Progressive Collapse Analysis of multi-story building under the scenario of multi-column removal

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Abstract. Recent studies regarding progressive collapse resistance of buildings considered only single critical column removal scenario. However, limited investigations have been conducted so far to assess multi-column removal scenarios. Hence this study is made to compare progressive collapse resistance of a multi-story building under both single and multi-column removal scenarios. An eight-storey reinforced concrete building was analyzed by using linear static analysis procedure and DCR values of the members are calculated to investigate the potential of progressive collapse as per GSA guideline. The values of DCR are compared for different cases. Comparisons of single and multi-column removal scenarios reveal that later scenarios are more critical because of their higher demand capacity ratios, and it is more critical when both corner and exterior columns are removed.

1 Introduction

Structural safety has always been a key preoccupation for the design of civil engineering projects. One of the mechanisms of structural failure that has gathered increased attention over the past few decades is referred to as progressive collapse and it is the phenomenon of ultimate failure or proportionately large failure of a portion of a structure due to the spread of a local failure from element to element throughout the structure [1]. Damage can be in form of chain reaction of failures that propagates either throughout the whole or a portion of the structure disproportionate to the original local failure [2]. The progressive collapse of building structure is initiated when one or more vertical load carrying members are removed. Once a column is made weak or removed, due to man-made or natural hazards, load carried by removed column is transferred to neighbouring columns in the structure and the collapsing system continually seeks alternative load paths in order to survive and if redistributed load exceeds member capacity it fails [3]. This process continues in the structure and eventually the building collapses. One of the important characteristics of progressive collapse is that final damage is not proportional to initial damage.

Although the number of such events is very limited, structural progressive collapse has been the focus of extensive research during the past few decades because of the consequences in terms of loss of human lives are dire, they can result from natural disasters (e.g., earthquakes and hurricanes) or human-made disasters (e.g., bomb blasts and vehicular impacts). One of the most evident examples is the accidental collapse of the

Ronan Point tower in Canning Town, UK on May 1968. The cause of the collapse was a gas explosion that knocked out the precast concrete panels near the 18th floor causing the floors above to collapse. Number of other progressive collapses around the world also took place like the collapse of Skyline Plaza in Virginia, the Civic Arena roof in Hartford, the Murrah Federal Building in Oklahoma City, WTC Towers in New York [4]. Those collapses generated considerable concern over the adequacy of existing building codes, so more and more researchers have started to refocus on the causes of progressive collapse in building structures, seeking ultimately the establishment of rational methods for the assessment and enhancement of structural robustness under extreme accidental events [5]. As progressive collapse as a structural engineering point of view started taking attention, the concept of column removal was developed and is now generally accepted by the engineering community.

Until now, outstanding achievements have been made towards understanding the failure mechanism to prevent progressive collapse [6]. Furthermore, depth study has been carried out to understand collapse patterns [7] and dynamic effects [8, 9], and developing various collapse resistant techniques [10] and codes. But not many studies have shown the effect of multi-column removal scenario on the progressive collapse of the building.

In this paper, an eight-storey building is considered as shown in Fig.1, to study the effect of single column failure as well as multi column failure of the building. Evaluation of progressive collapse for a typical designed building is carried out. Progressive collapse analysis is

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performed using SAP2000 [11] and the linear analysis procedure of the GSA guide-lines [12] is followed.

2 Modelling of Building

An eight-storey symmetrical reinforced concrete building of height 26.4m is considered as shown in Fig.1 and is modeled using SAP2000. The structure consists of five bays of 6m in the longitudinal direction and four bays of 6m in the transverse direction. The ground storey height is 4 m and the remaining stories are 3.2m high. Wall having 230mm thick-ness is considered on all the beams. The floor slabs are modelled as plates of 150mm thickness. Beam size is taken same for all the stories as 300×570mm. The column cross section is taken as 600×600mm and is considered for the eight-storey building. All the supports are modelled as fixed supports. Linear static analysis is conducted on each of these models. The compressive strength of concrete (f_c') is 30 N/mm² and yield strength of steel (f_y) is 413 N/mm². The model and the gravity load acting on the structure is carried out as per ACI 318 code [13].

2.1 Column Removal cases

The reinforced framed structure is designed using SAP2000 for dead and live loads. For progressive collapse analysis columns A1, A2, B1 and B2 are removed. The specified GSA load combination was applied, forces and the Demand Capacity Ratio (DCR) are calculated for all members. Four cases have been considered (as shown in Fig.1):

-Case 1: Analyze for the loss of a column for the first story located at the corner of the building (corner removal)

-Case 2: Analyze for the loss of a column for the first story located near the corner of the building (interior removal)

-Case 3: Analyze for the loss of 2 columns for the first story located at and near the corner of the building (corner + interior)

-Case 4: Analyze for the loss of 2 columns for the first story located at and near the corner of the building (corner + exterior)

The gravity loads are imposed on the structure and the analysis is carried out according to the load combination of ACI 318 [13]. The Bending Moment behavior in all the four cases are studied for structural elements. And the vulnerability of the building with respect to all the four cases is checked by determination of the demand capacity ratio (DCR) in each beam structural member. The member is considered as failed if the DCR value of a member exceeds the criteria for acceptance as per GSA guidelines.

2.2 Analysis procedure and acceptance criteria as per GSA guidelines

A progressive collapse analysis is required to determine the capability of a structure to resist abnormal loadings and to evaluate the potential for progressive collapse. An

eight-storey reinforced concrete building is analyzed by using the linear static analysis and four column removal cases are considered. Firstly, the building is designed using SAP2000 and according to ACI 318 [13]. Then separate linear static analysis is performed for each above-mentioned cases of column removal, 2 of which will be multi column removal scenarios. From the analysis results, demand at critical locations are obtained and from the original designed section the capacity of the member is determined which will be used to calculate Demand capacity ratio (DCR) for flexure at all stories for different cases, and this acceptance criteria for the structural components shall be determined as:

$$DCR = QUD / QCE$$

Figure 1. a) Plan of the Building & b) Isometric View of the Building

Where,

QUD = Member Force: Acting force (demand) determined in member or connection (moment, axial force, shear, and possible combined forces)

QCE = Member Strength: Expected ultimate, un-factored capacity of the member and connection (moment, axial force, shear and possible combined forces)

For the building having a typical structural configuration, the DCR of the primary structural components should be less than 2 for typical structural

configuration and less than 1.5 for atypical structural configuration to avoid failure in flexure and using the DCR criteria of the linear elastic approach, If the DCR of structural elements exceeds the acceptance criteria in flexure, the member is considered to be severely damaged or failed. The DCRs calculated from linear static procedure helps to determine the potential for progressive collapse of building.

2.3 Analysis Loading

Gravity loads were calculated as per ACI 318 [13] and design load combinations and service load combinations were given as ACI 318, for static analysis purposes the following vertical load shall be applied to the structure under investigation:

Load = $2DL + 0.5LL$; Where, DL = dead load; LL = live load

-Dead Load: Obtained from ACI 318. The unit weight of concrete is taken as 25 kN/m³.

Floor finish = 1.5 kN/m² and Wall load on all beams is 7.13 kN/m

-Live Load: Obtained from ACI 318; On roof 1.5 kN/m²; On floor 3 kN/m²

3 Summary and Discussion

All the columns were removed and analyzed by linear static method. The demand moment table obtained by SAP2000 software for loadings assigned as per GSA is exported and their demand capacity ratios are calculated for the 2 frames intersecting on the removed column. The observed structural behaviour can be summarized as follows:

Figure 2. DCR Values of frame 1 for case 1 a) Intact case b) Removed case

Figure 3. DCR Values of frame A for case 1 a) Intact case b) Removed case

-Summary of Beam DCR for Case1 (single corner column removal case)

The removal of column A1 caused increased moment demand on beams intersecting at the removed support. These values indicate that the major load is transferred to the connecting beams. Fig.2 and Fig.3 shows DCR

Values of frame 1 and frame A for case 1. The figures show that values of DCR has significantly increased in the beams of upper floors away from the vicinity of removed column. All the upper floor beam DCR values has exceeded 2 and with a maximum value of 4.205 on the 7th floor for frame 1 and 4.824 on the 1st floor for

frame A which suggest that structure is vulnerable to progressive collapse in this case.

-Summary of Beam DCR for Case2 (single interior column removal case)

The removal of column B1 caused increased moment demand on beams intersecting at the removed support. These values indicate that the major load is transferred to the connecting beams. Fig 4 and Fig 5 shows DCR

Values of frame 2 and frame B for case 2. The figures show that values of DCR has significantly increased in the beams of upper floors away from the vicinity of removed column. Most of the upper floor beams DCR values has exceeded 2 and with a maximum value of 3.475 on the 1st floor for frame2 and 4.265 on the 1st floor for frame B which suggest that structure is vulnerable to progressive collapse in this case.

Figure 4. DCR Values of frame 2 for case 2 a) Intact case b) Removed case

Figure 5. DCR Values of frame B for case 2 a) Intact case b) Removed case

-Summary of Beam DCR for Case3 (multi corner and interior column removal case)

The removal of column A1 and B2 caused increased moment demand on beams intersecting at the removed support. These values indicate that the major load is transferred to the connecting beams Fig 6 and Fig 7 shows DCR Values of frame 1, 2, A and B for case 3. The figures show that values of DCR has significantly increased in the beams of upper floors away from the vicinity of removed column. Most of the upper floor beam DCR values has exceeded 2 and with a maximum value of 4.499 on the 2nd floor for frame 1, 3.491 on the 1st floor for frame 2, 5.131 on the 1st floor for frame A and 4.327 on the 1st floor for frame B which suggest that structure is vulnerable to progressive collapse in this case.

-Summary of Beam DCR for Case4 (multi corner and exterior column removal case)

The removal of column A1 and A2 caused increased moment demand on beams intersecting at the removed support. These values indicate that the major load is transferred to the connecting beams Fig 8 shows DCR Values of frame A for case 4. The figure shows that values of DCR has significantly increased in the beams of upper floors away from the vicinity of removed column. Most of the upper floor beam DCR values has exceeded 2 and with a maximum value of 7.013 on the 2nd floor for frame A which suggest that structure is vulnerable to progressive collapse in this case.

Figure 6. DCR Values of frames 1&2 for case 3 a) Frame 1 b) Frame 2

Figure 7. DCR Values of frames A&B for case 3 a) Frame A b) Frame B

4 Conclusions

An eight-storey reinforced concrete symmetrical building is studied for linear static analysis to assess the potential for progressive collapse. Four column loss scenarios which include two single column loss scenarios and two multi column loss scenarios have been considered. A separate analysis is performed for each case of column failure. DCR for flexure obtained from the analysis is compared for each case with the intact structure. Demand capacity ratio for flexure are shown (see Fig. 3-8), which indicates that DCR for flexure exceeds permissible value specified by GSA guidelines thus there is a high possibility that the member components has failed and exceeded its elastic limits during column failure scenario and are vulnerable to progressive collapse in all cases, thus the structure reinforcement are inadequate and need additional reinforcement to meet GSA criteria. The following conclusions can be made from this study:

- The Considered RCC building has potential for progressive collapse for all the 4 cases studied
- 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.

- Decreasing pattern of DCR values is observed as storey increases which means collapse pattern is in a way that the DCR of the beam increases near the removed column and further away from it decreases.

- The multi column removal cases are more critical because of the observed higher DCR.

- Maximum DCR values are observed in the last case which suggests that removing a corner and exterior column is more critical than removing corner and interior column.

Figure 8. DCR Values of frames A for case 4

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