Analytical Study of Steel Buildings with Different Geometric Configurations and Bracings under Blast Load

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Abstract - *Effects of different structural configurations and charge weight on blast-induced failure of steel frame buildings are investigated by analytical method. Three steel frame buildings with different geometric configurations—square plan with rectangular shape in elevation, square plan with pyramidal shape in elevation, and trapezoidal plan—are analyzed under blast load by using ANSYS Structural mechanics. The steel frame buildings are modeled, analyzed, and designed for live load (LL), dead load (DL) and seismic load (SL) for the National Capital Region (NCR), India. Different steel bracings are used to assess the effects of different bracings in resisting the blast-induced load by explicit method of blast load by using ANSYS AUTODYN. Three concentrically braced frames(X, K and V braced frames) are analysed under blast load.*

***Key Words*: Peak incident pressure, Radial distance, Airburst blast, Standoff distance, Bracings, Structural configuration**

1.INTRODUCTION

An explosion is defined as a rapid chemical reaction that occurs in the few milliseconds resulting in the very fast release of energy and hot gases into the surrounding atmosphere. It results in the generation of high pressure and temperature. During explosion the hot gases that are generated occupy the space surrounding, resulting in wave propagation through space which is transmitted spherically or hemispherically through a surrounding medium. Explosions can be differentiated based on the nuclear, chemical and physical chaos, Physical Explosion - Energy release may be due to the dangerous explosion of compressed gas cylinders or a combination of two liquids at very high temperature etc. Nuclear Explosion - Energy release due to redistribution of protons and neutrons within nucleus resulting in the formation of atomic nuclei.Chemical Explosion - Energy release is due to high rate oxidation of hydrocarbon elements such as carbon and hydrogen atoms. Type of Explosion (fig.1) mainly classified as surface burst, air blast, high altitude blast, underground explosion and underwater blast.Blast load is considered to be a severe hazard because it can deliver a huge amount of energy to the structure causing potential damages to structural members[3].

A structure must be designed to resist the expected blast load to eliminate the consequences of an explosion on or near it, or suitable mitigation techniques must be employed to reduce the loading on the structure to acceptable levels.

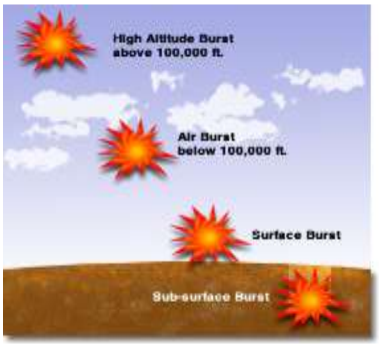

Fig -1: Types of explosion (emilms.fema.gov)

The mitigation techniques include the use of landscape and architectural planning, physical security measures, and advanced materials and structural forms [6]. Federal Emergency Management Agency (FEMA) guideline FEMA 453 (FEMA 2006) provides recommendations to select the location and suitable structural form for critical/emergency buildings such as safe houses. However, the selection of building orientation and structural shape is equally important to mitigate possible blast hazard, even for important office buildings and other facilities [4]. Smith and Rose (2006) presented the propagation of a blast wave through urban streets and its interaction with the surrounding structures. They investigated how the physical dimensions and location of a building influence the blast wave characteristic in an urban landscape. Several researchers highlighted the importance of architectural design considerations, such as planning and layout of the building, in dissipating or minimizing the blast load and damages due to projectile impacts on the structure. Gebbeken and Döge (2010) analyzed the blast effects on three-dimensional (3D) solid blocks to highlight the effectiveness of different shapes and sizes of the blocks in reducing the blast load effects. However, the behavior of 3D solid blocks does not truly represent the behavior of frame structures under blast load[6].Coffield et al. examined the impact of structural irregularity on the response of steel frame structures subjected to blast load and considered moment resisting frames(MRF),concentrically braced frames(CBF) and eccentrically braced frames(EBF)[1].Liew presented a numerical model for analyzing steel frame structures subject to localized damage by blast load and investigated their survivability under fire attack[1] .Dusenberry (2010) concluded that buildings with re-entrant corners and overhangs may suffer more damage from a blast because these corners and overhangs may amplify the effects of blast loading. Therefore architectural planning is an important stage for mitigation of blast effects. Ballantyne et al. (2010) investigated the effect of finite surface width of structural components on the induced blast pressure. They studied the diffraction of blast pressure waves around the leading edges (i.e., the edge facing the detonation point) of a column flange and propagation of the rarefaction wave from the edges to the centerline of the column. They observed more-rapid reduction of the reflected impulse when the surface exposed to the blast was assumed to be finite compared with an assumption of infinite surface. This was primarily due to the fact that the clearing time is significantly less for a finite surface[2]. Hence the surface exposed to the blast load is an important parameter to be considered in the analysis.

The present study focus on the effects of different charge weight on the fragility of the steel frame buildings under blast load and to assess the effects of different configurations of the building in resisting the blast-induced load. In this study modeling and analysis of steel frame buildings under the blast load can be done using the structural analysis software ANSYS 19.1 Structural mechanics. Modeled three steel frame buildings with different geometric configurations—square plan with rectangular shape in elevation, square plan with pyramidal shape in elevation, and trapezoidal plan. Then calculated blast load at each node by using set of equations for different explosives and charge weight. Analysed the buildings by applying blast loads and got the deflection and compared the results to find out building with which configuration is more efficient in resisting blast load. Different steel bracings are used to assess the effects of bracings in resisting blast by using Software AUTODYN 19.1.

2. Computation of Joint Load due to Blast

The joint load due to blast pressure is computed based on the tributary area corresponding to that joint of the building frame as shown in Fig.2. The figure shows a typical elevation of the building walls exposed to the blast pressure acting at a certain angle of incidence at different joints. The tributary areas corresponding to interior and exterior (side/corner) joints are also marked in the figure. The following steps are involved in computation of the joint loads, for all three building configurations:

1. Compute the radial distance (R) of the considered joint from the point of detonation and the angle of incidence (θ) at that joint, based on its location on the blast-facing surface, considered standoff distance, and height of the detonation point from the ground;
2. Compute the scaled distance (Z) based on the charge weight and calculated radial distance using Eq. (3);
3. Obtain the peak incident pressure (P_{pos}) corresponding to the calculated scaled distance using Eq. (1);
4. Obtain the coefficient of reflection (Cr) based on the angle of incidence at a joint and amplitude of the peak incident pressure following the Unified Facilities Criteria 3-340-02(UFC 2008);
5. Calculate the peak reflected pressure (P_{ref}) on the considered joint using Eq. (6);
6. Compute the equivalent joint load by multiplying the peak reflected pressure by the tributary area.

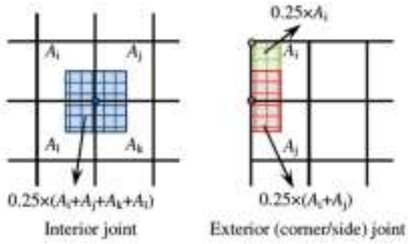

Fig -2: Tributary wall areas for calculation of joint loads due to blast pressure(Khan et al, 2017)

Goel et al. (2012) compared several empirical relationships available in the existing literature to compute the blast pressure profile and peak reflected blast pressure. They recommended using the empirical relationships reported by Kinney and Graham (1985) for computing the pressure time history parameters corresponding to an infinite surface[5].The peak incident pressure (P_{pos}) and positive phase duration (t_{pos}) are given as

$$P_{pos} = \frac{P_0 \times 808 \times \left[1+\left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{\left[1+\left(\frac{Z}{0.048}\right)^2\right] \times \left[1+\left(\frac{Z}{0.32}\right)^2\right] \times \left[1+\left(\frac{Z}{1.35}\right)^2\right]}} \text{ (bar)} \tag{1}$$

$$\text{and } t_{pos} = \frac{W^{\frac{1}{3}} \times 980 \times \left[1+\left(\frac{Z}{0.54}\right)^{10}\right]}{\left[1+\left(\frac{Z}{0.02}\right)^3\right] \times \left[1+\left(\frac{Z}{0.74}\right)^6\right] \times \sqrt{\left[1+\left(\frac{Z}{6.9}\right)^2\right]}} \text{ (ms)} \tag{2}$$

where the unit of P_0 is bars; W = charge weight presented in terms of mass of the equivalent trinitrotoluene (TNT) in kilograms; and Z = scaled distance expressed as

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

where R = radial distance (i.e., the distance to the source of detonation from the point under consideration) in meters. For brevity, the equivalent mass of TNT is called as charge weight in all the forthcoming discussions.

The pressure wave resulting from an explosion at any time instant (t) is expressed using modified Friedlander's equation (Baker 1973)

$$P(t) = P_0 + P_{pos}\left(1 - \frac{t}{t_{pos}}\right) e^{\frac{-bt}{t_{pos}}} \qquad (4)$$

where t = time measured after t_A; and b = unitless wave decay parameter (Lam et al. 2004)

$$b = Z^2 - 3.7Z + 4.2 \qquad (5)$$

where, Z is in m/kg$^{1/3}$. The peak reflected pressure can be computed using the coefficient of reflection (C_r) charts given in the Unified Facilities Criteria 3-340-02 (UFC 2008) as

$$P_{ref} = C_r P_{pos} \qquad (6)$$

This approach is used in the present study to determine the peak reflected pressure on the building surface based on the radial distance, angle of incidence at the point of computation, and strength of the incident pressure. A similar approach for computing the blast pressure imparted on the structure is adopted and validated with the test results reported by Gebbeken and Döge (2010). Gebbeken and Döge (2010) studied the pressure developed on different shapes and sizes of buildings under different blast load scenarios.The blast pressure computed using the procedure explained previously were validated with the experimental results from Gebbeken and Döge (2010), as presented in Fig.3.

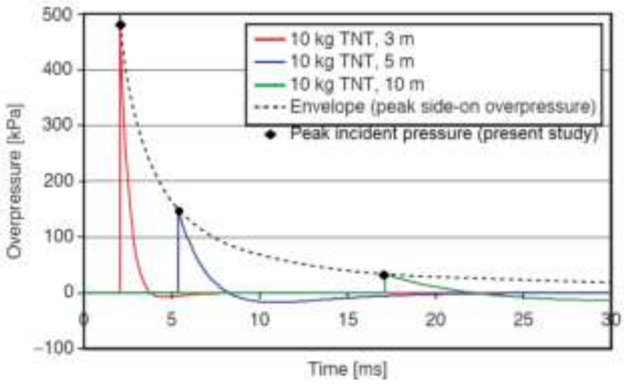

Fig -3: Validation of the present approach with Gebbeken and Doge(2010) experiment results

Considered an idealized model (rigid frame ABC, where BC is beam member, AB and CD are column members) and computed the blast load acting at a node for a charge weight of 200 kg(TNT) and radial distance R = 28.21 Hand calculation is done using slope deflection method and found out the bending moments The same frame is analysed by using ANSYS by applying blast load at joint.

Table -1: Comparison of results

Members	Bending moment(kNm)		% error
	slope deflection method	analytical	
AB	226.02	226.93	0.4
BC	156.46	156.25	0.13
CD	226.02	225.98	0.017

3. Structural Modeling and Analysis

Modeled regular, pyramidal and trapezoidal steel framed building with equal floor area. Structural analysis software ANSYS was used for modeling and analyzing the steel frame buildings under the blast loading. The 3D building frames were modeled using beam elements with rigid joints.

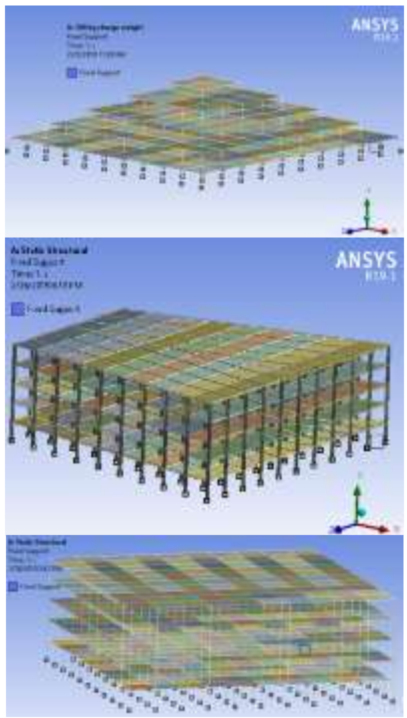

Fig -4: 3D Model of pyramidal, trapezoidal and regular building using ANSYS

Table -2: Details of Steel Section Properties for Frame Members

component	Height (mm)	Width (mm)	Flange thickness (mm)	Web thickness (mm)
Regular Building				
Beam	290	300	14	8.5
Column	416	406	48	30
Pyramidal Building				

Beam	190	200	10	6.5
Column	416	406	48	30
Trapezoidal Building				
Beam	290	300	14	8.5
Column	416	406	48	30

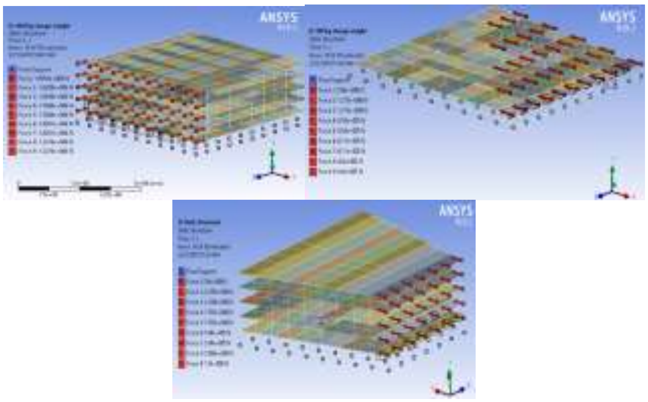

Fig -5: Calculated blast loads corresponding to 100 kg charge weight applied at nodes

4. STUDY ON THE EFFECT OF BRACINGS IN RESISTING BLAST

In this project the effect of different bracings in resisting the blast load on pyramidal building and frames are studied by using softwares ANSYS structural mechanics and AUTODYN. From studies it is found that concentrically braced frames(CBF) are more efficient in resisting blast load than eccentrically braced frames (EBF) and moment resisting frames(MRF).

Therefore in this study the effect of different types of concentrical bracings are compared ie, X,K and V bracings of ISA 200x200x12 mm in resisting blast load(fig.6). The bracings are provided throughout the building since the effect of arrangement of bracings is not focused in this work. Model at the beginning of the 3D analysis after mapping is shown in fig.7.

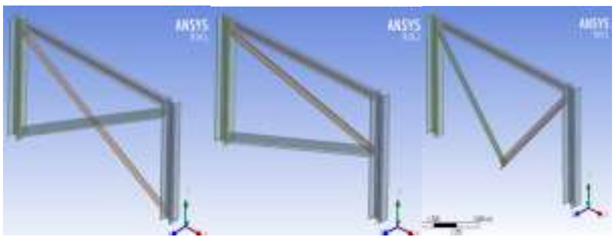

Fig -6: Model of X, K and V braced frame

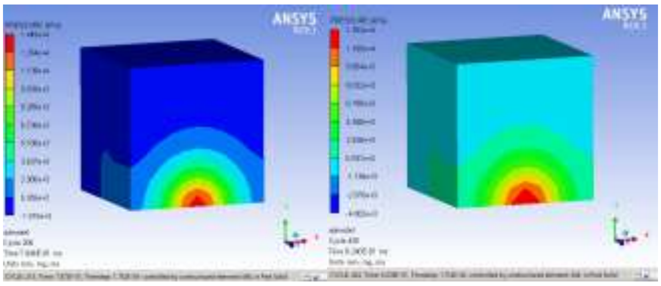

Fig -7: Model at the beginning of the 3D analysis after mapping

To measure the frame deflection and over pressure history gauges (monitoring points) are provided at different locations. After the completion of simulation after 20 ms, gauge histories are obtained from software AUTODYN.The gauge histories obtained for different gauge points is shown in fig.8.

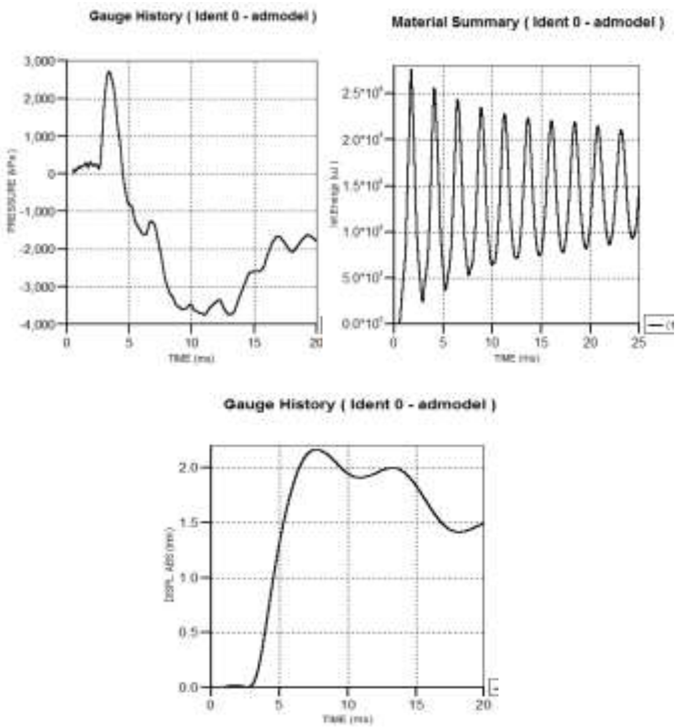

Fig -8: Gauge histories from AUTODYN

By comparing regular, pyramidal and trapezoidal building it is found that pyramidal building is more efficient in resisting blast load. Therefore pyramidal building is modeled and bracings are provided(fig.9) and analysed by applying blast load corresponding to 100 kg charge weight.

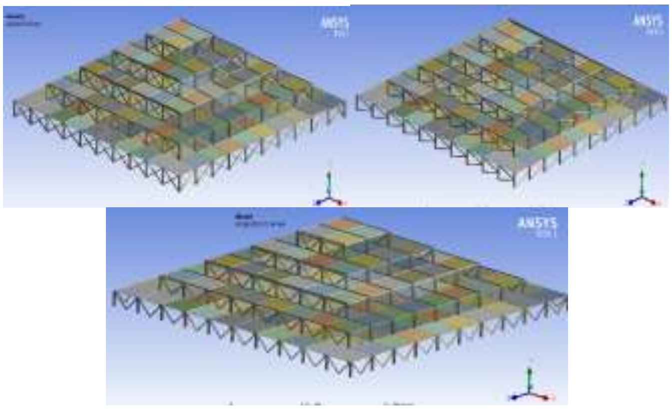

Fig -9: 3D Model of Pyramidal buildings with X, K and V bracings

5. RESULTS AND FINDINGS

Validated pressure equation used in this work by comparing with Gebbeken and Doge(2010)experiment results.Validated an idealized model by applying blast load at a joint and found out the values of bending moment by hand calculation (slope deflection method) and using ANSYS. By comparing both the values there is a variation of 0.4% which is acceptable. Regular, pyramidal and trapezoidal steel frame buildings are modeled and analyzed by applying blast loads at joints.

Table -3 : Total deflection values for different charge weight

Charge weight(Kg)	Maximum deflection(mm)		
	Regular building	Pyramidal building	Trapezoidal building
100	88.82	46.218	115.33
200	158.44	72.415	209.07
300	210.58	93.755	299.57
400	264.97	117.88	385.62
500	317.55	139.75	479.66
600	380.97	161.23	564.96

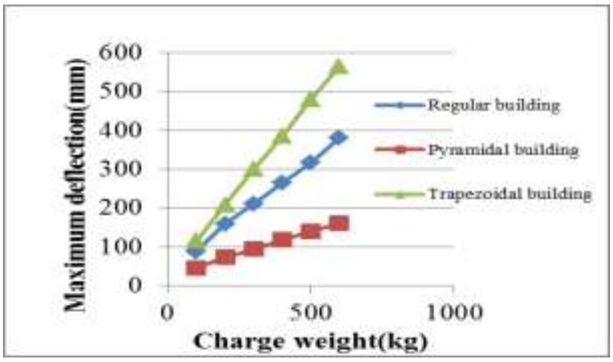

Chart -1: Deflection graph for different building configuration

Table -4: Results from AUTODYN corresponding to 50 kg TNT

X Braced Frame			
Gauge points	Displacement Z(mm)	Absolute displacement (mm)	Total energy (μJ)
1	0.015	0.025	$3X10^6$
2	$10X10^{-3}$	0.02	
3	$14X10^{-4}$	$14X10^{-4}$	
4	$5X10^{-3}$	0.035	
5	$3X10^{-4}$	0.015	
6	$18X10^{-4}$	$12X10^{-3}$	
7	$14X10^{-4}$	0.035	
8	$10X10^{-4}$	0.025	
Max value	0.015	0.035	

V Braced Frame			
Gauge points	Displacement Z(mm)	Absolute displacement (mm)	Total energy(μJ)
1	0.07	0.075	$2.5X10^6$
2	$6X10^{-4}$	0.03	
3	$4.5X10^{-4}$	0.03	
4	0.1	0.1	
5	0.04	0.042	
6	0.045	0.061	
7	$23X10^{-3}$	0.03	
8	0.1	0.1	
Max value	0.1	0.1	

K Braced Frame			
Gauge points	Displacement Z(mm)	Absolute displacement (mm)	Total energy (μJ)
1	0.17	1	$1.5X10^6$
2	1.7	1.8	
3	0.8	0.85	
4	0.05	0.09	
5	0.4	0.4	
6	2.2	2.1	
7	1.7	1.7	
8	1.4	1.4	
Max value	2.2	2.1	

Table -5: Total deflection values for different bracings on pyramidal building

	Bracing Type	Maximum Deflection(mm)
Pyramidal Building	X	6.069
	V	30.28
	K	37.44
	Without Bracing	46.21

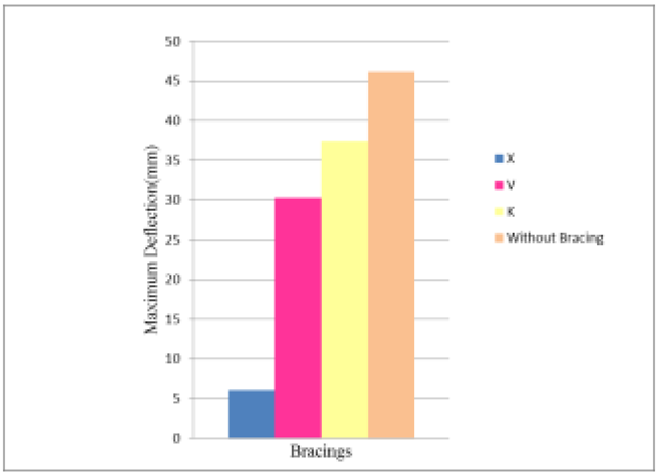

Chart -2: Deflection graph for different bracings

6. CONCLUSIONS

Validated pressure equation used in this work by comparing with Gebbeken and Doge(2010) experiment results. Validated an idealized model by applying blast load at a joint and found out the values of bending moment by hand calculation (slope deflection method) and using ANSYS. By comparing both the values there is a variation of 0.4% which is acceptable.

Modeled 5 storied regular, pyramidal and trapezoidal steel building and they are meshed and blast load at each nodes are computed for a standoff distance of 15m and charge weight of 100,200,300,400,500 and 600kg TNT and applied on blast facing surface. They are analyzed and found out the deflection. By comparing the results it is found out that pyramidal building is more resistant to blast load than regular and trapezoidal building. Maximum deflection of pyramidal building is 67.56% and 55.58% less than that of trapezoidal and regular building respectively

Three concentrically braced frames are modeled using software solid works(X,K and V braced frames) and they are imported to AUTODYN and analyzed for 50 kg TNT and found out total energy, internal energy, pressure ,deflection in Z direction and absolute deflection for different gauge locations and concluded that X braced frames absorb more energy and deflect less when compared to V and K braced frames.

Modeled pyramidal building with different types of concentrical bracings(X, K and V bracings) provided throughout the building and they are analysed by applying blast load on blast facing surface corresponding to 100 kg TNT and found out the deflection. Percentage reduction in deflection for X,V and K braced buildings when compared with unbraced building are 86.86%, 34.47% and 18.97% respectively. Therefore it is clear that pyramidal building with X bracing is more efficient in resisting blast load.

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