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EFFECT OF SHEAR WALL IN THE DYNAMIC RESPONSE OF STRUCTURE UNDER BLAST LOADING- AN ANALYTICAL APPROACH

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ABSTRACT

The consequences of lateral load are devastating in nature compared to gravity loads. In the present scenario the effect of blast load on structures is gaining importance and needs attention. During explosion impulsive load is developed which is highly nonlinear and lasts for milliseconds resulting in catastrophic events. Shear wall has high in plane stiffness and strength which can be used to simultaneously withstand large horizontal loads and support gravity loads. Provision of shear wall allows dissipation of energy in controlled manner in the near field explosion. This research paper concentrates on the effectiveness of shear wall in the dynamic response of the structure while resisting the high intensity blast load acting in the proximity of the structure. Lateral displacement and story drift are the primary parameters considered. The blast load is applied as a function of time in the form of triangular load on finite element model using commercially available software SAP2000.

KEYWORDS: Blast Load, Time-history Analysis, Shear Wall, Peak Reflected Pressure

INTRODUCTION

The most commonly used weapons by terrorists are TNT, C4 explosives and Improvised explosive device (IEDs). In addition, the engineered structures are under the threat of missile attacks by terrorists. The alarming attacks happening across the world on to the commercial buildings or buildings of national importance in the form of human bombs or explosives. When they are placed inside a truck parked at a near distance to the building creates more causalities and severe damage to the building resulting in the progressive collapse of the structure. The most common types of lateral loads on the structures are due to wind and earthquakes. The blast load acting on the structure is idealized as a lateral load and of extremely small duration in the order of milliseconds. Structures can be exposed to various types of explosions. They can be either external explosions such as suicidal car bombs or internal explosions such as LPG blast, or blasts inside petrochemical industries. This study considers an external explosive event, caused by TNT of differing charges placed in a truck. Since an explosion is a surface burst, the propagation of the blast wave is hemispherical in nature. When the angle of incidence exceeds 45 degrees, the impact is comparatively less. Hence the impact of blast on the top story is much lesser when compared to the bottom story; this is one of the primary reasons for the progressive collapse of the structure due to the failure of bottom story columns.

REVIEW OF LITREATURE

(Ngo et al. 2007) explained the impact of blast loading on the structures, propagation, modelling and the types of blast waves. When the structure was subjected to the blast load the dynamic behavior of the structure changed and it could also lead to the progressive collapse of the structure. The author summarized that, for high risk facilities such as military structures, buildings of national importance the impact of blast load should be considered in the preliminary stages of design. (Gebbeken, Norbert et al. 2010). In this paper author explained the importance of architectural features to effectively resist the blast wave. Through numerical simulations he proved the role of geometry and shape of the building to resist the blast load. He had summarized that structural hardening was not always the necessary remedy to resist the blast load, it could be achieved by proper planning and orientation of the building. He also suggested few of the architectural features that can effectively reduce the blast wave and attenuate it before it reaches the structure surface.(Draganić and Sigmund 2012) the research work involved to assess the behavior of the structure subjected to effect of explosion of a spherical charge TNT. The fictive structure surrounded by buildings in urban scenario had been considered in this study. The 3D modelling had been done using SAP2000. The charge weight was varied from 1 KG TNT to 100KG TNT. Material non-linearity has been taken into consideration. The strength of the material was increased by DIF of 1.25. The analysis involved plastic hinge formation at the end of beams and columns to observe the plastic behavior of the structure. The results showed the near field blast creates catastrophic damage to the structure resulting in primary and secondary fragments, electrical breakdown, partial or complete collapse of the structure. (Priyanka A. and Rajeeva S.V 2015) In this work the impact of free field blast load acting on the commercial building was taken into consideration. The blast load acting on the structure was calculated using TM5 manual. Various cases had been considered by varying the charge weight and standoff distance to carry out the numerical analysis. The numerical study was done by using SAP2000 software. The blast load acting on the structure was applied has a function of time history. The results of numerical analysis showed that with increase in standoff distance and decrease in charge weight the impact of blast load on the structure gradually decreases.

The papers discussed above provided the foundation to carry out the present research work. The literature review helped to understand the propagation of blast wave, material behavior, and the dynamic nature of the building subjected to blast load. With the help of information provided in the literature, it was observed that the importance of the shear wall or its contribution to resist the blast load was not assessed. This research work focused on the suitability of the shear wall and its contribution in resisting the blast load acting on the structure.

SHEAR WALL AND IT’S ROLE IN BLAST LOADING

The configuration of shear wall is of paramount importance. To resist the high intensity blast load the shear wall has to be placed in such a manner that it is symmetric about each axis and it is ideal to match the center of stiffness to the center of mass of the building. In that way the torsional moments can be avoided. When the blast wave impinges the structure, the structural member exposed should exhibit ductile flexural behavior rather than brittle failure. This can be achieved by providing the shear wall in suitable configuration without compromising the aesthetic of the structure. With the provision of shear wall greater part of the high intensity lateral load can be taken by shear wall without compromising the load carrying capacity of moment resisting frame. Which is not the case for structure without shear wall.

MATERIAL BEHAVIOR

The material behavior to the blast load plays a very important role in resisting the high intensity load. Blast loads typically produces very high strain rates in the range of 10^2 - 10^4 s^{-1}(Kassahun 2011). This high straining (loading) rate would alter the dynamic mechanical properties of target structures and the damage mechanisms sets in for various structural elements. For reinforced concrete structures subjected to blast effects the strength of concrete and steel reinforcing bars can increase significantly due to strain rate effects. In many blast cases most of the causalities are attributed to the primary fragments resulted from breakage of glasses, claddings and collapse of partition wall. The key structural components such as columns should exhibit more ductile flexural behavior(Malvar, et al., 2007), which allows the columns to dissipate large amount of energy. The shearing resistance of columns can be increased by simply increasing the shear steel, grade of the concrete and by increasing the concrete cover of the key structural components. It has been observed that increasing the concrete cover of beams and columns render them better resistance when subjected to blast loading.

MODELLING AND ANALYSIS

The details from the literature(BACIU et al., 2012)were used for finite element modeling in SAP2000. The typical floor plan is shown in Figure 1. A six-story reinforced concrete frame structure consisted of two bays in Y-direction of 6m each and four bays along X-direction. The first-floor height was 4m and the remaining story heights was kept as 3 meters. Sizes of the perimeter beams were 250*550mm and that of the central beams were 300*700mm, the columns were square of size 600 mm, and the thickness of the slab was 150mm. The reinforcement for columns included 4 numbers of 25mm diameter bars. Material non-linearity had been taken into consideration. Mander model for concrete and Simple model for steel were chosen. The concrete compressive strength at 28 days was 30MPa and the elastic modulus was 32.5GPa. The yield strength of reinforcement was 300MPa and the elastic modulus was 210 GPa. The beams and columns were generated as framed sections. A frame element has 3 degrees of freedom at each node. Modelling a column/beam using a frame element results in forming a 6x6 stiffness matrix to solve the equations. Generally, columns and beams are just modelled as frame elements because the length to cross section aspect ratio is very large. It may be of the order of 5:1. According to Timoshenko's shear deformation theory unless the aspect ratio of around 2:1 we do not see any large shear deformation. Slab was assigned as a shell element. A shell is a three or four-node area object used to model floor, wall etc., shell element has high bending stiffness and therefore resist a portion of the load through flexural deformation. At the base of the column fixed support condition was assigned. A shear wall of L shape of grade M60 was also modeled as an area element with fixed condition at the base and rigid connection to the columns. The minimum reinforcement ratio was 0.0025 of the gross area in each direction (IS:13920 1993). This reinforcement was assumed to be distributed uniformly across the cross section of the wall on both the faces.

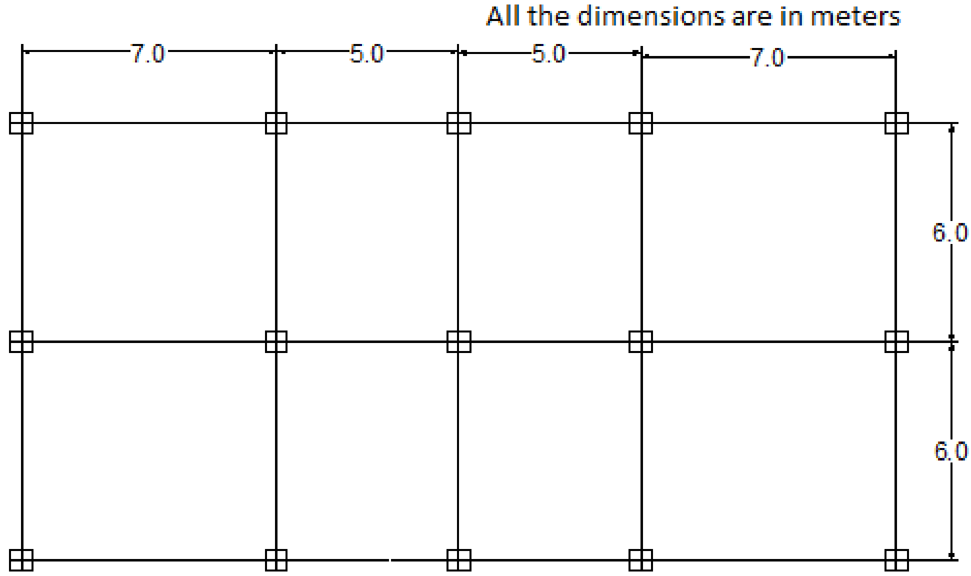

Fig. 1 Plan of the Building

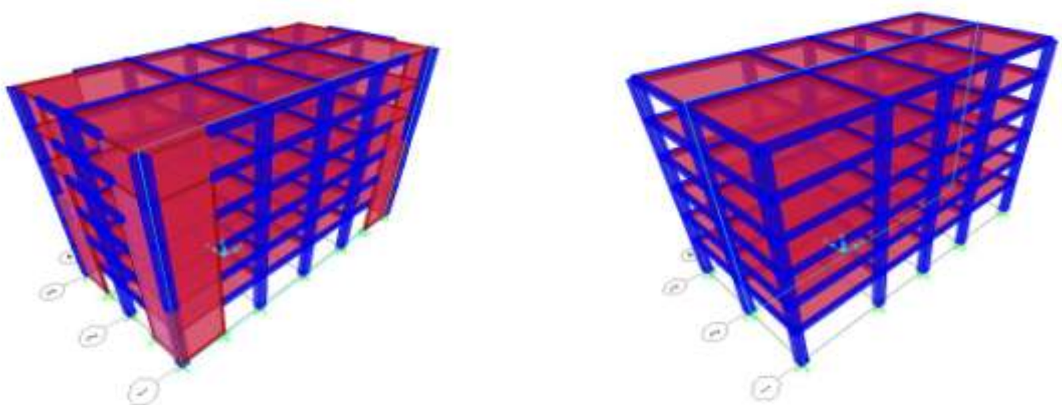

Fig. 2 3D Modelling in SAP2000 with and without shear wall

In this study loads considered for analysis were blast load and gravity load. TM 5-1300 – "Structures to Resist the Effects of Accidental Explosions", (U.S. Departments of the Army, Navy, and Air Force,1990 or UFC 3-340-02)(DoD 2008), was used to calculate the blast load acting on the structure. The various cases considered are shown below in table 1. Gravity load was applied according to the IS 875 (Part 1&2). A superimposed dead load of 1.75 kN/m^2 and a live load of 2.5 kN/m^2 were applied.

Blast always acts as pressure on the surface of the structure which is in kilo Pascal (KPa). It can be converted to blast load and applied as a point load on each node in the front face of the targeted building in the form of time history function. For this, pressure due to blast load (P_{ra}) was multiplied by surface area of the frame under consideration which has a column height of 4meters in ground level and bay width of 7 meters (4m x 7m) and divided by number of nodes (4 numbers) as shown below. The fast-nonlinear analysis (FNA) was carried out, in which blast load was applied as triangular load. A very small step time of $1*10^{-03}$ seconds was selected to obtain stable results. The dynamic behavior of the structure was investigated by calculating inter story drift and lateral displacement. According to the BIS 1893 (IS:1893 2002) the inter story drift shall not exceed 0.004 times the story height (H) and the allowable maximum lateral displacement is H/500.

$$\text{Peak reflected pressure } (P_{ra}) = 190 \text{ psi} = 190*6.89 = 1309.1 \text{ kN/m}^2$$

$$\text{Load on each node } = \frac{1309.1*(7*4)}{4} = 9163.7 \text{ kN}$$

The various cases considered are shown below in table 1.

Table 1: Cases Considered for Analysis

Cases	Story level	Charge equivalent to TNT (Kg)	Placement of charge	Stand-off distance (meters)	Shear wall provision
1	6	500	Longer edge	4	YES
2	6	250	Longer edge	4	YES
3	6	500	Longer edge	6	NO
	6	750	Longer edge	6	NO
4	6	500	Longer and Shorter edge	4	NO

Table 2 helps to understand the variation of blast pressure in Bay 1 along the height of the structure for a charge weight of 500kg at a standoff distance of 6m.

Table 2: Variation of Blast Pressure for Bay-1

Bay 1 / Story level	R (meters)	Angle of incidence α (degree)	Arrival time in (milliseconds)	Load duration time T_d in (milliseconds)	Peak over pressure in (kPa)	Peak reflected pressure in (kPa)	Load in (kN)
1	13.55	8.48	10.977	3.697	344.73	1310	9163.7
2	14.49	22.290	13.164	4.177	303.36	1122.46	5888.88
3	15.87	32.36	15.358	4.811	262	943.20	4948.39
4	17.66	40.60	17.552	5.48	199.94	799.79	4196.01
5	19.74	47.23	16.45	9.97	151.68	424.71	2228.22
6	22.04	52.58	23.03	13.46	117.21	269.58	1414.34

The load so calculated was applied as a function of time history in the form of triangular load.

RESULTS AND DISCUSSION

Formulation of the blast wave and assessment of the dynamic behavior of blast load is a complex phenomenon as it involves various parameters. The following figures and tables show the behavior of the structure for various cases considered. The lateral displacement and inter story drift are the primary parameters that were considered to evaluate the dynamic behavior of the blast load.

Case 1: 500KG TNT placed at a standoff distance of 4m with and without shear wall of thickness 200mm and 180mm.

Table 3: Lateral Displacement of 500KG TNT at 4m Standoff Distance with and without Shear Wall

Story level	Lateral displacement in mm		
	500KG TNT at 4m standoff without shear wall	500KG TNT at 4m standoff with shear wall 180mm thick	500KG TNT at 4m standoff with shear wall 200mm thick
0	0	0	0
1	21	4.4	4.6
2	32	10	10
3	40	17	17
4	45	24.7	24
5	46	32.7	31
6	46.8	40.2	38.1

Table 4: Inter Story Drift of 500KG TNT at 4m Standoff Distance with and without Shear Wall

Story level	Inter story drift in mm		
	500KG TNT at 4m standoff without shear wall	500KG TNT at 4m standoff with shear wall 180mm thick	500KG TNT at 4m standoff with shear wall 200mm thick
0	0	0	0
1	21	4.4	4.6
2	11	5.6	5.4
3	8	7	7
4	5	7.7	7
5	1	8	7
6	0.8	7.5	7.1

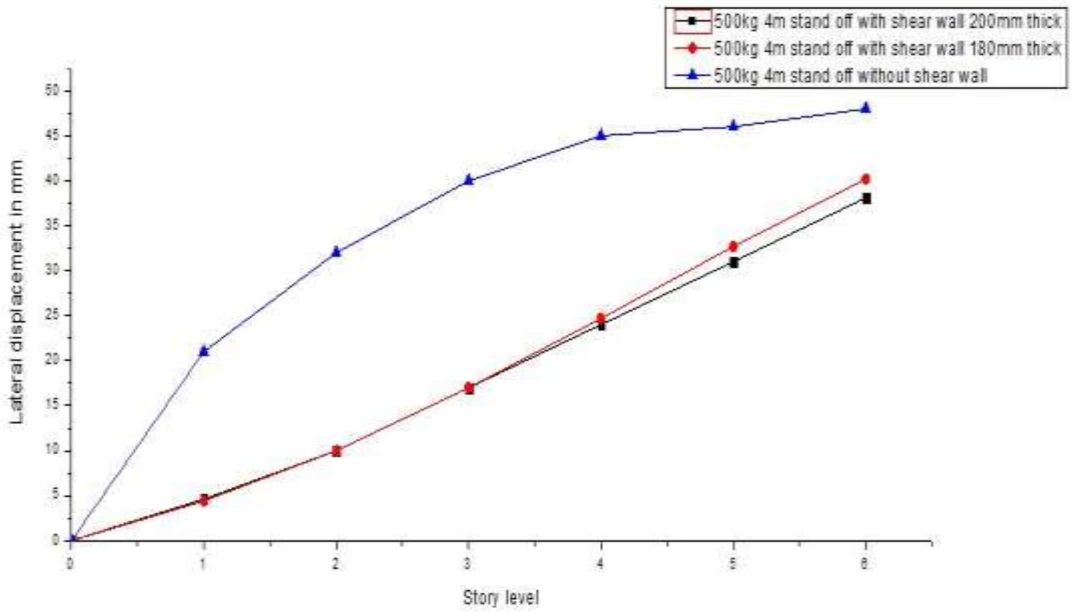

Fig. 3 Lateral displacement of 500KG TNT at 4m standoff distance with and without shear wall

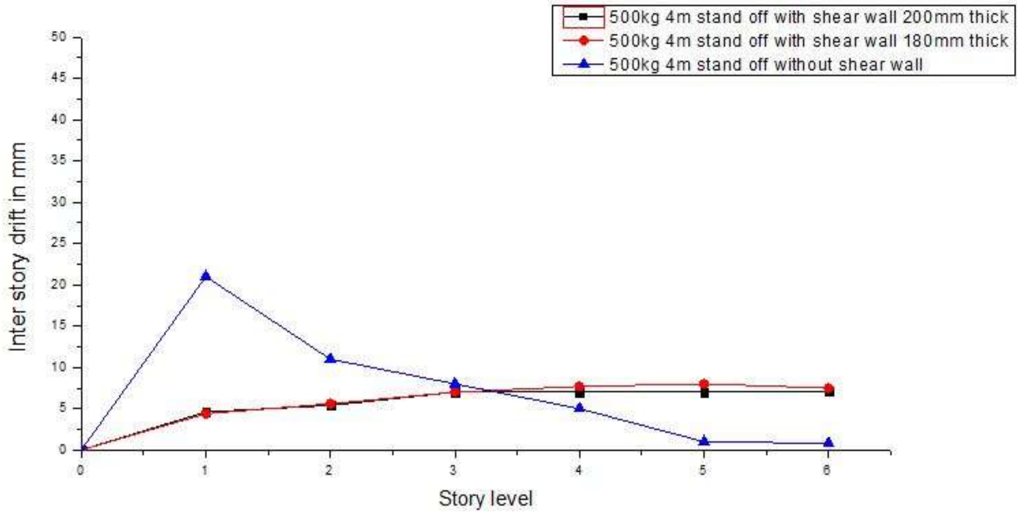

Fig. 4 Inter story drift of 500KG TNT at 4m standoff distance with and without shear wall

In case 1, the top story lateral displacement for 500KG TNT at 4m standoff distance for model with no shear wall and shear wall of 180mm thickness, exceeded the IS code limits of H/500 i.e., 38mm, where H is total height of the building. The model with no shear wall has higher inter story drift of 21mm, which is greater than IS code provisions of 0.004×H=16 mm. This may be due to the proximity of the explosion of TNT. But with the increase in thickness, use of high strength concrete the structure could sustain the blast load with inter story and top lateral displacement being within the permissible limits as specified in IS code. The rigidity of the structure can be increased by increasing the thickness and by using high strength concrete.

Case 2: 250kg TNT placed at a standoff distance of 4m with and without shear wall of thickness 180mm.

Table 5: Lateral Displacement of 250KG TNT at 4m Standoff Distance with and without Shear Wall

Story level	Lateral displacement in mm	
	250 kg TNT at 4m standoff without shear wall	250 kg TNT at 4m standoff with shear wall 180mm thick
0	0	0
1	14.4	4.1
2	21.8	7.4
3	27.9	9.7
4	30.6	16.2
5	31.3	23.6
6	30	30

Table 6: Inter Story Drift of 250 kg TNT 4m Standoff Distance with and without Shear Wall

Story level	Inter story drift in mm	
	250 kg TNT at 4m standoff without shear wall	250 kg TNT at 4m standoff with shear wall 180mm thick
0	0	0
1	14.4	4.1
2	7.4	3.3
3	6.1	2.3
4	2.7	6.5
5	0.7	7.4
6	1.3	6.4

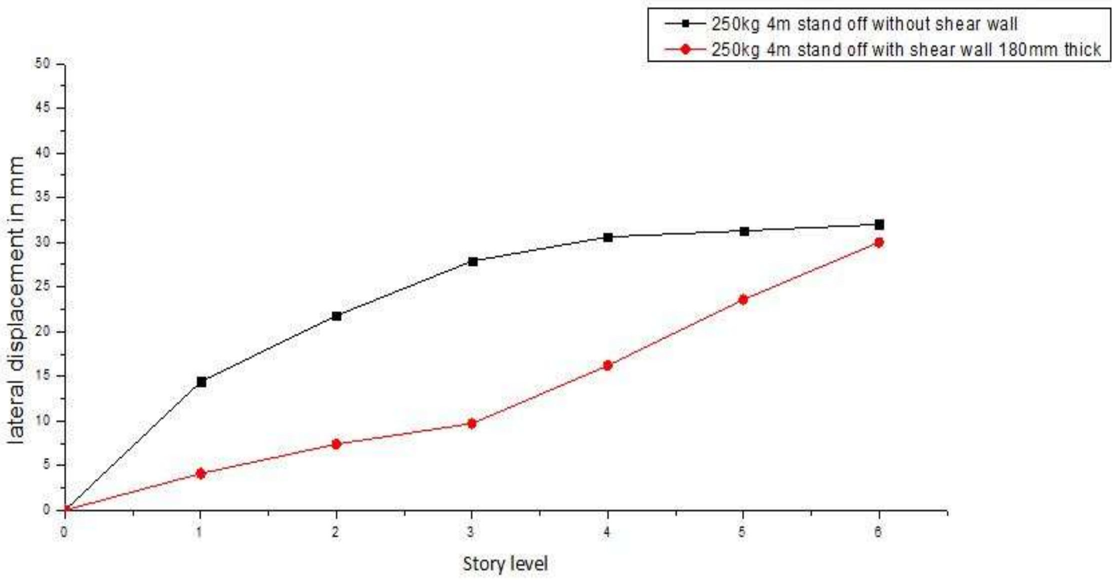

Fig. 5 Lateral displacement of 250kg TNT at 4m standoff distance with and without shear wall

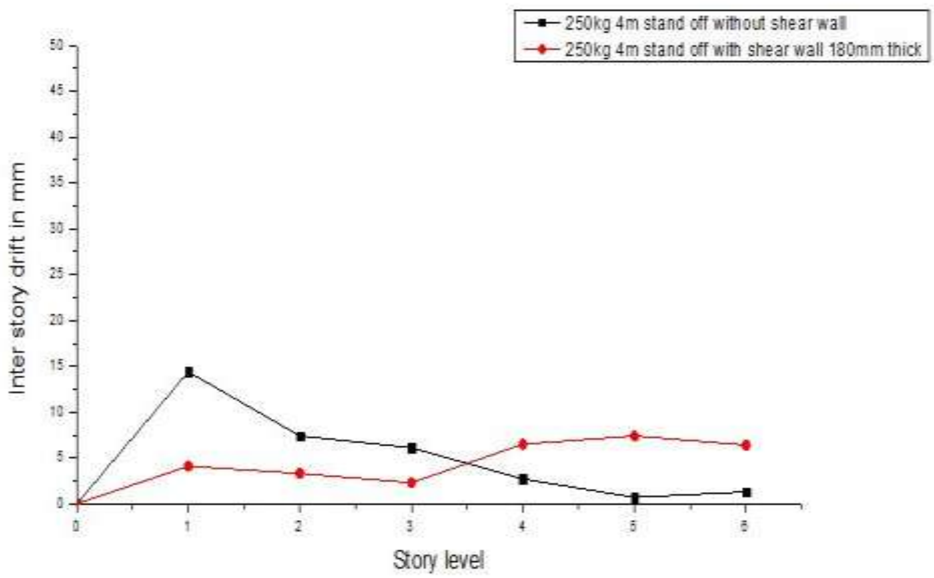

Fig. 6 Inter story drift of 250kg TNT at 4m standoff distance with and without shear wall

In case 2, for 250 kg TNT at 4m standoff distance, models with and without shear wall were satisfying the IS code limitations. This is due to the decreased amount of charge weight that produces less impulse and pressure on the structure.

Case 3: Variation of lateral displacement and Inter story drift for 500KG and 750KG TNT.

Table 7: Lateral Displacement of 500 kg TNT and 750 kg TNT for 6m Standoff Distance

Story level	Lateral displacement in mm	
	500 kg TNT at 6m standoff	750 kg TNT at 6m standoff
0	0	0
1	21.4	36
2	34	53
3	47	70
4	57	88
5	60	112
6	60.8	115

Table 8: Inter Story Drift of 500 kg TNT and 750 kg TNT for 6m Standoff Distance

Story level	Inter story drift in mm	
	500 kg TNT at 6m standoff	750 kg TNT at 6m standoff
0	0	0
1	21.4	36
2	12.6	17
3	13	46
4	10	18
5	3	24
6	0.8	3

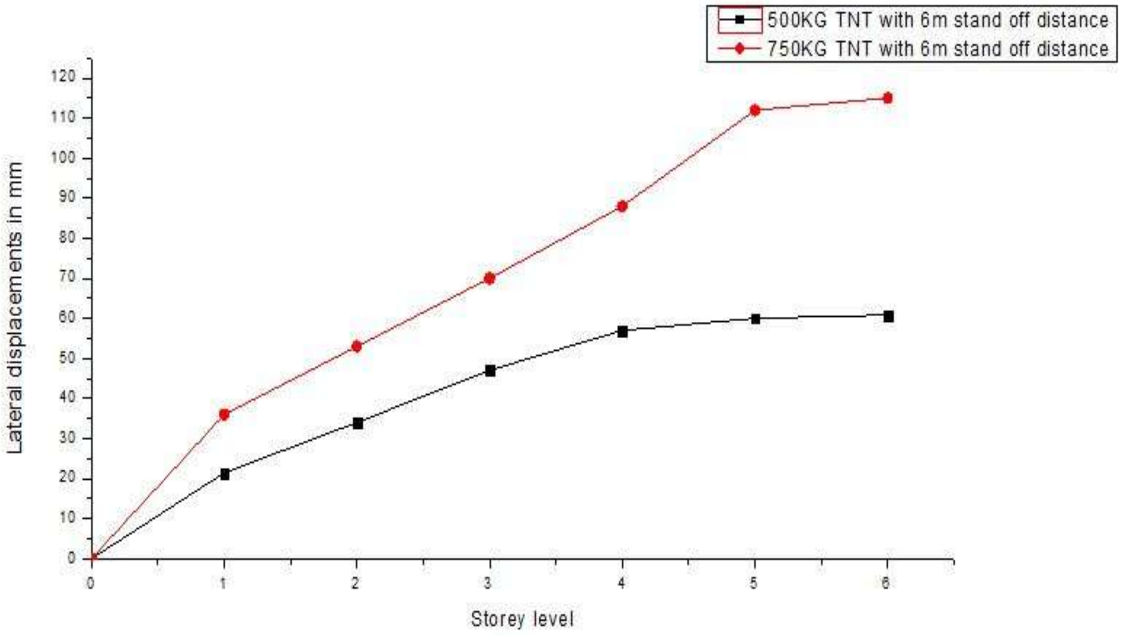

Fig. 7 lateral displacement of 500kg TNT and 750kgTNT for 6m standoff distance

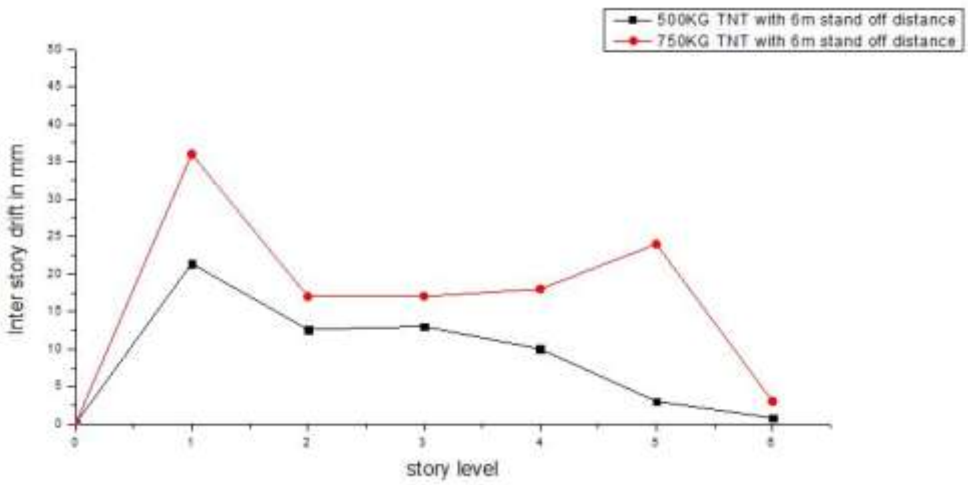

Fig. 8 Inter story drift of 500kg TNT and 750kg TNT for 6m standoff distance

Case 3 compares the effect of 500kg and 750kg TNT, for a constant standoff distance of 6m. For both explosive charges, the top story lateral displacements and inter story drifts failed to satisfy the IS code limitations. This is primarily due to the significant increase in the weight of explosive, as they produce high impulse on the structure which is unable to sustain the blast load. This might result in the severe damage or collapse of the structure.

Case 4: Comparison of 500kg TNT at 4m standoff distance placed at longer and shorter edge.

Table 9: Lateral Displacement of 500kg TNT at 4m Standoff Shorter and Longer Edge Comparison

Story level	Lateral displacement in mm	
	500kg TNT at 4m standoff along longer edge	500kg TNT at 4m standoff along shorter edge
0	0	0
1	21	13.9
2	32	20.2
3	40	24.6
4	45	27
5	46	27.2
6	46.8	27.5

Table 10: Inter Story Drift of 500kg TNT at 4m Standoff Shorter and Longer Edge Comparison

Story level	Inter story drift in mm	
	500kg TNT at 4m standoff along longer edge	500kg TNT at 4m standoff along shorter edge
0	0	0
1	21	13.9
2	11	6.3
3	8	4.4
4	5	2.4
5	1	0.2
6	0	0.3

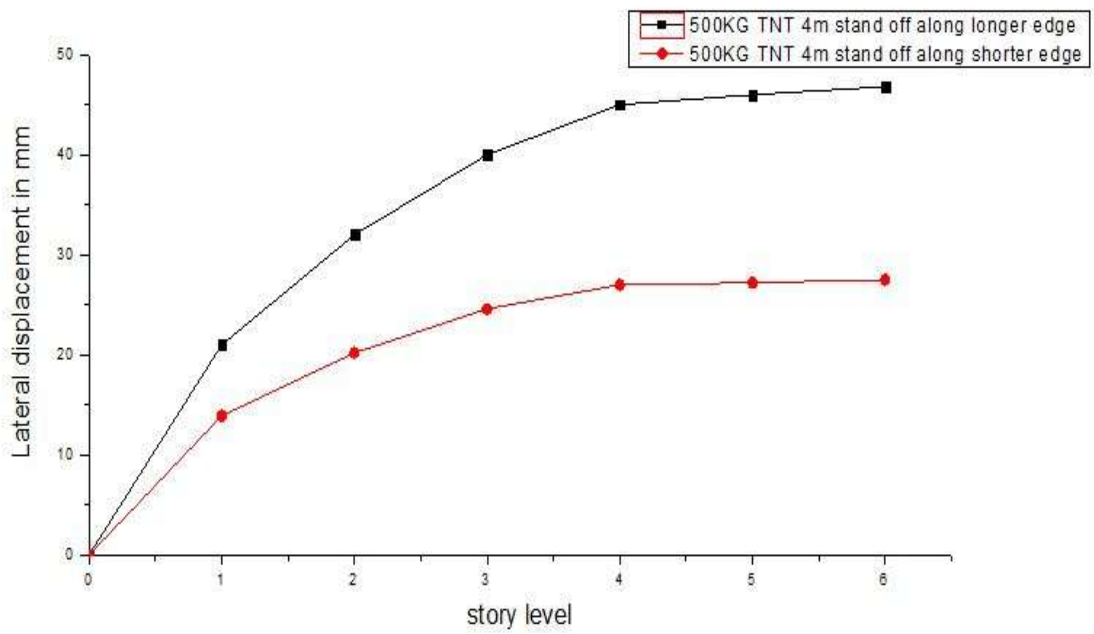

Fig. 9 Lateral displacement of 500kg TNT at 4m standoff shorter and longer edge comparison

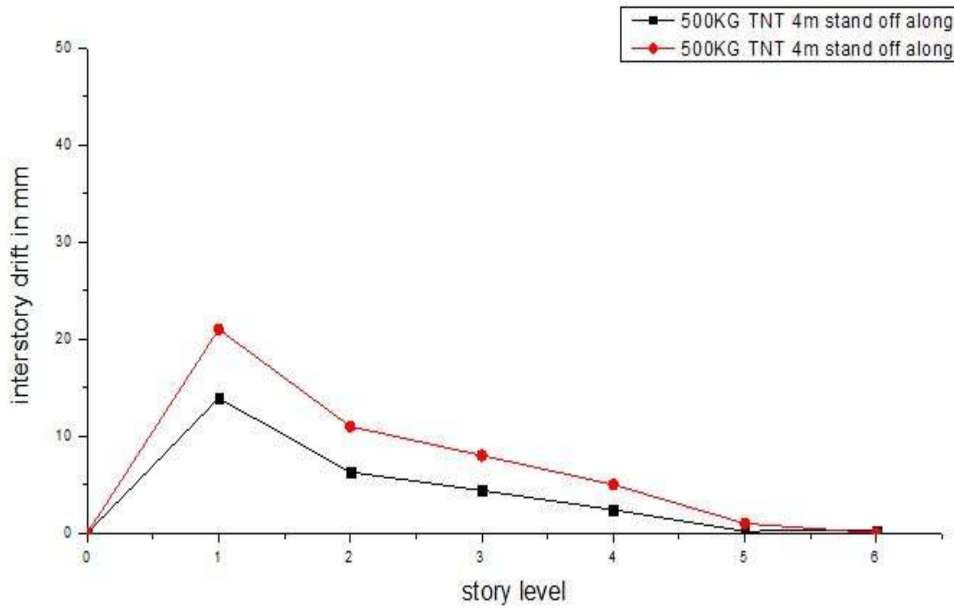

Fig. 10 Inter story drift of 500kg TNT at 4m standoff shorter and longer edge comparison

Case 4 shows the importance and orientation of the building to resist the blast wave. The rectangular buildings with near field explosion along the longer edge is more vulnerable than explosion in near field along the shorter edge. In this case the top story lateral displacements and inter story drift for charges placed along longer edge did not satisfy the IS code limitations. But for the shorter edge the sway and drift were well within the limits.

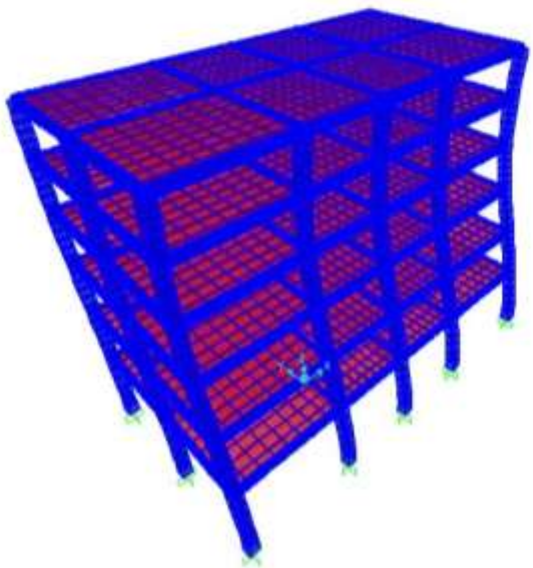

Fig. 11 Deformed shape of the model subjected to Blast load

CONCLUSION

From the above results following conclusions can be drawn.

The primary line of defense to make the structure blast resistant is to increase the standoff distance. This study showed that shear wall was very effective in reducing the adverse effects of blast loads on structures. Shear wall with L shaped configuration at the corners was more efficient in resisting blast loads. Providing shear wall had improved the performance of structure by increasing the rigidity under blast loading compared to its counterpart without shear wall.

The reinforcement in the shear wall must be distributed on the two faces equally in both horizontal and vertical direction which increases the ductility of the structure. Since the impact of blast load is minimal on the top floors, the steel percentage may also be reduced as the height of the shear wall increases. From the analysis it was observed that, longer side of the building is more vulnerable to blast load effects. The standoff distance should be increased along the longer edge of the building. Since the surface area available for the blast wave to act upon is more which in turn increases the top story lateral displacement. If not, the consequences are collapse of the structure and loss of life. The use of high strength concrete is recommended as it decreases the cross-sectional area of shear wall.

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