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Behaviour of moment resisting reinforced concrete frames subjected to column removal scenario

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Abstract. Researchers awarded a considerable attention to progressive collapse analysis in recent years to avoid the partial or entire failure of structures. General Service Administration guidelines (GSA) established the base to deal with such catastrophic failure. For multi-story building, these guidelines proposed column removal scenario in which one or more columns in different locations should be removed from a structure. Then, the response of entire structure with the column omitted should sustain the loading applied ensuring no global failure occurred. In this paper, three-dimensional reinforced concrete (RC) frame is constructed and analyzed using the commercial program SAP2000. Non-linear static analysis is employed to obtain Demand Capacity Ratios (DCR) for beams and the displacement of joint connecting beams to column in the selected frame. The response of moment resisting RC frame under column removal scenario is presented and discussed in terms of strength and displacements in critical locations in RC frame to evaluate the strength of such frame against progressive collapse.

Keywords: Progressive collapse, Column removal scenario, moment resisting frames and reinforced concrete.

1. Introduction

Progressive collapse in a building occurs when a structural member such as column or wall suddenly loses its carrying capacity due to abnormal loads. This type of failure came into attention post the well-known disaster of Ronan Point building located in, London in 1968. This catastrophic event alerts the structural engineers to present the solutions at which the danger of progressive or disproportionate collapse is minimized [1-3]. After World Trade Center (WTC) collapse, numerous authorities developed design guidelines for resisting progressive collapse. GSA [4] guideline can be considered the most efficient document that deals with this topic.

A large number of numerical investigations have been performed to obtain the efficiency of the recent design guidelines. On the other hand, limited experimental tests have been carried out to verify the design requirements proposed in such guidelines [5-7]. This is attributed to the high cost of constructing and testing full-scale building specimens. Hence, the researchers preferred using the numerical simulation to predict the progressive collapse resistance of structures . Four types of analysis were proposed to perform such analysis namely, linear static analysis, non-linear static analysis, linear dynamic analysis and non-linear dynamic analysis. Performing static analysis is easier than dynamic analysis in addition to its reliable prediction of collapse event [8-11]. In the current study, it is aimed to investigate the response of moment resisting RC frames against progressive collapse. SAP2000 was employed to perform 3D non-linear static analysis.

2. Progressive collapse requirements

The GSA guideline [4] provides a detailed criteria required for evaluating the vulnerability of different types of buildings to progressive collapse. Exterior consideration is represented by the loss of a column for the ground floor located at or near the middle of the short direction of a structural frame. Also, corner column removal should be considered as an exterior consideration. Whilst, the interior consideration conditioned the loss of an interior column. A single analysis for each case of column removal should be performed and the worst case should be considered in the design against progressive collapse. The load combination proposed by GSA guidelines when performing a non-linear static analysis is as follows:

$$W = 2\,(DL + 0.25LL) \qquad (1)$$

Where, DL is the dead load and LL is the live load.

To assess the findings of the analysis, the demand-capacity ratio (DCR) concept was proposed by GSA guidelines. The DCR for a structural component is defined as the ratio of demand in component to its capacity. Hence, this ratio should be applied for critical components that participate in the progressive collapse event such as shear, moment and tying force in beam and axial forces and moment in columns in addition to forces on beam-column joints. To account the dynamic effect of the progressive collapse event, GSA guidelines proposed a magnification factor of 2 to be used for such purpose. In another word, failure of a member is considered when the DCR value exceeds 2.0 at any component of a member.

3. Finite element model

A model of building was taken from a considerable design manual [12]. The structure contains of five bays in the long direction and three bays in the short one as shown in Figure. 1. Bay length was 7.3 m and story height was 3.7 m except the ground story, which was 4.6 m. Dead and live loads were assumed to be 2.4 and 2 kN/m^2, respectively. Concrete properties was taken as recommended by FEMA [13]. Elastic perfectly plastic relationship with a yield stress of 400 MPa and yielding strain and failure strain of 0.002 and 0.2, respectively, was assumed to simulate the plastic behavior of steel reinforcement [14]. Beam element is used to simulate the beams and columns of the frame, while shell element was used for slabs. All beams and slabs were meshed finely to obtain accurate results. Rigid beam to column joints were assumed. The cases of column removal selected in the current study were per GSA guidelines as mentioned in the previous section as shown in Figure 2.

4. Results and discussion

In order to obtain the results of analysis, the 3D models built for each case of column removal were submitted. The maximum displacements and DCR values for the failed frame were obtained as follows:

4.1 Maximum displacement

The maximum vertical displacement for each story in the failed frame is obtained using the FE model developed. It represents the displacement at the point of beam to column connection points for stories above the column removed. Fig. 3 shows the displacement for each story at such points. It can be seen that the maximum displacement occurred when an interior column is removed. Also, the maximum displacement of the critical case was greater than the corresponding cases by around 30-62%. This is definitely lead to develope higher bending stresses then accelerate the forming plastic hinges in the critical points. Also, it is good indicator that the frame collapsed behaved with acceptable ductile manner in which the collapse of the frame is delayed.

4.2 DCR for bending moments of beams
The most expected failure mechanism due to column removal scenario may be occurred due to the inability of beams to sustain the gravity loads. Hence, the columns start to transfer loads from beams above then to those below until the load reaches to the lower beam, which is known as catenary action. It is very important to enhance the reinforcement above the columns by additional steel reinforcement to resist the expected positive moment developed if a column is removed. Also, the depth of beams in the lower floors should be increased as one of the solutions used to prevent progressive collapse. Fig. 4a shows the DCR values for moments developed in beams for the reinforced concrete frame selected. The analysis results showed that plastic hinges were developed in the locations of maximum negative and positive moments at the lower beams for the four cases studied. Also, the critical case was case-4 with a DCR value of 2.51 in the negative moment location and 2.31 in the positive one. Therefore, the need to increase the section and the reinforcement in the lower beams is required. The beams in the sixth floor seem to be safe under column removal scenario.

4.3 DCR for shear forces of beams
DCR for shear forces of beams were also obtained from the non-linear analysis performed. The results indicated that all beams were safe against shear failure of beams. The maximum DCR was recorded for the lower beam of case-4 with a value of 1.66 as can be seen in Fig. 4b. Further analysis is required for different concrete strengths to evaluate their effect on the shear resistance of beams of RC frames under column removal scenario.

5. Conclusions
The current study demonstrates the ability of RC moment resistance frames to resist progressive collapse represented by column removal scenario. It also shows the efficiency of SAP2000 software to simulate such event using non-linear static analysis. This knowledge would assist structural to select the appropriate structural systems for buildings require progressive collapse mitigation. Based on the findings obtained in this study considering the GSA guidelines, a number of conclusions can be drawn:

- RC moment resisting frames provide a structure with appropriate ductility that delay the occurrence of progressive collapse.
- The worst case at which RC moment resisting frame failed under column removal scenario is the case of losing an interior column. More analysis is required to investigate the effect of using RC frames with different span length.
- SAP2000 is valuable tool to simulate RC moment resisting frames as it is capable to simulate collapse event easily without convergence difficulties.
- Moment resisting RC frames is not likely collapsed due to shear failure of beams.

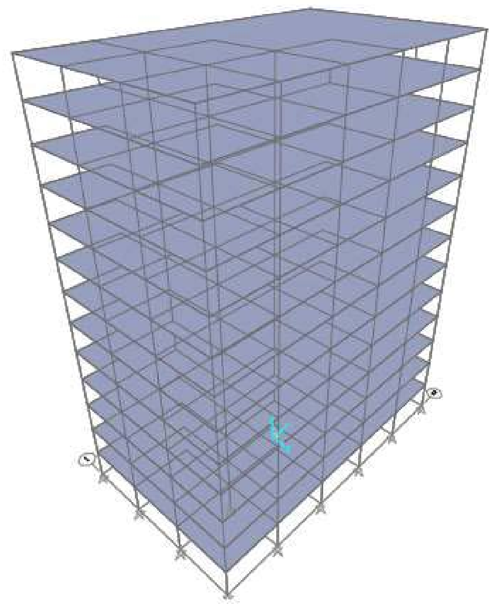

Figure 1. 3D model of the frame investigated.

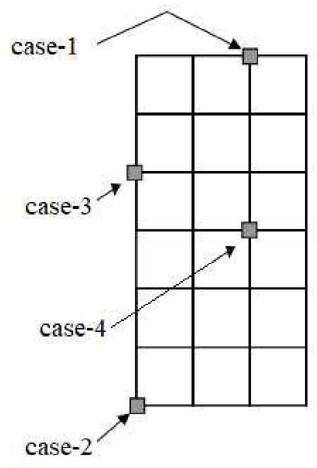

Figure 2. Cases of column removal scenario.

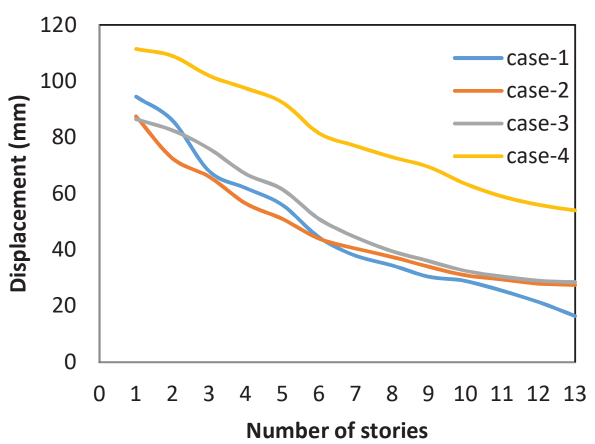

Figure 3. Displacements in the critical locations of moment resisting RC frame investigated.

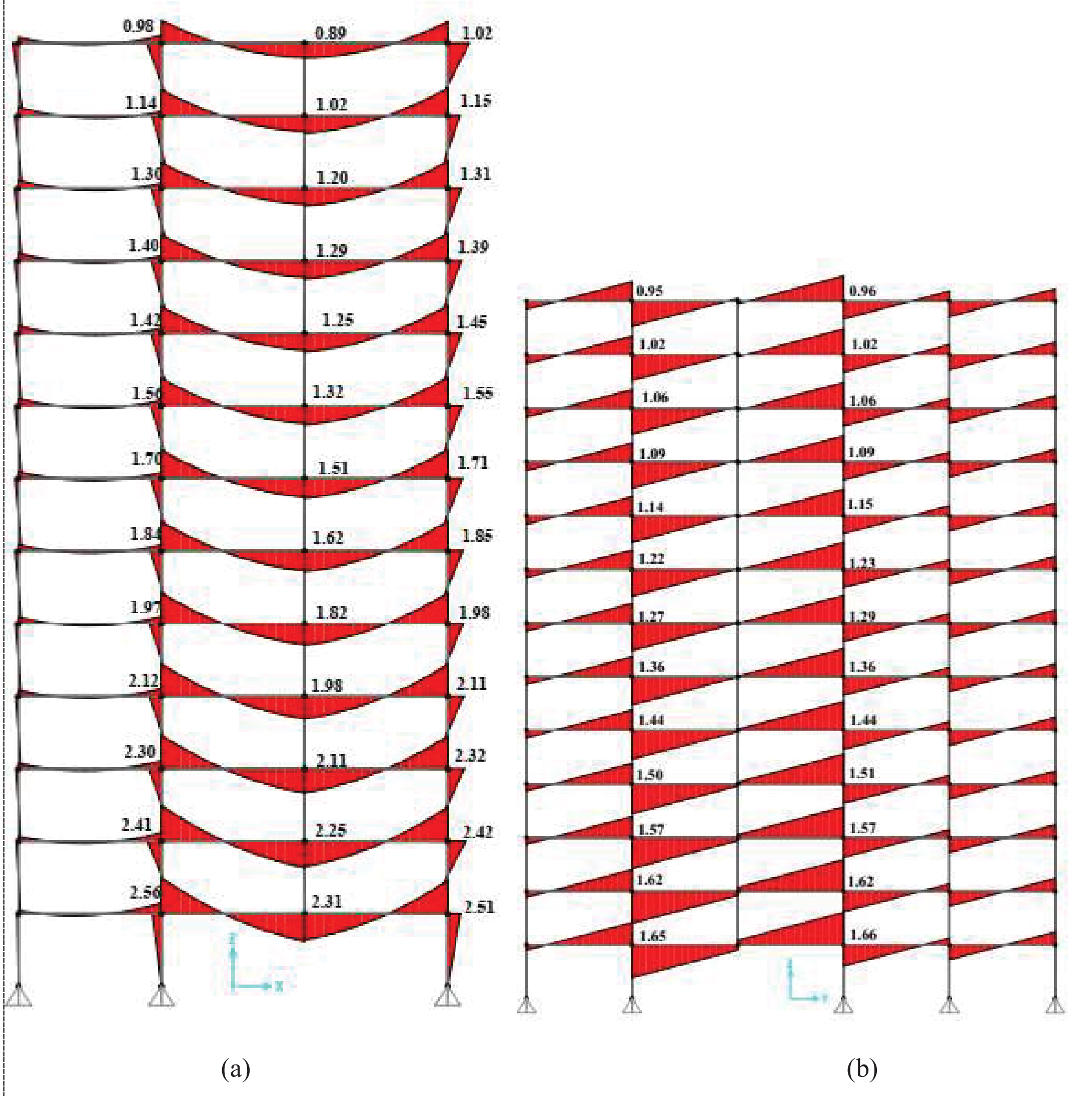

Figure 4. Critical cases of DCR values of beams (a) bending moment and (b) shear forces.

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