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Analytical and Statistical Analysis of Reinforced Concrete Frame Structure Subjected to Blast Loading

Gurpreet Singh Dhanoa[1], Kulwinder Kaur[2,*], Sisay Arega[3]

Abstract

Blast loading represents one of the most hazardous and destructive forces that structures may encounter throughout their life span. Understanding and mitigating the effects of such loading is crucial for ensuring the safety and resilience of buildings. This study focuses on analyzing the behavior of reinforced concrete (RC) frame structures when subjected to blast loading, with the aim of informing more robust and resilient building designs. The research specifically examines the deformation patterns of RC structures at varying standoff distances—namely, 3 m, 5 m, and 10 m—with an explosive weight equivalent to 113 kg of TNT. The study further investigates story displacement and drift across three types of building configurations: bare frame buildings, steel-braced buildings, and shear wall buildings. The findings reveal that the effects of explosive events diminish as the standoff distance increases, indicating the critical importance of distance in blast-resistant design. Moreover, the results show that story displacement is significantly lower in shear wall buildings compared to steel-braced buildings and bare frame structures, underscoring the superior performance of shear walls in mitigating blast-induced deformations. To ensure the reliability of the findings, the analytical results were validated through statistical analysis, which confirmed that all results follow a normal distribution. This comprehensive analysis not only provides valuable insights into the structural response under blast loading but also highlights the importance of considering different building configurations and standoff distances in the design process to enhance structural resilience against such extreme loading conditions.

Keywords: Blast loading, shear wall, standoff distance, plastic hinge, SAP 2000

INTRODUCTION

Across the globe, terrorist activities, accidental chemical blast, excavation or mining explosions, etc. all fall under blast loading, which is most risky and damaging load that structures encounter throughout their life span [1]. Explosive detonation produces a potential energy for a brief duration, suddenly rising and quickly falling pressure to achieve equilibrium with the atmosphere. Some part of this energy is released into the atmospheric air and rest of it travels into the earth crust as shock waves. These sub-surface waves had a tremendous effect on all the objects comes within the range, namely, injuries and fatalities to inhabitants, façade damage and structure collapse etc. In past few decades, worldwide many important buildings such as Word Trade Center in New Yark in 1993, Murrah Federal Building in Oklahoma City in 1995, Khobar Towers attack in Dhahran, Saudi Arabia in 1996 and American embassies in Nairobi, Kenya and Dar es Salaam, Tanzania in 1998 became the notable

***Author for Correspondence**
Kulwinder Kaur
E-mail: kaurk2012@gmail.com

[1]Assistant Professor, Civil Engineering Department, Punjabi University, Patiala, Punjab, India
[2]Assistant Professor, Civil Engineering Department, Punjabi University, Patiala, Punjab, India
[3]Research Scholar, Civil Engineering Department, Punjabi University, Patiala, Punjab, India

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victims of blast loading [2]. In addition, explosions of the Somalia Education Ministry building in Mogadishu City on 29 October 2022 have recently highlighted the necessity of a thorough investigation into the behavior of reinforced concrete (RC) buildings subjected to blast loads [3].

Regular building design does not consider the blast loading design process because of complex nonlinear analysis along with the high construction cost. However, as per building vulnerability, the impact of this type of loading must be consider in building design. Analyzing the behavior of RC structures under blast loading can help to protect and ensure that they continue to function as intended. In the past two decades, numbers of researchers done an experimental and analytical investigation on building subjected to blast loading. For instance; Luccioni et al. [4] analyzed the terrorist victim building in term of detonation of the explosive to the complete failure, propagation, and interaction of blast wave with structure. Elsanadedy et al. [5] studied the effect of stand-off distance as 1, 4, and 15 m with charge weight of 100, 200, 500, and 1000 kg on exterior RC circular column. They claimed that lateral deflection of column decreased with the increased standoff distance as-well-as by strengthening the column with carbon fiber–reinforced polymer (CFRP). Li and Hao [6] established a finite element (FE) model in LS-DYNA by using SDOF (single-degree-of-freedom) approach to simulate the blast load response analysis. Shallan et al. [7] established that the effect of blast load reduced with the rose in standoff distance.

Ibrahim et al. [8] used the ABAQUS technique to investigate the behavior of four-story frame structure subjected to blast loading. The outcome of this study showed that the behavior of the structure can be improved by altering the external column design. Habib et al. [1] analyzed the RC structure with 100 kg TNT explosion at a 40 m standoff radius and concluded that story displacement under blast effect is 87.93% higher when compared with seismic and wind loads. Sai [9] used the SAP 2000 software to analyze the structure with 10, 20, and 30m standoff distance along with 100 kg, 200 kg, and 300 kg TNT. Mishra and Netula [10] evaluated the overpressure and reflected blast pressure on the framed structure and observed that story displacement was decreased with the increase in floor height. Ning et al. [11] investigated the concrete slab fragment bahavior with 1.5 kg explosion at different standoff distances. Also, a fragment model was established to analyze the fragment degree of structure due to blast effect. Layas et al. [12] studied the behavior of RC structure subjected to blast loading during the Libyan war. They prove that blast forces are depended upon the standoff distance and explosion material weight.

Outcome of the referred works show that standoff distance as well as power of detonation strongly influence the response of the blast victim RC structures. Present research aimed to study the effect of strain loading on the blast prone panel of four-storied RC frame using nonlinear analysis in SAP 2000 software. The main parameters of the study are: (1) to examine principal stress and deformation of structure with different standoff distance, namely 3 m, 5 m, and 10 m with explosive weight of 113 kg TNT; (2) to study story displacement and drift in three types of buildings like bare frame building, steel braced building, and shear wall building; and (3) for statistical validation, analysis of variance was run to verify the displacement occur in different building types are either by chance or by statistical significance.

METHODOLOGY AND ANALYSIS

Material Properties and Load Assignment

Four story moment resisting framed structure as shown in Figure 1(a) with 3 m story height was used in this study. The plan of frame along with the position of removed columns C1, C2, and C3 is depicted in Figure 1(b). Columns are removed so that plastic hinges are permitted to from along the members for the nonlinear analysis. The structure is designed to resist the dead load (DL), live load (LL), and wind load (WL) assigned as per IS 4661-1968 [13] guidelines. Blast load is assigned as triangular time history function in SAP 2000 with 113 kg TNT overpressure variation at different standoff distances. The connection between column and foundation is assigned as fixed connection. The details of all parameters assigned to the model like concrete compressive strength, steel grade, density etc. are summarized in Table 1. In beams, equal amount of reinforcement has been provided in tension as well as in compression zone during the preliminary stage.

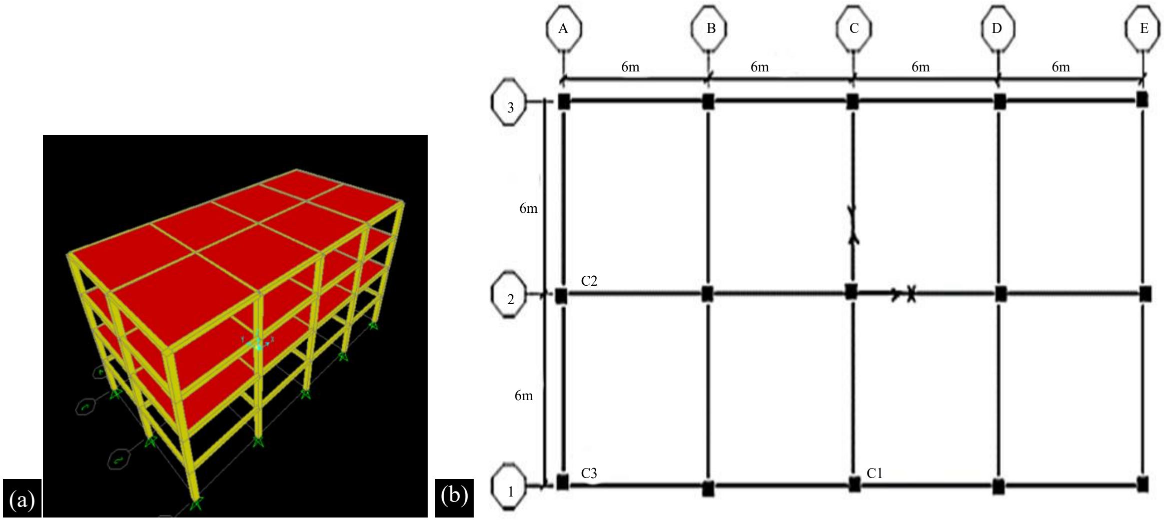

Figure 1. (a) 3D frame structure view. (b) Plan view of frame with removed column position.

Table 1. Material and structural parameters.

Material Parameters	**Concrete Properties**		**Steel Properties**	
	Grade	***Density***	***Grade***	***Density***
	M20	25 kN/m^3	Fe 300	78.5 kN/m^3
Structural parameters	***Element***	***Column***	***Beam***	***Slab***
	Size	0.40 × 0.40 m	0.40 × 0.25 m	0.15 m
	Reinforcement	2500 mm^2	1200 mm^2	–

Effect of column removal and finalization of structural elements

Typically, that load bearing structural component which is directly exposed to explosive source considered as a most vulnerable like external columns or shear wall, etc. Thus, the main consideration corresponds to the design of external column to enhance the blast-resistant capacity of the structure. SAP2000 "nonlinear staged construction" capability was employed to simulate the removal of the column. A total of 100 steps were assigned for each of the two stages of the model's analysis. Every component was assigned the total load in the first stage; The column was eliminated in the second and the responses counting was continued until the building began to settle. The greatest rotations of a plastic hinge were noticed once the structure got stabilization. Figures 2(a), 3(a), and 4(a) depict the outcomes of removing columns C1, C2, and C3, respectively, in terms of deformed morphologies and the development of hinges accordingly. All figures show that formation of plastic hinges exceeded the rotation permitted in standard UFC 2008 [14]. Thus, redesign of the members is necessary.

In the redesign, beam size and steel ratio both are raised as 0.50 × 0.25 m and 1500 mm^2 in tension as-well-as in compression zone, respectively; while in column only percentage of steel is raised as 2850 mm^2. The redesigned building will thereafter follow the same process and outcome of the raised section and steel ratio is depicted in Figures 2 to 4. Figures 2(b), 3(b), and 4(b) show the deformed shape of the revised structure after removal of C1, C2, and C3, column respectively. It can be clearly observed that no plastic hinge has been broken in the revised structure, demonstrating that the new structure complies with the UFC 2008 [14]. specification. Formed pink color hinges refer to the low stress development in revised structure irrespective to the position of column to be removed, hence the revised sections of the structure can able to withstand the gravity and blast load.

Analysis of Structure Using Nonlinear Dynamic Procedure

It is crucial to accurately assess the behaviors of structural elements in their respective damaged states that were not eliminated from the structure by the blast loads. Thus, the building was first analyzed by using a nonlinear static analysis and on the exterior explosion occurrence, nonlinear direct integration time-history analysis was done. Newmark integration techniques available in SAP 2000 with $\gamma = 0.5$ and $\beta = 0.25$ was assigned on the current model. Radial distance between the point of explosion and the middle of each member, the blast pressure exerted on the members is calculated and presented in Figure 5.

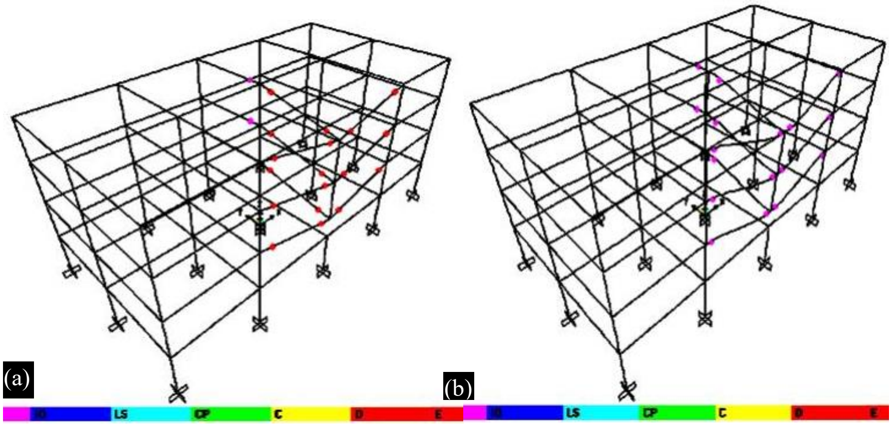

Figure 2. Deformed shape and hinge formation after removal of C1: (a) earlier section and (b) revised section.

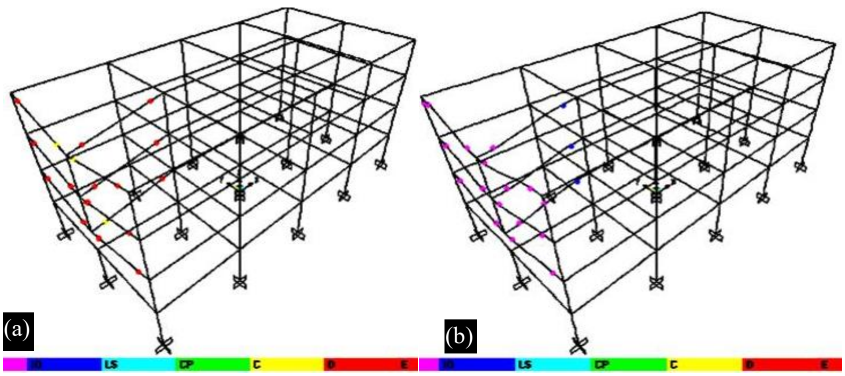

Figure 3. Deformed shape and hinge formation after removal of C2: (a) earlier section and (b) revised section.

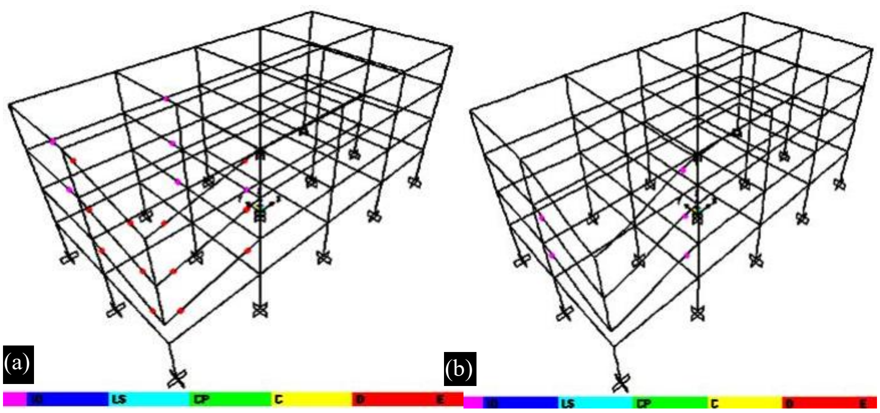

Figure 4. Deformed shape and hinge formation after removal of C3: (a) earlier section and (b) revised section.

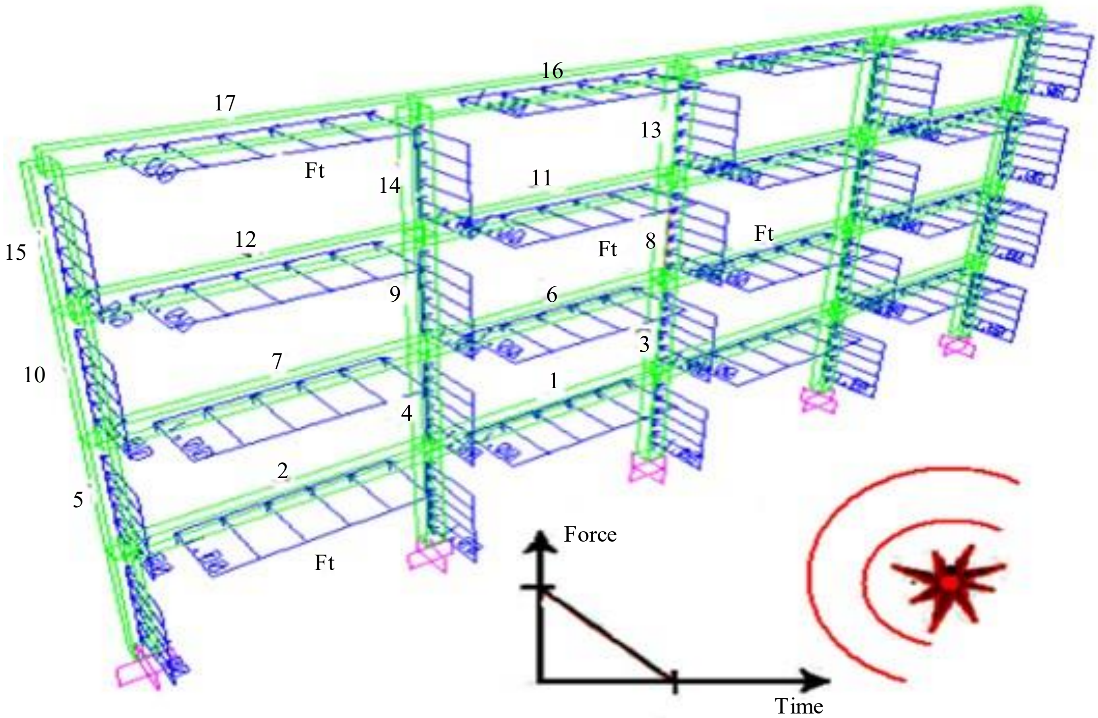

Figure 5. Exterior panel with application of blast load.

RESULTS AND DISCUSSION

Effect of Standoff Distance on Hinge Formation and Deformation of Structure

Figure 6 shows the final stage hinges and deformed shape of structure at a standoff distance of 3 m, 5 m, and 10 m from the center point of the bare frame building. It is clearly observed from Figure 6 that the effect of the explosive event is reduced with increase in stand-off distance. The developed high stress and deformed shape refer to the damage cause by 113 kg detonation at 3 m and 7 m of standoff. However, building is secure against blast-induced progressive collapse at a 10 m standoff distance. The observed behavior complies with finding made by Layas et al [12]. They claimed that larger and closer the detonation site cause more significant damage.

To calculate dynamic reaction, SDOF approach was used to evaluate a resistance deflection function. After obtaining the load and resistance functions, mass and resistance function are multiplied by the mass and load factors (typically 0.72 for fixed end members), which calculate the actual percentage of the load that is contributing to the member span-depth deflection. The blast characteristics for the calculated load are summarized in Table 2. To make the building as blast resistant, various structural system such as shear wall and steel bracing are provided at the corner periphery of the building.

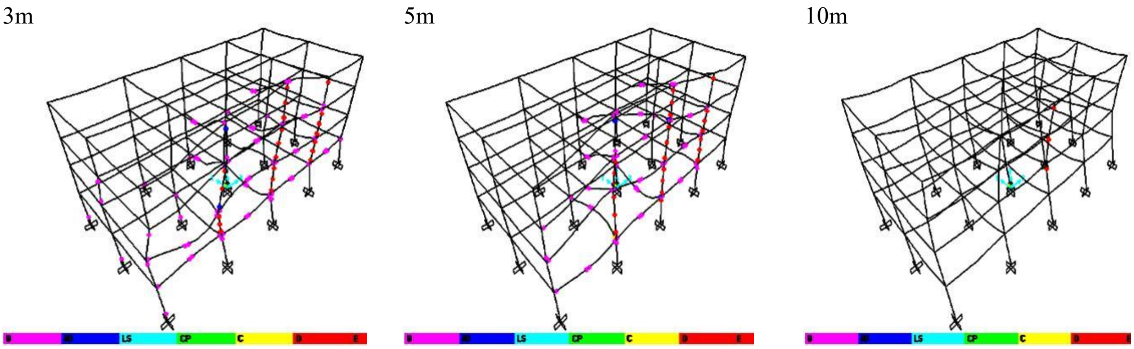

Figure 6. Final stage hinge formation and deformed shape of the structure at different standoff distances.

Table 2. Blast load characteristics at different standoff distances.

Standoff Distance (m)	Shock Velocity (m/s)	Arrival Time (ms)	Pressure (MPa)	Impulse (MPa mc)	Load Duration (ms)
3 m	1.075	2.776	6.020	537.02	1.239
5 m	0.871	4.164	3.191	403.06	1.751
10 m	0.572	10.343	0.735	219.57	4.162

Story Displacement and Drift

Figures 7 and 8 clearly depicts that displacement rose with the increase in story height irrespective of building types. In the first story, approximately 77% lower displacement occurred as compared to fourth story in a bare frame building. However, in case of steel braced and shear wall building, this value is 87.5% and 80%, respectively. On the other side, provision of bracing and shear wall reduced the effect of blast loading in the building. The structural frame with end corner shear wall reduces the displacement and drift by 65.5% and 30.4%, respectively, in story-4 when compared to bare frame. On making a comparison between steel braced and bare frame building, this reduction is 44.8% in displacement and 13% in drift (Figure 8). Thus, it may be concluded that the implementation of the shear wall at end corner is more effective in the building against blast load effect, when compared with bare frame and steel braced building.

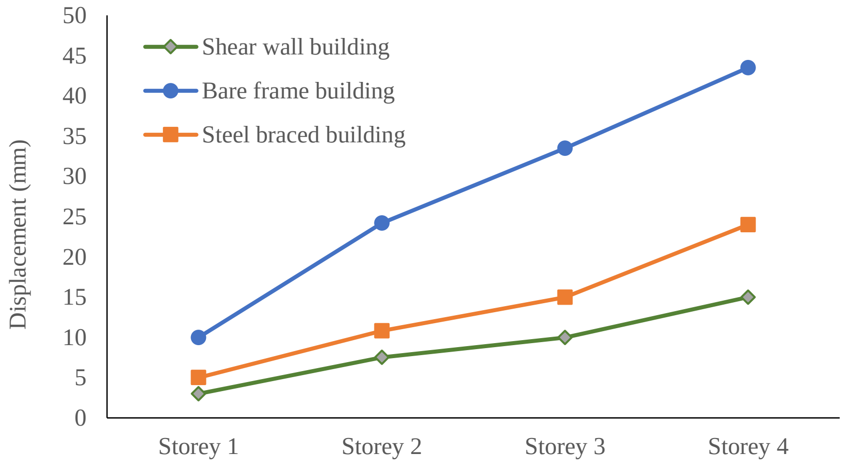

Figure 7. Displacement of different building types at different story levels.

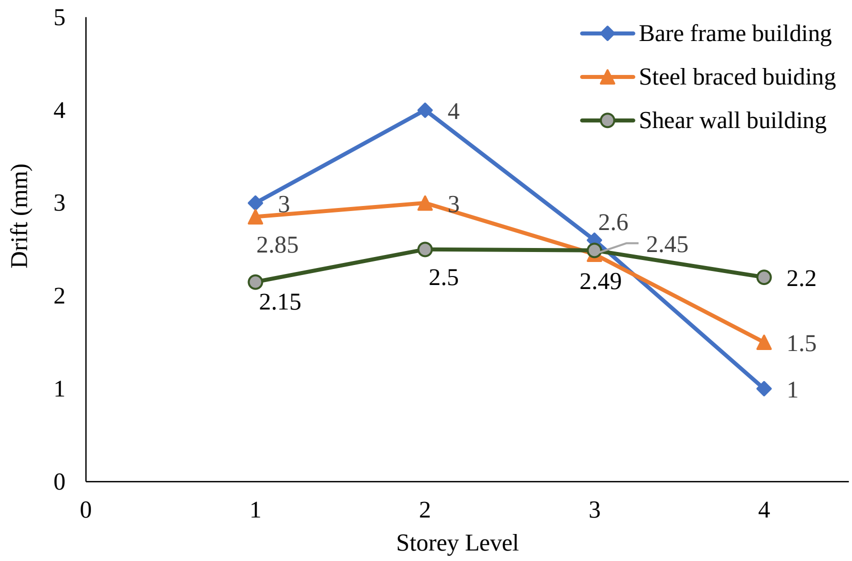

Figure 8. Drift of different building types at different story levels.

Statistical Analysis

For statistical validation, analysis of variance (ANOVA) was run by using SPSS software to verify the displacement occur in different building types levels are either by chance or by statistical significance. Normality was assessed by performing descriptive analysis: Skewness and kurtosis, Shapiro test, and box plot. The output of statistical analysis is reported in Table 3. The table shows that all the building types shows small variation in mean, medium and mode, thus displacement occur in all building is not significantly different. Despite, building provided with shear wall shows the smallest difference in mean, medium and mode. Furthermore, Z score calculated from skewness and kurtosis analysis lies between –1.96 and 1.96, proving that displacement belong to the normal distribution. The *p*-value calculated from Shapiro-Wilk test is higher than the 0.05 for all buildings, which means that the null hypothesis will be accepted. The results of one-way ANOVA (Table 4) also led to the acceptance of the null hypothesis as significance level is 0.58, which is higher than 0.05 alpha level. As the null hypothesis is accepted, no further post analysis is required.

From all statistical output, it is clearly depicted that displacement occur in all building is normal. The provision of shear wall and steel bracing significantly help the building to resist the effect of blast loading. All the statistical parameters such as descriptive, Z score, Shapiro-Wilk, prove that shear wall building can resist the blast load more efficiently followed by steel braced building. While bare frame building can resist least blast load effect among the tested buildings due to negatively skewed distribution of data and lower value of mean than the medium and mode. Box plot (Figure 9) clearly shows that the interquartile range for the bare frame building is higher, followed by steel braced and shear wall building. Furthermore, no outlier and T-shaped whiskers with the 1.5 times the interquartile range was observed in box plot, proving the normal distribution of data.

Table 3. Analysis of variance for different building types.

Building Type	Descriptive Parameters			Z Score		Shapiro-Wilk	
	Mean	*Medium*	*Mode*	*Skewness*	*Kurtosis*	*Test p-value*	*Decision*
Bare frame	27.80	28.85	30.95	-0.37	0.14	0.966	Normal
Steel braced	13.70	12.90	11.3	0.53	0.15	0.938	Normal
Shear wall	8.87	8.75	8.51	0.13	0.12	0.994	Normal

Table 4. One-way analysis of variance results

	Sum of Squares	*df*	Mean Square	*F*	Significance
Between groups	773.662	2	386.831	3.975	.058
Within group	875.848	9	97.316		
Total	1649.509	11			

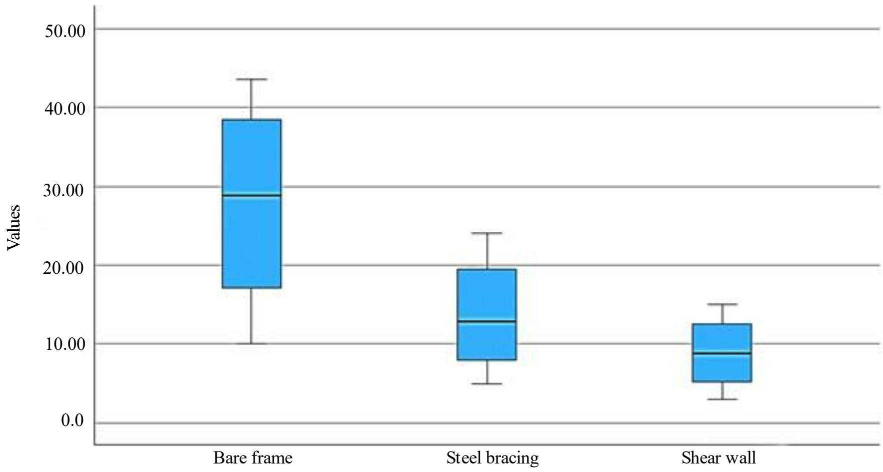

Figure 9. Box plot showing median for all building types.

CONCLUSION

The following conclusions can be drawn from the nonlinear analysis performed on the RC frame:

1. The section should be selected in such a way so that no plastic hinge can be broken after the removal of any of the exterior column because the blast load effect is more operative on the periphery of RC structure.
2. Structure designed in accordance with IS 4661-1968 criteria can withstand a blast load of 113 kg at a standoff distance of 10 m; however, at 7 m or less distance, the observed stress exceeds the safe limit in bare frame building.
3. To make the building blast resistant, various structural system such as shear wall and steel bracing are provided at the corner periphery of the RC building. The RC structure with end corner shear wall and steel bracing reduces the story displacement by 65.5% and 44.8%, respectively, as compared to bare frame building.
4. Statistical test of analysis of variance proven the significance of displacement occur in all building types, while the provision of shear wall and steel bracing significantly help the building to resist the effect of blast loading.

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