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Collapse Analysis of Concrete Frame Structures Subjected to Extreme Loading

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ABSTRACT: An increase in deliberate and accidental explosions in recent years has prompted an urgent need to investigate the response and behavior of structures subjected to blast loadings. Many of government structures must be capable of sustaining various loading conditions including the blast load. The present paper entails finite element analysis of multistory frame structures subjected to blast loadings. Nonlinear dynamic analysis was performed due to the large amount of literature supporting it as the superior method of analysis as compared to nonlinear static analysis. The accuracy of the multistory frame model was also confirmed through comparison of its response under blast loading with that of an existing study in the literature, and the results were in good agreement. Retrofitting was simulated by relocating the plastic hinge formations in structural members of the frame. The load factors initiating plastic hinge formation under varying degrees of retrofitting for various frame shapes were compared to reveal the best and worst possible scenarios.

1 INTRODUCTION

After the collapse of the World Trade Center towers in 2001, research on progressive collapse analysis has increased significantly with the focus on identifying ways to improve the structural capacity to resist the collapse under extreme loads such as blast. Much of existing studies to predict the behavior of structures for blast scenario have focused on column removal and progressive collapse under gravity load only using finite element analysis. Field tests along with numerical analysis have also been performed on existing reinforced concrete and steel frame buildings under gravity load to analyze progressive collapse (Morone and Sezen 2014; Song et al. 2014). In addition, researchers have considered linear static analysis for various cases of column removal under gravity load through finite element analysis (Ilyas et al. 2015).

To predict the progressive collapse, few studies have analyzed the effects of column removal under triangular and distributed lateral loads and under external blast load. With respect to column removal scenarios, the corner and external column removal scenarios created higher possibility of progressive collapse under lateral and blast loads (Tavakoli and Alashti 2013; Tavakoli and Kiakojouri 2013).

The impact of blast load on building frames without column removals has also been investigated. One study analyzed the effect of explosion distances on the behavior of a reinforced concrete (RC) frame. Either of explosive quantity or explosion distance affected the damage level of the RC frame (Cheng et al. 2014). Another study focused on a comparison between a slurry infiltrated fiber reinforced concrete (SIFCON) frame and a regular three-story RC frame under blast load. Using SIFCON improved the response of the frame under blast load (Jayashree et al. 2013).

Some studies also have been performed on FRP retrofitting of beams, columns, or beam-column connections and relocating the plastic hinges to improve the load carrying capacity of structures when subjected to earthquake load by pushover analysis. FRP strengthening significantly improved the behavior of these elements and structures (Niroomandi et al. 2010; Eslami and Ronagh 2013; Van Cao and Ronagh 2014; Ronagh and Eslami 2013; Eslami et al. 2013).

The review of the literature indicates the investigations on the impact of blast load on structures are sparse, in particular, when it comes to strengthening and relocating the plastic hinges to improve the overall building response. The objective of this research is to study the response of RC buildings under external blast loading and to improve their response through simulating FRP strengthening by relocating the plastic hinges.

2 FINITE ELEMENT ANALYSIS MODELING OF CONCRETE FRAMES

SAP2000 finite element analysis software program was used to model a three-story reinforced concrete frame building. To simulate blast loading condition, a time history air pressure wave was applied to the frame. Nonlinear dynamic time history response of the frame model was validated with that of an existing study in the literature (Jayashree et al. 2013) and they were in good agreement.

2.1 Geometry and material properties of the frame

The simulated frame consisted of two bays in *x* one bay in *y*, and three story elevations in *z* directions of the global coordinate system. All bays were equally spaced at 8 m in *x* and *y* directions. The floor to floor height of each story was equal to 3 m [Figures 1(a and b)].

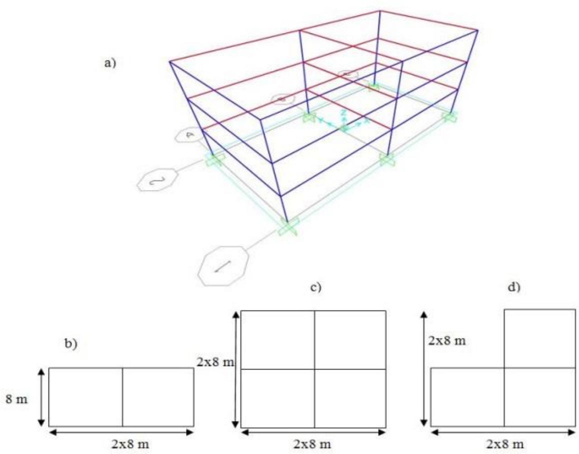

Figure 1. a) Base rectangular model with *x y* and *z* coordinates b) plan view of rectangle c) plan view of the square model d) plan view of the L-shaped.

The beams were assumed to be 45 x 25 cm reinforced concrete sections. All story columns were 30 x 30 cm RC sections with eight longitudinal bars (29 mm). The hoop reinforcement bars were assumed to be 13 mm with 15 cm longitudinal spacing and concrete cover of 4 cm. The floor diaphragms were treated as thin shell sections with two layers of reinforcement. The thickness of the slab was 10 cm with 1 cm of concrete cover. The concrete compressive strength and modulus of elasticity were 25 MPa and 23,158 MPa, respectively. The bars were made of grade 60, with the yield strength of 414 MPa and modulus of elasticity of $2x10^5$ MPa, respectively.

2.2 Loading and boundary conditions

All beam-column joints were considered as moment connections while all columns at the ground were modeled as fixed supports. Additionally, the end length offset option in SAP2000 was used to connect the beams and columns properly. All floor systems were assumed to work as diaphragms.

The dead loads of structural elements were calculated by SAP2000 software program based on the 23 KN/m^3 for concrete weight per volume, and 77 KN/m^3 for the steel bars. The walls distributed load had magnitudes of 4 KN/m and 2 KN/m applied on the beams in the first and second stories, and the roof, respectively. Additionally, a 3 KN/m^2 uniform live load was applied on the first and second story slabs. A time history blast load was applied to the building frames as an air pressure blast load (Figure 2) (Jayashree et al. 2013).

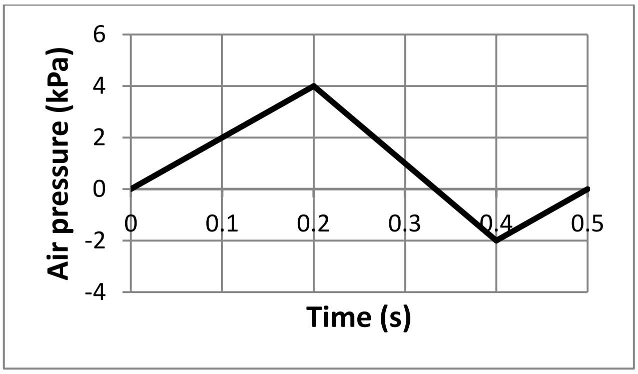

Figure 2. Air pressure wave of basic blast load (Jayashree et al. 2013).

2.3 Analysis procedure

The blast load was applied to the validated reinforced concrete frame by performing nonlinear time history analysis. P-M2-M3 and M3 plastic hinges were applied to both ends of columns and both ends of the beams, respectively. P-M2-M3 plastic hinges have a moment rotation curve which is used to describe a combination of axial and bending behavior of column elements (SAP2000 2014). 'Automatic plastic hinges' option in SAP2000 software program was used for this purpose. All plastic hinge definitions are based on tables 6-7 and 6-8 of FEMA 356 (FEMA 2000)[14]. A 5 percent constant damping ratio was assumed. The analysis was performed for 2 seconds with 2500 time steps. The default nonlinear parameters of SAP2000 software program were used.

2.4 Nonlinear solutions and failure criterion

Iteration method was used to predict the required load value to form the first plastic hinges as they exceeded the collapse prevention condition. Based on the GSA, for the nonlinear dynamic analysis, the moment and rotation values should not exceed the collapse prevention condition. The magnitude of blast load was changed by increasing or decreasing the load scale factors (GSA, 2003).

3 FINITE ELEMENT ANALYSIS RESULTS OF VALIDATED MODELS

The finite element analysis model of the frame generated in the present study was compared to nonlinear dynamic analysis performed by Jayashree et al (2013). Figure 3 shows that the roof's displacement time history curves of the two models are in good agreement under basic blast load**.** As the time gradually increased the displacement damped out since the blast load was applied for the first half second and the response was captured in the first two seconds. The 5 percent assumed damping ratio was able to stabilize the displacement.

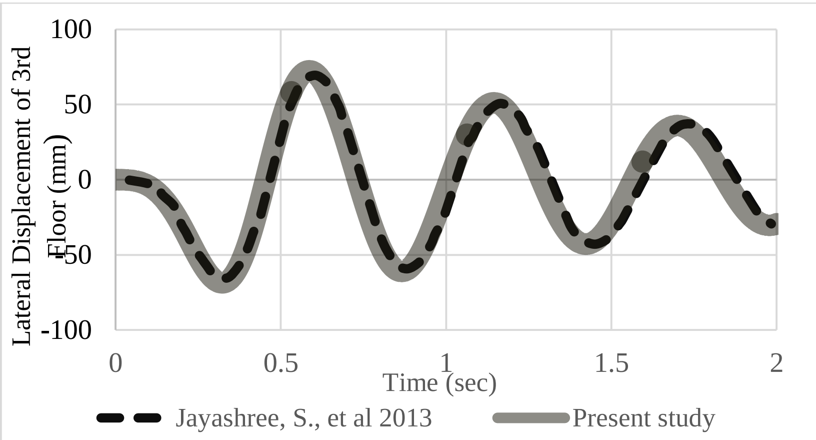

Figure 3. Verification of finite element analysis results.

4 PARAMETRIC STUDY

Parametric study was performed to further investigate the behavior of the three-story RC frame under blast loading. Parameters considered were various retrofitted lengths for the beams, and frame shapes. To simulate the locations of plastic hinge formation, the retrofitting lengths of 1, 2, 3, and 4 times the beam depth named as 1D, 2D, 3D, and 4D were analyzed. The frame geometries were rectangle, square, and L-shaped.

To identify members requiring retrofit, the control frame of each shape was examined under increasing blast load scale factors, until the minimum load level that causes the formation of plastic hinges and the collapse prevention condition limit was reached. Next, the critical members were retrofitted for all different frame shapes and similar procedure was applied to determine the minimum load to reach the collapse prevention criteria. The rectangular validated RC frame model [Figure 1 (a)] was used first to access the effectiveness of varying retrofit lengths under blast loading. Finite element analysis revealed that the plastic hinges formed in the beams and there was no failure in the columns. As a result the beams were the primary members selected for strengthening. Initially, retrofit was only applied to the beams with plastic hinges. Eventually, all the beams had to be strengthened, since retrofit of selected beams with plastic hinges did not increase the load carrying capacity, but rather were shifted into other beams with no prior plastic hinges.

4.1 *Comparison of control and retrofitted concrete frames results*

To analyze the response of various frame shapes, the blast load was applied in the *x* and *y* directions [Figure 1 (a)]. Table 1 shows comparative analysis of control and retrofitted frames. The control and retrofitted rectangular frames showed a higher load carrying capacity for the *y* direction load. For the control rectangular frame, the plastic hinge did not occur until a load factor of 0.6 and 0.48 for the *x* and *y* directions of the blast load, respectively. For rectangular frame, the percentage of blast load scale factor increase was higher in *x* as compared to *y* direction for 1D and 2D retrofitted lengths. While retrofitting with the length of 3D was equally effective for load in either directions, and retrofitting with length of 4D was more effective in increasing load carrying capacity for *x* rather than *y* direction of blast loading.
In summary, the rectangular frame performed better in *y* direction of blast loading, when the load was directed against the longer side. Retrofitting was effective for increasing load carrying capacity of the model for both *x* and *y* directions of blast loading.

Table 1. Comparative analysis of control and retrofitted frames

Frame shape	Retrofitted length	Scale factor	Scale factor increase compared to control (%)
Rectangle (blast load in *x* direction)	0	0.48	0
	1D	0.52	8
	2D	0.55	15
	3D	0.8	67
	4D	0.9	88
Rectangle (blast load in *y* direction)	0	0.6	0
	1D	0.7	17
	2D	0.8	33
	3D	1	67
	4D	1	67
Square (blast load in *x* or *y* directions)	0	0.4	0
	1D	0.51	28
	2D	0.6	50
	3D	0.75	88
	4D	0.75	88
L Shape (blast load in *x* or *y* directions)	0	0.22	0
	1D	0.23	5
	2D	0.3	36
	3D	0.6	173
	4D	0.8	264

4.2 *Comparison of rectangular square and L-shaped frames results*

Besides rectangular frame, the results of square, and L-shaped frames were also compared (Table 1). In an effort to minimize the effects of other variables on shape modification, the square and L-shaped models used the same member properties and bay dimensions as the rectangular model (Figure 1). The effect of frame shape was investigated using blast load intensity which initiates the formation of plastic hinges (Figure 4). The square and L-shaped models were subjected to an *x* and *y* directions blast load, however, due to symmetry and the results being the same in either directions, each is represented only once in the figure.

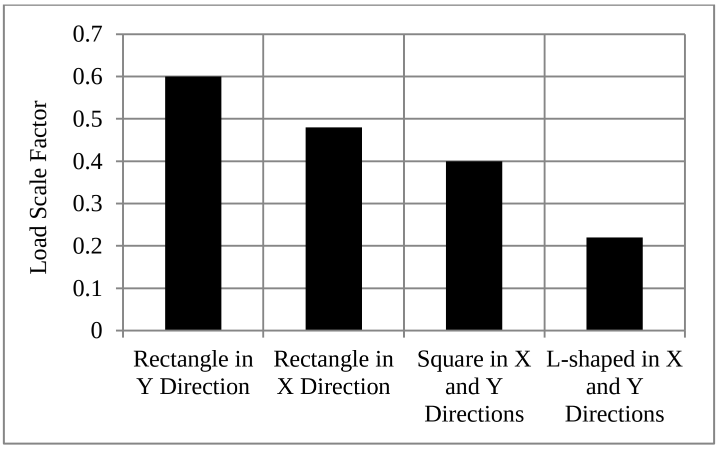

Figure 4. Load capacity of control frames with various shapes.

Figure 5 shows the effect of shape on load carrying capacity of control and retrofitted frames. The blast load scale factor can be compared for various retrofit lengths and frame shapes. The general trend in the retrofit analysis was that shifting the plastic hinge formation in the beam away from the column core center (beam-column joint core center) by three times the beam depth resulted in reaching a plateau in load carrying capacity. The outlier in this trend was that for control models, the plastic hinges initiated at much lower load scale factors in L-shaped model than the other shapes. However the L-shaped model response had similar increases in the load carrying capacity when retrofitted the beams with one and two times the depth. Unlike the other shapes, the load capacity of the L-shaped model kept increasing after applying the retrofit to three times the depth; however it still reached a final load factor similar to the other shapes.

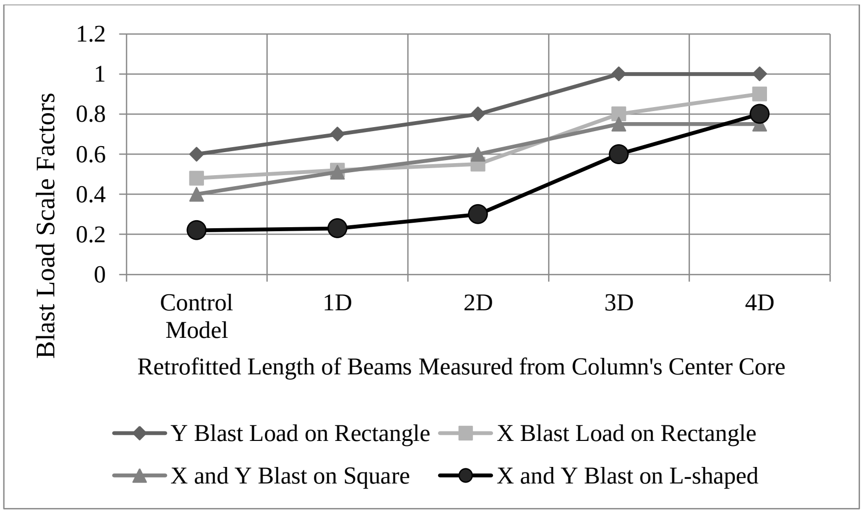

Figure 5. Shape effect on load carrying capacity of control and retrofitted frames.

5 CONCLUSIONS

The present study involves nonlinear dynamic analysis using SAP2000 software program to investigate the behavior of three-story RC frames under blast loading. Parameters considered were various retrofitted lengths for the beams and different frame shapes. The following conclusions are drawn:

- The accuracy of finite element model of RC frame was confirmed through comparison of lateral displacement time history results with an existing study in the literature.
- Depending on the shape of the frame and the retrofitted length of the beam members, the load carrying capacity of RC frames could increase significantly.
- Rectangular and square shaped frames are more desirable due to higher blast load resistance. Special consideration should be given for the irregular L-shaped frame in which the plastic hinges formed at lower blast load level.
- The locations of plastic hinges were simulated through strengthening the beam members with different retrofitting lengths. As the plastic hinges moved further from beam-column joints' core center by changing the retrofitted length, the frame was able to provide higher load capacity under the blast loads.
- The threshold for the retrofitted length was approximately equal to three times the depth of the strengthened members. However, for the L-shaped frame, higher retrofit length (four times the depth of the strengthened member) was desired to achieve greater load capacity for the frame under blast load.

6 REFERENCES

Cheng, X., Jing, W., and Ma, J. 2014, Dynamic response of concrete frame structure under a blasting demolition environment. *The Electronic Journal of Geotechnical Engineering Structures*, 19(7):17823-17837.

Eslami, A., and Ronagh, H.R. 2013, Effect of FRP wrapping in seismic performance of RC buildings with and without special detailing–a case study. *Composites Part B: Engineering,* 45(1):1265-1274.

Eslami, A., Dalalbashi, A., and Ronagh, H.R. 2013, On the effect of plastic hinge relocation in RC buildings using CFRP. *Composites Part B: Engineering*, 52, 350-361.

FEMA, 2000, Commentary for the seismic rehabilitation of buildings, *FEMA-356, Federal Emergency Management Agency*, Washington, DC.

GSA, 2003, Progressive collapse analysis and design guidelines for new federal office buildings and major modernization projects. *General Services Administration*, Washington, DC.

Ilyas, U., Farooq, S.H., and Ilyas, M. 2015, Progressive collapse of reinforced concrete frame structure under column damage consideration. *Pak. J. Engg. & Appl. Sci*., 16, 61-66.

Jayashree, S.M., Bharatwaj, R.R., and Santhi, M.H. 2013, Dynamic response of a space framed structure subjected to blast load. *International Journal of Civil & Structural Engineering*, 4(1):98-105.

Morone, D.J., and Sezen, H. 2014, Simplified collapse analysis using data from building experiment. *ACI Structural Journal,* 111(4):925-934.

Niroomandi, A., Maheri, A., Maheri, M.R., and Mahini, S.S. 2010, Seismic performance of ordinary RC frames retrofitted at Joints by FRP sheets, *Engineering Structures*, 32(8):2326-2336.

Ronagh, H.R., and Eslami, A., 2013, Flexural retrofitting of RC buildings using GFRP/CFRP–a comparative study, *Composites Part B: Engineering,* 46, 188-196.

SAP2000, 2014, Integrated finite element analysis and design of structures-basic analysis reference manual. *Computers and Structures Inc*, Berkeley, California.

Song, B.I., Giriunas, K.A., and Sezen, H. 2014, Progressive collapse testing and analysis of a steel frame building. *Journal of Constructional Steel Research***,** 94, 76-83.

Tavakoli, H.R, and Kiakojouri, F. 2013, Influence of sudden column loss on dynamic response of steel moment frames under blast loading. *International Journal of Engineering*, 26(2): 197-206.

Tavakoli, H.R., and Alashti, A.R. 2013, Evaluation of progressive collapse potential of multi-story moment resisting steel frame buildings under lateral loading. *Scientia Iranica*, 20(1):77-86.

Van Cao, V., and Ronagh, H.R. 2014, Reducing the potential seismic damage of reinforced concrete frames using plastic hinge relocation by FRP. *Composites Part B: Engineering*, 60, 688-696.