Improved progressive collapse resistance of irregular reinforced concrete flat slab buildings under different corner column failures

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Abstract. As the flat slab building with irregular geometric configurations is commonly designed to advance urban development and for architectural demands, its behaviour to resist progressive collapse must be examined. The building’s progressive collapse occurs when one or more vertical structural load-bearing elements such as columns are removed due to an extreme load caused either by natural or manmade hazards. The present analytical research examines the failure criteria and improvement in the progressive collapse resistance of five and ten-storey irregular R.C flat slab building by incorporating perimeter beams along with strengthened perimeter columns in the building. The progressive collapse study is conducted by removing different corner columns on the ground floor as per the GSA guidelines (2003) and assessing the spread of damage. Static analysis is performed using the structural analysis program ETABS 2016. For each case, the results have been taken in terms of demand capacity ratio (DCR) at critical sections and, chord rotation and joint displacement at locations of removal of columns. The results showed that the presence of strengthened columns provides sufficient stiffness and the perimeter beam provides load paths for the building's gravity loads, thus making it resistive to progressive collapse under column failure.

Keywords: Flat Slab; Perimeter Beam; Progressive Collapse; Linear Static Analysis; Demand Capacity Ratio; Vertical Displacement

1. Introduction

When the system collapses progressively, initial localized disruption is distributed to adjacent components that could cause the whole structural system to fail. The most effective way to limit the spread of localized destruction is to preserve the stability and ductility of the building structure. The ASCE 7-05 [1] provides design guidelines for enhancing the progressive collapse resistance of building structures but does not provide explicit rules for their execution. In two design guidelines released by the United States, General Service Administration (GSA) [2] and the Department of Defense (DoD) [3], recent design approaches to minimize the risk for progressive collapse in structures could be found. The guidelines of the GSA and DoD suggested the Alternate Path Method (APM) for progressive collapse analysis where a single column in the ground level is assumed to be unexpectedly missing and analyses are carried out to assess the ability of the weakened structure to pass through the missing column. The APM focuses on the vertical deflection of the building after the column has been suddenly removed. It is thus a threat-independent design-oriented approach for introducing additional redundancy into the system to prevent the spread of collapse.
Irregular flat slab structures are a common form of structural reinforced concrete constructions in buildings, which enable architects to view picturesque and perspective by using obtuse and acute angles in the plan and to take advantage of low floor heights. Flat slabs are more likely to collapse compared to conventional slab-beam-column structures, due to non-existence of beams that could contribute to redistributing the load previously held by lost columns. The collapse of South Korea Department store in 1995 [4], and the 16-story flat slab structure during construction in Boston, Massachusetts in 1971 [5], are the result of brittle column-slab connections [6-8].

In resisting progressive collapse of RC flat slab structures, Kokot et al. [9] studied the problem by instantaneously eliminating three different columns alternately, and in each scenario, the structural response is determined by linear and nonlinear dynamic time-history analyses. Liu et al. [10] numerically accessed an older reinforced concrete flat plate system against progressive collapse using a macro model incorporated with a punching failure criterion for slab-column connections. The results showed that the RC flat plate buildings are highly vulnerable to progressive collapse when an interior or exterior column is immediately removed without the use of either shear or integrity reinforcement. Qian and Li [11,12] analyzed the load resisting mechanism and quasi-static behaviour of reinforced concrete flat slab systems and evaluated the influence of drop panels on the efficiency of RC flat slabs in preventing progressive collapse. The research findings showed that flat slabs without drop panels were highly susceptible to progressive collapse.

The purpose of this paper is to evaluate the effectiveness of perimeter beams along with strengthened perimeter columns on the static response of 5 and 10-storey irregular flat slab building when exposed to four damage circumstances by the sudden removal of different corner columns at the ground level. The enhancement in the resistance of progressive collapse is evaluated by comparing the vertical displacements ($\Delta_{cr}$) and chord rotation at the locations of removal of columns, and Demand Capacity Ratios (DCR) for the critical columns adjacent to the removed column.

| Notations | Meaning |
|-----------|---------|
| GSA       | General Services Administration |
| APM       | Alternate Path Method |
| UFC       | Unified Facilities Criteria (DOD 2005) |
| B-N       | Building without Perimeter Beam |
| B-PBSC    | Building with Perimeter Beam and Strengthened Perimeter Column |
| ACC       | Acute Corner Column |
| OCC       | Obtuse Corner Column |
| RICC      | Right Corner Column |
| RECC      | Re-Entrant Corner Column |
| $\Delta_{cr}$ | Vertical Displacement under column removal location |
| $\theta$ | Chord Rotation at column removal location |
| DCR       | Demand Capacity Ratio |
| $Q_{UD}$  | Acting force determined in the member |
| $Q_{CE}$  | Expected ultimate unfactored capacity of the member |
| DL        | Dead Load applied to the structure |
| LL        | Live Load applied to the structure |

2. Description of Analytical Models
The 3-D models of 5 and 10-storey flat slab buildings having 4x4 bays with a storey height of 3.0 m and span of 8.0 m in the plan are constructed using the ETABS software [13]. The Figure 1 shows the 3-D view while the plan of the studied building is shown in Figure 2. The studied flat slab building is considered irregular as per the GSA [2] guidelines, having geometrical irregularities like Acute, Obtuse, Right and Re-entrant corners in the building plan, as shown in Figure 2. Two types of building models are studied, i.e. building without any perimeter beam (B-N) and building with perimeter beams and strengthened perimeter columns (B-PBSC). The flat slabs are modelled using the Equivalent Frame Method [14-16]. The thickness of the flat slab is considered as 200 mm. For each building, the interior and exterior flat slab beams are of size 1933 x 200 mm and 966 x 200 mm, respectively. The perimeter
beams considered are of size 450 x 450 mm throughout its length. For each building, the column size is taken as 450 x 450 mm and the size of the strengthened perimeter column is considered as 750x750 mm. A live load of 3.0 kN/m² (office loading) and a superimposed dead load of 2.0 kN/m² (interior partition, mechanical and plumbing load) is applied to the floors. The grade of steel and concrete are considered as Fe500 and M25, respectively. The buildings are designed for gravity loads according to IS 456:2000 [17].

![Figure 1. 3D view of the studied 10-storey building.](image1)

![Figure 2. Plan of the studied 5 and 10-storey buildings.](image2)

3. Analysis Methodology
The four cases of removal of columns (ACC, RICC, RECC and OCC) at ground level are shown in Figure 2 and the deflected shapes of buildings in ACC, RICC, RECC and OCC are shown in Figures 3, 4, 5 and 6, respectively. The effect of perimeter beams together with the strengthened column on Demand Capacity Ratios for the columns and chord rotations at locations of removal of columns was evaluated for each case. With normal structures, the DCR should not exceed 2 and for irregular structures 1.5 or else they are considered as susceptible to progressive collapse as being severely damaged. GSA has defined DCR according to Equation 1. The calculation of the connection rotation is determined in a frame via the chord rotation. The chord rotation is compared to the permissible plastic rotation angle for this connection according to the GSA and DoD recommendations. The chord rotation as per DoD is calculated according to Eq. 2.

$$DCR = \frac{Q_{UD}}{Q_{CE}}$$  \hspace{1cm} (1)

Where, \(Q_{UD}\) = Acting force computed in the component (shear, moment, axial force)

\(Q_{CE}\) = Expected ultimate, unfactored capacity of the component.

$$\theta = \frac{\Delta}{L}$$  \hspace{1cm} (2)

Where, \(\theta\) = chord rotation (plastic rotation angle) in radians,

\(\Delta\) = vertical displacement, \(L\) = length of member.
4. Results and Discussion

4.1. Impact of Perimeter Beams with Strengthened Columns on DCR of Columns adjacent to Removed Column

The responses of columns C2 and C5 are evaluated when Acute Corner Column ACC (C1) is removed in the ground floor. In the scenario of removal of Right Corner Column RICC (C4), the responses of columns C3 and C8 are evaluated. The responses of columns C8, C11, C13 and C16 are evaluated when Re-Entrant Corner Column RECC (C12) is removed in the ground floor. In the situation of removal of Obtuse Corner Column OCC (C18), the responses of columns C14 and C19 are evaluated.

For the irregular flat slab building without any retrofitting measure, under GSA factored loading 2(1.2DL+0.5L), in all four circumstances of removal of columns (ACC, RICC, RECC and OCC), the analysis results in Tables 1, 2, 3, 4 and 5 show the development of progressive collapse in the columns adjacent to the removed column as their DCR values exceed the limit 1.5 [2] for irregular buildings. The addition of perimeter beams along with the strengthening of perimeter columns has significantly reduced the DCR values for the axial force and moments of the critical columns for most of the column removal.
cases. This could be due to the reason that the strengthened columns provided extra stiffness and rigidity to the perimeter frame. The DCR values of critical columns of the 10-storey building are found marginally higher than that of the 5-storey building but the effect of perimeter beams together with strengthened columns on DCR is similar for both 5 and 10-storey buildings.

**Table 1.** DCR of C2 and C5 (axial force and moments) when C1 (ACC) removed.

|        | DCR (C2) | DCR (C5) |
|--------|----------|----------|
|        | AXIAL    | MOMENTS  | AXIAL    | MOMENTS  |
| 5-Storey |          |          |          |          |
| B-N    | 1.86     | 1.85     | 1.81     | 1.82     |
| B-PBSC | 1.43     | 1.42     | 1.38     | 1.40     |
| 10-Storey |        |          |          |          |
| B-N    | 1.88     | 1.87     | 1.83     | 1.83     |
| B-PBSC | 1.45     | 1.45     | 1.41     | 1.40     |

**Table 2.** DCR of C3 and C8 (axial force and moments) when C4 (RICC) removed.

|        | DCR (C3) | DCR (C8) |
|--------|----------|----------|
|        | AXIAL    | MOMENTS  | AXIAL    | MOMENTS  |
| 5-Storey |          |          |          |          |
| B-N    | 1.72     | 1.75     | 1.76     | 1.78     |
| B-PBSC | 1.38     | 1.42     | 1.40     | 1.43     |
| 10-Storey |        |          |          |          |
| B-N    | 1.77     | 1.81     | 1.78     | 1.82     |
| B-PBSC | 1.40     | 1.47     | 1.44     | 1.48     |

**Table 3.** DCR of C8 and C11 (axial force and moments) when C12 (RECC) removed.

|        | DCR (C8) | DCR (C11) |
|--------|----------|-----------|
|        | AXIAL    | MOMENTS  | AXIAL    | MOMENTS  |
| 5-Storey |          |          |          |          |
| B-N    | 1.62     | 1.65     | 1.66     | 1.68     |
| B-PBSC | 1.37     | 1.43     | 1.65     | 1.67     |
| 10-Storey |        |          |          |          |
| B-N    | 1.72     | 1.74     | 1.68     | 1.72     |
| B-PBSC | 1.47     | 1.48     | 1.67     | 1.70     |

**Table 4.** DCR of C13 and C16 (axial force and moments) when C12 (RECC) removed.

|        | DCR (C13) | DCR (C16) |
|--------|-----------|-----------|
|        | AXIAL    | MOMENTS  | AXIAL    | MOMENTS  |
| 5-Storey |          |          |          |          |
| B-N    | 1.61     | 1.64     | 1.65     | 1.68     |
| B-PBSC | 1.37     | 1.42     | 1.63     | 1.65     |
| 10-Storey |        |          |          |          |
| B-N    | 1.71     | 1.73     | 1.71     | 1.75     |
| B-PBSC | 1.48     | 1.49     | 1.69     | 1.73     |
Table 5. DCR of C14 and C19 (axial force and moments) when C18 (OCC) removed.

| Storey | C14 (AXIAL) | C14 (MOMENTS) | C19 (AXIAL) | C19 (MOMENTS) |
|--------|-------------|----------------|-------------|----------------|
| 5      | 1.96        | 1.92           | 1.89        | 1.90           |
| 10     | 1.47        | 1.46           | 1.42        | 1.42           |

4.2. Impact of Perimeter Beams with Strengthened Columns on Vertical Displacement and Chord rotation at the location of removal of column.

For the building B-N, under GSA factored loading, the worst case of OCC removal gives the highest deflection of 763.2 mm, whereas the lowest displacement is in the case of the removal of RECC with 525.5 mm, as shown in Table 6. This may be explained by the fact that the OCC is tied to only two edge columns (comparatively far apart) whereas the RECC is tied to four columns. The influence of the addition of perimeter beams with strengthened columns on the restriction of $\Delta_{crl}$ is much greater in OCC, ACC and RICC removal than that in case of RECC removal. When buildings B-N and B-PBSC are compared, it is noticed that the inclusion of perimeter beams with strengthened columns has reduced $\Delta_{crl}$ by 61.19 % (ACC), 62.64 % (RICC) and 60.24 % (OCC) in comparison to 30.59 % (RECC). This can be attributed to the better stiffening of the perimeter of the irregular flat slab and connecting the enlarged span created by the removal of the column by the perimeter beams in the cases of ACC, RICC and OCC removals in comparison to RECC removal, where the two interior columns C11 and C16 are left untied. Additionally, removal of OCC showed higher $\Delta_{crl}$ when compared to that with the removals of ACC and RICC. This could be due to the larger area covered in the obtuse shape compared to smaller areas protected in the cases of ACC and RICC. Table 7 shows the chord rotation at different locations of removal of columns. Further, Figure 7 shows that the addition of perimeter beams with strengthened columns decreased the chord rotation and kept it below the 0.05 limit (for flat slab structures) defined in GSA and DoD.

Table 6. Vertical Displacement at the location of removal of column.

| Storey | C1 (ACC) | C4 (RICC) | C12 (RECC) | C18 (OCC) |
|--------|----------|-----------|------------|-----------|
| 5      | 734.2    | 717.8     | 525.5      | 763.2     |
| 10     | 284.9    | 268.1     | 364.7      | 303.4     |

Table 7. Chord Rotation at the location of removal of column.

| Storey | C1 (ACC) | C4 (RICC) | C12 (RECC) | C18 (OCC) |
|--------|----------|-----------|------------|-----------|
| 5      | 0.091    | 0.089     | 0.065      | 0.095     |
| 10     | 0.035    | 0.033     | 0.045      | 0.037     |
Figure 7. Chord rotation at different locations of removal of columns compared to the limit of 0.05 radians.

5. Conclusion
Adding the perimeter beams and the strengthened perimeter columns to the irregular flat slab building, performance enhancement is assessed in view of critical column DCR, chord rotation and vertical displacement at removed column joint using progressive collapse analysis following the GSA guidelines. The building underwent four circumstances of the removal of different corner columns at its ground level. From the findings of the cases reviewed, the conclusions drawn are as follows:

- In all four cases of removal of corner columns (ACC, RECC, OCC and RICC), the irregular flat slab building B-N demonstrated the evolution of progressive collapse as the DCR values in the critical columns and the chord rotation values in the removed column joint exceeded the 1.5 and 0.05 limits, respectively.
- Among all the four corner column removal scenarios, the effect of the addition of perimeter beams with strengthening perimeter columns to the irregular flat slab building is more significant in the ACC, OCC and RICC removal cases than in the RECC removal case.
- The addition of perimeter beams, in order to form moment frames throughout the perimeter of the building, bridges the enlarged span created by the removal of the column whereas the strengthened columns provide sufficient rigidity and strength to carry the extra dead weights.
- The incorporation of perimeter beams along with strengthened periphery columns, in all the column removal cases, is found to be very effective in preventing the progressive collapse of the irregular flat slab building considered in this study. It enhances all the performance indicators; DCR of the critical columns, joint displacement and subsequently the chord rotation at the locations of removal of columns.
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