Journal of
Geotechnical Engineering

ISSN: 2394-1987
Volume 12, Issue 3, 2025
September–December
DOI (Journal): 10.37591/JoGE

https://journals.stmjournals.com/joge

Research JoGE

Structural Integrity Analysis of Reinforced Concrete Frames Under Progressive Collapse Scenarios

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Abstract

This study examines how a tall reinforced concrete (RC) frame may gradually collapse under several column removal situations, such as edge, end, center, zigzag, and two-column failures. The study assesses the structural reaction based on displacement, inter-story drift, and Demand–Capacity Ratio (DCR) using nonlinear static pushover analysis carried out in ETABS. According to the analysis, the frame's stability is seriously jeopardized when two nearby columns and end columns are removed, which results in the highest degrees of displacement and drift. Due to the changed pathways for loads and a drop in lateral resistance such situations become the most vulnerable. Structurally, the Center and Zig-Zag column removal proposals work slightly better than the other two scenarios. The symmetrical design and balanced way in which loads are shared help a bridge withstand failure situations better. The structure stays within its elastic or near-elastic range in all circumstances because the DCR values stay below acceptable bounds (below 1.0), meeting the safety requirements set forth in GSA 2016 and IS 456:2000. To measure the reliability of structures, displacement and drift-based robustness indices are introduced to make a comparison across different failure cases. As well, the places where nonlinear behavior happens are recognised by studying the way plastic hinges are formed, as this shows where collapse might occur. All in all, the study proves that keeping structures connected and organized, as well as including extra supports, greatly reduce the chance of progressive collapse. The study gives structural designers knowledge to build safer and stronger reinforced concrete frames under different types of stresses.

Keywords: Progressive collapse, reinforced concrete frame, column elimination, pushover analysis, ETABS, structural resilience, Drift ratio, displacement, Demand-Capacity Ratio (DCR), GSA guidelines, nonlinear static analysis, collapse mechanism, structural integrity

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Received Date: May 30, 2025
Accepted Date: July 11, 2025
Published Date: July 15, 2025

Citation: Pragati Bibhishan Sirsat, R.S. Londhe. Structural Integrity Analysis of Reinforced Concrete Frames Under Progressive Collapse Scenarios. Journal of Geotechnical Engineering. 2025; 12(3): 1–15p.

INTRODUCTION

If there is local weakening in a structure, it can lead to progressive collapse, in which the initial injury creates a series of other problems that ultimately bring down a major section or the entire building. This study assesses the risk of progressive collapse in high-rise reinforced concrete (RC) buildings by examining different column removal scenarios, including edge, end, center, two-column, and zig-zag configurations. This study employs nonlinear static pushover analysis to investigate structural responses such as displacement, inter-story drift, demand-to-capacity ratio (DCR), and the formation of plastic hinges, following the guidelines of the General Services Administration (GSA) and the provisions of the Indian Standard (IS 456:2000). Using displacement robustness and drift robustness, it analyzes how strong and stable the structure is, while also examining how the locations of the columns impact their overall stability.

The purpose is to find weak points in tall RC buildings and share suggestions for improvements that help the structures resist the process of collapse, thus adding safety and reliability to them. Events such as the collapse of the Ronan Point in 1968 and the World Trade Center in 2001 show what can happen when progressive collapse occurs. These incidents led to the creation of design standards, such as the GSA (2003) and Unified Facilities Criteria (UFC, 2009), which use alternate path methods to evaluate structural integrity in the event of sudden column loss. As a result, many areas that refer to IS 456 codes find that they have no rules against progressive collapse, meaning that new research should align with the local code requirements (Figure 1).

Figure 1. Progressive collapse of building.

This study enhances the understanding of progressive collapse in high-rise reinforced concrete frames by combining local (IS 456) and international (GSA) standards, offering engineers practical guidance for designing structures that can endure unforeseen failures (Figure 2).

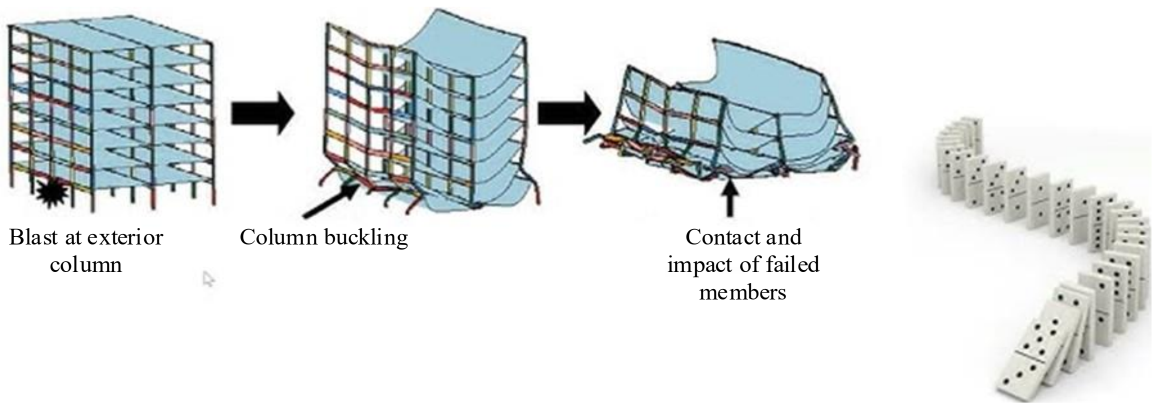

Figure 2. Collapse scenario of building.

This study advances the understanding of progressive collapse in high-rise RC frames by integrating local (IS 456) and international (GSA) standards, providing practical insights for engineers to design structures capable of withstanding unexpected failures. Progressive collapse analysis involves simulating scenarios, such as column or beam removal, to assess the ability of the structure to redistribute loads without further failure.

LITERATURE REVIEW

vertical load capacity of frames with partially encased (PE) beam after column removal. A validated fiber-based model aligned with Eurocode standards was used for Alternate Load Path and pushdown analyses. The results underscored the robustness of PE beams and the efficacy of ALP methods in collapse resistance evaluation [1].

3D models of RC buildings with detailed rebar configurations to study progressive collapse using the Alternate Path Method. The study highlighted the significant influence of building plan geometry on collapse susceptibility despite the high computational demands [2].

In this study, flat-slab RC buildings were analyzed a 4-story model under various column removal sequences. Three strengthening techniques were tested, which demonstrated improved collapse resistance, particularly for corner and interior column losses [3].

RC structures under sudden and gradual column loss simulating fire-induced degradation. The gradual removal approach provides realistic collapse predictions, emphasizing the need for designs that account for progressive deterioration [4].

The progressive collapse resistance of steel-concrete composite floors was assessed using parameters such as deck thickness and reinforcement. The findings suggest refinements to the design guidelines to enhance floor system robustness [5].

A 3D finite element model of a 20-story building was analyzed using ABAQUS for progressive collapse. The accuracy of the model was validated against experimental data, thereby offering insights into column removal scenarios and design improvements [6].

Nonlinear static and dynamic analyses, this study found that static analysis with a Dynamic Amplification Factor (DAF) of 2.0 underestimated the dynamic behavior. These results highlight the importance of incorporating inelastic dynamic effects [7].

Large-scale quasi-static tests of the collapse resistance. Using an energy-based approach, the study revealed vulnerabilities owing to insufficient continuous reinforcement, advocating for enhanced design provisions [8].

The RC building collapses under blast loads using a hydrocode to accurately capture the damage mechanisms. Validation against real-world data supports improved modeling and mitigation strategies [9].

Analytical framework, ranging from linear elastic static to nonlinear dynamic methods. Nonlinear dynamic analysis was identified as the most accurate method for assessing collapse potential [10].

AIM AND OBJECTIVES

Aim

The purpose of this study was to analyze the strength and ability of RC frames to resist collapse under various circumstances in which columns have been removed.

Objectives

1. Deal with situations in which the GSA considers it reasonable to remove parts of the room, including the conventional, edge, end, zigzag, two-column, and center column removal patterns. Look into the process of hinge development and collapse using pushover analysis.
2. Study DCR, displacement and inter-story drift under different building conditions.
3. Evaluate how well the design performs for different amounts of drift and displacement.
4. Determine the major failure situations and determine which options are better for handling them.

METHODOLOGY

This study uses nonlinear static pushover analysis in ETABS V21 to examine the progressive collapse behavior of reinforced concrete (RC) moment-resisting frames. The model building was symmetrical, with a G+12 structure that reached a height of 42 m when placed on a 30 x 30-m matrix. For comparison, column placement scenarios, including conventional, edge, end, two-column, zigzag, and center, are tested on the baseline model that describes the entire structure. They check whether the structure is secure in the event of progressive collapse by suddenly removing several important columns in the first story [11–15].

Modeling Process

Beams, columns, and slabs are defined as frame and shell components in the ETABS 3D finite element model of the building. Following are the important qualities of matter: IS 456:2000 explains that HYSD Fe500 steel has a yield strength of 500 MPa, while the main type of concrete for the building has a typical compressive strength of 30 MPa. The density of the brick masonry walls (230 mm thick) was 20 kN/m^3, whereas the density of the concrete was set at 25 kN/m^3. The beams had dimensions of 450 mm × 600 mm, the columns were 800 mm × 900 mm, and the slab was 150 mm thick. The model included five bays 6 m apart in both the X and Y directions. Stiff boundary conditions were used at the bottom to reproduce stiff foundations. Once the element sizes are chosen strategically, refining the mesh ensures that the stress pattern is balanced across the design [16–19].

Load Application

While setting up Loads, that GSA's recommendations for progressive collapse analysis and IS 875 (Parts 1 and 2) for dead and live loads, respectively, are adhered to. The self-weight of the frame and masonry walls is an instance of dead loads, whereas the live loads for residential floors are specified as 3 kN/m_2 under IS 875 (part 2). The GSA recommends using load combinations designed for progressive collapses [20–25].

To determine this effect, a new load was applied to a column that did not include the removed column. In accordance with IS 1893:2016, lateral loads should be equivalent to static forces used to represent seismic or wind influences, even though gravity-induced collapses are the main concern. When performing a pushover analysis, loads are applied progressively, and nonlinear effects are noticed by monitoring the displacement.

Nonlinear Hinge Assignment

FEMA 356 explains that nonlinear hinge properties are used to capture the inelastic action when a structure is heavily loaded. Columns are given axial-flexural interaction hinges (P-M2-M3) to allow for combined axial and bending effects, whereas beam components are given flexural hinges (M3) at their ends to simulate the moment-rotation behavior. Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) are the performance levels of hinge qualities, which are calibrated based on section properties and material strengths. Sectional analysis is used to obtain the moment-rotation curves for the hinges, so the curves can represent the right yielding and ultimate capacities. During the analysis, hinges are positioned at crucial points (beam ends and column bases) to monitor plastic deformations and local failures [26–28].

Analysis Procedure

To determine the performance of a building structure under loaded and gravity conditions, the normal condition model was initially tested. At this stage, important columns were removed one by one from the bottom floor, as prescribed in every scenario. The analysis relies on slowly adding displacements, eventually reaching the collapse limit set by defined criteria, such as excessive drift or hinge failure. To assess the collapse processes and structural robustness, important reaction metrics of the analysis record, such as story displacement, inter-story drift, and demand–capacity ratio (DCR).

Model Validation

The normal frequencies and method shapes of the baseline prototype were calculated and compared with theoretical values derived via simplified dynamic analysis (such as Rayleigh's strategy) to ensure model reliability. In addition, the displacements from manual IS 456 estimates were checked against the maximum deflections caused by the system's live and dead loads. To ensure complete consistency in the displacement and drift trends, the model's reaction was further verified against related research in the literature. To ensure the correct representation of the physical piece, any problems were solved by changing the values of the hinges or fine-tuning the mesh Table 1.

Scenarios Analyszed

The following models are analysed

1. *Model I:* Conventional Building (intact structure). In this scenario, a conventional building was studied, and all scenarios were compared with this case.
2. *Model II:* End-column removal (corner column). The end column from the first floor was removed, and all the results were studied.
3. *Model III:* Edge Column Removal (perimeter column, noncorner). The edge column of the first floor was removed and the results were compared.
4. *Model IV:* Two-column (zigzag) removal (diagonally opposite columns). One edge column from the first floor and one from the second floor were removed.
5. *Model V:* Center column removal (interior column). The center column of the building was removed and the results were calculated.

Table 1. Description of building data.

S.N.	Building Data	Parameters	
1	Type of Building	Residential Building	
2	Plan Dimension	30 m x 30 m	
3	Number of stories	G+12	
4	Height of building	42 m	
5	Floor height	3.5 m	
6	Number of bays in X-direction	5 No. @6m c/c	
7	Number of bays in Y-direction	5 No. @6m c/c	
8	The building frame system	Without Shear Wall	
9	Support condition	Fixed	
10	Grade of concrete	M30	
11	Grade of steel	HYSD reinforcement of Fe 500	
12	Column size	Typical Floor	Rectangular Columns
	a)	0 to 12	800 mm x 900 mm
13	Beam size	450 mm x 600 mm	
14	Method of analysis	Non-linear static	
15	Thickness of Slab	150 mm	
16	Thickness of Wall	230 mm	
17	Column removal Scenario	[1] End column removal [2] Edge column removal [3] Centre column removal [4] Two column removal	
18	Density of concrete	25 kN/m3	
19	Density of brick	20 kN/m3	

Structural elements are illustrated in both the plan and 3D views using ETABS V21, as depicted in Figures 3–8.

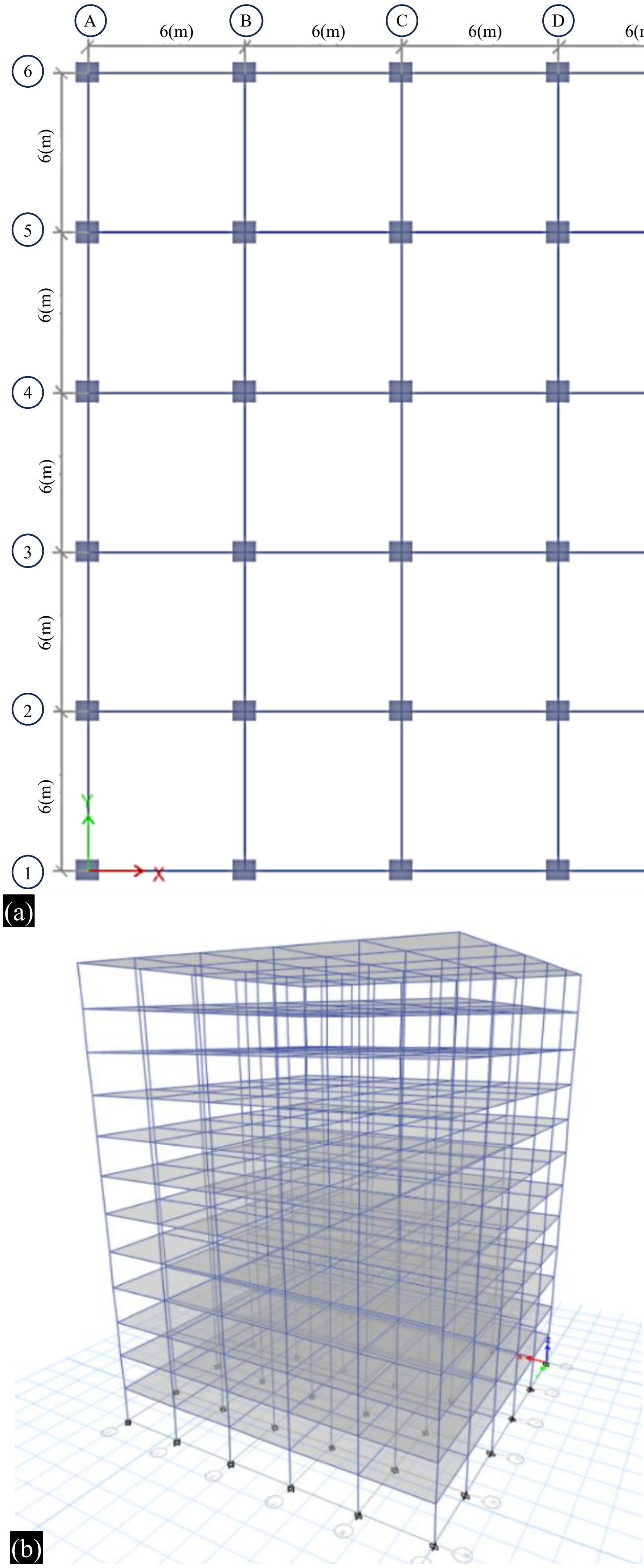

Figure 3. *Model I:* Conventional building.

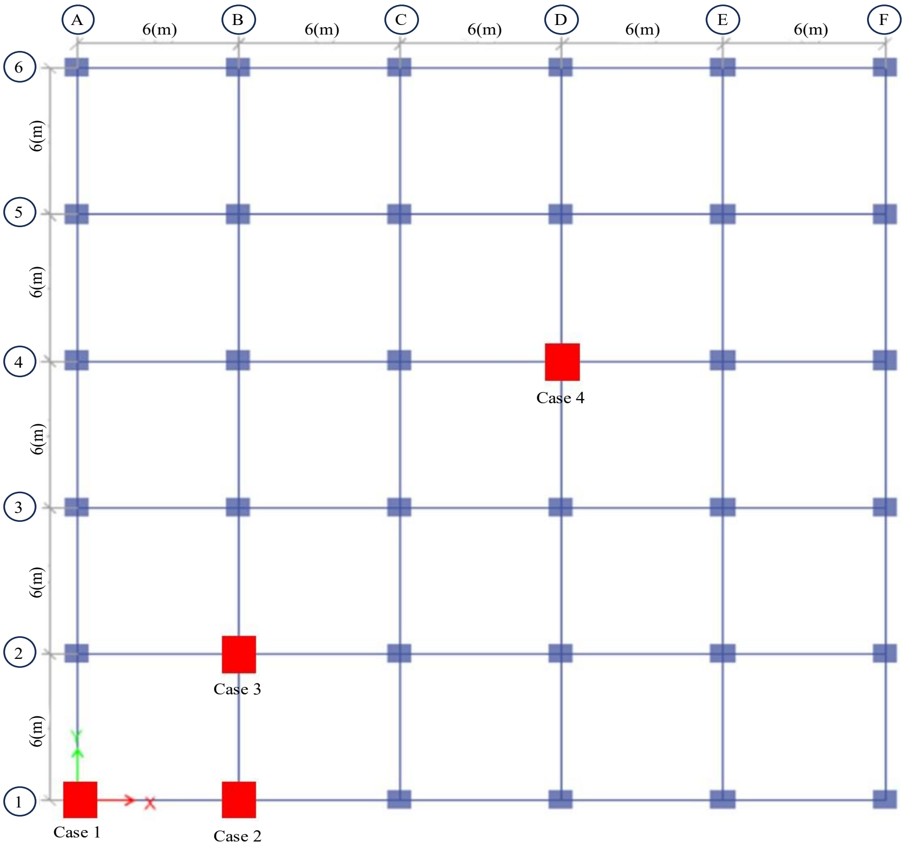

Figure 4. Column removal cases.

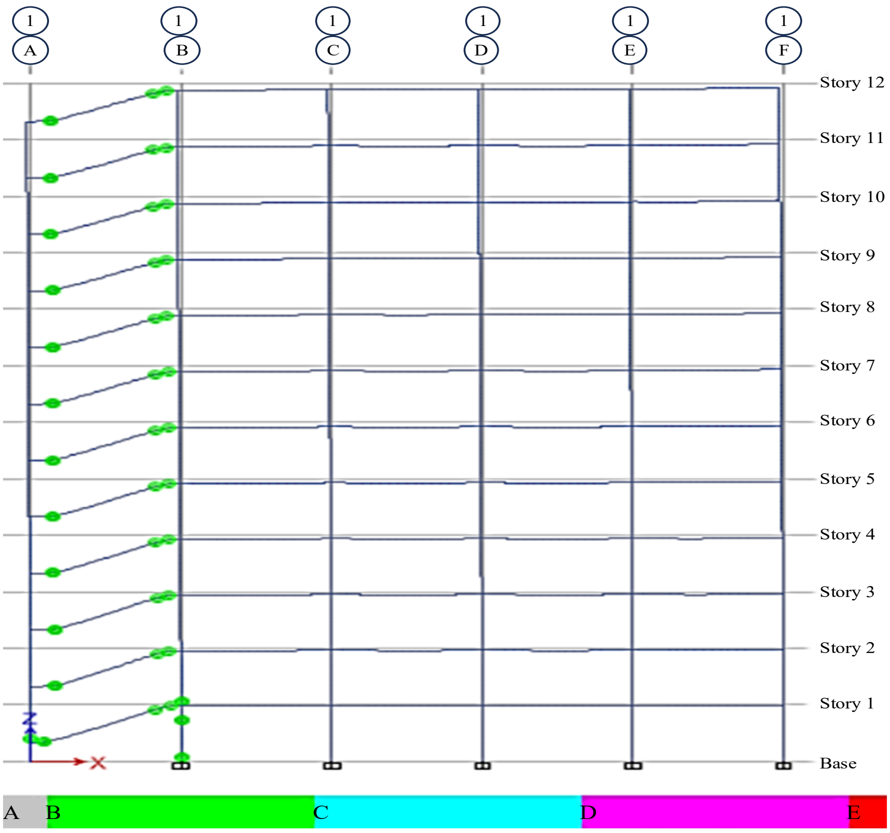

Figure 5. *Model II:* End column removal.

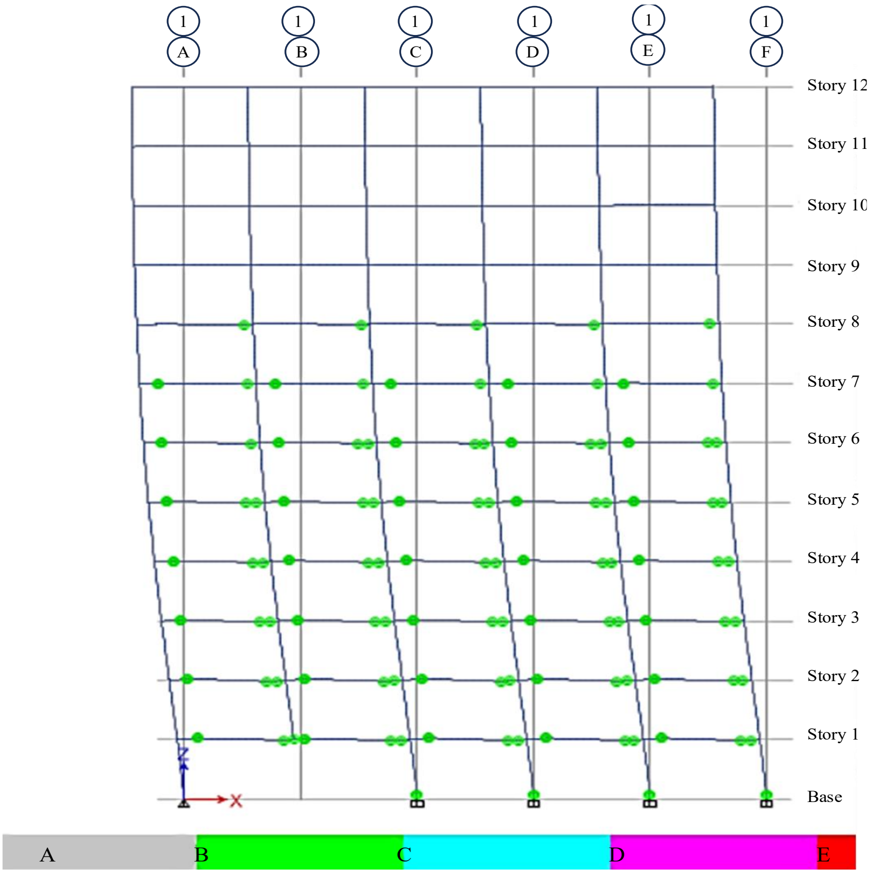

Figure 6. *Model III:* Edge column removal.

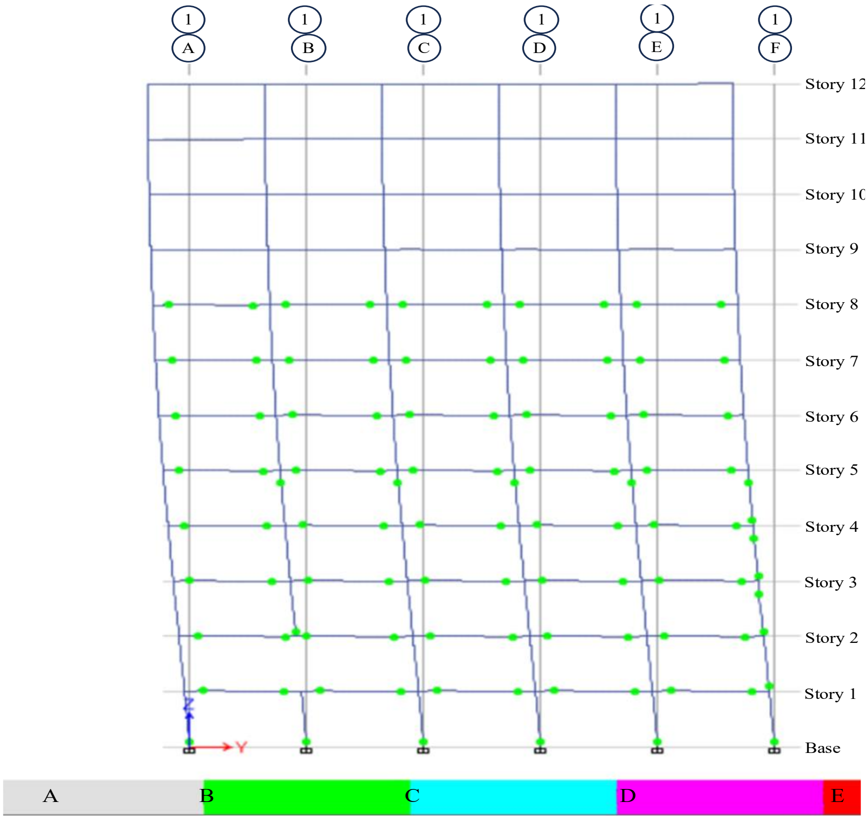

Figure 7. *Model IV:* Two column removal.

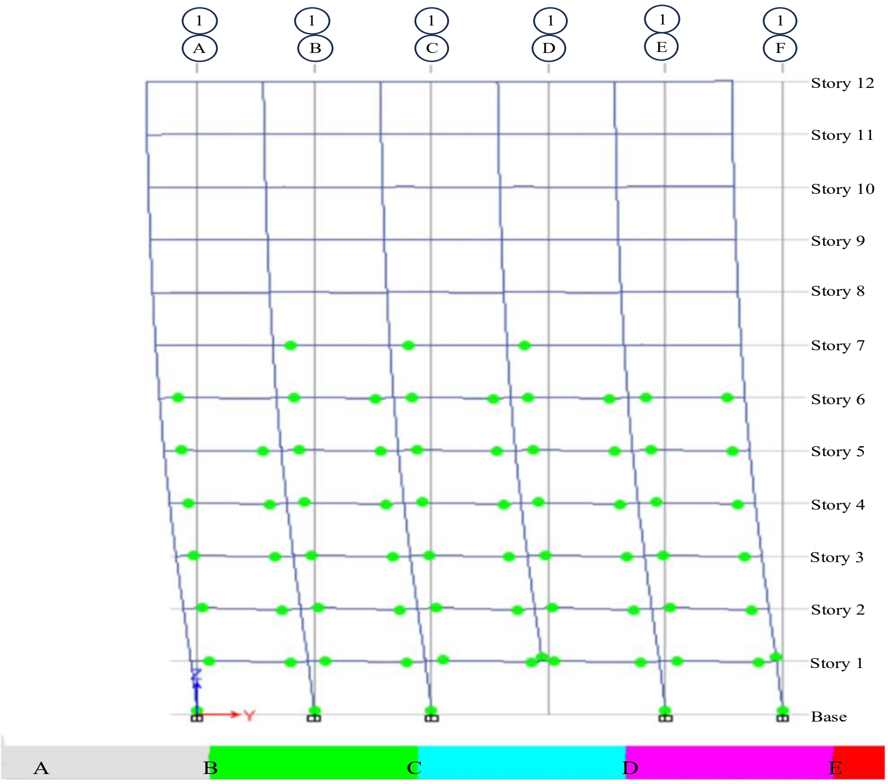

Figure 8. *Model V:* Centre column removal.

RESULT AND DISCUSSIONS

Significant results regarding story drift, lateral displacement, DCR, and robustness ratio demonstrate that gradual collapse influences seismic behavior.

Story Displacement

To ensure structural safety and serviceability, particularly under seismic and accidental strains, the Indian Standard (IS) guidelines define the allowed displacements in buildings. Table 2 shows the displacement in the column removal scenario, and Figure 9 represents the graph, which is a brief synopsis that pertains to a 12-story, 42-meter-tall building in the context of progressive collapse analysis.

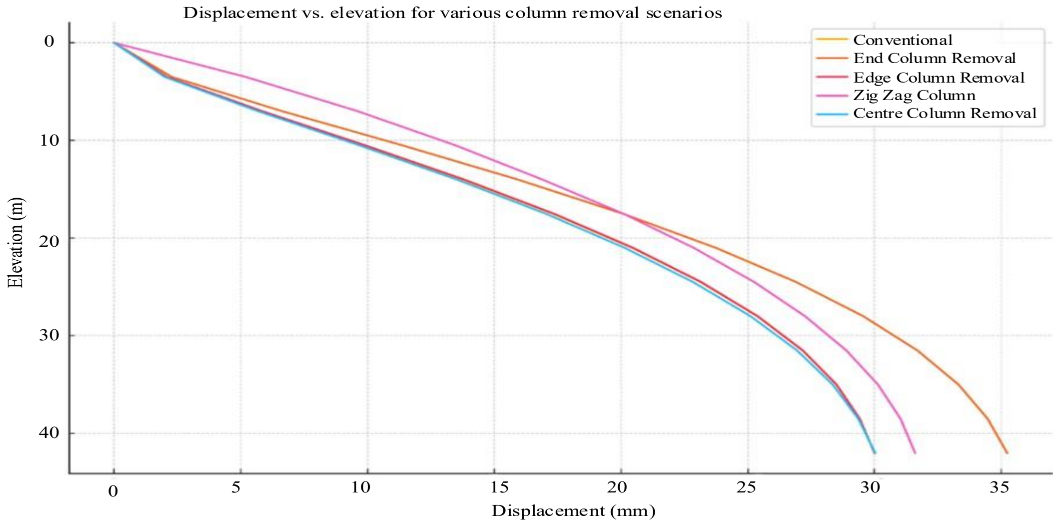

Figure 9. Displacement in column removal scenario (graph).

Table 2. Displacement in column removal scenario.

	Displacement in column removal scenario						
S.N.	*Story*	*Elevation*	*Conventional*	*End column*	*Edge column*	*Zig- zagcolumn*	*Center*
		m					
1	Story12	42	30	35.231	30	31.6	30.028
2	Story11	38.5	29.414	34.462	29.417	31.025	29.356
3	Story10	35	28.493	33.313	28.501	30.136	28.35
4	Story9	31.5	27.155	31.689	27.168	28.886	26.943
5	Story8	28	25.369	29.557	25.391	27.259	25.11
6	Story7	24.5	23.129	26.908	23.16	25.254	22.844
7	Story6	21	20.434	23.742	20.477	22.868	20.147
8	Story5	17.5	17.294	20.07	17.35	20.091	17.029
9	Story4	14	13.736	15.921	13.806	16.893	13.513
10	Story3	10.5	9.828	11.371	9.91	13.468	9.668
11	Story2	7	5.756	6.622	5.841	9.602	5.669
12	Story1	3.5	2.023	2.28	2.084	5.2	1.998
13	Base	0	0	0	0	0	0

Removal of the end column produces the largest displacements, which indicates severe instability. The lower stories are greatly impacted by zig-zag removal, although the edge and center scenarios differ from the typical case only slightly.

Story Drift

For the earthquake and collapse performance, the story drift of the relative displacement between successive floors is important. According to IS requirements, the permissible drift was 0.004 (0.4%).

Table 3. Drift in column removal scenario.

	Drift values						
S.N.	*Story*	*Elevation*	*Conventional*	*Edge*	*End*	*Two*	*Centere*
		m	*Column*	*Column*	*Column*	*Column*	*Column*
1	Story12	42	0.000167	0.000027	0.000221	0.000396	0.000192
2	Story11	38.5	0.000263	0.000028	0.00033	0.000617	0.000287
3	Story10	35	0.000382	0.000029	0.000465	0.000871	0.000402
4	Story9	31.5	0.00051	0.00003	0.00061	0.001135	0.000524
5	Story8	28	0.00064	0.000031	0.000758	0.0014	0.000647
6	Story7	24.5	0.00077	0.000032	0.000905	0.001663	0.000771
7	Story6	21	0.000897	0.000033	0.00105	0.001921	0.000891
8	Story5	17.5	0.001017	0.000035	0.001185	0.002161	0.001004
9	Story4	14	0.001116	0.000036	0.0013	0.00219	0.001099
10	Story3	10.5	0.001164	0.000036	0.001357	0.002184	0.001143
11	Story2	7	0.001067	0.000033	0.001241	0.001834	0.001049
12	Story1	3.5	0.000578	0.000012	0.000651	0.000886	0.000571
13	Base	0	0	0	0	0	0

Table 3 shows drift values and Figure 10 represent the graph for it. In every level, the two-column removal scenario has the highest drift values, indicating the most serious structural instability. Elevated drifts are another outcome from removing the end columns, especially in the centre to higher stories. The edge column illustration, which is closest to the conventional situation, has the least amount of drift. Moderate drift increases after the removal of the centre column indicate localized impact but not severe instability.

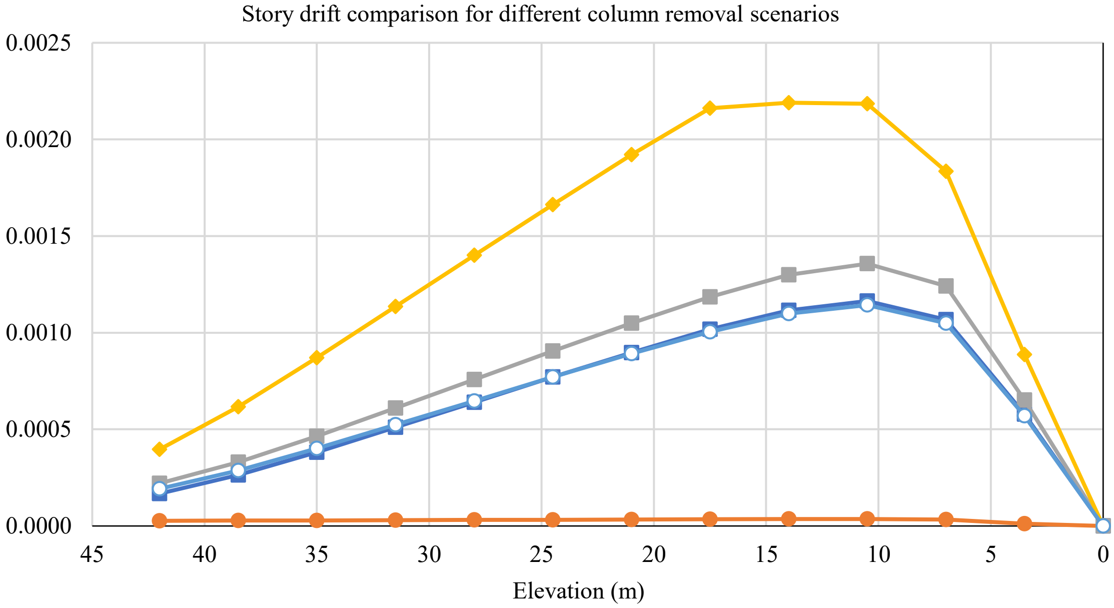

Figure 10. Drift values in column removal scenario (graphical prasentation).

Significant instability is indicated by the largest drift generated by two-column removal. The elimination of the end columns additionally boosts the drift in the middle to higher stories. While the center removal exhibits modest increases, the edge column removal matches the conventional scenario.

Robustness Index for Displacement and Drift

A quantitative metric called the Robustness Index is used to assess the resistance of a structure to local damage (such as the removal of a column) without experiencing disproportionate or gradual collapse. In this thesis, we analyze the impact of several column removal situations (such as end, edge, center, and two-column removal). The robustness index facilitates the comparison of the resilience of each scenario. Figure 11 and Table 4 show the displacement robustness indices for different scenarios of the column removal cases.

Table 4. Displacement robustness index.

S.N.	Scenario	Max displacement (mm)	Robustness index
1	Edge Column	30	0.643
2	End Column	35.231	0.581
3	Zig-Zag Column	31.6	0.624
4	Centre	30.028	0.643

Drift Robustness Index

The capability of a building to sustain local impairment (such as the removal of a column) without undergoing disproportionate or gradual collapse is statistically determined by the Robustness Index. As we examine the impact of several column removal scenarios (such as end, edge, center, and two-column removal) in the framework of this thesis, the robustness index allows us to compare the resilience of each scenario. Figure 12 and Table 5 show the displacement robustness indices for different scenarios of the column removal cases.

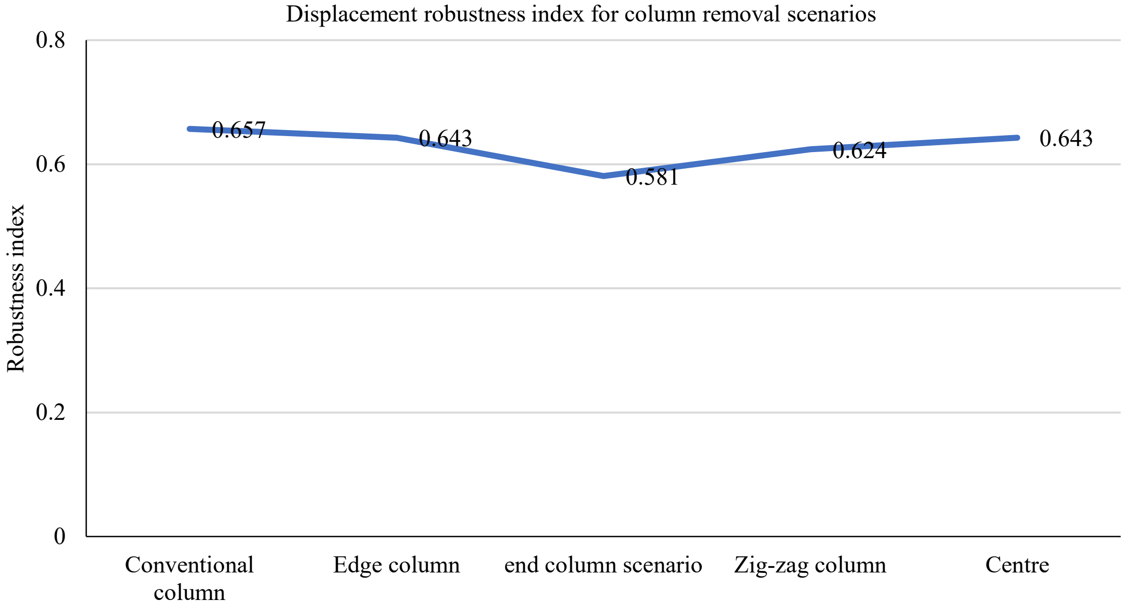

Figure 11. Displacement robustness index (graphical prasentation).

Table 5. Drift robustness index.

S.N.	Scenario	Max drift	Story of max drift	Robustness index
1	Conventional Column	0.000382	Story10	0.981
2	Edge Column	0.000036	Story 3/Story 4	0.998
3	End Column	0.001357	Story3	0.932
4	Two Column	0.002165	Story5	0.892
5	Centre	0.001143	Story3	0.943

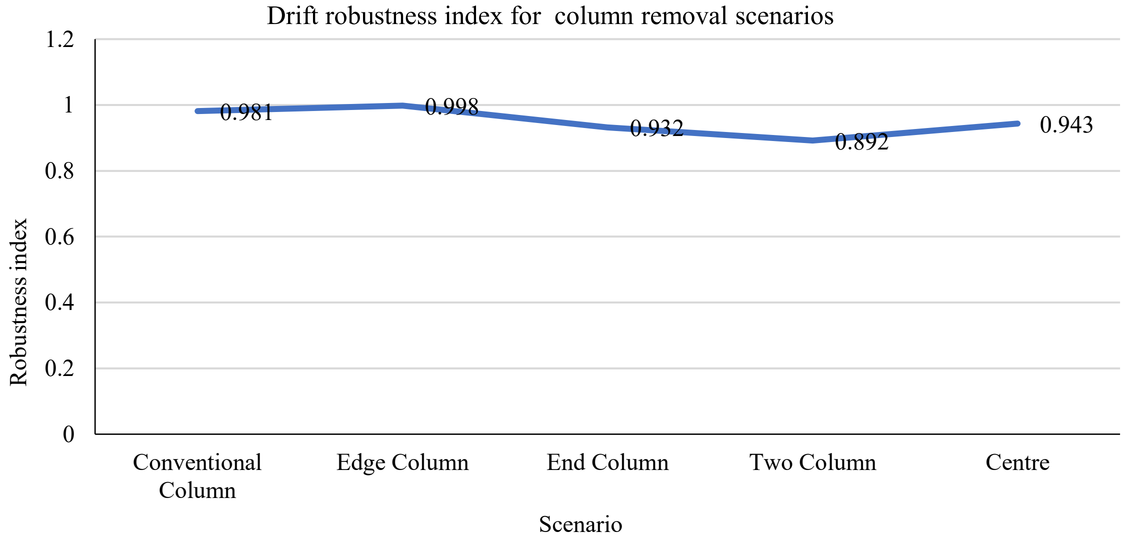

Figure 12. Drift robustness index (graphical prasentation).

Demand Capacity Ratio

In structural engineering, the demand–capacity ratio (DCR) is a frequently employed statistic for evaluating the safety and performance of construction components under practical loads. This was designated as such in this study. Figure 13 and Table 6 show the demand capacity ratios for different column removal scenarios.

Demand is a term used to describe how applied loads, such as moment, shear, or axial force, affect a member of the structure. Based on the material strength and cross-sectional features, capacity shows the most resistance an element may offer without breaking.

Table 6. Demand capacity ratio.

S.N.	Scenario	Demand (scaled moment, (Nm))	Capacity (kNm)	DCR	Status (per GSA/IS 456)
1	Conventional Column	26.57	448.27	0.059	Safe (DCR ≤ 1.0)
2	Edge Column	281.29	448.27	0.627	Safe (DCR ≤ 1.0)
3	End Column	325.45	448.27	0.726	Safe (DCR ≤ 1.0)
4	Zig-Zag Column	299.63	448.27	0.668	Safe (DCR ≤ 1.0)
5	Two Column	179.94	448.27	0.401	Safe (DCR ≤ 1.0)
6	Centre Column	276.1	448.27	0.616	Safe (DCR ≤ 1.0)

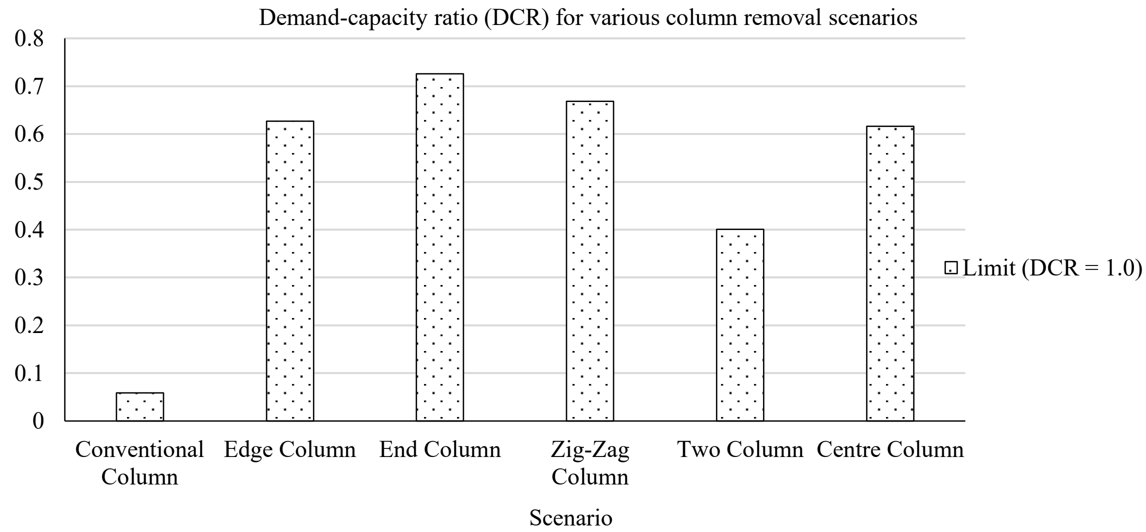

Figure 13. Demand capacity ratio (graphical prasentation).

CONCLUSION

1. Using nonlinear static pushover analysis, this study evaluated the robustness of a high-rise RC frame under edge, end, center, zig-zag, and two-column removal scenarios.
2. The most vulnerable method was two-column removal, which showed the highest displacement and drift.
3. The loss of the end column also greatly enhanced the instability, especially close to the corners, with little redundancy.
4. Zig-Zag topologies improved the lateral stiffness, while the Edge and Zig-Zag scenarios demonstrated moderate effects.
5. Owing to symmetry, the removal of the center column allowed for balanced load redistribution, preserving the improved performance.
6. Every scenario met the IS 456 and GSA safety standards by achieving DCR values below 1.0.
7. Robustness indices guided design enhancements by highlighting each scenario's relative resilience

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