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Seismic Response of RCC Building under Column Removal Scenario

Snehal Kaushik[1]

[1]*Assistant Professor, Department of Civil Engineering, Girijananda Chowdhury Institute of Management and Technology, Guwahati, Assam, INDIA*

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Abstract - *Various buildings have gone through partial or total progressive collapse during an earthquake shaking throughout the past several decades. Progressive collapse resistance of RC buildings can be analysed by considering column loss scenarios. To obtain a better understanding of the complex progressive collapse resistance of symmetrical and asymmetrical multi-storied RC frame buildings, time history analysis of different RC buildings were carried out using SAP 2000 program to study their collapse mechanisms under five different column removal scenarios, namely, a central column removal scenario, an exterior column removal scenario along longer and shorter direction, a corner column removal scenario at the longer direction and shorter direction, for analysing structural resistance against progressive collapse. Also, the study is extended to compare progressive collapse resistance of a multi-story building under multi-column removal scenarios. Displacement in the upper node of the removed column, redistribution of forces after removing the column, plastic deformations in adjoining elements, and the deformation of the beams adjacent to the removed column in single and multi-column removal scenarios are studied. Comparisons of single and multi-column removal scenarios for both symmetrical and asymmetrical buildings reveal that multi-column removal scenarios in case of asymmetrical buildings are more critical because of their higher demand capacity ratios.*

***Key Words*: progressive collapse, asymmetrical building, structural response, sudden column loss, single and multi-column removal.**

1. INTRODUCTION

When a column is suddenly removed, the compressive forces in all columns above the target column will get reduced and subsequently will be redistributed to the neighbouring supports. The redistribution of the dynamic gravity loads of each floor is carried out by the horizontal structural members, bridging over the lost column and deflecting until a new equilibrium position is reached. Collapse will take place if this equilibrium is not possible or if the vertical load bearing elements fail due to the supplementary compression forces. However, columns generally are capable to accommodate this increase and consequently only the behaviour of the horizontal structural components and their connection with the supports are relevant for the collapse resistance of buildings. Design codes and guidelines currently in place are not considered to completely satisfy the requirements for progressive collapse design. Also, to obtain a better understanding of the mechanisms of progressive collapse resistance of structures, further research is necessary. Many efforts have been made to carry out research on the behavior of building structures with the loss of a column. Much attention has been given to the behaviour of beams that bridge over removed column areas, which are under amplified gravity loads in beam-column substructures or planar frames (Mehrdad et al. 2011 ; Choi and Kim 2011 ; Su et al. 2009 ; Yi et al. 2008 ; Hou and Yang 2014 ; Kim and Choi 2015 ; Kang et al. 2015). There have been reports of studies that have analyzed progressive collapse behavior of RC frames or beam-slab substructures by experiments or numerical analyses (Mehrdad et al. 2007 ; Pham and Tan 2013a, b ; Pachenari and Keramati2014; Qian et al. 2015). It was found that tensile membrane actions in slabs that inevitably develop in large deformation stage play a key role in its collapse resistance. Until now, outstanding achievements have been made towards understanding the failure mechanism to prevent progressive collapse (Li et al. 2016). Furthermore, depth study has been carried out to understand collapse patterns (Sagiroglu et al. 2014) and dynamic effects (Tsai et al. 2008 and Li et al. 2014), and developing various collapse resistant techniques (Xu and Ellingwood 2011) and codes. But not many studies have shown the effect of multi-column removal scenario on the progressive collapse of the building.

In this study, a four-storey building with symmetric and asymmetric plan is considered as shown in Figure1, to study the effect of single column failure as well as multi column failure of the building. The dynamic response time-history of reinforced concrete moment-resisting frame buildings to records of Kobe (1995) earthquake has been considered. Progressive collapse analysis is performed using SAP2000 (CSI 2013).

2. BUILDING MODELS

The study focuses on the progressive collapse resistance of 3D symmetrical and asymmetrical 4-storeyed column-beam-slab systems under different column removal scenarios. To study the effect time history analysis is performed for the ground motion of Kobe (1995) earthquake using SAP2000. Five different column removal scenarios, namely, a central column removal scenario, an exterior column removal scenario along longer and shorter direction, a corner column removal scenario at the longer direction and shorter direction, for analysing structural resistance against progressive collapse. Also, the study is extended to compare progressive collapse resistance of a multi-story building under multi-column removal scenarios. Two cases are considered for the multi-column removal, namely, (i) multi corner and exterior column removal and (ii) multi corner and central column removal.

The symmetric structure consists of two bays of 4.5m in both the longitudinal direction and in the transverse direction (Figure 1a). The ground storey height is 4.4 m and the remaining stories are 3.2m high. The floor slabs are modelled as thin shell of 150mm thickness. Beam size is taken as 400×400mm for ground story and 300×400mm for all other stories. The column cross section is taken as 500×500mm for ground story and 400×400mm for all other stories above. For asymmetric structure, the first bay along longitudinal direction is 2.5m and the second bay is 6.5m (Figure 1b). All other details are remains same as that of symmetrical structure. All the supports are modelled as fixed supports. Tie history analysis is conducted on each of these models. The compressive strength of concrete (f_c') is 25 N/mm2 and yield strength of steel (f_y) is 415 N/mm2. Analysis is carried out for the loss of a column for the first story located at the various locations mentioned in Figure 1. The following models are considered for the analysis for both symmetric and asymmetric structure:

Model 1: Intact structure (without column removal)

Model 2: Structure with single column removal at location 1 (Figure 1)

Model 3: Structure with single column removal at location 2 (Figure 1)

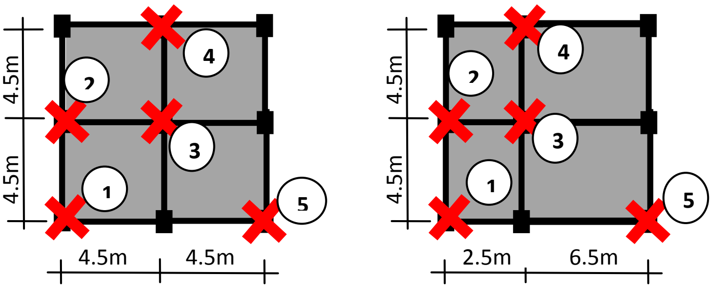
Model 4: Structure with single column removal at location 3 (Figure 1)

Model 5: Structure with single column removal at location 4 (Figure 1)

Model 6: Structure with single column removal at location 5 (Figure 1)

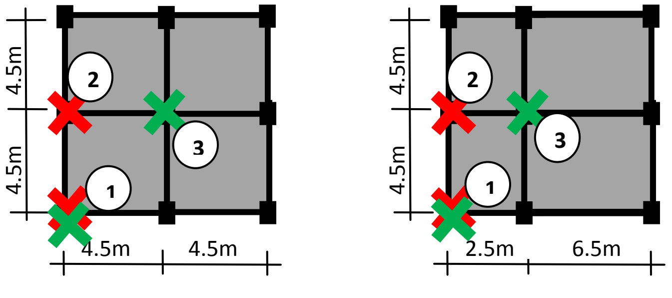
Model 7: Structure with multi-column removal at location 1 and 2 (Figure 2)

Model 8: Structure with multi-column removal at location 1 and 3 (Figure 2)



(a) (b)

Fig -1: Single column removal scenario: (a) symmetric structure (b) asymmetric structure



(a) (b)

Fig -2: Multi-column removal scenario: (a) symmetric structure (b) asymmetric structure.

The beams and columns are modelled using two noded frame elements and floor slab are modelled using four noded shell elements. The total intensity of loading on slab including live load and floor finish is considered as 3kN/m2. The mentioned models are analyse during time history method underground motion recorded during 1995 Kobe earthquake in Japan with Peak Ground Acceleration (PGA) values of 0.344g. In the dynamic analysis, acceleration time history is applied to each specimen and the entire ground motion ensemble is scaled so that the PGA values become 1g. The ground acceleration time history of 1995 Kobe earthquake is shown in Figure 3.

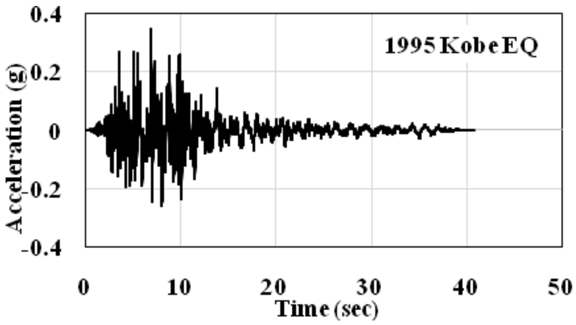


Fig -3: 1995 Kobe (Japan) ground acceleration time history.

3. COLUMN REMOVAL CASES

In the present study the reinforced concrete framed structure is considered and two types of column removal methods are applied, that is, the single column removal and multi column removal scenario. Both the methods are applied to symmetric as well as asymmetric structure. Nonlinear time history analysis is carried out to compare the behaviour of the structure by removing single column at a time with the intact structure. Linear static analysis cannot provide the complete picture about the performance of the structure under dynamic loading. Firstly, the corner column at ground storey (Model 2) at location 1(Figure 1) is removed and the behaviour is compared with the intact structure (Model 1). In the next case, an exterior column along Y-direction (Model 3) of the structures is removed at location 2 in Figure 1 and the behaviour is compared. All the columns that are removed in various models is located at ground floor region The interior column of the structure in removed in the next case (Model 4) and the behaviour is compared with the intact structure. In Model 5 the exterior column along X-direction is removed and compared with the intact structure. The last model in the single column removal scenario is Model 6 where again the corner column is removed at the other end of the structure along X-direction (location 5 in Figure 1)

In the multi-column removal scenario, two different models are considered (Figure 2). In the first structure one corner and one exterior columns along Y-direction are removed simultaneously (Model 7) and the performance is compared with the intact structure. Corner and interior columns are removed simultaneously in the next model (Model 8) and the comparison of the storey displacement, storey acceleration, time period and the vertical displacement at the upper node of the removed column is carried out.

3. VALIDATION OF THE MODEL

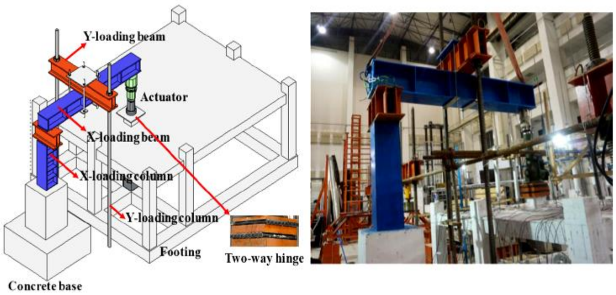


Fig -4: Test setups of the specimens at interior column removal scenario (INT) (Du et al, 2019)

For any detailed finite element study, the material parameters and the modelling methodology need to be validated for judging the consistency, reliability and accuracy of the obtained results. In the past, several analytical and numerical studies have been carried out on the behavior of buildings considering the column removal scenario. However, very few experimental works are available on this topic. Du et al. (2019) studied the column removal scenario to obtain a better understanding of the complex progressive collapse resistance of 3D asymmetrical column-beam-slab systems, five one-third scale 2 × 2bay asymmetrical reinforced concrete (RC) spatial frame substructure specimens were tested to analyse their collapse mechanisms under five different column removal scenarios. The test results showed that INT had the highest progressive collapse resistance capacity among the scenario substructures. Hence, similar modelling of the structure and column removal techniques are considered in the present study to compare the behavior with the intact structure. The test setup of the specimen is shown in Figure 4.

4. ANALYSIS RESULTS AND DISCUSSION

Time-history analysis provides the structural response of the considered building models over time during and after the application of the seismic load. A four-storey reinforced concrete framed building is modelled and the behaviour is observed with different column removal scenario. The ground motion of 1995 Kobe (Japan) earthquake has been selected to do the analysis. Storey displacements and storey acceleration are obtained along the height of the building models and presented in the comparative way. Peak displacement pattern of all the building models at different levels under the Kobe earthquake records are presented in Figure 5. The earthquake motion is applied in two orthogonal directions. As shown in Figure 5, the removal of columns causes the increase in the peak displacements. The multi-column removal models produce higher peak story displacements compared to the intact model.

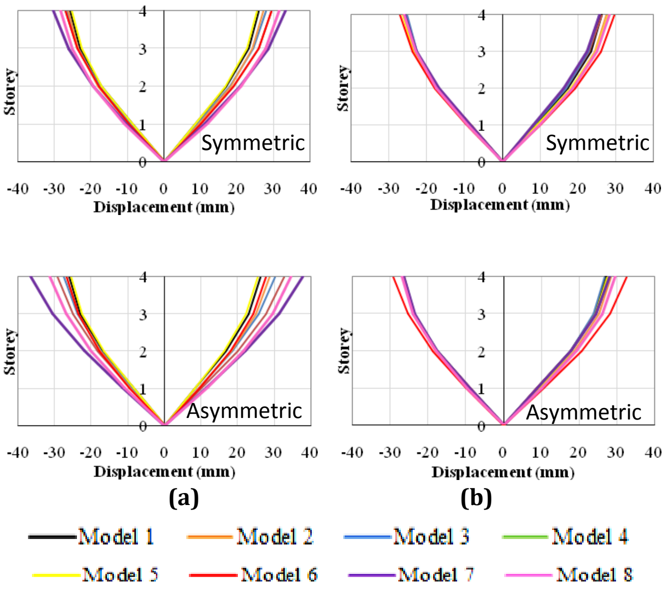


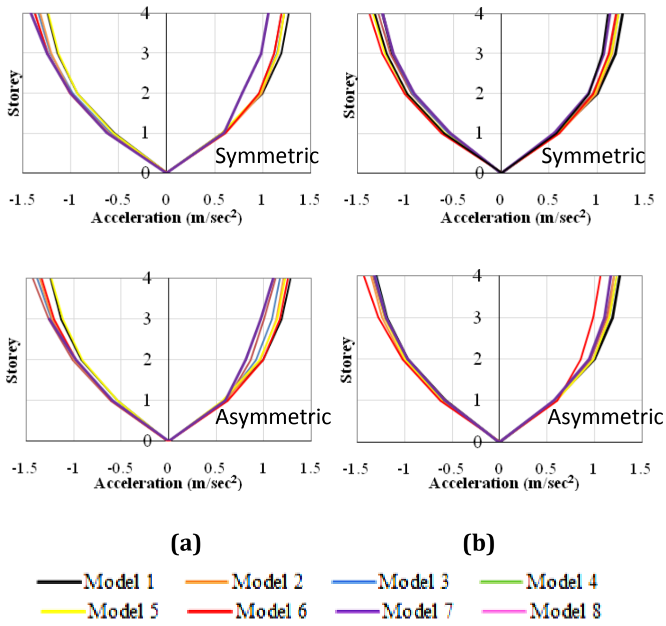
Fig -5. Induced peak storey displacements under the Kobe earthquake record for: (a) X-direction loading and (b) Y-direction loading.

If the induced lateral deflections due to the removal of columns are too large which, may lead to an instability to the building structure and potentially results in collapse. It is also observed that the peak displacements are on higher side in case of asymmetric building comparing to symmetric one in all the models considered.

Figure 6 shows the results of maximum acceleration under the Kobe ground motion records. These obtained results show the differences among the acceleration profiles of the building structure modelled as intact one, single column removal and multi-column removal scenarios. As it can be seen from the figures, the multi-column removal structure has storey acceleration of higher values than those associated with the considered fully intact building model.

The values are again on higher side in case of asymmetric models compared to symmetric models. The increase in the storey acceleration in the column removal scenario may lead to the collapse of the structure.

Modal analysis of various models is carried out before the time history analysis and the fundamental natural time period is tabulated in Table 1. As the column is removed, the overall stiffness of the structure decreases hence the natural period of the structure increases.



(a) (b)

Fig -6. Induced storey acceleration under the Kobe earthquake record for: (a) X-direction loading and (b) Y-direction loading.

It can be observed from the Table 1 that the fundamental time period of all the column removal models are more than that of the intact model. Also, the time period for multi-column removal models are quite high. The fundamental time period of asymmetric structures with various column removal criteria is more than that of the symmetric structures.

Table 1. Fundamental time period.

	Symmetric Structure	Asymmetric Structure		Symmetric Structure	Asymmetric Structure
Model 1	1.116	1.126	**Model 5**	1.161	1.208
Model 2	1.191	1.230	**Model 6**	1.191	1.230
Model 3	1.161	1.194	**Model 7**	1.301	1.358
Model 4	1.155	1.170	**Model 8**	1.237	1.287

Nonlinear dynamic analysis was performed for almost 41 sec by removing columns at various locations mentioned in Figure 1. First the corner column is removed from the first floor. Figure 7 shows the comparison of time history for vertical displacement at the upper node of column for intact model with the column removal models at various positions. The maximum vertical displacement is 4.55mm occurring at t=9.7 sec for column located at position 1 (Model 2). The displacement at the same location for the intact model is negligible when compared with it. The maximum vertical displacement is 2.68mm occurring at t=9.6 sec when the exterior column along Y direction is removed located at position 2 (Model 3). When the interior column and exterior column along X-direction is removed the vertical displacement at the upper node is very negligible and can be considered almost zero. In both the cases (Model 4 and Model 5) the vertical displacement is almost similar to that of intact structure and hence the comparison is not plotted. When the corner column along the X-direction is removed the maximum displacement at the top of the node is -4.55 mm at t=9.7 sec. It is observed that the displacements are more at the upper node of the column in all the models when the column is removed than that of the intact structure. Maximum displacement occurs when the corner column is removed and minimum on removal of interior column. It is also observed that the displacements at the upper node are on higher side in case of asymmetric structures than that of symmetric one. Also, the removal of column caused increased moment demand on beams intersecting at the removed support.

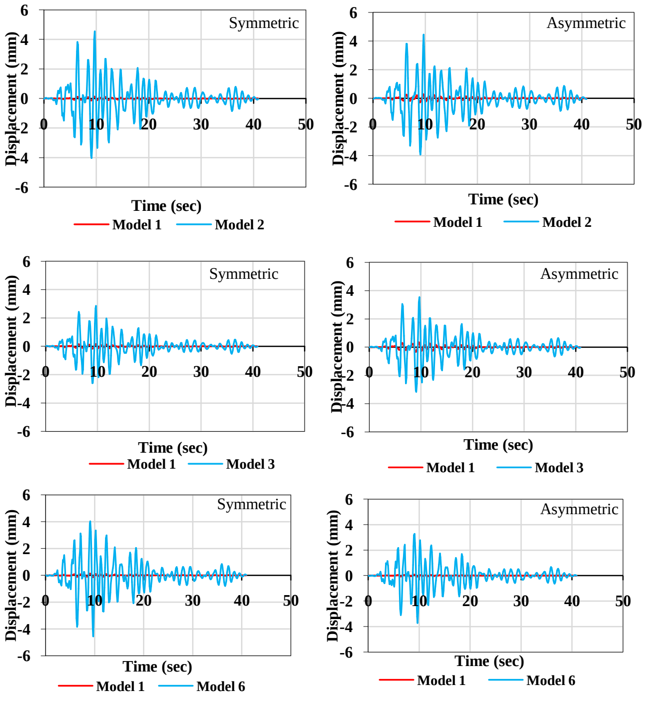


Fig -7. Comparison of time history for vertical displacement of upper node of the column in the single column removal model with the intact model for both symmetric and asymmetric structures.

Figure 8 shows the comparison of time history for vertical displacement of upper node of the column in the multi-column removal model with the intact model for both symmetric and asymmetric structures. It is observed that the displacement at the upper node of the removed column is almost double compared with the single column scenario. When the corner and exterior column along y-direction (Model 7) is removed together the vertical deflection at the upper node of the corner column is 8.65mm at t=9.8 sec which is almost double compared with the single corner column removal model. The vertical deflection at the upper node of the exterior column is 5.79 mm at t=9.8 sec. In case of Model 8, the vertical displacement at the upper node of the corner column and central column is 4.52 mm at t=9.7 sec. The deflection is more in multi-column removal scenario than the single column removal scenario. In all the cases due to the asymmetry of the structure the vertical displacement is more.

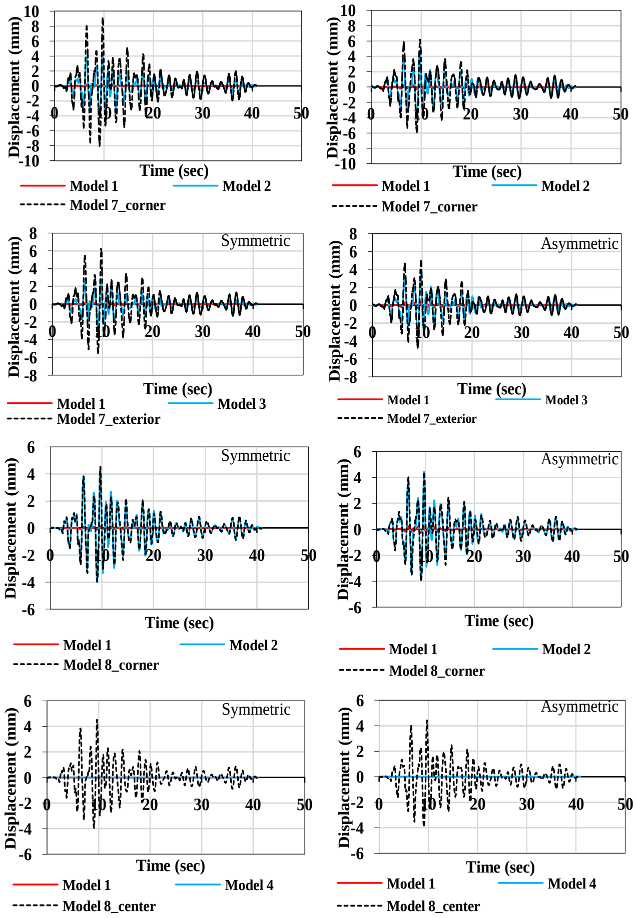


Fig -8. Comparison of time history for vertical displacement of upper node of the column in the multi-column removal model with the intact model for both symmetric and asymmetric structures.

5. CONCLUSION

A four-storey reinforced concrete symmetrical and asymmetrical building is studied for nonlinear time history analysis using 1995 Kobe ground motion to assess the potential for progressive collapse. Seven column loss scenarios which include five single column loss scenarios and two multi column loss scenarios have been considered. A separate analysis is performed for each case of column failure. Also, one intact structure model is analysed.

Following are the conclusions made from the study:

- The Considered RCC building has potential for progressive collapse for Model 2, Model 3 and Model 6 cases studied for single column removal scenario and for both Model 7 and 8 for multi-column removal scenario.
- The beams that are adjacent to the removed column have maximum demand bending moment compared to the beams which are away from the damaged column joint.
- The peak displacements and acceleration at each storey are on higher side in case of asymmetric building comparing to symmetric one in all the models considered. The maximum peak displacement occurs for multi-column removal cases.
- The multi-column removal cases are more critical because of the observed higher vertical displacements.
- Maximum upper node vertical displace values are observed in Model 7 which suggests that removing a corner and exterior column is more critical than removing corner and interior column.

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