Progressive Collapse of RC Structure Using Non-Linear Static Analysis

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Abstract - *Progressive collapse implies disproportionate failure of structure originated by local structural damage. It is a rare event, as it necessitates an initiation of local element removal criteria either due to natural causes or due to manmade hazards. The progressive collapse of reinforced concrete structures is initiated when one or more vertical load carrying members get damaged forming chain reaction of structural element failures, resulting in partial or full collapse of the structure. Progressive collapse mitigation measures reduce the chances of catastrophic building collapse due to failure of small part of the building structure. The intent of progressive collapse requirements is to allow the damaged building to remain standing long enough for those inside to safely evacuate. The General Services Administration (GSA) and Department of Defense have issued general guidelines for evaluating a building's progressive collapse potential.*
In this paper, two methods of analysis are adopted for evaluating the progressive collapse hazard: linear analysis and nonlinear static analysis. In this paper, progressive collapse analysis of 10 storey RC frame building situated in earthquake zone V is carried out by removing the column at different locations one at a time as per GSA guidelines. Building consists of 6 bays at 6m in longitudinal direction and 4 bays at 5m in transverse direction with the typical storey height of 4m designed according to the Indian Standards. Building is designed and analyzed in ETABS software. Three column removal conditions for ground floor are adopted as suggested in GSA guidelines.

Key Words: *Progressive collapse, GSA guidelines, linear analysis, non-linear analysis, ETABS, column removal.*

1.INTRODUCTION

Progressive collapse came into attention of engineers and researchers after the collapse of 22 storey Ronan point apartment building in London. This accident showed that the special considerations are required for the design of structure to mitigate the possible progressive collapse.

A building undergoes progressive collapse when a primary load carrying structural element fails, resulting in the failure of adjoining structural elements, which in turn causes further structural failure. ASCE 7-05 defines progressive collapse as "the spread of an initial local failure from element to element resulting, eventually, in the collapse of an entire structure or a disproportionately large part of it". The progressive collapse can be initiated by many causes, including design and construction mistakes and load events that are over the designed dimensions or are not considered, pressure loads or impact loads.

2. GSA Guidelines

The General Service Administration (GSA) guideline provides a detailed methodology and performance criteria needed to assess the vulnerability of new and existing buildings to progressive collapse. For the analysis of progressive collapse following column removal cases are given in guidelines.

2.1 External Columns: Remove external columns near the middle of the short side, near the middle of the long side, at the corner of the building, and adjacent to the corner of the building as shown in Fig 1.

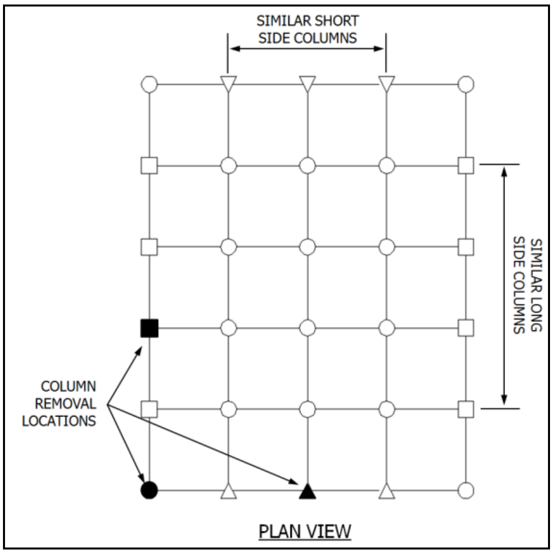

Fig -1: Location of external column removal

2.2 Internal Columns: For structures with underground parking or areas of uncontrolled public access, remove internal columns near the middle of the short side, near the middle of the long side as shown in fig 2.

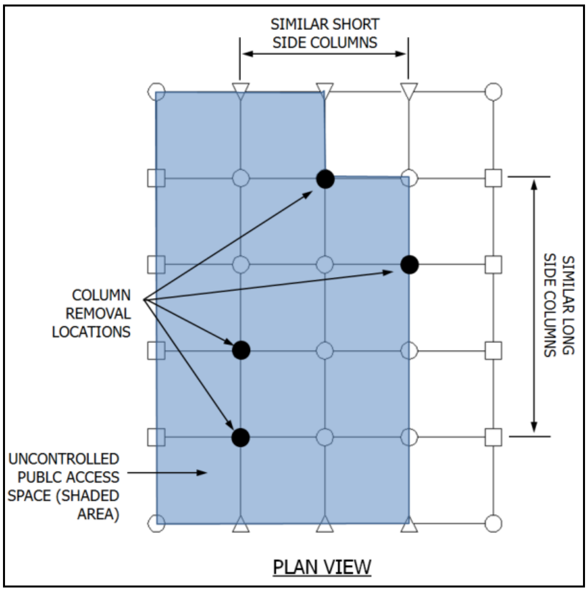

Fig -2: Location of internal column removal

3. Modelling of Structure

The building considered for the study is 10 storey symmetrical R.C. Building situated in earthquake zone V. The structure consists of six bays of 6m in the longitudinal direction and four bays of 5m in transverse direction as shown in Fig 3. The typical floor to floor height is 4m. Slab thickness considered is 200mm. M40 grade of concrete and Fe 500 steel is considered. Plastic hinges are assumed at 10% of span length from the joint.

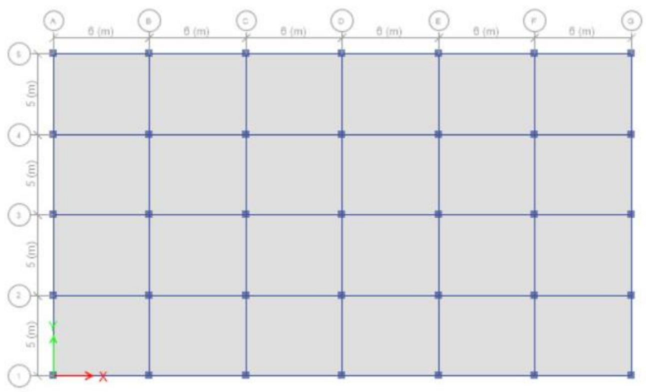

Fig -3: Typical Plan of ETABS Model

Table -1: Modelling Details for Structure

Sr. No.	Particulars	Description
1	Type of Structure	RCC Framed Structure
2	Number of Stories	10
3	Spacing in Longitudinal Direction	6m
4	Spacing in Transverse Direction	5m
5	Storey Height	4m
6	Earthquake zone	Zone V
7	Slab Thickness	200mm
8	Beam Sizes	300mm x 450mm
9	Column Sizes	500mm x 500mm
10	Material	M40, Fe500
11	Codes	IS 456:2000, IS 1893: 2016, GSA 2016

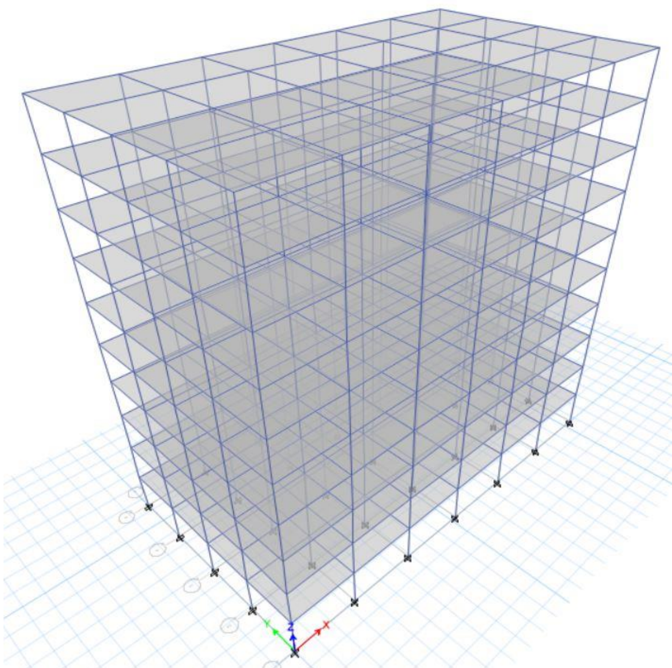

Fig -4: Elevation of Structure

4. Methodology

In this paper, 10 storey RCC structure is designed and analyzed for progressive collapse considering different locations for the sudden removal of column and its effect on progressive collapse. The aim of this paper is to study the effect of column removal on the localized area and comparative study for the same in different earthquake zones.

There are several methods for the analysis of progressive collapse as linear static method, linear dynamic method, non-linear static method, non-linear dynamic method.

In this study, three different column removal cases are considered for the study as:

Case 1: Sudden loss of center column C12

Case 2: Sudden loss of edge column C4

Case 3: Sudden loss of corner column C1

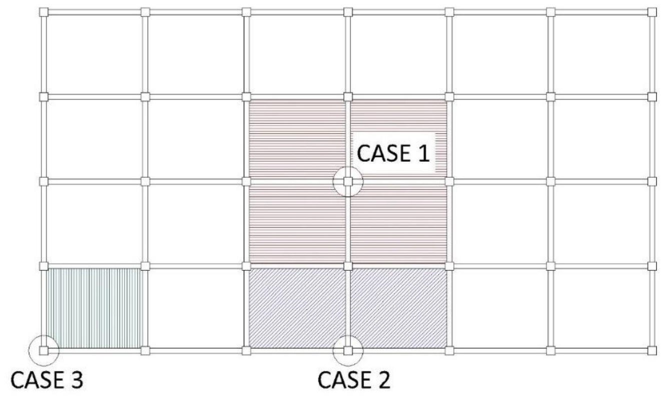

Fig -5: Column Removal Cases

4.1 Linear Analysis: To evaluate the potential for progressive collapse of a 10-storey building 3 column removal cases are considered. The building is designed in ETABS for IS 1893 load combinations. Then separate linear analysis is carried out for each case of column removal. Change in the member forces of the adjacent beams and columns are observed.

Table – 2: Loading considered on the building

Sr. No.	Particulars	Description
1	Dead Load	Self-weight of structure
2	Live Load	4 kN/m^2
3	Floor Finish	2 kN/m^2
4	Seismic load	IS 1893: 2016
5	Importance factor	1
6	Soil Type	Medium
7	Response reduction factor	5

4.2 Non-Linear Analysis: GSA Guidelines has provided stepwise procedure to carryout non-liner static analysis. After performing the linear static analysis, the model is unlocked. Pushover cases are defined for both X and Y direction. The plastic hinges are assigned to beam and column members at a distance 10% of span length for the pushover cases. After defining the cases the desired column is removed and non-linear static analysis is performed, and hinge formation pattern is observed.

Then non-linear dead load case and pushover cases are defined for both longitudinal and transverse direction. Loading is applied as per given in GSA guidelines and analysis is performed.

4.2.1 Load Cases for Non-Linear Static Analysis:

For deformation-controlled action, apply the following combinations of gravity load:

Increased gravity load for floor area above the removed column:

$G_N = \Omega_N\ [1.2\ D + (0.5\ L \text{ or } 0.2\ S)]$

where,

G_N = increased gravity loads for deformation-controlled actions for non-linear static analysis

D = Dead load (kN/m^2)

L = Live load (kN/m^2)

S = Snow load (kN/m^2)

Ω_N = Load increase factor for calculating deformation-controlled actions for non-linear static analysis.

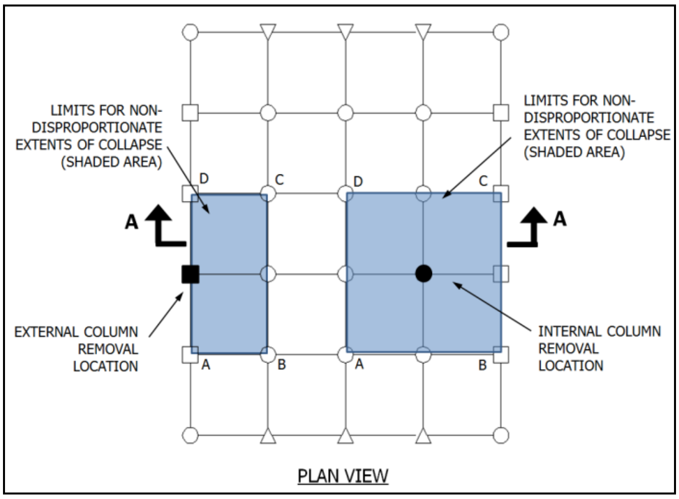

Fig -6: Allowable extents of collapse for interior and exterior column removal

Gravity load for the floor areas away from removed column:

G = 1.2 D + (0.5 L or 0.2 S)
Where,
G = gravity loads

5. Results and Discussion

5.1 Forces in Columns:

Change in forces developed in adjacent column to the column removal cases are as tabulated in Table 3. Due to the sudden loss of load carrying element i.e., column, the additional force gets redistributed in adjacent members due to which there is sudden increase in member forces of the adjacent columns. Due to the symmetry of building only a part is considered for the observation. The nomenclature of considered columns is as shown in fig 7.

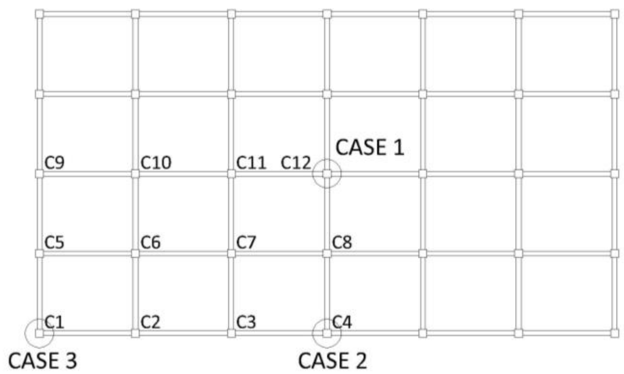

Fig -7: Column nomenclature

Table – 3: Forces developed in columns for case1

Particular	Column	C12	C7	C8	C11
Axial Force (kN)	Without column removal	5724	5546	5542	5727
	After column removal	**Removed**	5729	9920	9335
Bending Moment (kN/m²)	Without column removal	136	132	133	136
	After column removal	**Removed**	137	261	270

After the removal of center column C12, i.e., case 1, axial force in adjacent column C8 and C11 becomes 1.8 times and 1.6 times the initial force, respectively. Bending moment in adjacent columns C8 and C11 becomes almost equal to 2 times the initial moment whereas there is very small increase in axial force and bending moment of diagonal column C7.

Table – 4: Forces developed in columns for case2

Particular	Column	C4	C3	C7	C8
Axial Force (kN)	Without column removal	1605	1606	5546	5542
	After column removal	**Removed**	4071	5715	8535
Bending Moment (kN/m2)	Without column removal	132	132	132	133
	After column removal	**Removed**	323	136	220

After the removal of edge column C4, i.e., case 2, axial force and bending moment in adjacent column C3 becomes 2.5 times the initial and C8 becomes 1.5 times the initial, respectively. There is very small increase in axial force and bending moment of diagonal column C7.

Table – 5: Forces developed in columns for case3

Particular	Column	C1	C2	C5	C6
Axial Force (kN)	Without column removal	984	1582	1505	5452
	After column removal	Removed	4020	4012	5565
Bending Moment (kN/m2)	Without column removal	141	132	145	130
	After column removal	Removed	290	310	132

After the removal of corner column C1, i.e., case 3, axial force in adjacent column C2 and C5 becomes 2.5 times and 2.6 times the initial force, respectively. Bending moment in adjacent columns C2 and C5 becomes 2.2 times and 2.1 times the initial moment, respectively. Whereas there is very small increase in axial force and bending moment of diagonal column C6.

5.2 Forces in Beams:

Change in forces developed in adjacent beams to the column removal cases are as tabulated in Table 4. Due to the sudden loss of load carrying element i.e., column, the additional force gets redistributed in adjacent members due to which there is sudden increase in member forces of the adjacent beams. Due to the symmetry of building only a part is considered for the observation. The nomenclature of considered beams is as shown in fig 8.

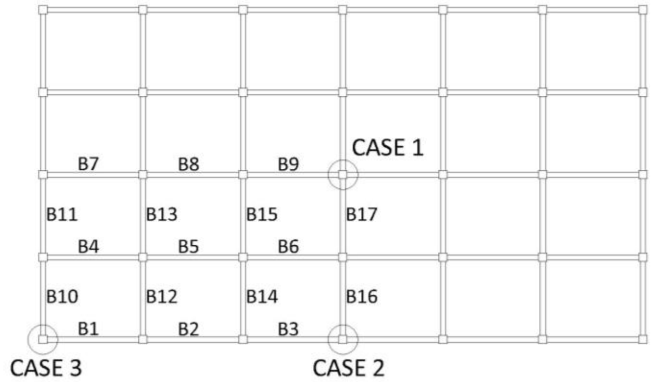

Fig -8: Beam nomenclature

Table – 6: Forces developed in beams for case 1

Particulars	Beam	B9	B17
Bending Moment (kN/m²)	Without column removal	187	168
	After column removal	370	315
Shear Force (kN)	Without column removal	135	132
	After column removal	207	199

After the removal of centre column C12, bending moment in adjacent beams B9 and B17 becomes 1.9 times and 1.8 times initial bending moment, respectively. Shear force in beams B9 and B17 becomes 1.5 times the initial shear force.

Table – 7: Forces developed in beams for case 2

Particulars	Beam	B3	B16
Bending Moment (kN/m²)	Without column removal	154	180
	After column removal	340	349
Shear Force (kN)	Without column removal	94	139
	After column removal	169	222

After the removal of edge column C4, bending moment in adjacent beams B3 and B16 becomes 2.2 times and 1.8 times initial bending moment, respectively. Shear force in beams B3 and B16 becomes 1.9 times and 1.6 times the initial shear force, respectively.

Table – 8: Forces developed in beams for case 3

Particulars	Beam	B1	B10
Bending Moment (kN/m²)	Without column removal	163	157
	After column removal	261	258
Shear Force (kN)	Without column removal	100	102
	After column removal	135	156

After the removal of corner column C1, bending moment in adjacent beams B1 and B10 becomes 1.6 times the initial bending moment. Shear force in beams B1 and B10 becomes 1.3 times and 1.5 times the initial shear force, respectively.

5.3 Performance point:

Performance point is found out by performing non-linear static analysis i.e., pushover analysis. It is the point where demand spectrum intersects the capacity spectrum. The pictorial representation of performance point is as shown in fig 9.

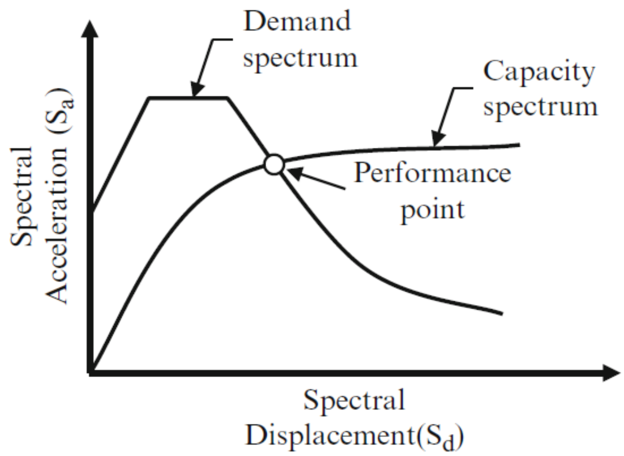

Fig -9: Performance point

For this study, the pushover curve obtained is as shown in fig 10 and the shear force and corresponding displacement at the performance point for 3 different column removal cases is as tabulated below in table 9.

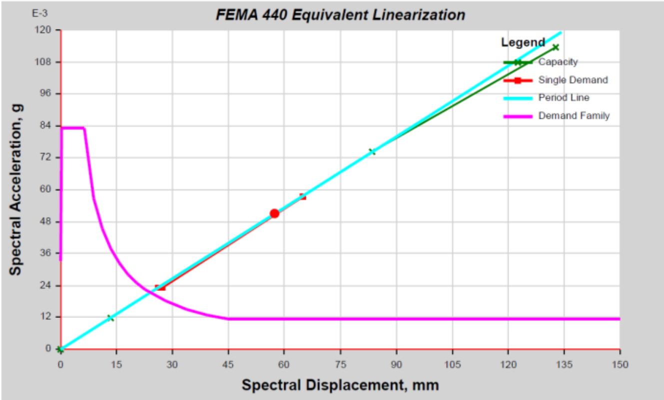

Fig -10: Pushover Curve

Table – 9: Performance point

Column removal cases	Shear force, V (kN)	Displacement, mm
Case 1	3876.1	72.4
Case 2	3112.9	58.4
Case 3	5070.9	96.5

From the above table, case 3, i.e., loss of corner column has maximum shear force and displacement at the performance point, which is at the collapse prevention state.

6. CONCLUSIONS

In this study, linear static and non-linear static analysis were performed on the model of 10 storey RC moment resisting frame building in accordance with GSA guidelines. Three cases of column removal were considered in the analysis: removal of center, edge, and corner column. The findings from the study are summarized as follows.

- From the above results for all the column removal cases, it is observed that there is almost twice the increase in the forces of beams and columns than that of intact building.
- Failure of beams and columns adjacent to the removed column occurred due the additional load distribution of the forces. It is observed that, the increase in forces in adjacent columns and beams is more as compared to the far columns and beams.
- Significant deformations are developed in the beams adjacent to the location where column is removed.
- Case 1 i.e., sudden loss of center column has more potential to collapse than the other two cases as the affected area is more for the case 1.
- To mitigate the progressive collapse caused due to failure of beams and columns, adequate reinforcement should be provided, or the alternate path must be provided like bracing or column sizes can be increased.

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