}$ and scaling pressure relative to Po, where E is the energy release (kJ) and Po the ambient pressure (typically 100 kN/m^2). For convenience, however, it is general practice to express the basic explosive input or charge weight W as an equivalent mass of TNT. Results are then given as a function of the dimensional distance parameter. Scaling laws provide parametric correlations between a particular explosion and a standard charge of the same substance.

$$\text{Scaled distance(Z)} = \frac{R}{W^{1/3}}$$

Where, R is the actual effective distance from the explosion W is generally expressed in pounds or kilograms.

1.2 Methods for Determination of Blast Pressure

The estimations of peak overpressure due to spherical blast based on scaled distance $Z=R/W^{1/3}$ was introduced by Brode [3] as:

$$P_{so} = \frac{6.7}{Z^3} + 1 \; bar \; (P_{so} > 10 \, bar)$$

$$P_{so} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \; bar \; (0.1 < Pso < 10 \; bar)$$

In 1961, Newmark [4] introduced a relationship to calculate the maximum blast pressure (P_{so}), in bars, for a high explosive charge detonates at the ground surface as:

$$P_{so} = 6784 \frac{W}{R^3} + 93 \left(\frac{W}{R^3}\right)^{1/2}$$

In 1987, Mills [5] introduces another expression of the peak overpressure in kPa, in which W is the equivalent charge weight in kilograms of TNT and Z is the scaled distance.

$$P_{so} = \frac{1772}{Z^3} + \frac{114}{Z^2} + \frac{108}{Z}$$

If the blast wave encounters an obstacle perpendicular to the direction of propagation, reflection increases the overpressure to a maximum reflected pressure P_r as:

$$P_r = 2 \, P_{so} \left(\frac{7P_0 + 4P_{so}}{7P_0 + P_{so}}\right)$$

A full discussion and extensive charts for predicting blast pressures and blast durations are given by Mays and Smith [6] and UFC 3-340-02 (2008).

P_r=Peak Reflected Overpressure
P_{so} = Peak Static Pressure
i_r= Impact due to reflected overpressure
i_s= Impact due to static pressure
t_A= Arrival time
t_O = Positive phase duration
U = Blast wave velocity
L_w=Length of Blast wave

For design purposes, reflected overpressure can be idealized by an equivalent triangular pulse of maximum peak pressure $P_r$and time duration t_d, which yields the reflected impulse (i_r).

$$\text{Reflected Impulse} \; (i_r) = \frac{1}{2} P_r t_d$$

Duration t_d is related directly to the time taken for the overpressure to be dissipated. Overpressure arising from wave reflection dissipates as the perturbation propagates to the edges of the obstacle at a velocity related to the speed of sound (U_s) in the compressed and heated air behind the wave front. Denoting the maximum distance from an edge as S(for example, the lesser of the height or half the width of a conventional building), the additional pressure due to reflection is considered to reduce from $P_r - P_{so}$ to zero in

time $3S/U_s$. Conservatively, U_s can be taken as the normal speed of sound, which is about 340 m/s, and the additional impulse to the structure evaluated on the assumption of a linear decay. After the blast wave has passed the rear corner of a prismatic obstacle, the pressure similarly propagates on to the rear face; linear build-up over duration $5S/U_s$ has been suggested. For skeletal structures the effective duration of the net overpressure load is thus small, and the drag loading based on the dynamic pressure is then likely to be dominant. Conventional wind loading pressure coefficients may be used, with the conservative assumption of instantaneous build-up when the wave passes the plane of the relevant face of the building, the loads on the front and rear faces being numerically cumulative for the overall load effect on the structure. Various formulations have been put forward for the rate of decay of the dynamic pressure loading; a parabolic decay (i.e. corresponding to a linear decay of equivalent wind velocity) over a time equal to the total duration of positive overpressure is a practical approximation.
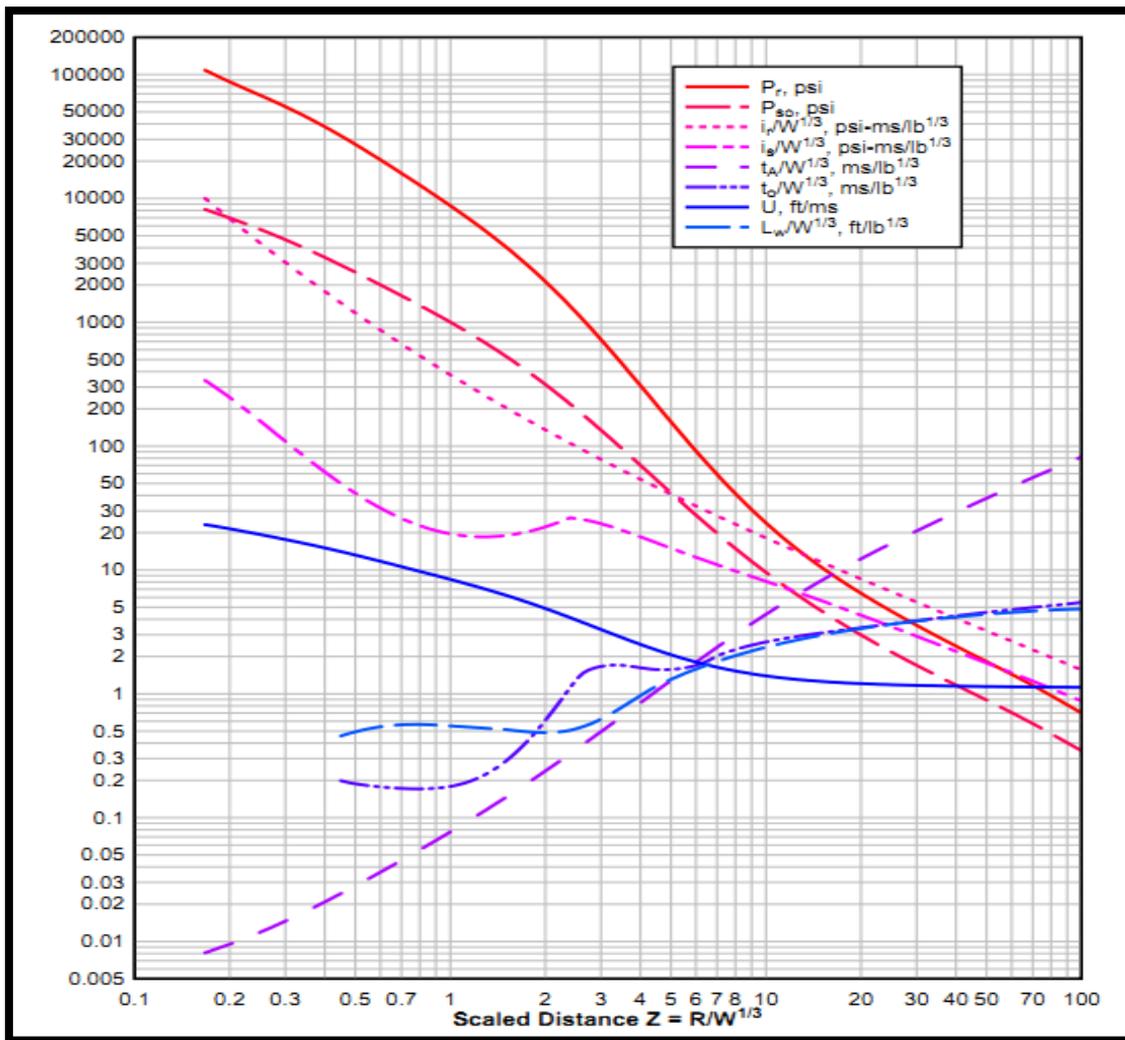
Fig-3: Positive phase shock wave parameters for a hemispherical TNT explosion on the surface at sea level [2]
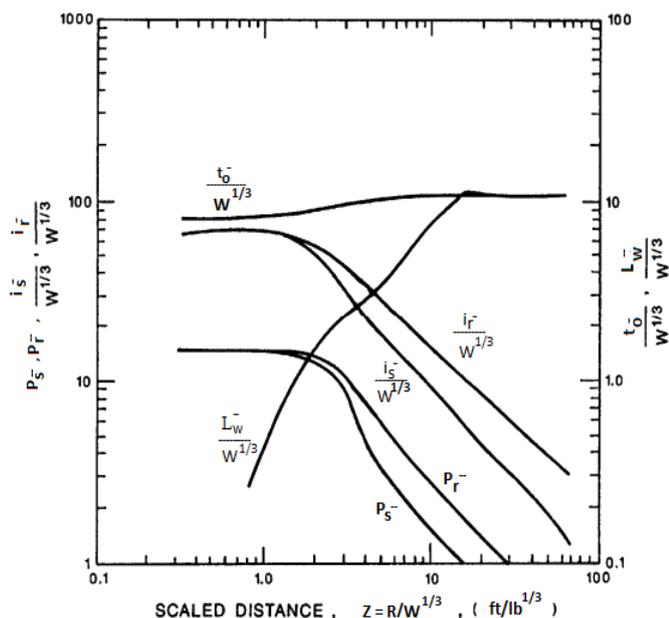

Fig-4: Negative phase shock wave parameters for hemi spherical TNT explosion on the surface at sea level [2]

2. COMPUTATION OF BLAST LOADING FOR A THREE STOREYED FRAMED BUILDING

Computation of blast loading for a three storeyed framed building has been carried out for the three cases of blast loading. Three categories of buildings are considered as per IS code 4991:1968 for blast resistant designing purposes. In the first case the equivalent TNT charge weight W has been taken as 100 Kg and the actual effective distance from explosion i.e. R is taken as 20 m, 30 m, and 40 m. In the second case W has been taken as 200 Kg and R as 20 m, 30 m, 40 m and in the third case charge weight W has been taken as 300 Kg & R is again varied as 20 m, 30 m, 40m. Height of building is 9 m. The plan and elevation of the building is shown below:
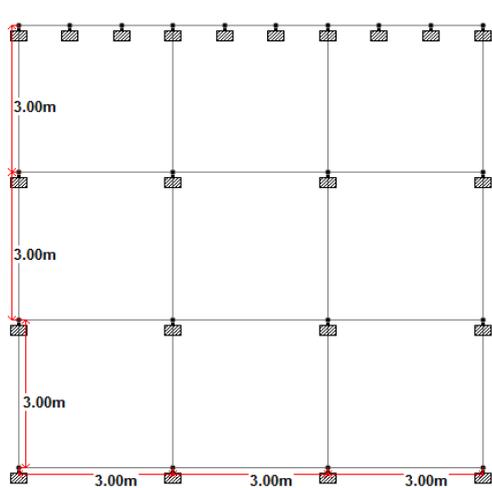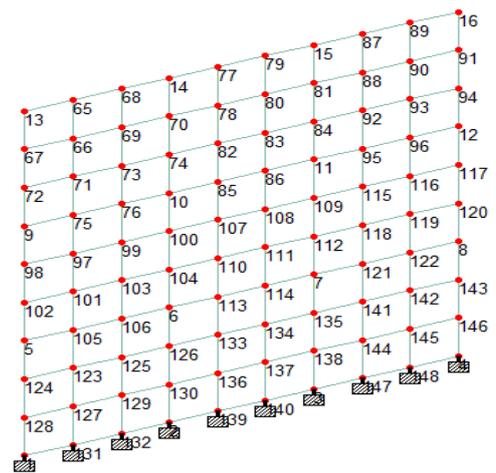
Fig-5: Plan of the building

Fig-6: Elevation of the building

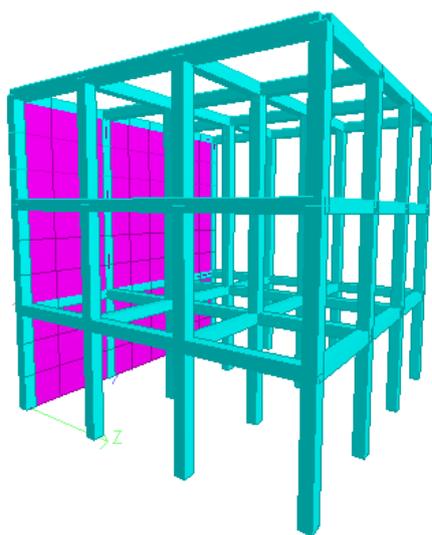**Fig-7:** Isometric view of the building

Fig-8: Nodes which are subjected to blast forces

2.1 Blast Pressure Parameters as per UFC 3-340-02

Case 1(a)
W= 100 kg or 220.46 lbs
Stand-off distance at ground level, R = 20 m or 65.61ft
Factor of safety = 1.2
W' = 1.2 x 220.46 = 264.55 lbs
Scaled Distance $Z = R/W^{1/3} = 10.22$ ft/lb$^{1/3}$
For Z = 10.22 ft/lb$^{1/3}$, (Refer Fig.3)
Peak Reflected Overpressure P_r = 22 psi
Peak static pressure P_{so} = 9 psi
$t_A/W^{1/3} = 4.5$
Arrival Time t_A= 28.88 ms
$t_o/W^{1/3} = 2.5$
Duration of positive blast wave t_o = 16.04 ms
Z At 1 m Height = 10.23 ft/lb$^{1/3}$,
Peak Reflected Overpressure P_r = 21.99 psi
Peak static pressure P_{so} = 8.99 psi
$t_A/W^{1/3} = 4.5$
Arrival Time t_A= 28.88 ms
$t_o/W^{1/3} = 2.5$
Duration of positive blast wave t_o = 16.04 ms

As the height of building increases, Scaled distance increases correspondingly and the value of blast pressure reduces by some amount. The blast parameters along the height of the building are shown in Table 2 to Table 8 for all the three categories of buildings.

Table-2: Blast parameters for W= 100 kg and R= 20 m

Ht. (m)	Z	P_r(psi)	P_{so}(psi)	t_A(ms)	t_o (ms)
0	10.22	22	9	28.88	16.04
1	10.23	21.99	8.99	28.88	16.04
2	10.27	21.95	8.96	29.08	16.24
3	10.33	21.91	8.90	29.27	16.49
4	10.42	21.87	8.86	29.40	16.62
5	10.53	21.84	8.83	29.52	16.69
6	10.66	21.80	8.79	29.59	16.75
7	10.82	21.77	8.76	29.65	16.81
8	11.00	21.74	8.71	29.72	16.88
9	11.20	21.70	8.68	29.78	16.88

Table-3: Blast parameters for W= 200 kg and R= 20 m

Ht. (m)	Z	P_r (psi)	P_{so} (psi)	t_A(ms)	t_o (ms)
0	8.11	39	15	25.07	18.76
1	8.12	38.99	14.99	25.15	18.76
2	8.15	38.95	14.96	25.39	19
3	8.20	38.92	14.91	25.55	19.16
4	8.27	38.86	14.88	25.72	19.33
5	8.36	38.70	14.72	25.88	19.49
6	8.46	38	14.50	25.96	19.65
7	8.59	37.92	14.35	26.04	19.735
8	8.73	37.80	14.29	26.12	19.816
9	8.89	37.70	14.24	26.20	19.89

Table-4: Blast parameters for W= 200 kg and R= 30 m

Ht. m)	Z	P_r (psi)	P_{so} (psi)	t_A(ms)	t_o (ms)
0	12.16	18.5	8	41.24	22.64
1	12.16	18.5	8	41.24	22.64
2	12.19	18.47	7.98	41.41	22.88
3	12.22	18.40	7.5	41.65	23.05
4	12.27	18.2	7.3	41.89	23.45
5	12.33	18.1	7.1	41.97	23.53
6	12.40	18.0	7	42.05	23.69
7	12.49	17.98	6.99	42.13	23.77
8	12.59	17.95	6.95	42.21	23.79
9	12.70	17.90	6.90	42.30	23.82

Table-5: Blast parameters for W= 200 kg and R= 40 m

Ht. (m)	Z	P_r (psi)	P_{so} (psi)	t_A(ms)	t_o (ms)
0	16.28	10	4.5	66.87	24.97
1	16.28	10	4.5	66.87	24.97
2	16.30	9.99	4.49	67.03	25.21
3	16.33	9.97	4.46	67.11	25.21
4	16.36	9.95	4.45	67.19	25.30
5	16.41	9.92	4.43	67.20	25.30
6	16.46	9.91	4.42	67.22	25.33
7	16.53	9.90	4.41	67.23	25.34
8	16.60	9.89	4.40	67.24	25.35
9	16.69	9.87	4.39	67.25	25.36

Table-6: Blast parameters for W= 300 kg and R= 20 m

Ht. (m)	Z	P_r (psi)	P_{so} (psi)	t_A(ms)	t_o (ms)
0	7.08	55	20	22.22	18.51
1	7.09	54.9	19.9	22.22	18.51
2	7.12	54.00	19.00	22.31	19.44
3	7.16	53.5	18.5	22.49	19.72
4	7.22	53.0	18.0	22.68	19.99
5	7.30	51.0	17.9	22.86	20.09
6	7.39	50	17.5	22.96	20.18
7	7.50	49.5	17.1	23.14	20.27
8	7.63	49	16.9	23.33	20.36
9	7.76	48.5	16.7	23.42	20.46

Table-7: Blast parameters for W= 300 kg and R= 30 m

Ht. (m)	Z	P_r (psi)	P_{so} (psi)	t_A(ms)	t_o (ms)
0	10.63	21.80	8.80	42.58	24.07
1	10.63	21.80	8.80	42.58	24.07
2	10.65	21.78	8.79	42.58	24.25
3	10.68	21.77	8.78	42.77	24.25
4	10.72	21.75	8.75	42.86	24.25
5	10.77	21.70	8.71	42.95	24.35
6	10.83	21.6	8.67	43.05	24.44
7	10.90	21.55	8.65	43.19	24.48
8	10.98	21.51	8.61	43.29	24.51
9	11.08	21.48	8.57	43.33	24.55

Table-8: Blast parameters for W= 300 kg and R= 40 m

Ht. (m)	Z	P_r (psi)	P_{so} (psi)	t_A(ms)	t_o (ms)
0	14.17	12	5.1	64.80	26.84
1	14.17	12	5.1	64.80	26.84
2	14.19	11.98	5.0	64.90	26.94
3	14.21	11.96	4.99	65.27	26.94
4	14.24	11.93	4.97	65.55	27.03
5	14.28	11.91	4.96	65.73	27.12
6	14.33	11.90	4.95	65.82	27.12
7	14.38	11.89	4.94	65.92	27.22
8	14.45	11.88	4.93	66.01	27.31
9	14.52	11.87	4.92	66.10	27.40

These blasts reflected overpressures are applied to the front side of building in form of blast force. To obtain blast forces these pressures are multiplied with the contributing area of each node. Sample calculations for forces acting on the nodes due to blast weight of 100 kg at standoff distance of 20 m are shown below:
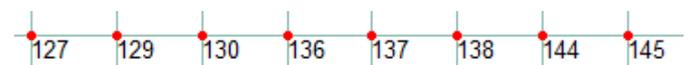
At Ground Floor

For outer nodes (Node no 1, Node no. 4)
P_r = 22 psi = 0.022 ksi = .022 x 6.895 = 0.15169MPa
Blast Force P_1 = 0.15169 x 0.25 x 1000 = 37.92 kN
For inner nodes P_{ro} = 0.15169MPa

Blast Force P_2 = 0.1516 x 0.5 x1000 = 75.84 kN

At 1 m Height of Building

For outer nodes, (Node no 128, Node no. 146)
P_r = 21.99 psi = 0.15162MPa
Blast Force P_3 = 0.15162 x 0.5 x 1000 = 75.81 kN
For inner nodes,

P_r = 0.15162MPa
Blast Force P_4 = 0.15162 x 1 x1000 = 151.62 kN

At 2 m Height of Building

For outer nodes, (Node no 124, Node no. 143)
P_r = 21.95 psi = 0.15134MPa
Blast Force P_5 = 0.15134 x 0.5 x 1000 = 75.67 kN
For inner nodes,

P_{ro} = 0.15134MPa
Blast Force P_6 = 0.15134 x 1 x1000 = 151.34 kN

At 3 m Height of Building

For outer nodes,(Node no 5, Node no. 8)
Blast Force P_7 = 75.53 kN
For inner nodes,

Blast Force P_8 = 151.06 kN

At 4 m Height of Building

For outer nodes,(Node no 102, Node no. 120)
Blast Force P_9 = 75.39 kN
For inner nodes,

Blast Force P_{10} = 150.79 kN

At 5 m Height of Building

For outer nodes, (Node no 98, Node no. 117)
Blast Force P_{11} = 75.29 kN
For inner nodes,

Blast Force P_{12} = 150.58 kN

At 6 m Height of Building

For outer nodes,(Node no 9, Node no. 12)
Blast Force P_{13} = 75.15 kN
For inner nodes,
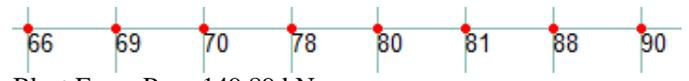

Blast Force P_{14} = 150.311 kN

At 7 m Height of Building

For outer nodes, (Node no 72, Node no. 94)
Blast Force P_{15} = 75.05 kN
For inner nodes,

Blast Force P_{16} = 150.10 kN

At 8 m Height of Building
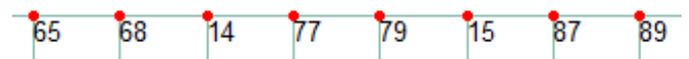
For outer nodes,(Node no 67, Node no. 91)
Blast Force P_{17} = 74.94 kN
For inner nodes,

Blast Force P_{18} = 149.89 kN

At 9 m Height of Building

For outer nodes,(Node no 13, Node no. 16)
Blast Force P_{19} = 37.50 kN
For inner nodes,

Blast Force P_{20} = 74.81 kN

3. VARIATION OF BLAST PRESSURES

Table-9: Blast parameters for W = 100 kg with different values of stand-off distance 'R'

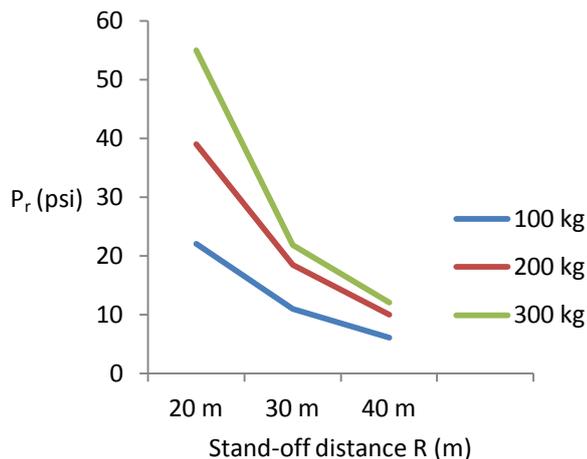| R (m)	Z (ft/lb$^{1/3}$)	P_r (psi)	P_{so} (psi)
20	10.22	22	9
30	15.33	11	4.9
40	20.44	6.1	2.9

Table-10: Blast parameters for W = 200 kg with different values of stand-off distance 'R'

R (m)	Z (ft/lb$^{1/3}$)	P_r (psi)	P_{so} (psi)
20	8.11	39	15
30	12.16	18.5	8
40	16.28	10	4.5

Table-11: Blast parameters for W = 300 kg with different values of stand-off distance 'R'

R (m)	Z (ft/lb$^{1/3}$)	P_r (psi)	P_{so} (psi)
20	7.08	55	20
30	10.63	21.80	8.80
40	14.17	12	5.1

Fig-9: Peak reflected overpressure v/s Stand-off distance R for different blast weights.

From above results it is clear that as the stand-off distance increases from the building, the magnitude of blast pressure reduces significantly. Fig 9 shows that blast parameters are greatly dependent on weight of blast and stand-off distance. As the weight of blast increases i.e. from 100 kg to 200 kg at stand-off distance of 20 m, the pressure increases by 77.27% and when the blast weight increases from 100 kg to 300 kg at same distance then the pressure increases by 150%. For all the three cases which are discussed above, blast pressure increases as weight of blast increases and blast pressure decreases when stand-off distance increases. If the stand-off distance increases from 20 to 30 m for 100 kg blast weight then the blast pressure reduces by 50% and if distance changes from 20 to 40 m for 100 kg blast, then the pressure reduces by 72.27%. It was also observed that if the distance of blast changes from 20 to 30 m for 200 kg of blast then the blast pressure reduces by 52% and if distance of blast changes from 20 to 40 m for 200 kg blast, then the pressure reduces by 74.35%. For 300 kg blast weight, the pressure reduces by 60.36% and 78.18% if the stand-off distance changes from 20 to 30 m and 20 to 30 m respectively. It clearly depicts the dependency of blast parameters on R/W ratio.

4. CONCLUSION

The following observations and conclusions are drawn from this study:

1. Peak static pressure P_{so} is found to be increasing as the weight of blast increases. Peak static pressure increases by 66.6% if the blast weight increases from 100 kg to 200 kg. If the value of blast weight increases from 100 kg to 300 kg then the value of peak static pressure increases by 122% at a stand-off distance of 20m. It shows the dependency of blast pressures on weight of TNT or blast.

2. Peak static pressure P_{so} is decreasing as the stand-off distance increases. Peak static pressure decreases by 45% to 50% if the stand-off distance changes from 20 to 30 m. On further increasing the stand-off distance i.e. from 20 to 40 m, the value of pressure decreases by approximately 65% to 70%. It shows the dependency of blast pressures on stand-off distance of explosion from the building.

3. Peak reflected overpressure P_r is increasing as the weight of blast increases. Peak reflected overpressure increases by 77.27% if the blast weight increases from 100 kg to 200 kg. If the value of blast weight increases from 100 kg to 300 kg then the value of peak reflected pressure increases by 150% at a stand-off distance of 20m. It shows the dependency of blast pressures on weight of TNT or blast.

4. Peak reflected overpressure P_r was decreasing as the stand-off distance increases. Peak reflected overpressure decreases by 50%, if standoff distance changes from 20 to 30 m. On further increasing the stand-off distance i.e. from 20 to 40 m, the value of pressure decreases by approximately 75%. It shows the dependency of blast pressures on stand-off distance of explosion from the building.

5. Effect of peak static pressure and peak reflected overpressure was more at ground storey than upper storeys and their effect decreases almost linearly by 3.5% to 10 % approximately at a height of 9 m.

6. Blast waves take milliseconds to reach the building from site of explosion and affect the building.

7. From above computations of blast pressures, it was observed that blast pressure was inversely proportional to blast scaled distance (Z).

REFERENCES

[1] Draganic, H. & Sigmund, V., "Blast Loading On Structures." J.J Strossmayer University of Osijek.

[2] UFC 3-340-02, 5 December 2008. United Facilities Criteria, "Structures to resist the effects of accidental explosions."

[3] Brode, H.L., 1995, "Numerical solution of spherical blast waves", *Journal of Applied Physics*, June, No.6.

[4] Newmark, N. M., and Hansen R.J. 1961, "Design of blast resistant structures." *Shock and vibration Handbook*, Vol. 3, Eds. Harris and Crede, McGraw-Hill, New York, USA.

[5] Mills C.A., "The design of concrete structure to resist explosion and weapon effects," *Proceedings of the first International conference on concrete for hazard protections*, Edinburgh, UK, pp 61-73, 1987.

[6] Mays, G.C., and P.D. Smith., 1995, Blast effects on Buildings. London: Thomas Telford Publications.