Progressive Collapse Study of RC Frame Building with Removal of Column at Different Locations

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Abstract

Progressive collapse is nothing but failure of structural member step by step due to accidental or earthquake load. Literature emphasizes the criticality of understanding load redistribution mechanisms and structural robustness, particularly in multi-storey reinforced concrete (RC) buildings. Paper presented here is taking into account a study of G+7 regular buildings to know the reasons for failure of building under accidental loads like earthquake. Response spectrum analysis with soil type II (medium soil) as per IS 1893 is considered for the analysis purpose. Alternate Path method with nonlinear staged collapse is adopted as per General Service Administration (GSA) and Unified Facilities Criteria (UFC) guidelines, USA considering different column removal cases both in elevation and plan. Based on demand capacity ratio (DCR) it is inferred that the removal of middle column alone at ground floor from both long and short side has partially affected the performance of building. While, removal of middle column at ground and mid (4th) floor level shows tendency of partial or complete collapse of building. DCR values for all columns is below 1, indicates that it has capacity to redistribute the moment to the adjoining members.

Keywords: Progressive collapse; RC frame; Symmetrical building; Demand capacity ratio.

Introduction

Progressive collapse of a reinforced concrete (RC) building is a catastrophic process in which a localized failure-caused by events such as explosions, impacts, or earthquakes-triggers a chain reaction that can lead to partial or total structural collapse. This occurs when remaining members cannot adequately redistribute the loads previously carried by the damaged components. Traditional design approaches mainly focused on the superstructure's ability to bridge over lost elements. However, modern research recognizes that structural stability is strongly influenced by the supporting ground.

As per General Service Administration (GSA) and Unified Facilities Criteria (UFC) for progressive collapse analysis, 4 column removal locations were recommended in plan and elevation. With this, in present study four column loss scenarios at ground and middle storey are considered as:

Case 1: a) Middle column removal at ground floor of long side; b) Middle column removal at ground floor of short side

Case 2: a) Middle column removal at ground floor and mid storey of long side; b) Middle column removal at ground floor and mid storey of short side

The plan of building model considered for analysis is shown in Fig. 1 and the location of column removal in plan and elevation are shown in Fig. 2 and Fig. 3.

The basic objective of this study is to verify a RC structure by eliminating column from different locations (middle column) of long and short side of rectangular building. Removal of column at different locations results in distribution of bending moment, shear force and axial forces of the

adjoining members (beams and column). According to GSA guidelines two types i.e. G and GLD load combination were used in the modelling along with 14 load combinations suggested by IS 456-2000, G = 1.2DL + 0.5LL and GLD = 2 (1.2DL + 0.5LL) where DL – dead load and LL – live load. GLD is nothing but the increased gravity load combination considered for those bays which were immediately near to the column removed and the slabs above it. The G is load combination which is applied on remaining bays and slabs which are not loaded with GLD combination Vinay et al. (2022).
Demand Capacity Ratio (DCR) is the ratio of the moment or force carried by the member (after removal of column) to its ultimate capacity. The values of DCR are suggested by GSA and UFC guidelines are less than 2 for flexural members of regular building in plan and less than 1.5 for irregular building in plan. DCR values for column should be less than 1.

The moment capacity of flexural member as per IS 456 is given by; $M_u = 0.87 f_y A_{st} d \left(1 - \frac{A_{st} f_y}{b d f_{ck}}\right)$ with usual meanings. The capacity of column is given by code is $P_{uz} = 0.45 f_{ck} A_c + 0.75 f_y A_{sc}$. Using these expressions, the moment of resistance (Mu) is calculated for beam considered (details shown in Table 1) is 141.82 kNm and that of column load carrying capacity is calculated is 5262 kN.

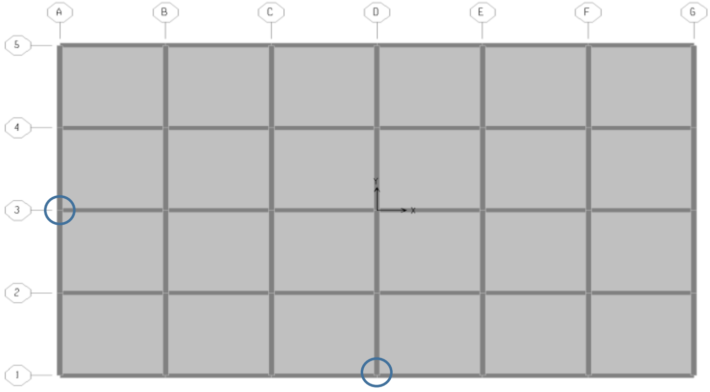

Fig. 1. Plan of building with location of column removal at GF & MF

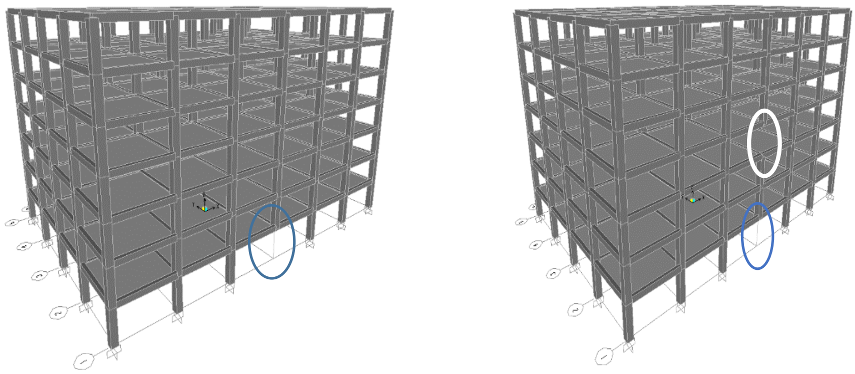

Fig. 3. Case 1: Long side column removal at GF & MF (4th) floor level

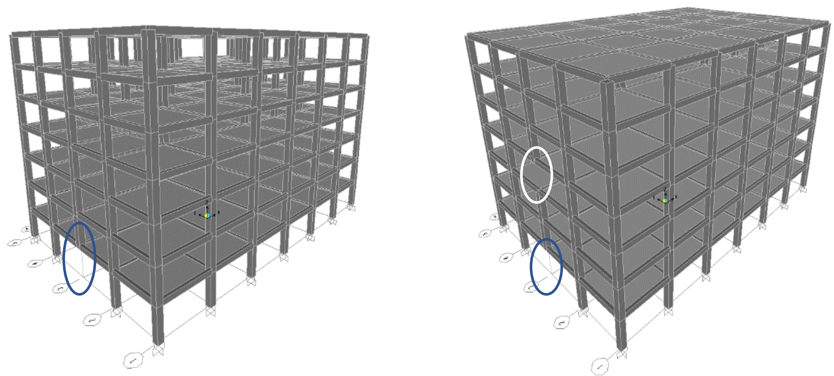

Fig. 4. Case 2: Short side column removal at GF & MF (4th) floor level

Literature Review

Kwasniewski, 2010 presented a case study of progressive collapse of certain multistore buildings. He focused on non-linear dynamic FEM following GSA guidelines. Model were developed considering increasing vertical loading and column removal. He proposed a hierarchical verification and validation program to reduce outcome uncertainties. Tsai and Huang, 2011 studied effect of non-structural RC walls on the progressive collapse of RC frame. They conducted both linear and non-linear analysis of RC frames with and without non-structural walls under different column loss scenarios. They found increase in collapse resistance with panel type walls and wing type exterior walls seems to be better option than other types. They also found that panel-type wall may be problematic in shear failure. Eren et al., 2019 carried simulations of large number of building considering progressive collapse, quantifying the effects of infill walls. They developed micro-level model to evaluate the effectiveness of structure with infill wall and proposed that infilled frames resisted vertical forces that are 3 times more than that of bare frames. Quiel et al., 2019 documented the experimental development of a spandrel to column connection for progressive collapse resistance in precast concrete building frames. Prototype of 10 storey precast concrete frame building with special moment frames were tested that includes removal of ground floor column. They inferred that nonlinear dynamic analysis shows the system taken for study resist progressive collapse even in event of column loss scenario. Parisi and Scalvenzi, 2020 carried a study on gravity –load designed RC building complying with international standards considering both simultaneous and sequential removal of ground floor columns. They observed that sudden loss of two consecutive columns can drastically reduce the load capacity that cause collapse of structure whereas sequential loss of column shows positive or negative variations in load capacity. Ghobadi and Yavari, 2020 noticed effects of opening in the low and mid-rise irregular voided structures under seismic area with progressive collapse consideration. They found that structural robustness analysis for internal columns away from opening of the voided buildings should be considered as critical and controllable member in progressive collapse capacity of buildings. They also concluded that increase in height of structures reduces the amount of stress development in columns adjacent to the demolished column. Panahi and Zahrai, 2021 focused on disproportion of initial and final damage during progressive collapse that leads to collapse of entire building. They used alternate path method considering GSA and UFC regulations. It is found that removal of corner column has more intense effect with doubling collapse rate, increase in shear and axial forces in columns by 1.5 times.

Elsanadedy and Abadel, 2022 discussed about buildings constructed in Saudi Arabia which has discontinuous bottom beam rebars across all beam-column joints, which they found susceptible to progressive collapse of buildings. Several half scale assemblies were investigated using FE model to check how collapse takes place under event of middle column removal. They also suggested best assemblies based on risk levels to reduce the collapse of building. Yosef and El-Mandouh 2020 analysed high strength concrete building and normal strength concrete building under central column removal to check progressive collapse pattern. The analysis showed that outcome in both the cases were approximately similar. They also observed the ratio between maximum and minimum dynamic displacement for normal and high strength is very close. Zhang et al. 2022 investigated progressive collapse behaviour of RC building isolated by friction pendulum bearings using FEM analysis. They found that equivalent radius, friction coefficient and applied axial load has limited effect on the progressive collapse response of FRB isolated buildings, while external column has significant influence on progressive collapse resistance capacity of building.

Numerical Study and Discussions

Sample buildings described herein were selected as typical G+7 story reinforced concrete building modelled using FEM software SAP 2000 as shown in Fig. 4. At first the building is analysed considering no column loss situation. Moment of resistance of flexural member and load carrying capacity of column is calculated and discussed in introduction part. In next part selected column as prescribed by

GSA and UFC is removed from different locations and load combinations were applied to bays and slabs by non-linear staged construction facility available in SAP 2000. Following data were used in modelling G+7 RC building as given in Table 1-6.

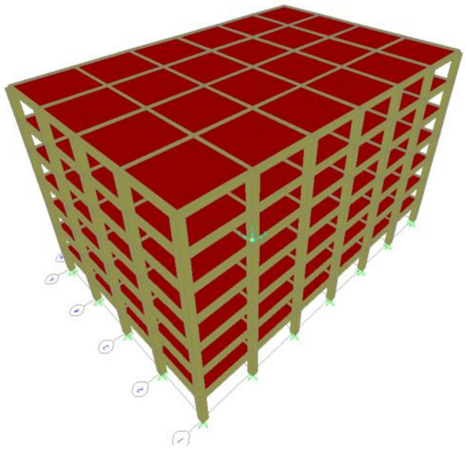

Fig. 4. 3-D view of RC building using SAP 2000

Table 1. Model Dimensions

Details	Dimensions/Units
Total floors (Nos.)	7 (G+6)
Building height (m)	21
Storey height (m)	3
Plan dimension (Regular) m	22
Column size (m)	0.6 x 0.6
Beam size (m)	0.3 x 0.5
Slab tk. (m)	0.15

Table 2 Material properties used in modelling

Grade of concrete, f_{ck} (MPa)	30
Grade of Steel, f_y (MPa)	500
Modulus of Elasticity, Ec (MPa)	27.38E03
Modulus of Elasticity, Es (MPa)	210E03
Poisson's ratio	0.25

Table 3 Total structural elements in FEM model

No. of bays in x-axis	6
No. of bays in y-axis	4
No. of columns	254
No. of beam	406
No. of slab panels	168
No. of joints	208
No. of supports	35
Types of support	Fixed, SSI

Table 4 Load on structural elements of building

Live load on roof (kN/m^2)	1.5
Live load on floor (kN/m^2)	3.0
Masonry load (Ext. wall) (kN/m)	11.5
Masonry load (Int. wall) (kN/m)	7.5
Floor finish (kN/m^2)	1.5
Masonry load (Parapet) (kN/m)	7.0

Table 5 Seismic analysis details

Zone factor, Z	0.24 (Zone IV)
Soil type	II (Medium)
Importance factor, I	1
Response reduction factor	5
Time period (Calculated)	0.74 sec.

Table 6 Load combinations for analysis as per IS 456-2000

1.5(DL)	1.5(DL-EQY)
1.5(DL+LL)	0.9(DL) + 1.5(EQX)
1.2(DL+LL+EQX)	0.9(DL) - 1.5(EQX)
1.2(DL+LL-EQX)	0.9(DL) + 1.5(EQY)
1.2(DL+LL+EQY)	0.9(DL) - 1.5(EQY)
1.2(DL+LL-EQY)	Where; DL-Dead Load, LL-Live Load, EQ-Earthquake Load
1.5(DL+EQX)	
1.5(DL-EQX)	
1.5(DL+EQY)	

DCR for flexural member

After removal of column as discussed in introduction section and shown in Fig. 6, DCR is calculated for different beams just adjacent (left and right side) of the column removed. The DCR calculated is shown in Table 7. As per the guidelines, the beams having DCR value above 2 has higher possibility to be collapsed. Similar scenario of failure is observed along short side as shown in Table 8.

Table 7. Beam moment after column removal at GF and mid floor along long side

Floor No	Member ID	Max. Load Combination	Max. Moment (kNm)	DCR	Remarks
7	266	7, 8, 9, 10	160.39	1.13	Safe
6	265	7, 8, 9, 10	280.11	1.98	Safe
5	264	7, 8, 9, 10	410.22	2.89	Unsafe
4	263	7, 8, 9, 10	525.59	3.71	Unsafe
3	262	7, 8, 9, 10	611.41	4.31	Unsafe
2	261	7, 8, 9, 10	643.19	4.54	Unsafe
1	260	7, 8, 9, 10	539.86	3.81	Unsafe

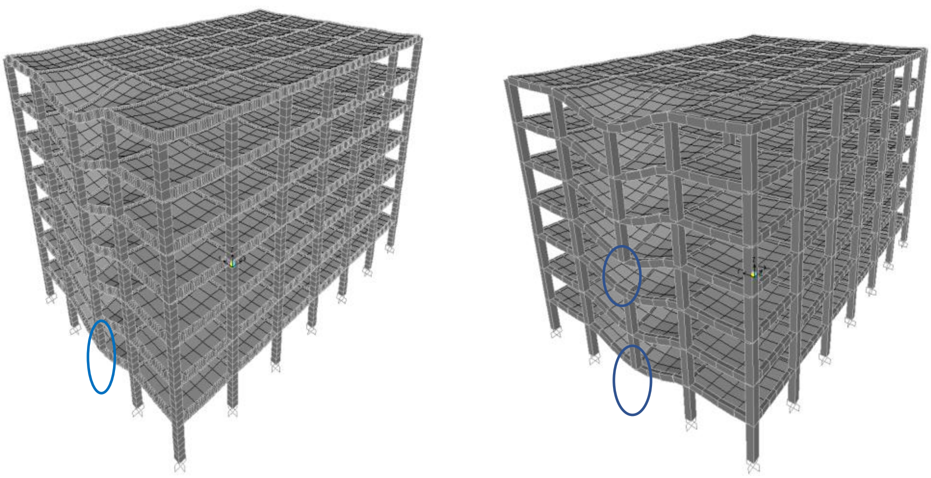

Fig. 6. Deformed shape for column removal at GF and MF in short side

Table 8. Beam moment after column removal at GF and mid floor along short side

Floor No	Member ID	Max. Load Combination	Moment in (kNm)	DCR	Remarks
7	469	10	198.44	1.40	Safe
6	468	10	228.16	1.61	Safe
5	467	10	246.48	1.74	Safe
4	466	10	270.47	1.91	Safe
3	465	10	291.47	2.06	Unsafe
2	464	10	303.73	2.14	Unsafe
1	463	10	286.98	2.02	Unsafe

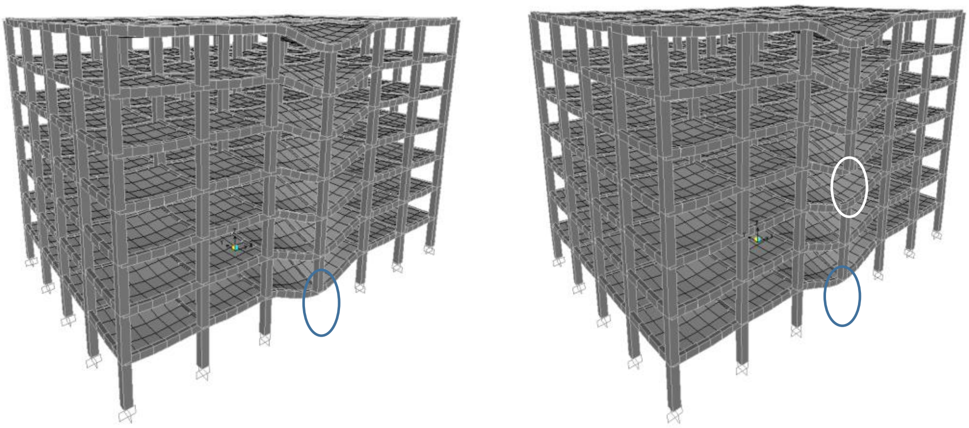

Fig. 5. Deformed shape for column removal at GF and MF in long side

DCR for column

As per guidelines of GSA and UFC, the DCR is calculated for all columns on the left side, right side, and above the column removed at ground floor and mid floor are as shown in Table 9. It is seen from the values and specification given, if DCR is less than 1 which shows no column failures. Also, it is observed in any case may it be ground floor column removal or mid storey column removal (both long side and short side), the DCR value is less than 1. This indicates that, the column has ability to share or distribute the load from removed column to the nearby adjacent column.

Table 9. Column moment (left and right side) after column removal at GF and mid floor along long side

Floor No	Member ID	Max. Load Combination	Axial force in Column (kN)	DCR	Remarks
7	77	7, 8, 9	178.39	0.034	Safe
6	76	8 & 9	347.50	0.066	Safe
5	75	4 & 5	521.93	0.099	Safe
4	74	4 & 5	728.89	0.139	Safe
3	73	4 & 5	937.54	0.178	Safe
2	72	4 & 5	1147.08	0.218	Safe
1	71	4 & 5	1351.65	0.257	Safe

Concluding Remarks

The progressive failure analysis study is carried with different positions of column removal using SAP 2000 software. Following conclusions are drawn:

- Due to removal of column at ground floor only (Case 1 (a) and (b)), it is observed that DCR value is less than 2 for all beams along short side, indicating no damage while along long side DCR of beams up to 5th floor is above 2, that indicates failure possibility.
- Due to removal of column at ground floor and mid floor (4th storey) (Case 2 (a) and (b)), it is observed that DCR value of beams up to 3rd floor in short side and up to 5th floor along long side is above 2, that indicates failure possibility. This may result in pounding effect and results in partial or complete collapse of building.
- The DCR value for all the columns in all four cases considered in the analysis is less than 1 as prescribed by GSA and UFC guidelines, shows that all columns are intact even after removal of columns at different locations. This reflect the case of strong column and weak beam, which is permitted by IS 1893.

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