



# Parametric study of blast loads on structures

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## Abstract

The detrimental effects of blast loads can lead to severe damage in buildings, causing the collapse of structural components. This study focuses on a parametric analysis of blast loads on a Reinforced Concrete (RC) structure in SAP2000 for analysis. The research aims to assess how blast pressure, base reaction, and deformation vary with changes in explosive mass and standoff distances. To determine blast reactions, non-linear time history analysis is conducted through 16 different cases, involving varying distances and explosive masses. The findings reveal that an increase in explosive mass and a decrease in standoff distance result in elevated blast pressure, rendering the structure more susceptible to performance deterioration.

**Keywords** Blast loads · Parametric analysis · Explosive mass · Non-linear time history analysis

## Introduction

In a world characterized by global interconnectivity, attacks on infrastructure by assailants present a substantial threat to the security and stability of nations globally. Acts of violence, frequently directed at vital facilities such as transportation hubs, energy installations, and communication networks, possess the potential for extensive and devastating consequences, especially when incorporating explosions and blast loads. National Funeral Directors Association of the United States, Inc. (NFDA)'s report highlights an increase in death rates when comparing home fires in the 1980s to the period of 2005–2014, underscoring the importance of investigating blast loadings (Sesseng et al., 2017). In India, a study reveals a significant risk from accidental explosions in fireworks and match industries, with 398 fatal incidents reported in a prominent firecracker hub.

The Puttingal Goddess Temple explosion in Kerala in 2016 resulted in extensive damage, emphasizing the critical need for enhanced studies on blast loadings due to the collapse of concrete structures (Iliyas & Mani, 2018). Blast waves subject structures to pressure loads that can be many times greater than normal structural loads because the load acts on the building quickly without giving it the time to react or resist and then immediately decreases in magnitude. As a result, the peak strength of the blast phenomena lasts only briefly. The explosion can be broadly divided into exterior and interior explosions. Air burst explosions occur when the explosion is far away from the structure and above it, whereas surface blasts happen when the explosion occurs close to or on the ground. Compared to shock pressure from an external explosion, this pressure has a longer duration. Progressive collapse is the eventual collapse of an entire structure or a disproportionately big portion of it as a result of the spread of an initial local failure from element to element. Air burst is associated with explosive events, whether accidental (e.g., industrial accidents) or intentional (e.g., terrorist attacks). Progressive collapse, on the other hand, may result from a range of factors, including structural design flaws, inadequate construction practices, or unforeseen events leading to localized failures. It is challenging to develop a building that is blast-proof due to the significant degree of variability in blast load predictions. However, a number of structural and non-structural safety measures can be taken to reduce physical injuries and structural damage. In a comprehensive investigation of

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blast-resistant structures, various studies utilized advanced computational tools such as AUTODYN, LS Dyna, and SAP2000 to analyze the behavior of structures exposed to accidental explosions and terrorist attacks (Goel et al., 2011; Janney, 2007; Luccioni et al., 2004). The impact of blast loads on semi-buried structures, including soil-structure interaction, was explored using Finite Element Analysis with ABAQUS software (Kumar et al., 2012). Additionally, researchers investigated the design of blast-resistant structures and proposed measures such as sacrificial walls for pre-existing structures (Goel, 2015). Studies also assessed the effects of blast loads on specific structures, including G+4 RC structures and domed-shaped structures, employing LS Dyna for dynamic analysis (Kashif & Varma, 2017; Sahu & Gupta, 2015). The importance of shear walls, bracings, and specific structural elements, and their role in reducing top storey deflection, were highlighted in the context of blast load analysis on multistoried structures (Bharath & Guruprasad, 2021). While existing literature underscores the significant influence of specific design parameters on the structural behavior of reinforced concrete (RC) buildings, insufficient attention has been devoted to understanding the variations in blast pressure, base reaction, and deformation concerning changes in explosive mass and standoff distances. The inadequacy of the Indian Code for Blast Load Calculation (IS:4991-1968, 1968) in addressing blast pressure, particularly for short distances, and its restriction to the TNT explosive type have been recognized. To fill these gaps, this study proposes alternative methods for blast pressure calculation and presents a comprehensive conversion table for various explosives. Furthermore, the current research lacks diverse analysis methods for different collapse scenarios. This study aims to address this deficiency by introducing distinct analysis methods tailored to various cases of progressive collapse. The thrust of the study is (1) to determine the blast pressure on faces of building using IS Code method. (2) to analyze the response of a structure subjected to blast load. (3) to perform the parametric study of the structure subjected to blast load for various TNT mass charge and standoff distances.

## Blast Pressure

In this section we will discuss the definition, concept of blast pressure on a rectangular closed structure, methodology to calculate blast pressure, the application of blast pressure on structures in SAP2000 and the response of the structure subjected to blast loads. A parametric study is also performed to calculate the effects of blast loads when the standoff distances and explosive mass changes.

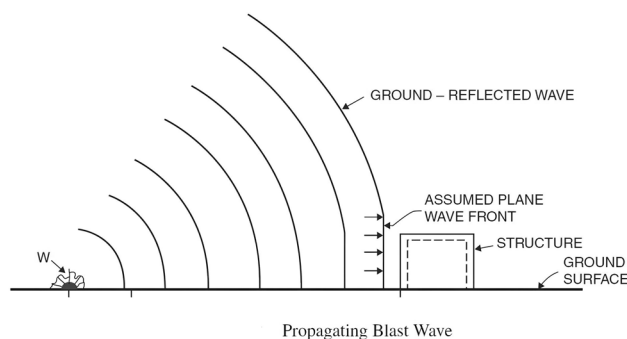


Fig. 1 Propagation of blast wave (Design, 2010)

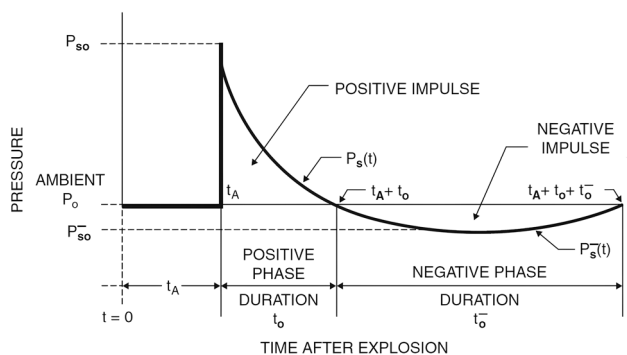


Fig. 2 Pressure variation with respect to time after an explosion (Design, 2010)

A blast is a pressure rise caused on by an abrupt energy release. The load resulting from the explosion is produced by the rapid expansion of the energetic material, creating a pressure disturbance or pressure wave that radiates from the source of the explosion. The adjacent figure, Fig. 1, shows the propagation of pressure waves in the ground up to the facade of the building.

Figure 2 depicts the idealized pressure profile for the case of a free air blast wave reaching a place at a certain distance from the detonation. When the shock front gets at the element at time  $t_A$ , the pressure immediately around it rises to a peak pressure  $P_{so}$  from its original value of ambient pressure  $P_o$ .  $P_o$  is considered to be zero because the pressure reaches its greatest value in such a short period of time. The peak pressure is also known as the side-on overpressure, or  $P_{so}$ . The peak overpressure and shock wave propagation velocity both decrease as one moves away from the explosion point.

The positive incident pressure falls off rapidly, as seen in Fig. 2. It has been suggested that Friedlander's equation take the following form Eq. (1), and this rate of drop in pressure values is commonly described in this way.

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

where,  $t_0$ : positive phase duration,  $\alpha$ : decay coefficient of the waveform and  $t$  is the time elapsed, measured from the instant of blast arrival.

Due to their large magnitude and short duration, blast loads differ from the normal loads to which structural engineers are accustomed. The velocity at which explosive loads are applied is several orders of magnitude faster than the velocity at which seismic loads are applied.

To determine the effect of a blast pressure on a structure, it is necessary to calculate the pressure that the structure can withstand without damage. This value is known as the “blast resistance” or “blast load capacity”. If the calculated blast pressure exceeds the blast resistance, the structure may experience damage ranging from minor cracks to complete collapse. It is important to design structures to withstand the expected blast pressure for the specific location and potential explosive hazards. The principle of how blast loads have an effect on the different sides of the building is covered in this section.

### Concept of blast pressure on a rectangular closed structure

The shock wave's behavior when it strikes a closed rectangular structure is depicted in Fig. 3a–d. This image shows the shock front's position and the diffracted and reflected wave's behavior across the structure's center in a close rectangular section. When the shock front strikes the building's front face, a reflected shock wave is produced (Fig. 3a), raising the overpressure there above the incident shock wave's peak overpressure. The enhanced overpressure, also known as the reflected overpressure, is determined by the incident shock front's peak overpressure and the shock front's angle of incidence with the front wall, which is zero degrees in this instance. The lower overpressure of the incident blast wave, which was present when the reflected shock front developed near the top edge of the front face (Fig. 3b), began a rarefaction wave, or a wave with a lower overpressure than that of the reflected shock wave. The reflected shock wave conveys this rarefaction wave at the speed of sound towards the front face's base. The occurrence shock wave and the reflected shock wave both crumble inside a short time-frame known as the clearing time, and the front face's overpressure is decreased to a level that is in harmony

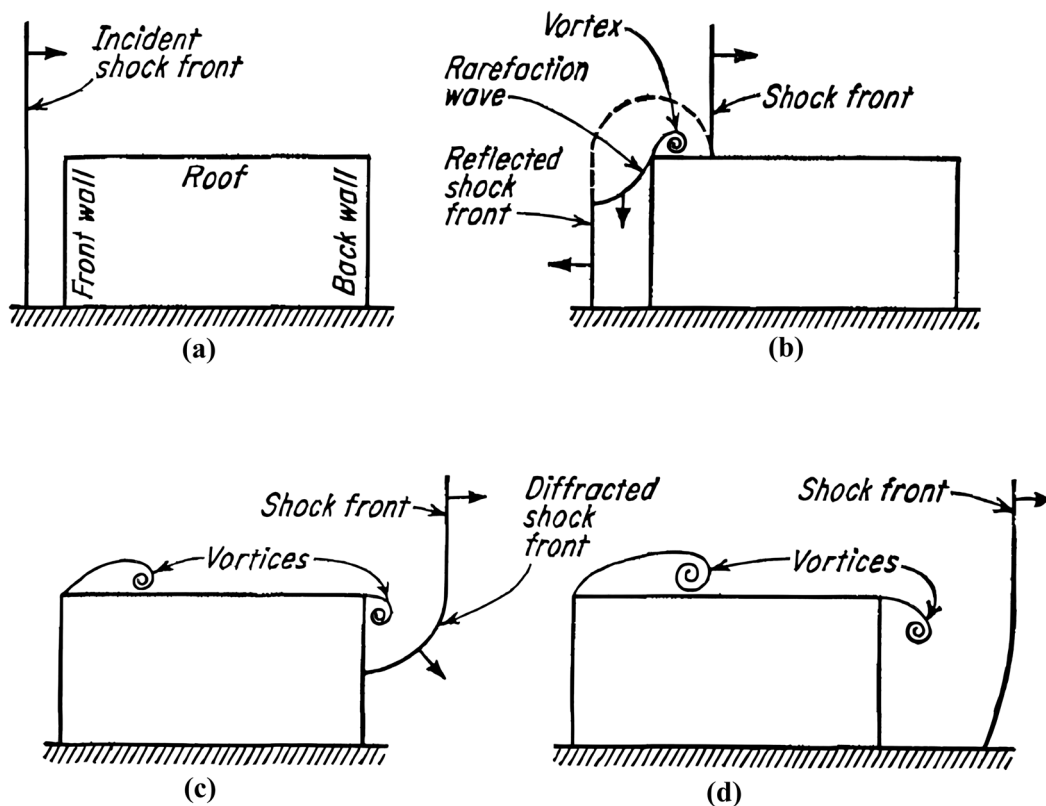
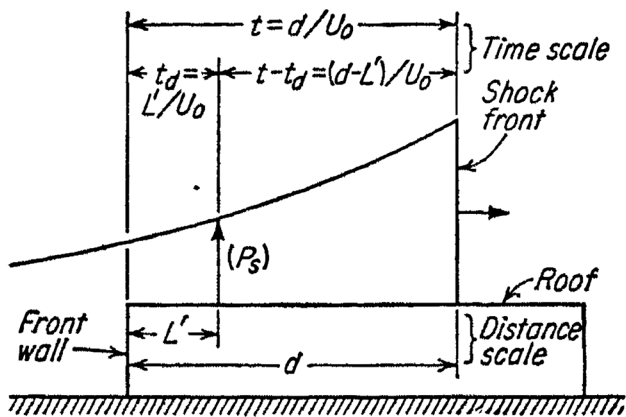
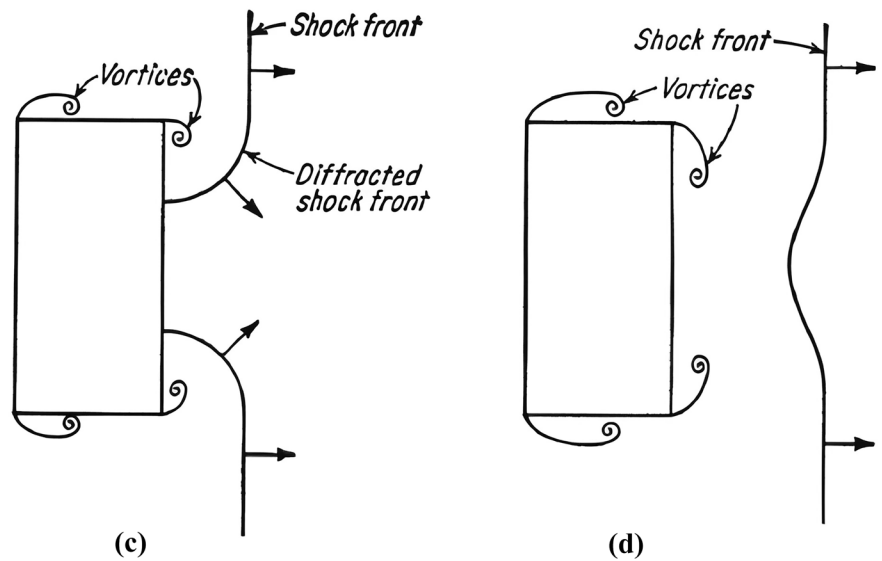
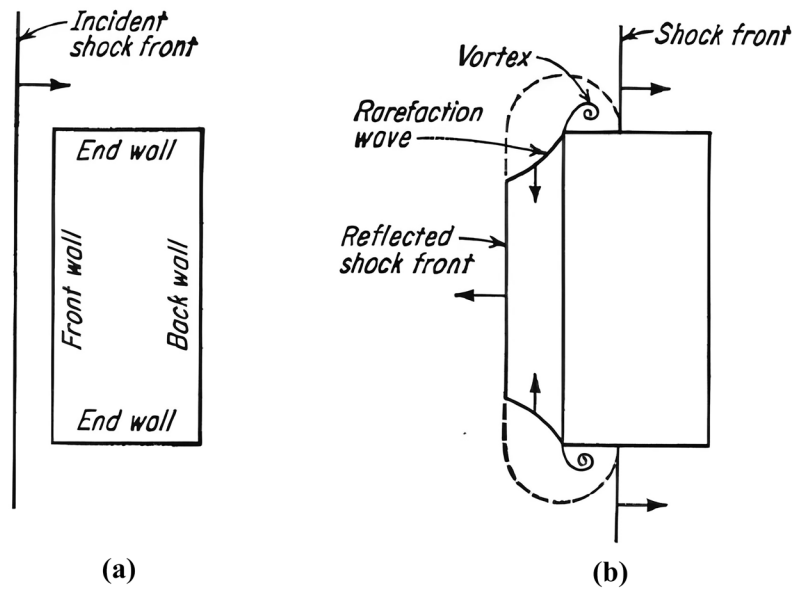


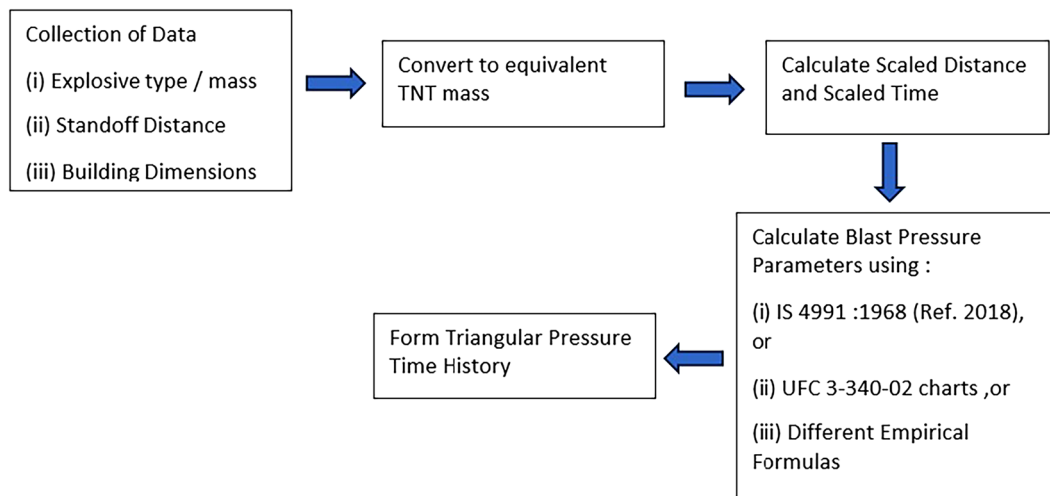
Fig. 3 Behaviour of a blast wave along the center of a closed rectangular structure (Norris, 1959)

**Fig. 4** Blast wave behaviour along a horizontal part of a closed rectangular structure (Norris, 1959)



**Fig. 5** Time displacement factor convention illustration (Norris, 1959)

with the high-speed air stream related with the episode shock wave. Overpressure on the front face equals the overpressure caused by stagnation at the base of the front face. This is slightly less than the overpressure caused by the blast wave at the top edge of the front face when equilibrium with the high-velocity air stream is established. The expression “stagnation overpressure” refers to an overpressure that exists in a space where the streaming air has altogether quit moving, expanding the strength of the tension by how much the active energy of movement. The shock front arrives at the back boundary of the structure and starts streaming down towards the lower part of the back wall after the shock wave influences the front mass of the design by a period equivalent to the length of the construction separated by the shock-front speed (Fig. 3c).



**Fig. 6** Flow Chart for blast pressure calculation

**Table 1** Conversion factors for various explosive (Shirbhate & Goel, 2020)

S. no.	Explosive type	Heat of explosive Q <sub>x</sub> (kJ/kg)	TNT equivalent Q <sub>x</sub> /QTNT
1	Compound B (60% RDX 40% TNT)	5190	1.148
2	RDX (Cyclonite)	5360	1.185
3	HMX	5680	1.256
4	Nitroglycerien (liquid)	6700	1.481
5	TNT	4520	1
6	Blasting Gelatin (91% nitroglycerin, 7.9% nitro-cellulose, 0.9% antacid, 0.2% water)	4520	1
7	60% Nitroglycerine dynamite	2710	0
8	Semtex	5660	1.25
9	Hexogen	6334	1.38
10	Octogen	6538	1.46
11	Tetryl	5920	1.13
12	Pentolite 50/50	5860	1.129
13	PETN (90/10)	6406	1.23
14	Pentrite	6400	1.13

The back wall begins to experience higher stresses as soon as the shock front moves past it. The effect moves down from the top of the back wall to the bottom. A vortex is framed on the back wall and extends in size, going towards the base from the top edge and furthermore creating some distance from the wall (Fig. 3c). A vortex is a locale of air turning on a hub at a fast with low overpressures existing at its middle because of the Venturi impact. The maximum back-wall overpressure slowly develops as a result of two factors: (1) vortex phenomena; and (2) the amount of time required for the back wall to be encompassed by the blast wave.

The structure's roof experiences an initial overpressure that is nearly identical to the incident shock wave's overpressure as the shock front moves beyond the front wall.

On the other hand, a vortex forms along the top edge of the front wall due to the pressure difference between the blast-wave overpressure on the roof and the reflected overpressure on the wall. Along the roof of the structure, the vortex moves at a rate that is slower than the shock-front velocity, and its intensity gradually decreases (Fig. 3d). As a result, the incident shock wave's excess pressures begin to decrease. After this vortex passes, a second buildup of overpressures along the roof occurs as the shock wave's higher overpressure takes back control. A horizontal section of the structure reveals that these phenomena have the same effect on the roof as they do on the sides. As a result, the general discussion in the preceding paragraph explains how the structure's sides and roof are affected by the shock wave. This behavior is shown in Fig. 4.

**Table 2** Blast pressure parameters from ground burst of 1 tonne explosive (ref. Table 1 IS 4991:1968)

Distance (m) x	Peak side on over-pressure ratio $P_{so}/P_a$	Mach No. M	Positive phase duration $t_m$ (milli-sec)	Duration of equivalent triangular pulse, $t_d$ (milli-sec)	Dynamic pressure ratio $q_0/P_a$	Peak reflected overpressure ratio $P_{ro}/P_a$
{1}	{2}	{3}	{4}	{5}	{6}	{7}
15	8	2.8	9.5	5.39	10.667	41.6
18	5	2.3	11	7.18	5.208	22.5
21	3.3	1.96	16.38	9.33	2.643	12.94
24	2.4	1.75	18.65	11.22	1.532	8.48
27	1.8	1.6	20.92	13.3	0.92	5.81
30	1.4	1.48	22.93	15.39	0.583	4.2
33	1.2	1.42	24.95	16.31	0.439	3.45
36	1	1.36	26.71	17.94	0.312	2.75
39	0.86	1.32	28.22	19.2	0.235	2.28
42	0.76	1.28	29.74	20.2	0.186	1.97
45	0.68	1.25	31.25	21.6	0.142	1.66
48	0.59	1.23	32.26	22.7	0.115	1.46
51	0.53	1.2	33.52	23.7	0.093	1.28
54	0.48	1.19	34.52	24.7	0.077	1.14
57	0.43	1.17	35.53	26.4	0.062	1.01
60	0.4	1.16	36.29	26.6	0.054	0.93
63	0.37	1.15	37.3	27.8	0.046	0.85
66	0.34	1.14	38.05	28.76	0.039	0.77
69	0.32	1.13	38.81	29.25	0.035	0.72
72	0.3	1.12	39.56	29.87	0.031	0.67
75	0.28	1.11	40.32	30.71	0.027	0.62
78	0.26	1.104	40.82	31.85	0.023	0.58
81	0.25	1.1	41.58	31.92	0.022	0.55
84	0.24	1.098	42.34	32	0.02	0.53
87	0.23	1.095	42.84	32.26	0.018	0.5
90	0.22	1.086	43.6	33.39	0.016	0.47
93	0.2	1.082	44.35	34.7	0.014	0.43
96	0.19	1.077	45.46	35.37	0.013	0.41
99	0.18	1.072	45.61	36.22	0.012	0.4

When determining a structure's loads, it is appropriate to use the instant the shock front impacts the front face as a reference time ( $t_0$ ). A time-displacement factor  $t$ , which is the amount of time it takes for the shock front to travel from the structure's front face to the surface or point under consideration, must be included in this method. This kind of behavior is shown in Fig. 5.

### Blast pressure calculation

The calculation of blast pressure is the first step involved to calculate the response of any structure subjected to blast. The blast pressure calculation involves the following steps as shown in Fig 6.

### Collection of data

The initial parameters such as explosive type and mass and the standoff distance are needed for the calculation of blast parameters.

### Conversion into equivalent Trinitrotoluene (TNT) mass

If the explosive taken into consideration is not TNT explosive, the above explosive should be converted into equivalent TNT mass using the below expression and the given conversion factors (Table 1)

$$W_e = W_{\text{exp}} \frac{H_{\text{exp}}^d}{H_{\text{tnt}}^d} \quad (2)$$

**Table 3** Drag pressure coefficients (IS:4991–1968 1968)

S. no.	Shape of element	Drag coefficient $C_d$	Remarks
{1}	{2}	{3}	{4}
	<i>For Closed Rectangular Structures</i>		
(i)	Front Vertical Face	1.0	
(ii)	Roof, rear and side faces for $q_0 = 0-1.8 \text{ kg/cm}^3$ $q_0 = 1.8-3.5 \text{ kg/cm}^3$ $q_0 = 3.5-9.0 \text{ kg/cm}^3$	- 0.4 - 0.3 - 0.2	For Structures above ground
(iii)	Front Face Sloping 4-1 1.5-1	0 0.4	For Semi Buried Structures
	<i>For Open Drag Type Structures</i>		
(iv)	Sphere	0.1	
(v)	Cylinder	1.2	This covers steel tubes used as columns, truss members etc
(vi)	Structural Shapes	2	This covers flats, angles, tees, I-Section, etc
(vii)	Rectangular Projection	1.3	This covers beam projection below or above slabs etc

where,  $W_e$  is the TNT equivalent weight (kg).  $W_{exp}$  is the weight of actual explosive (kg).  $H^{dexp}$  is the heat of detonation of actual explosive (kJ/kg) and  $H^{dtnt}$  is the heat of detonation on TNT (kJ/kg)

#### Calculation of scaled distance and scaled time (IS:4991–1968 1968)

**Scaling Laws:** The cube root scaling laws are shown below and can be used to calculate the peak pressures and time durations for any explosion other than the reference explosion from the peak values.

$$\text{Scaled Distance, } x = \frac{\text{Actual Distance}}{W^{\frac{1}{3}}} \quad (3)$$

$$\text{Scaled Time, } t_0 = \frac{\text{Actual Time}}{W^{\frac{1}{3}}} \quad (4)$$

where,  $W$  = Explosive mass in tonnes,  $x$  = Scaled distance used to read the peak values from Table 4.2, and  $t_0$  = Scaled time.

The *Actual Distance* is calculated from the origin to the target location. The time for the real detonation is the *Actual Time*.

#### Calculation of blast pressure parameters

**IS code method** After calculating the scaled distances and scaled time the blast parameters such as Peak Side on Overpressure, Duration of Equivalent Triangular Pulse, Dynamic

Pressure, Peak Reflected overpressure can be calculated as given in Table 1 (here Table 2) and Table 2 (here Table 3) of (IS:4991-1968 1968). The values can be interpolated for intermediate values of scaled distances.

Note 1: The value of  $P_a$  the ambient air pressure can be taken as  $= 1 \text{ kg/cm}^2$ .

Note 2: One tonne explosive referred in this table is equivalent to  $1.5 \times 10^9$  calories.

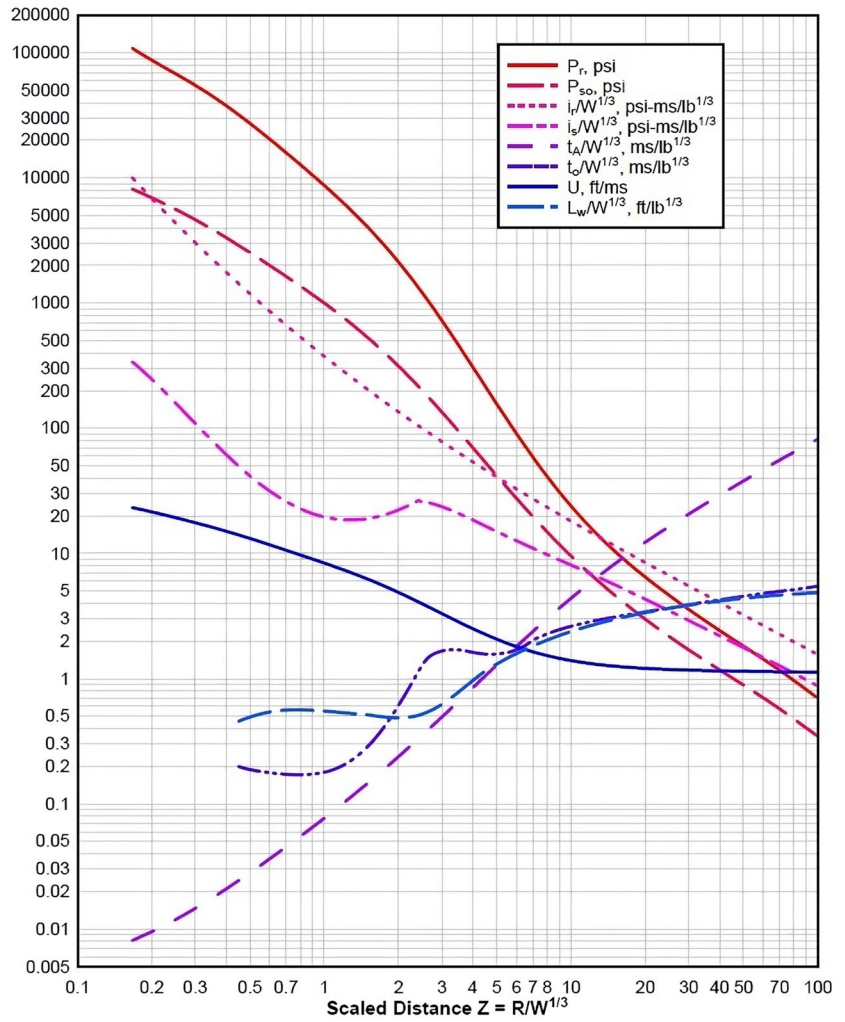
Table 3 has the drag pressure coefficients which is required to calculate the dynamic pressure caused by wind.

When using IS 4991:1968 we encountered that we had a limited values of scaled distances and hence therefore for the calculation of blast pressures and other parameters for nearby distances UFC 3-340-02 charts and other empirical relations can be used after obtaining the scaled distances which are discussed in the adjoining points.

**UFC-3-02 charts** UFC (United Facilities Criteria): 3-340-02 Structures to Resist the effects of Accidental Explosion (DoD, 2008) is a standard proposed by the defense forces of United States for the purpose of identifying the damages caused to a structure when subjected to an explosion. This standard gives the values of all the blast wave parameters in FPS units which can be found after calculating the scaled distance and plotting it with the graph as shown below.

**Using empirical solutions** The blast wave characteristics can also be calculated by the use of empirical formulas given by various researchers.

**Fig. 7** Positive phase shock wave parameter for hemi-spherical TNT Explosion on the surface at sea level (Ref. UFC 3–340-02)



**Table 4** Comparison of results

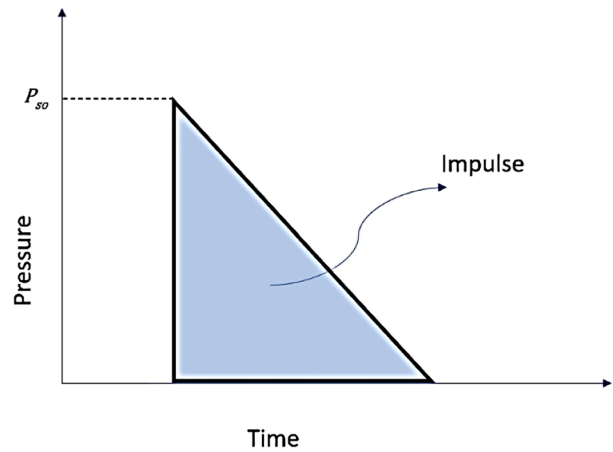
Parameters	IS 4991:1968	Excel calculation
Front face pressure	0.810 kg/cm <sup>2</sup>	0.806 kg/cm <sup>2</sup>
Roof and side faces pressure	0.330 kg/cm <sup>2</sup>	0.337 kg/cm <sup>2</sup>
Rear face pressure	0	0
Duration of equivalent triangular pulse	13.15 ms	13.15 ms

According to Wilson and Paxson (2002), estimates of the peak overpressure brought on by a spherical explosion based on scaled distance  $Z = R/W^{1/3}$  are as follows:

$$P_{so} = \frac{6.7}{Z^3} \text{ 1 bar } (P_{so} > 10 \text{ bar}) \tag{5}$$

$$P_{so} = \frac{0.0975}{Z^1} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \text{ bar } (10 \text{ bar } P_{so} > 0.10 \text{ bar}) \tag{6}$$

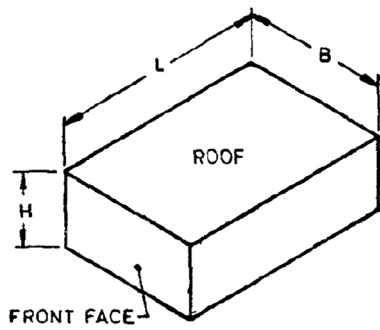
When a high explosive charge detonates at the ground's surface, (Karlos & Solomos, 2013) for calculating the maximum blast overpressure,  $P_s$ , in bars, is as follows:



**Fig. 8** Equivalent triangular representation of a blast wave for design purpose

$$P_{so} = 6784 \frac{W}{R^3} + 93 \left( \frac{W}{R^3} \right)^{2.1} \tag{7}$$





**ABOVE GROUND RECTANGULAR STRUCTURE**

**Fig. 9** Closed rectangular structure above ground (Ref. IS 4991:1968 page 12)

Note: Here  $W$  is in tonnes.

Mills (1987) introduced a different way of expressing the peak overpressure in kPa, in where  $W$  is the equivalent charge weight in kilograms of TNT and  $Z$  is the scaled distance:

$$P_{so} = \frac{1772}{Z^3} - \frac{114}{Z^2} + \frac{108}{Z^1} \tag{8}$$

As  $P_{so}$  is calculated from the above equations the other parameters can be mathematically calculated as:

The dynamic pressure  $q$  can be calculated as:

$$q = \frac{5P_{so}^2}{2(P_{so} + 7Pa)} \tag{9}$$

The reflected pressure can be calculated as:

$$P_r = 2P_{so} \left\{ \frac{7Pa + 4P_{so}}{7P + Pa} \right\} \tag{10}$$

**Formation of Triangular pressure time history**

Clause 2.5.1 of the AISC 26 (AISC26, 2013) Design Code states that the time history for design is often reduced to a triangular distribution with an immediate increase and a linear decrease. For design purposes, the blast wave's negative phase is often disregarded, just its positive phase being taken into consideration.

**Calculation Of Blast Pressure On Each Face As Per IS 4991:1968 (Reaffirmed 2018)**

The front face of the structure experiences the reflected overpressure after the shock wave hits the face of the structure. The reflected overpressure  $P_{ro}$  is given by:

$$P_{ro} = P_{so} \left( 2 + \frac{6P_{so}}{Pa + 7P_{so}} \right) \tag{11}$$

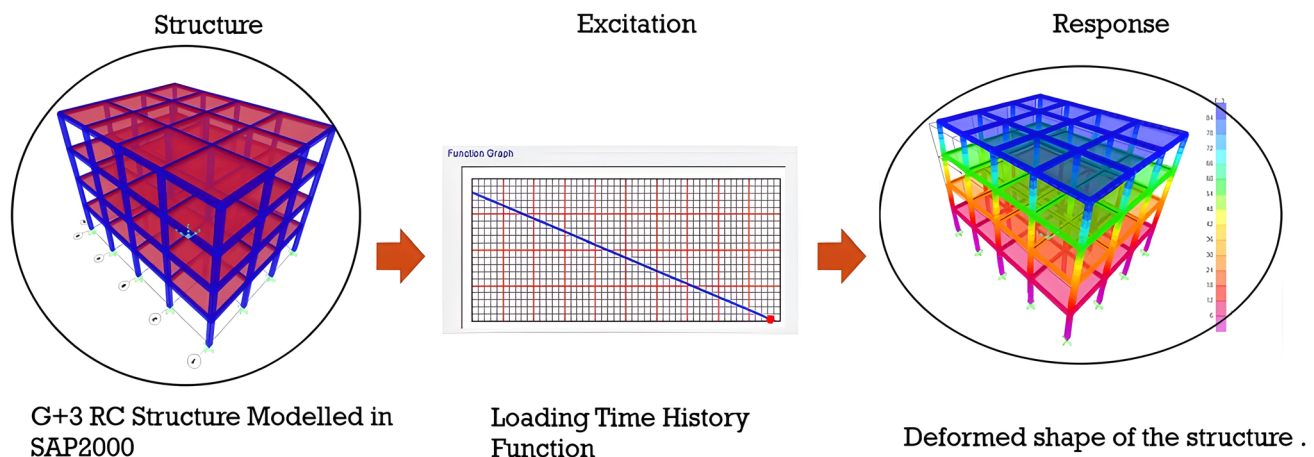
If  $P_a = 1 \text{ kg/cm}^2$ , the values of  $P_{ro}$  are given in Table 2.

As per clause 6.2.1.1 of IS 4991 :1968, the net pressure on the front face is taken as  $P_r$  or  $(Ps+ Cdq)$ , whichever is greater. Where  $Cd$  -drag coefficient given in Table 3, and  $P_r$  is the reflected overpressure which drops from the peak value  $P_{ro}$  to overpressure  $(Ps+ Cdq)$ , in clearance time  $t_c$  given by:

$$t_c = \frac{3S}{U} \text{ or } t_c \text{ whichever is less.} \tag{12}$$

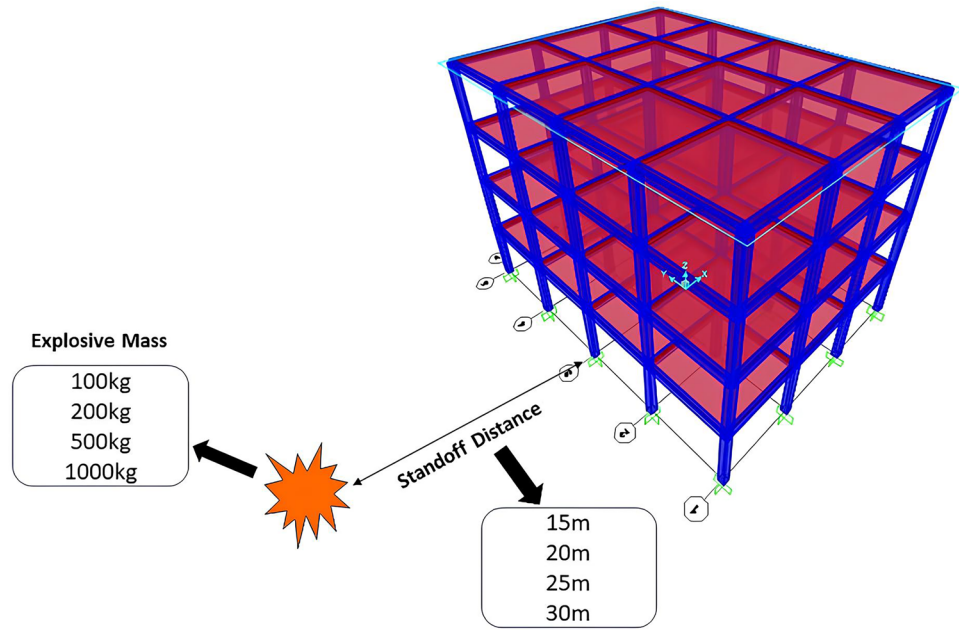
where  $S = H$  or  $B/2$ , whichever is less (see Fig.7)

$$U = \text{Shock Front Velocity} = M \cdot a \tag{13}$$



**Fig.10** Application of blast pressure in SAP2000

**Fig.11** Description of parametric study performed



where  $a$  = velocity of sound in air which may be taken as 344 m/s at mean sea level at 20°C, and  $M$ = Mach Number of the incident pulse given by

$$M = \sqrt{1 + \frac{6P_{so}}{7P_a}} \tag{14}$$

The values of  $M$  for various conditions are also tabulated in Table 2.

**Example validation problem for pressure calculation on each face**

For the validation of pressure calculation on each face of structure an example from Appendix A1 of IS 4991:1968 (Reaffirmed 2018) is taken.

*Example statement:* An above-ground, rectangular structure measuring 3 m high, 10 m wide, and 8 m long, located 30 m from the explosion site, is used to analyze the blast parameters caused by the detonation of a 0.1 tonne explosive.

Complete solution (both analytical and Excel Spreadsheet) of the above example has been solved in Appendix (Table 4).

So from the above table it is clearly evident that the Excel program and the analytical are matching. Hence for the calculation of pressure the results are validated (Figs. 8, 9, 10).

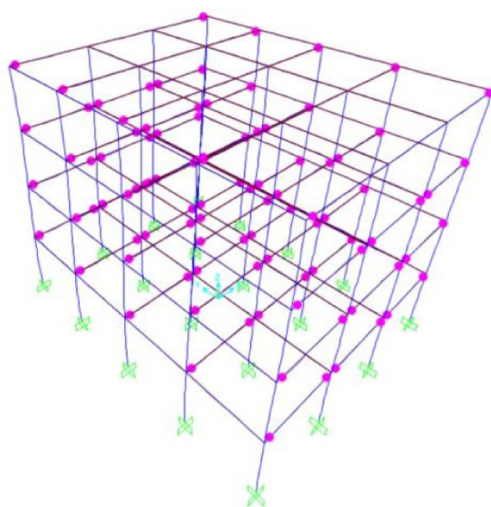
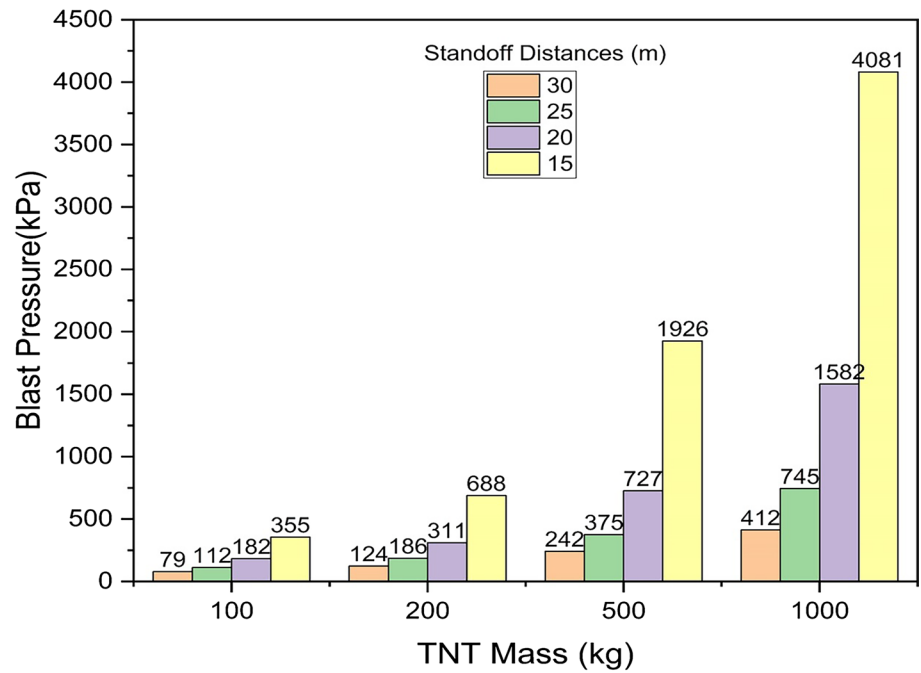
**Table 5** Blast pressure calculation for the parametric study performed

Charge weight (kg)	Standoff distance (m)	Blast pressure on front face (kN/m <sup>2</sup> )	Equivalent triangular duration (milli-sec)
100	15	355	7.47
200	15	688	7.23
500	15	1926	6.21
1000	15	4081	5.39
100	20	182	9.61
200	20	311	9.92
500	20	727	9.56
1000	20	1582	8.61
100	25	112	11.44
200	25	186	12.02
500	25	375	12.58
1000	25	745	11.91
100	30	79	13.15
200	30	124	13.92
500	30	242	14.84
1000	30	412	15.39

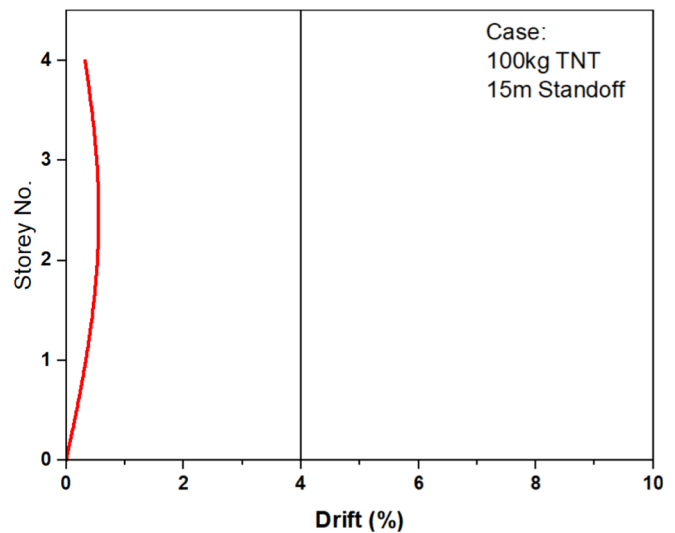
**Application of blast pressure in SAP2000**

After obtaining the pressure v/s time graph for a blast load, the pressure can be converted into load v/s time graph so that it can be put into SAP2000 as a time history function and also from Bharath et al. (2021). The pressure can be converted into concentrated point load as multiplying the pressure and a panel area and dividing it by four. For example, if the blast pressure calculated as 100 kN/m<sup>2</sup> and the

**Fig. 12** Variation of blast pressure for various TNT mass charge and standoff distances



**(a)** Hinge formation for Case 1.



**(b)** Storey Drift for Case 1

**Fig.13** Response of blast loads for Case 1

panel area is 12 m<sup>2</sup>, the force on each corner node of the panel will be 300 kN.

**Parametric study for the response of blast loads on structure**

In this section the response of blast loads is calculated for various standoff distances and various TNT mass charges. Figure 11 shows the description of the parametric study performed on a G+3 RC Building.

**Blast pressure calculation**

The blast pressure is calculated as per the recommendations of IS 4991:1968 (Reaffirmed 2018). Table 5 and Fig. 12 shows the blast pressure on the façade of the structure for the various cases of parametric study.

The above graph (Fig. 12) shows that there is a significant rise in the blast pressure when the TNT mass is increased and also when the standoff distance is reduced.

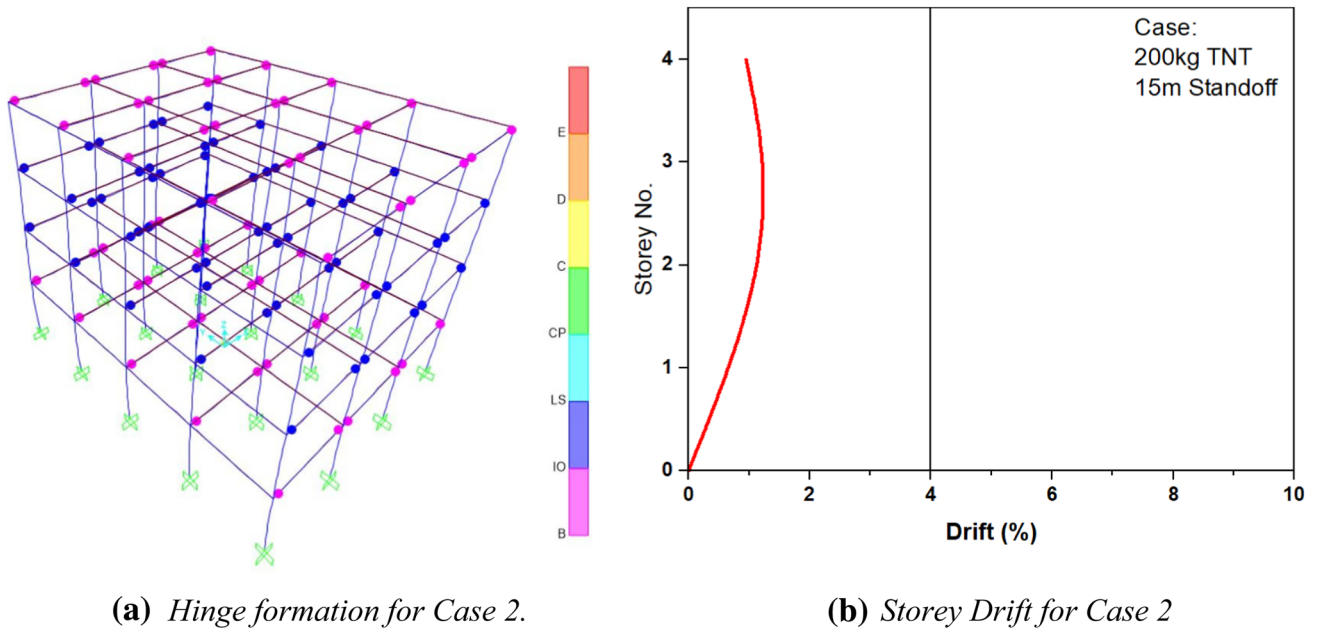


Fig.14 Response of blast loads for Case 2

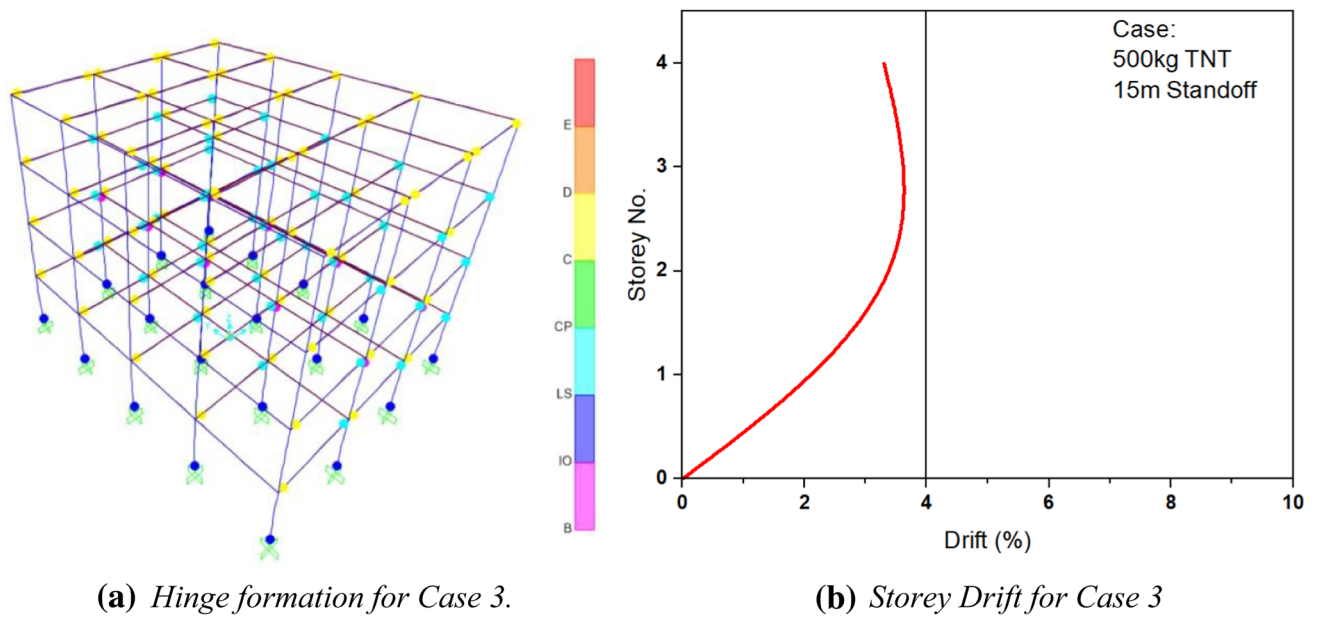


Fig.15 Response of blast loads for Case 3

**Results and discussion on response of blast load on structure**

As discussed in Sect. 2.2, the same methodology is applied for the application of blast pressure on the face

of the building. The hinges are provided and non-linear dynamic analysis is done accordingly in SAP2000 software.

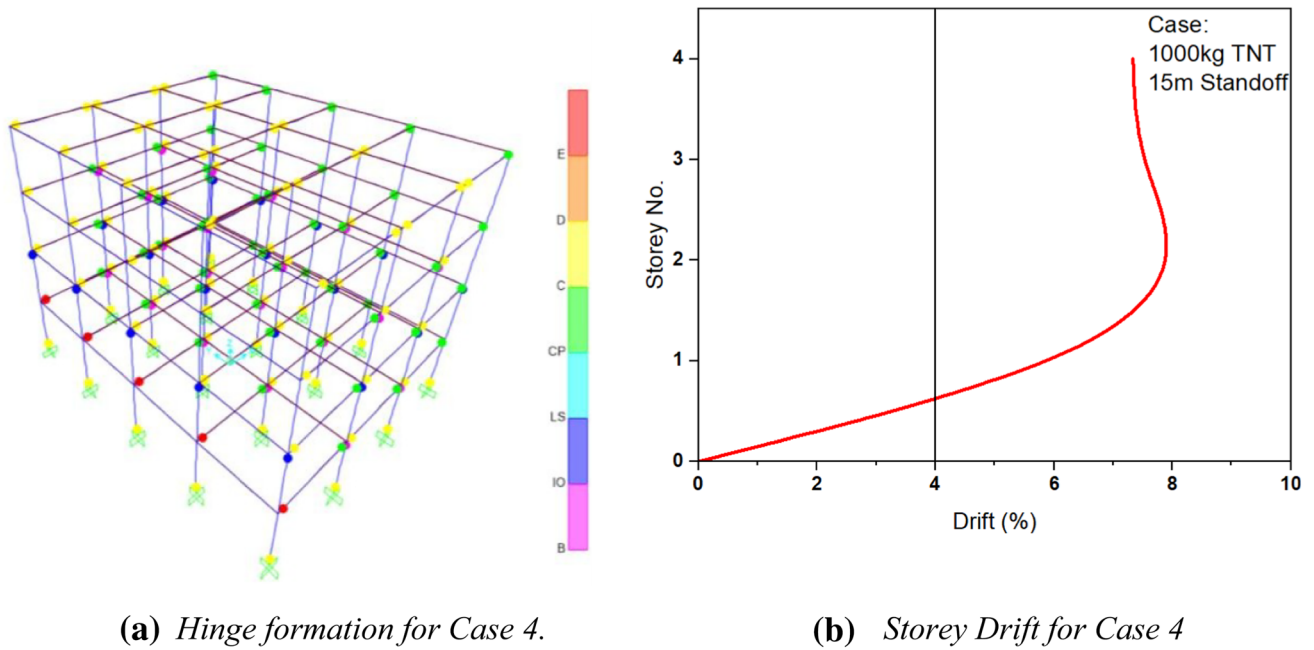


Fig.16 Response of blast loads for Case 4

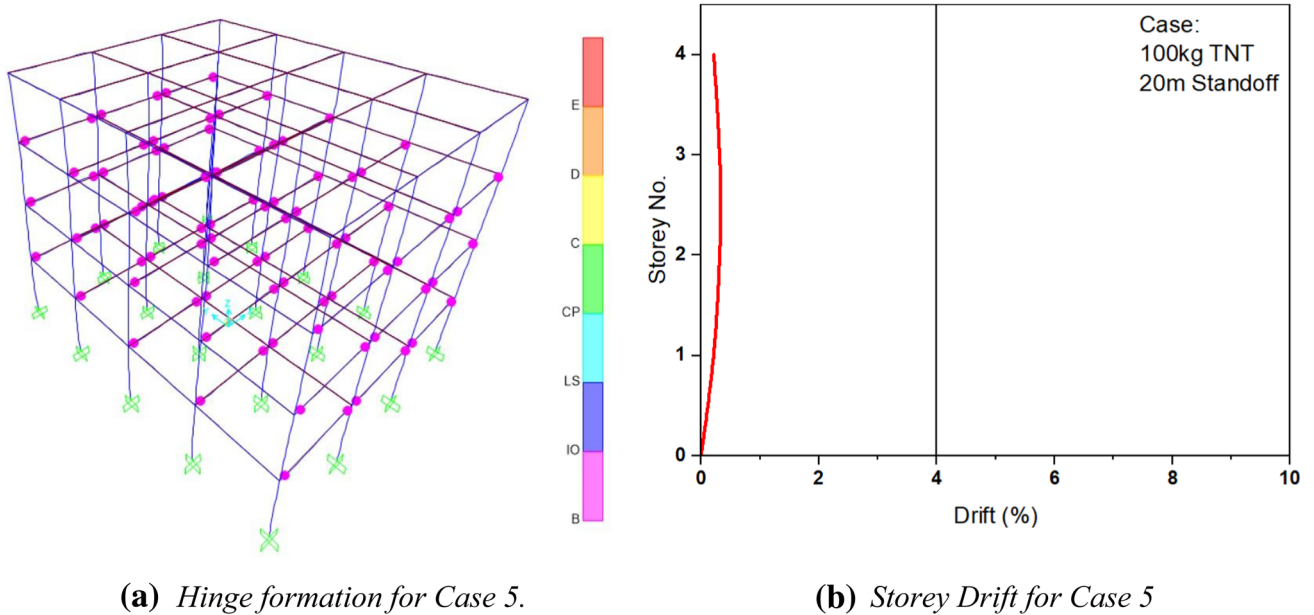


Fig.17 Response of blast loads for Case 5

**Case 1: 100 kg TNT mass and 15 m Standoff distance**

Maximum Top Storey deflection = 54.1 mm and Base Reaction in X-direction = 7444.36 kN (Fig. 13).

**Case 2: 200 kg TNT mass and 15 m Standoff distance**

Maximum Top Storey deflection = 123.5 mm and Base Reaction in X-direction = 14353.4 kN (Fig. 14).

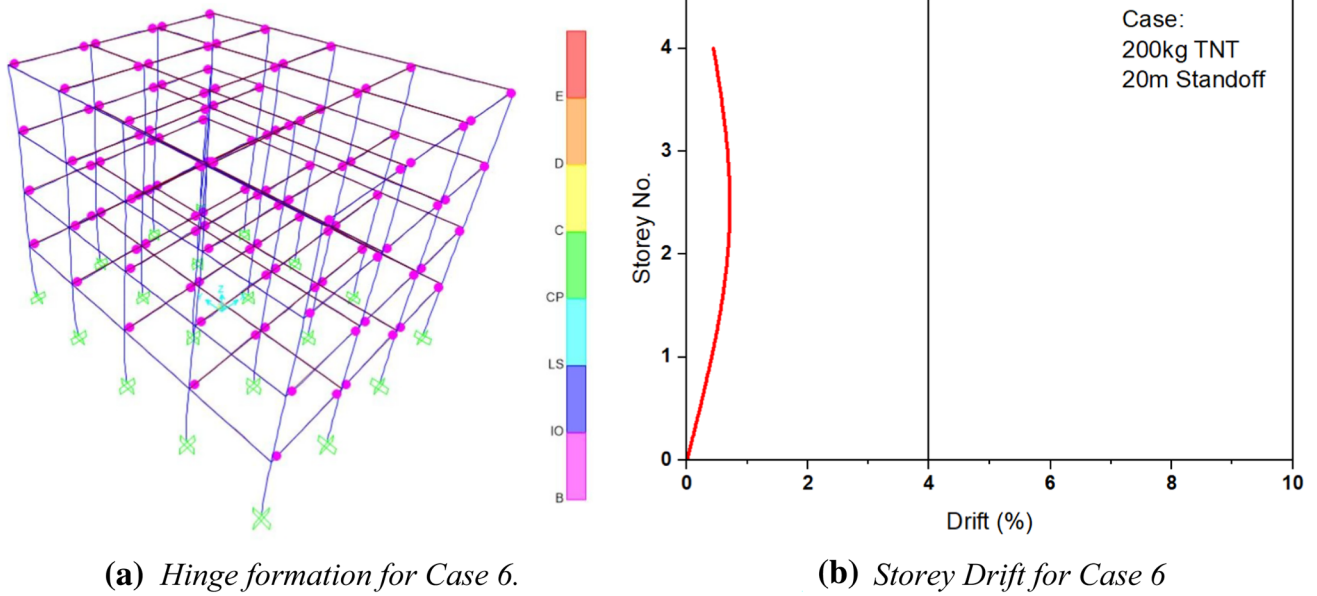


Fig.18 Response of blast loads for Case 6

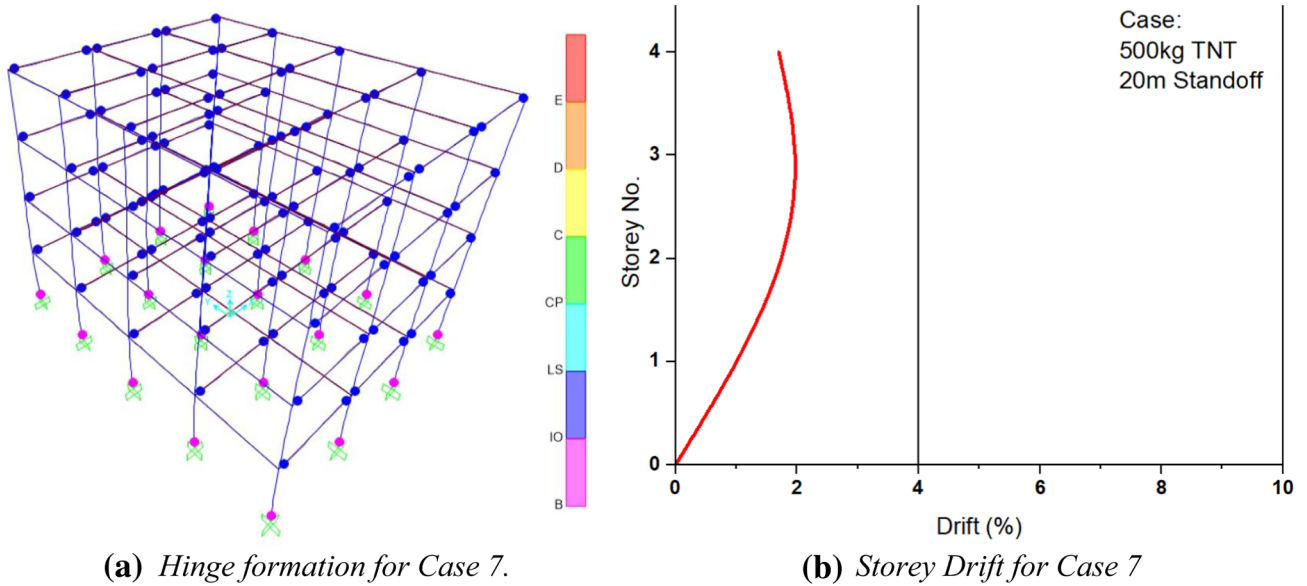


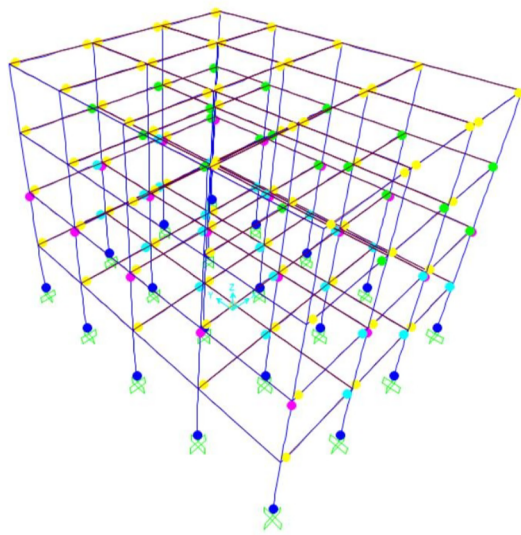
Fig.19 Response of blast loads for Case 7

**Case 3: 500 kg TNT mass and 15 m Standoff distance**

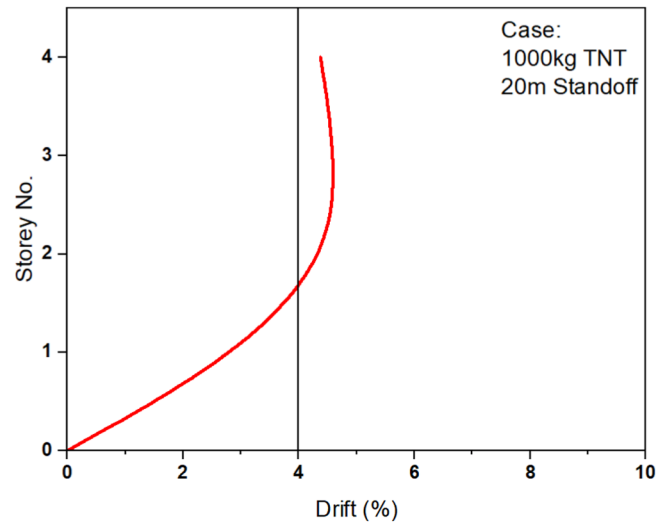
Maximum Top Storey deflection = 385.1 mm & Base Reaction in X-direction = 39121.7 kN (Fig. 15).

**Case 4: 1000 kg TNT mass and 15 m Standoff distance**

Maximum Top Storey deflection = 892.3 mm and Base Reaction in X-direction = 80474.4 kN (Fig. 16).

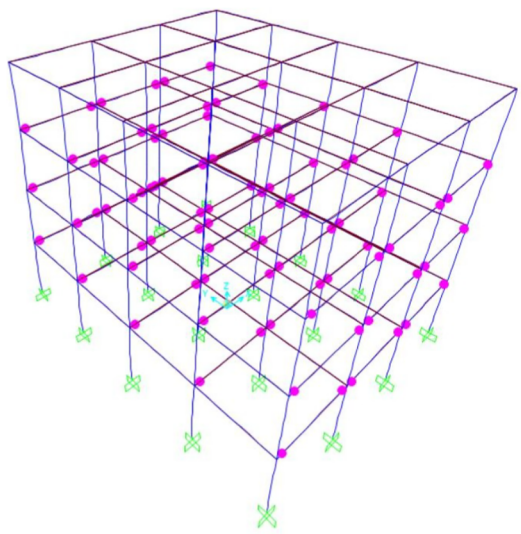


(a) Hinge formation for Case 8.

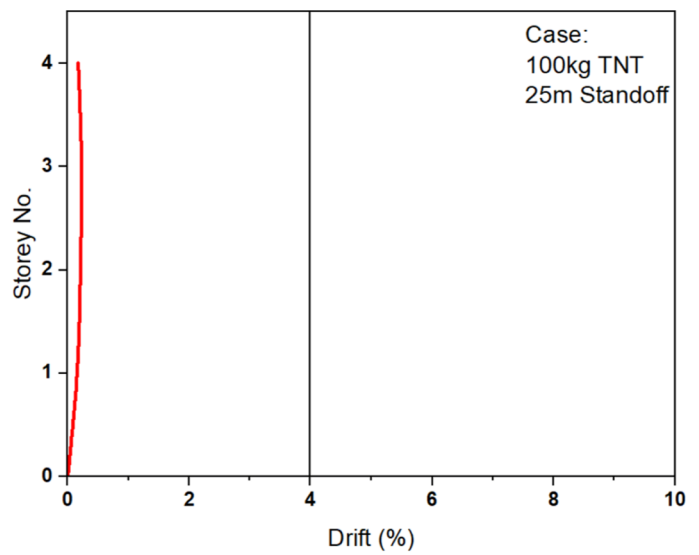


(b) Storey Drift for Case 8

Fig.20 Response of blast loads for Case 8



(a) Hinge formation for Case 9.



(b) Storey Drift for Case 9

Fig.21 Response of blast loads for Case 9

**Case 5: 100 kg TNT mass and 20 m Standoff distance**

Maximum Top Storey deflection = 33.6 mm and Base Reaction in X-direction = 3947.9 kN (Fig. 17).

**Case 6: 200 kg TNT mass and 20 m Standoff distance**

Maximum Top Storey deflection = 69.2 mm and Base Reaction in X-direction = 6770.6 kN (Fig. 18).

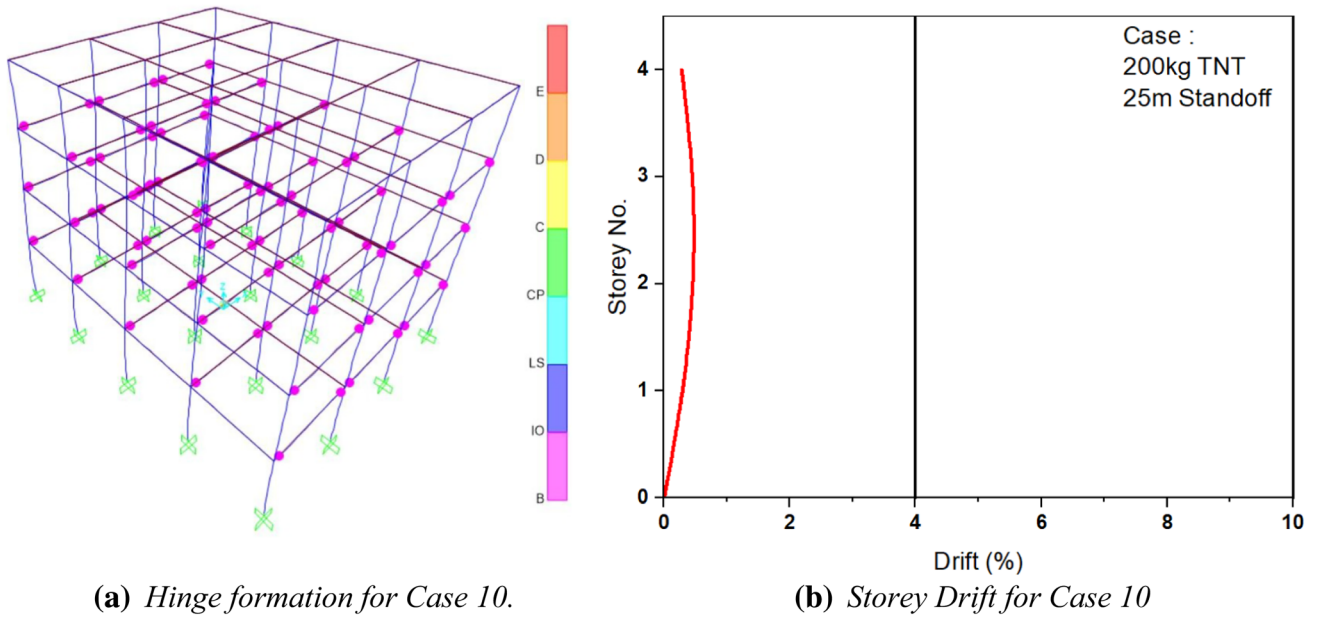


Fig.22 Response of blast loads for Case 10

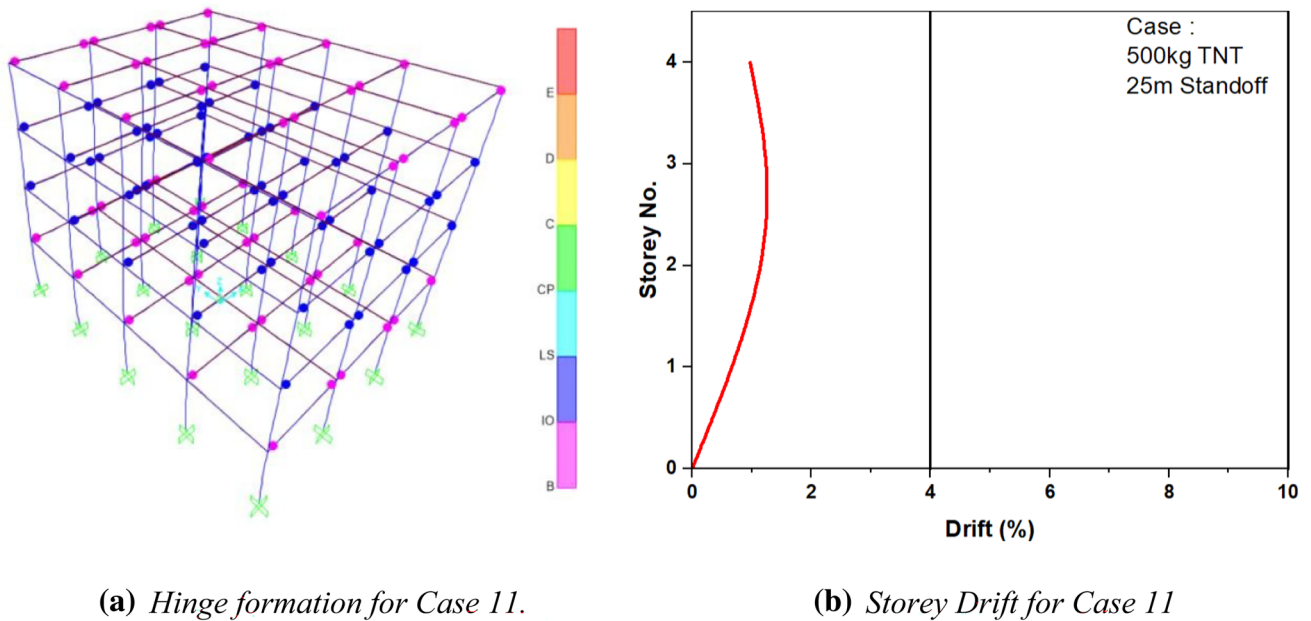


Fig.23 Response of blast loads for Case 11

**Case 7: 500 kg TNT mass and 20 m Standoff distance**

Maximum Top Storey deflection = 199.5 mm and Base Reaction in X-direction = 15760.35 kN (Fig. 19).

**Case 8: 1000 kg TNT mass and 20 m Standoff distance**

Maximum Top Storey deflection = 498.8 mm and Base Reaction in X-direction = 33853 kN (Fig. 20).



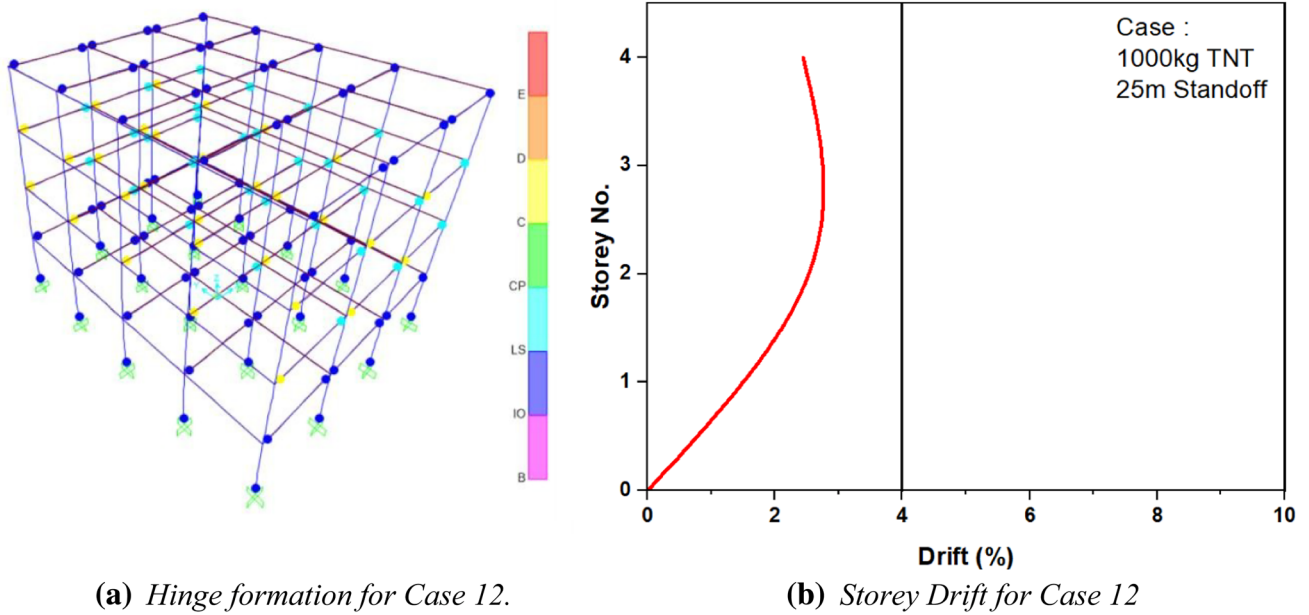


Fig.24 Response of blast loads for Case 12

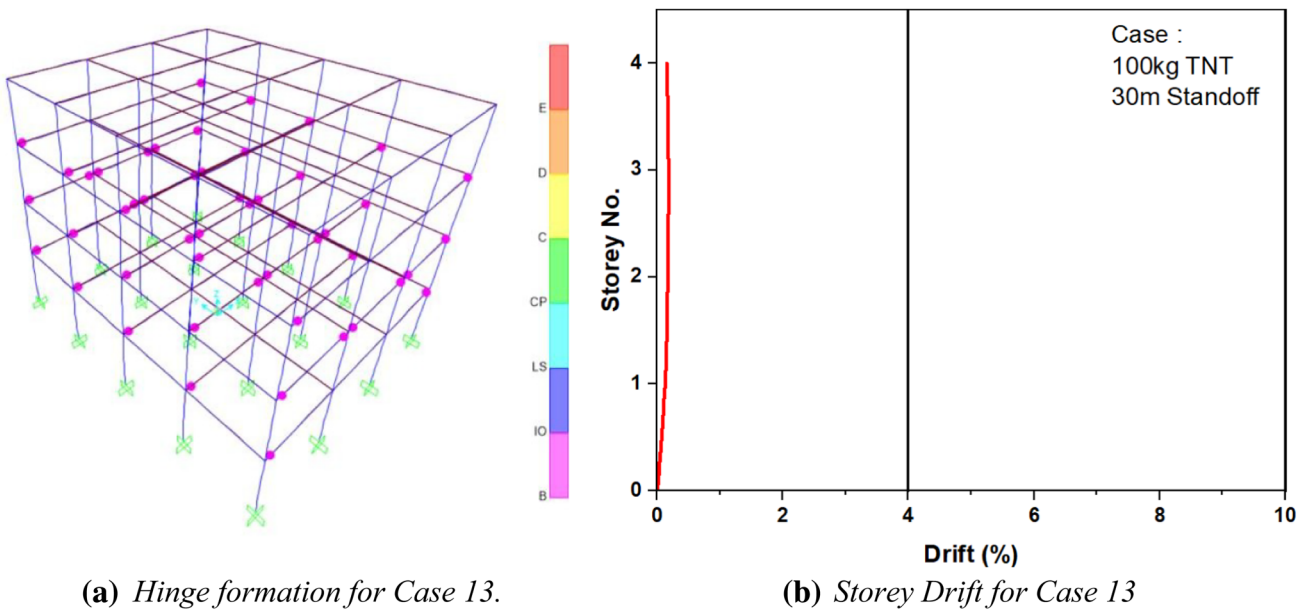


Fig.25 Response of blast loads for Case 13

**Case 9: 100 kg TNT mass and 25 m Standoff distance**

Maximum Top Storey deflection = 23.8 mm and Base Reaction in X-direction = 2473 kN (Fig. 21).

**Case 10: 200 kg TNT mass and 25 m Standoff distance**

Maximum Top Storey deflection = 46.7 mm and Base Reaction in X-direction = 4128 kN (Fig. 22).

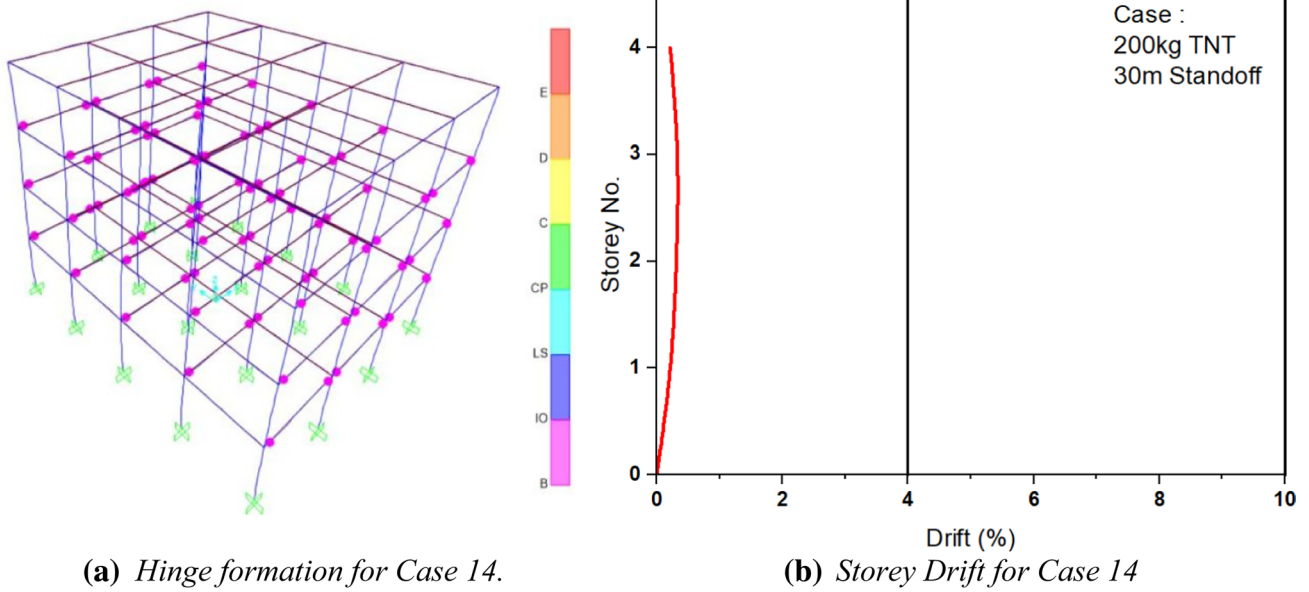
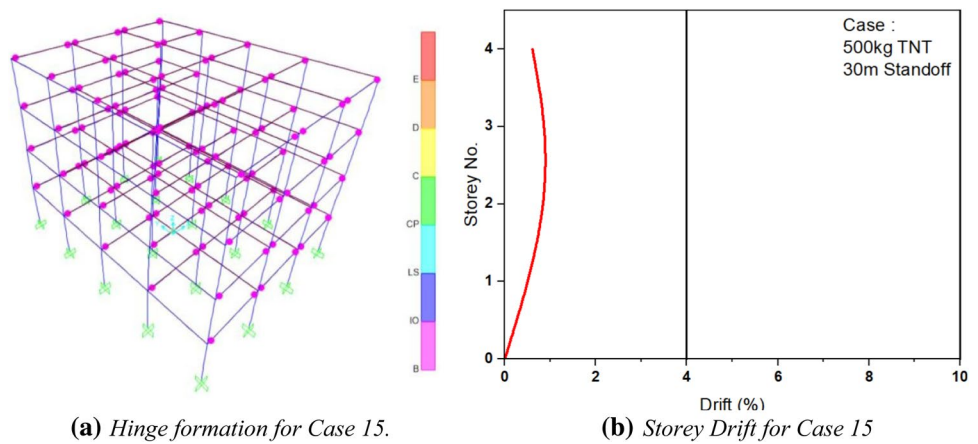


Fig.26 Response of blast loads for Case 14

Fig.27 Response of blast loads for Case 15



**Case 11: 500 kg TNT mass and 25 m Standoff distance**

Maximum Top Storey deflection = 125.9 mm and Base Reaction in X-direction = 8358.6 kN (Fig. 23).

**Case 13: 100 kg TNT mass and 30 m Standoff distance**

Maximum Top Storey deflection = 19.5 mm and Base Reaction in X-direction = 1767.8 kN (Fig. 25).

**Case 12: 1000 kg TNT mass and 25 m Standoff distance**

Maximum Top Storey deflection = 286.3 mm and Base Reaction in X-direction = 16521.57 kN (Fig. 24).

**Case 14: 200 kg TNT mass and 30 m Standoff distance**

Maximum Top Storey deflection = 34.4 mm and Base Reaction in X-direction = 2786.2 kN. (Fig. 26).

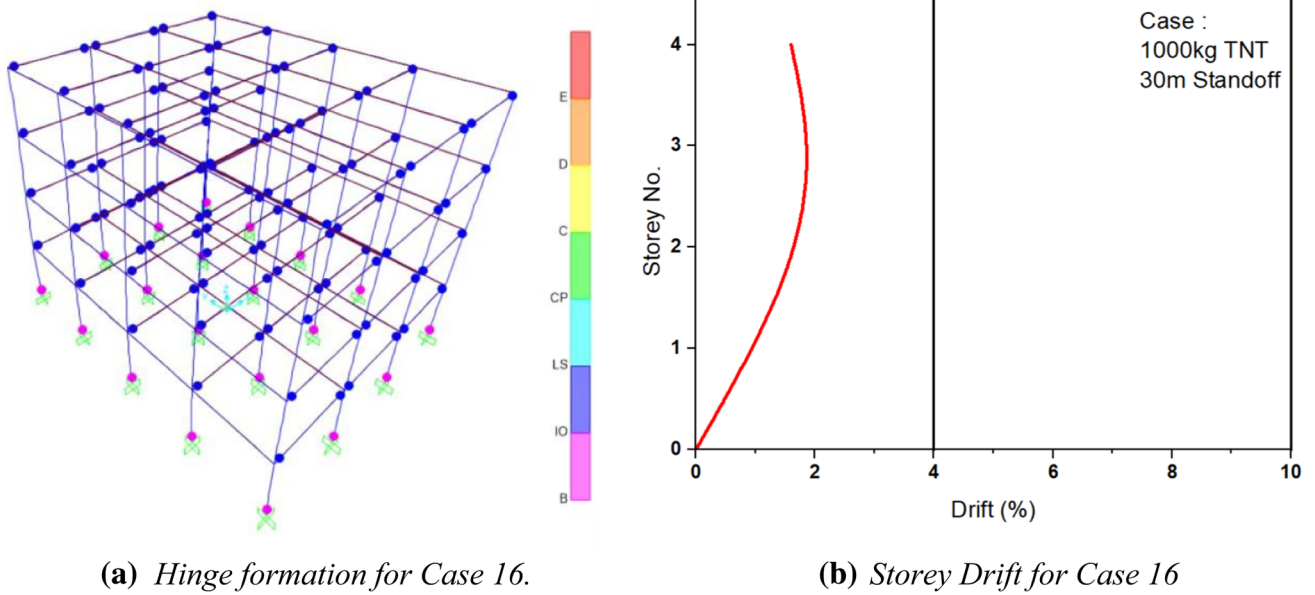
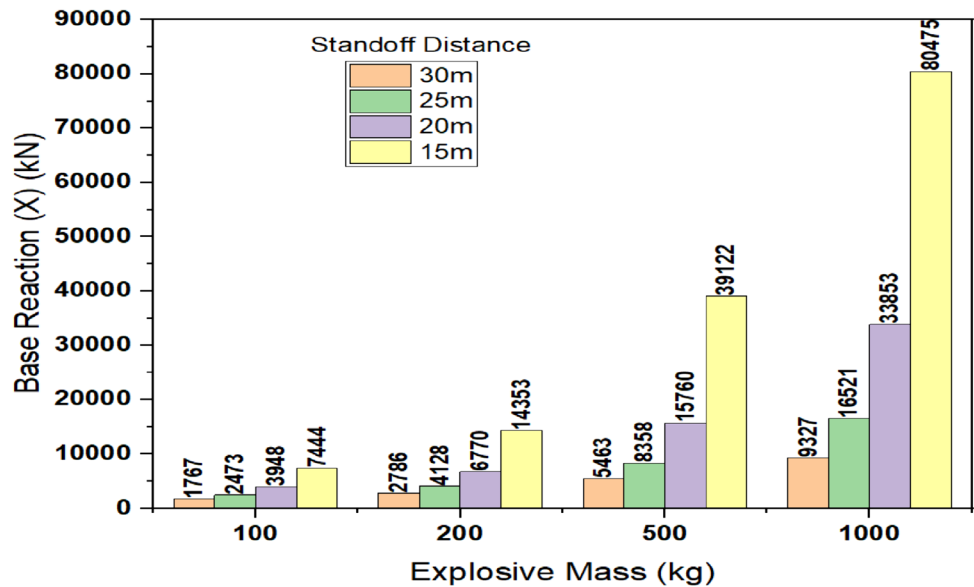


Fig. 28 Response of blast loads for Case 16

Fig.29 Base reaction for all the cases of the parametric study



**Case 15: 500 kg TNT mass and 30 m Standoff distance**

Maximum Top Storey deflection = 88.6 mm and Base Reaction in X-direction = 5463.2 kN. (Fig. 27).

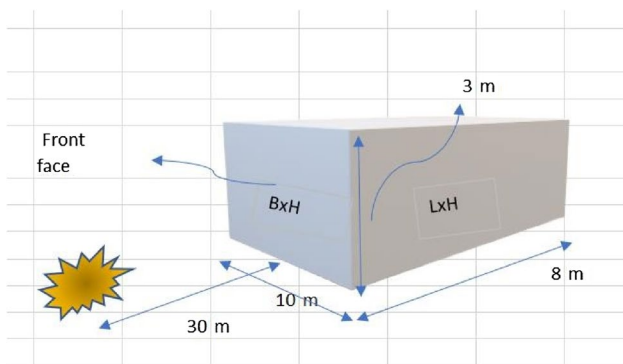
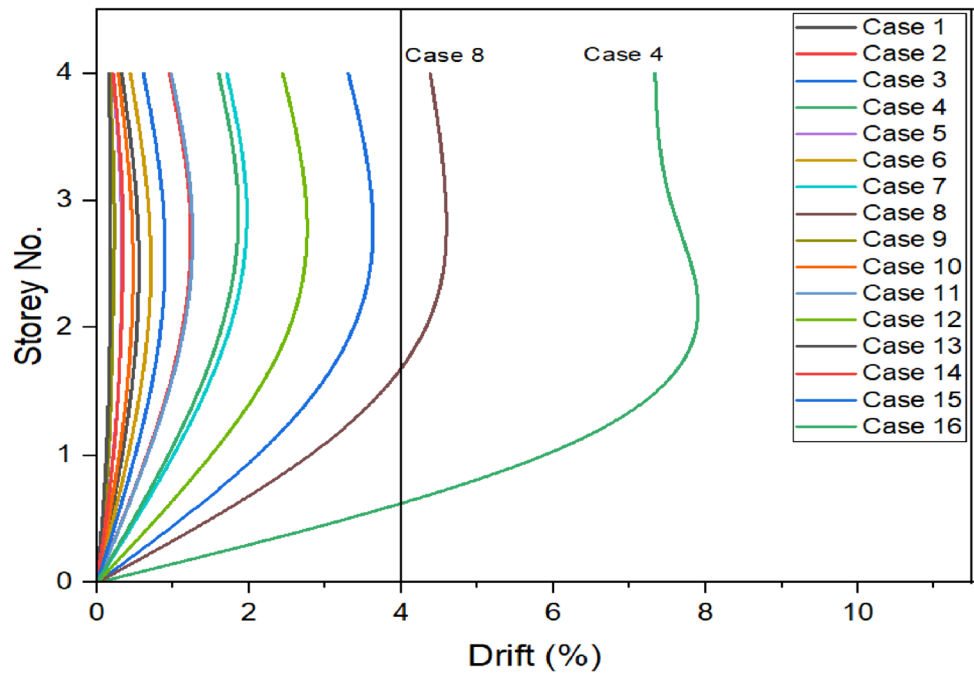
**Case 16: 1000 kg TNT mass and 30 m Standoff distance**

Maximum Top Storey deflection = 187.3 mm and Base Reaction in X-direction = 9327.27 kN. (Fig. 28).

Figure 29 shows results for the Base Reaction (in X-direction) for all the cases.

It is quite evident that as the blast pressure increases the base reaction increases. For case 4 (i.e., 1000 kg TNT mass and 15m standoff distance) maximum base reaction of 80457 kN is obtained.

**Fig. 30** Comparison of drifts for all cases



**Fig. A.1** Diagrammatic representation of blast load on a closed structure

Figure 30 presents the comparison of drifts for all the 16 cases, and it is clearly visible that in case 4 (1000 kg TNT mass and 15m standoff distance) and case 8 (1000kg TNT mass 20m standoff distance) the drift values exceed the FEMA 273 drift limits (i.e., 4%) which is an indication of the collapse of the vertical members.

## Conclusions

The study of blast loading on structures is critical for public and commercial buildings as military exercises and terrorist acts become more common around the world.

An overview of blast pressure calculations and how to apply them on structures is given in this chapter. When the explosive mass is large and the standoff distance is less, the parametric study performed shows that the structural performance of the building becomes vulnerable.

1. It is quite evident that with increase in explosive charge mass the blast pressure significantly increases on the structure. Hence, the structural performance of the building taken into consideration reached the collapse point when the standoff distance is less and the explosive mass is high.
2. Similarly, the base reaction also increases with increase in explosive mass and decrease in standoff distance. The base reaction obtained for the most extreme situation is around 45 times that of the least extreme case. Also, the maximum storey drift for most extreme case is 44 times that of the least extreme case.
3. For Case 4 (1000 kg TNT and 15 m standoff), Case 3 (500 kg TNT and 15 m standoff), Case 8 (1000 kg TNT and 25 m standoff) and Case 9 (1000 kg TNT and 15 m standoff), the performance level of the building reaches the collapse point.
4. For Case 4 and Case 8, the inter storey drift percentage is above 4%, which is also an indication of collapse of vertical members. [FEMA 273, Tables 2, 3, 4].
5. Plastic hinges are developed in all cases and in almost all structural members.

**Table A.1.** Blast load example validation in MS Excel

Parameters	Notation	Magnitude	Units
<i>Given data</i>			
Amount of explosive	W	0.1	Tonne
Standoff distance	R	30	m
Height Of building	H	3	m
Length of building	L	8	m
Width of building	B	10	m
Velocity of sound	A	344	m/s
Ambient air pressure	$P_a$	1	kg/cm <sup>2</sup>
<i>Calculations</i>			
Characteristics of the Blast			
Scaled Distance	X	64.63	m/(tonne) <sup>1/3</sup>
Peak Sideon overpressure	$P_{so}$	0.354	kg/cm <sup>2</sup>
Reflected Overpressure	$P_{ro}$	0.806	kg/cm <sup>2</sup>
Peak Dynamic Pressure	$q_0$	0.042	kg/cm <sup>2</sup>
	$t_{dS}$	28.32	milli sec
	$t_{oS}$	37.71	milli sec
Duration of equivalent triangular pulse	$t_d$	13.15	milli sec
Time of positive phase	$t_0$	17.50	milli sec
Mach no	M	1.142	
Shock front velocity	U	392.69	m/s
	U	0.393	m/millisecond
<i>Calculation of pressures on buildings</i>			
	S	3	M
	$t_c$	22.92	milli sec
	$t_t$	20.37	milli sec
	$t_r$	30.56	milli sec
Drag coefficient for front face	Cd	1	
Drag coefficient for roof, rear and side faces	Cd	− 0.4	
Pressure on the front face		<b>0.806</b>	kg/cm <sup>2</sup>
Pressure on roof and sides		<b>0.337</b>	kg/cm <sup>2</sup>
Pressure on Rear wall		<b>0</b>	kg/cm <sup>2</sup>
	tr > td, hence no force on back face is considered		

## Appendix: Solved problem from Sect. 2.2.7

*Example statement:* Blast parameters due to the detonation of a 0.1 tonne explosive are evaluated on an above ground rectangular structure, 3 m high, 10 m wide and 8 m long, situated at 30 m from ground zero (Fig. A.1)

The adjoining table shows the calculation of blast pressure on the faces of a structure as per IS Code recommendations (Table A.1):

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**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

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