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Progressive Collapse and Post Impact Damage Assessment in a Regular Beam-Slab Building & Flat-Slab Building on the Intermediate Floor

Chinmay Achpal [a*], R. S. Shekhawat [a] and Trilok Gupta [a]

[a] Department of Civil Engineering, College of Technology and Engineering, MPUAT, Udaipur, Rajasthan, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Progressive collapse, where a localized member failure causes widespread structural collapse, has become a critical concern nowadays, due to its potential to cause significant financial losses and loss of human life. Triggers include natural disasters like earthquakes and floods, as well as accidents, attacks and explosions. Reinforced concrete flat slab structures, which are eminent for their architectural flexibility and have larger spans, are particularly susceptible to disproportionate collapse, due to the lack of floor beams, which can redistribute loads after a column failure, unlike moment frame buildings. This research examines how multi-story reinforced concrete flat slab buildings behave, under prescribed gravity load combinations, compared to conventional framed

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*Corresponding author: E-mail: chinmayachpal1996@gmail.com;

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buildings. The effects of removing columns at specified locations from an intermediate floor of the multistorey building are also examined. However, this investigation covers both the column removal approaches to check a possibility of disproportionate collapse which are; static removal and dynamic instantaneous removal. Furthermore, the research also assesses the efficacy of perimeter beams, in minimising the risk of gradual collapse in flat slab structures, by scrutinising their ability to reduce joint displacement, chord rotation, and demand capacity ratio.

ETABS v18 was used to analyze all the 18 models. The findings revealed that buildings are more prone to progressive collapse when corner columns are removed, as opposed to edge and interior columns, due to higher Demand-Capacity Ratios (DCR) and joint displacement. In comparison to dynamic analysis, the static evaluation exhibited greater DCR values and vertical joint displacement. Furthermore, since they have a more efficient load redistribution mechanism, traditional framed structures performed better than flat slab models. The simulations additionally indicated that, adding edge perimeter beams, substantially lowered the possibility of progressive collapse in flat slab structures. Moreover, the tested flat slab building models, with and without perimeter beams showed no indications of progressive collapse, when specified columns were removed from the intermediate floors, since the DCR values of the crucial columns stayed within the permissible range of 2.0. In conclusion, structures built in compliance with IS 1893:2016 code and designed to withstand seismic loads demonstrate stronger resistance against significant damage, brought about by column failures.

Keywords: Demand capacity ratio; joint displacement; flat slab; edge beams; ETABS v18; conventional framed structure; time-step function.

1. INTRODUCTION

In buildings and other commercial or industrial structures, local failure of a structural member (columns, retaining walls, etc.) can occur due to substandard materials, construction errors, or excessive loading. They can also be caused by malicious or unfortunate incidents such as automobile, ship, or aircraft collisions, explosions caused by gas leaks, terrorist strikes, or missile attacks. Local damage of structural components can be caused by natural environmental factors as well, such as floods, storms, or fire accidents [1]. In structural engineering, progressive collapse is defined as a phenomenon in which the loss of one or more structural members, results in a series of failures, eventually leading to the partial or total collapse of a building structure. This procedure arises as a consequence of a certain structural member's localized failure in isolation. Since this fractured structural component is unable to sustain its intended load, the additional load is transferred to other components in the vicinity. These adjacent components may then experience excessive stresses, which may result in more failures [2]. Therefore, modern structural engineering need to take this phenomenon into account, and the building structures shall be designed accordingly, to reduce the likelihood of gradual collapse by implementing techniques such as redundancy and alternate load routes. There are numerous design guidelines, regulations, and building codes available, such as the General Services Administration (GSA, 2003), the Department of Defence (DoD, 2005) and American Concrete Institute (ACI 318 08), which help engineers in preventing progressive collapse failure across the globe. The DoD and GSA design guidelines provide the most comprehensive and practically enforceable specifications among them, in order in order to avoid progressive collapse [3]. To ensure that structures can endure localised failures and maintain overall stability, these recommendations clearly define approaches, which include redundancy in structural elements, robust connections, and alternative load routes.

The U.S. General Services Administration (GSA) developed the "Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects" in order to make sure that the possibility of progressive collapse is considered, when planning, designing, and building of new and renovated structures is undertaken. These recommendations rely on an indirect design method, called the Alternate Path Method (APM), which simulates the abrupt removal of load-bearing elements (columns), in order to evaluate the effects on the overall structure. The alternate load path technique is given prominence in current U.S. building design standards, which include those issued by the GSA (2003) and the DoD (2005), in order to reduce the risk of progressive collapse. This research explores into the possibility of progressive collapse using the APM.

The APM can avert a significant collapse, despite of a local failure, by offering distinct load paths. The loads are then transferred to a member adjoining the damaged member or component, when a vertical structural member breaks, changing the direction of the loads. If the adjacent members have sufficient strength and ductility, then alternative load paths are established by the structural system [4]. This method determines a building's potential to prevent progressive collapse by removing a load-bearing component and assessing the remaining structure's ability to sustain additional failure. The primary benefit of this approach is that it remains independent of the initial load, implying it may be used for any situation that produce member loss.

The suggested positions for the removal of columns are summarised as follows: 'an exterior column at the outer edges, close to the middle of longer and shorter sides of the building; a column situated in a corner of the building; a column in the interior with respect to the perimeter column lines (for facilities that consist of underground parking or unregulated floor areas of building’s ground floor with public access) [5]. As per the guidelines provided by the GSA (2003), the building's potential collapse areas must be determined using the outcomes of the progressive collapse analysis. This will enable us to predict, the extent and distribution of potential loads on the structural components.

In this study, we’re going to conduct both linear static and dynamic analysis to evaluate the performance of the structure in a possible scenario of disproportionate collapse; in terms of Demand Capacity Ratio (DCR), joint displacements and chord rotation. The speed at which an element gets removed has no influence on a static analysis, but it can have significant effects on how the structure responds in a dynamic analysis. However, as dynamic processes take into account damping forces, inertia, and dynamic amplification factors, their accuracy is significantly greater than that of static analytic procedures. So this study includes an analysis, which takes dynamic factors under consideration, by applying a time step function to simulate an instantaneous removal of a column [4].

2. LITERATURE REVIEW

Park et al. (2013) carried out a study of the collapse of Sampoong Department Store in Seoul, South Korea. In order to ascertain the collapse mechanism, the investigation involved evaluating the collapsed structure, studying the ground conditions, testing the strength of concrete and steel samples, and to identify the collapse mechanism through a structural analysis. The building's structural system was a flat slab without beams. This flat slab structure system was found to be more susceptible to progressive collapse than standard reinforced concrete frame structures due to the inability to redistribute loads after column failure [6].

Qian et al. (2013) carried out an experimental research of drop-panel effects on response of flat slab reinforced concrete building, following the loss of a corner column. In addition, the drop panels significantly mitigated the likelihood of a brittle failure. Subsequently, punching failure in the corner column-slab connection was observed experimentally to be one of the possible failure modes for the flat-plate structures in resisting progressive collapse induced by the loss of a ground corner column. Since integrity reinforcement had been provided at the bottom and top of the slab, the punching failure deteriorated slowly and the testing could go on. Furthermore, it was discovered that the addition of drop panels significantly enhanced the system's overall resistance to progressive collapse, illustrated by a 124.7% increase in its peak-carrying capacity [7].

Russell et al. (2015) used seven 1/3 scale simplified substructures to study the behaviour of in situ reinforced concrete (RC) flat slab structures. Based on the following parameters: support reactions, deflections, strains, and cracking patterns, two types of tests were carried out: static column removal and sudden dynamic column removal. Although flexural cracking was discovered in the sagging areas above adjacent columns, this did not lead to the ultimate failure. Rather, the main cause of failures was punching shear, which typically appeared at corners where columns punched through the slab [8].

Divya et al. (2016**)** In this study, Static progressive collapse study was conducted for each case in accordance with GSA guidelines by eliminating the column and shear wall at critical positions and determining the extent of damage. In order to ascertain the structure's vulnerability to progressive collapse, the results were examined in terms of DCR at the critical locations for each case. The study found that a shear wall in a building structure may avert progressive collapse possibility following the collapse of a vertical load-bearing element, by providing enough stiffness and alternate load routes for gravity loads [9].

Tian et al. (2015) In this study, two 1/3 scale RC flat plate specimens, each with a 2 x 2-bay configuration, underwent quasi-static testing under severe deformation to examine their structural response caused by the removal of an interior column, accounting for realistic live load scenarios. The study identified three methods by which the applied load was resisted: tensile membrane action, flexural action and one-way dowel and catenary action. Unbalanced moments and load transfer which was excessive, significantly increased the risk of punching shear failure in edge columns, as they withstood up to 98% of the concentrated force applied, leading to the development of punching-shear cracks. The redistribution of forces resulting from the elimination of the column and the resulting unbalanced moments, induced additional punching-like cracks around adjacent edge columns. This showed that the loss of an interior column, could result in a gradual progressive collapse [10].

Attia et al. (2017) used the Alternate Path Method (APM) to quantitatively evaluate the resilience of medium-rise reinforced concrete flat slab structures against progressive collapse. Their research concentrated on seven-bay structures that met ACI 318 and UFC standards, measuring six metres in span and thirty-one metres in height. It demonstrated that upper floors in flat slab systems were found to be more vulnerable to failures of vertical supports, that lead to larger deflections and a higher probability of disproportionate collapse. Moreover, it was determined that the key factor leading to partial collapse on upper floors was edge shear wall failure. [11]

Reichmann et al. (2018) studied "Improved Design of Concrete Flat Slab Buildings for Seismic Effectiveness," in which they focused on how effectively the structural system could withstand a seismic event. Their objective was to evaluate the possibility of progressive collapse in a 20-story office building with flat slabs, assuming an unfortunate scenario of explosion, which caused a first-floor column to collapse. Detailed examination of the building revealed that loss of an exterior columns on the first floor would lead to a progressive failure of the slabs throughout the entire height of the structure that might expand to other parts. Therefore, in addition to the central pier, a modification was suggested in the form of adding exterior beams to the lateral force resisting system, which assisted in producing moment frames along the building's perimeter. This upgrade prevented a progressive collapse and proved to greatly enhance the building's response to seismic excitation [12].

Khattab et al. (2019) addressed recommendations for mitigating the risk of progressive collapse in structural systems, composed of flat slabs, with an emphasis on the prevalent failure mechanisms, observed in such constructions. It was deemed necessary to have reinforcement that was both continuous and sufficiently anchored, with slabs extended beyond columns, which utilised bottom reinforcing bars. The addition of edge beams to the outer periphery had been established to be an effective method to improve performance, because it stiffened the floor edges and allowed for two-way membrane action, which was crucial for load distribution; while also preventing punching shear failure. Moreover, an effective method to reduce progressive collapse was to ensure continuity, good lap splicing, and sufficient anchorage of bottom reinforcement across the slab [13].

Garg et al. (2021) conducted the study which assessed the effectiveness of three distinct strengthening techniques in mitigating the risk of progressive collapse in an experimentally validated 4-storey flat slab building simulation model. Each building model's corner, edge and internal columns were removed statically and instantly, and the building's dynamic and static responses were compared for various removal orders. The building under study was evaluated, by utilising the GSA's acceptance criteria for DCR. Also, the vertical displacements at the top of the removed columns and the DCR of the sectional forces of critical adjacent columns were taken into account. The results showed that perimeter beam, shear wall, and a combination of perimeter beam and shear wall improved the progressive collapse resistance of the building under study by reducing DCR of critical columns by up to 67.0% and vertical displacements at the top of the removed column by up to 81.0% depending on the column removal cases [5].

Anandakrishnan et al. (2022) The purpose of this study was to examine how a multistorey flat slab building performed under progressive collapse and how a drop panel affected the building's progressive collapse potential, in accordance with Indian codes, for various column removal locations. ETABS was used to perform the linear static progressive collapse study on an 11-storey flat slab building. Given that the greatest DCR value was achieved in that particular case, the removal of the corner column was the most crucial column removal case in both structures, with and without drop panels. Moreover, the flat slab building with drop had a larger DCR value than the flat slab building, resulting in it being more crucial in progressive collapse scenario. Also adding drop panels to flat slab buildings reduced vertical displacement by 14.6, 14.7, and 13.6% for column removal at corners, middle short sides, and middle long sides, respectively rendering them to be better in serviceability criteria [14].

Pujari et al. (2023) studied the effects of geometrical (horizontal and vertical) irregularities, on the Progressive Collapse Analysis (PCA) of reinforced concrete structures with flat slabs, for a ten-story reinforced concrete skyscraper. Regular flat slabs, flat slabs with an enormous aperture, re-entrant corners, mass irregularities, and vertical geometrical irregularities were the five types of models that were examined. Numerical results demonstrated that the static analysis yielded larger DCR of sectional forces and vertical displacements, at the top of removed columns, than the dynamic analysis. Also the majority of model simulations showed that, the largest values of vertical joint displacement (Δ) occurred, when corner columns were removed. Eventually, they came to the conclusion that structures with adequate continuity, redundancy, and ductility in their detailing and design, could develop alternative load paths, hence reducing the risk of progressive collapse [15].

Raja et al. (2023) In this study, the Demand Capacity Ratio values of two buildings were compared using linear static analysis, in accordance with the standards of IS 1893 (part 1) - 2016 and Probabilistic Seismic Hazard Assessment (PSHA). Using the ETABS programme, the analysis was carried out in accordance with IS:456-2000 and IS:1893 (part 1) - 2016, with the failure of the corner column and the peripheral column being investigated using DCR as an indicative parameter. After analysing the two models, the model built using IS 1893 (part 1) - 2016 was found to have a smaller DCR value, which indicated a greater resistance to progressive collapse and a greater margin of safety. The DCR values for the columns were found to be almost equal determined by PSHA analysis and IS 1893 (part 1) - 2016. Furthermore, the robustness indicator showed an overall rating of 1, suggesting that the structure was able to offer an alternative load path [16].

Cardoni et al. (2024) examined the collapse of Champlain Tower South Condo in Surfside, Florida. This study employed the Applied Element Method (AEM) to investigate the potential causes of its disproportionate collapse. The analysis took into account several scenarios for deterioration and column failures, and it established that deep beam failures at the pool deck level connected to perimeter columns were the cause of the eastern wing collapse. To enhance resistance to progressive collapse, two design modifications were proposed: disconnecting the pool deck beam from the perimeter columns to prevent local collapse spread, and increasing the torsional strength and stiffness of the core to avoid the collapse of the building's eastern portion [17].

3. MODELLING AND ANALYSIS

Using ETABS software, twelve 3-D finite element models of an eight-story structure with flat slab and conventional slab systems were analysed. These models vary in slab construction technique, column removal location (corner, edge, interior), and the strengthening technique used (with and without perimeter beams). To proceed with analysis, these columns were eliminated from the middle storey of the building to emulate column failure at specified locations. All models maintained a consistent layout without plan irregularity. It also meets the DOD's minimum three-story criteria, to check for resistance against progressive collapse. The first storey height of each model is 4 metres, while the heights of the remaining stories are 3 metres. Column removal locations were in accordance with GSA requirements (2016). In addition, the method that is used for column removal is critically important to this investigation. Columns were eliminated both dynamically, by utilising a time step function to imitate instantaneous column removal and statically, by applying linear static analysis.

3.1 Detailed Data of Building

3.1.1 Model specifications of flat slab and regular framed structures with different positions of column removal on middle floor

Eighteen models of building simulations, which consist of eight-storeys and which have a similar plan layout were generated using ETABS software, with three different types of configurations; regular moment framed structure, flat slab structure with drop panels, and structure containing flat slabs with drop panels and perimeter beams.

3.2 Study Parameters to Compare the Performance of Different Structures, in a Progressive Collapse Scenario

3.2.1 Demand Capacity Ratio (DCR)

It is the ratio of the force or moment carried by the member (after column loss) to its ultimate capacity. {DCR = Q_{UD} / Q_{CE}}, where Q_{UD} is acting force from alternate path and Q_{CE} is ultimate un-factored capacity of the member. A very crucial characteristic of DCR is that it helps in identifying progressive collapse resistance of the buildings and offers in-depth analysis and numerical modeling of the force-transfer mechanisms of composite and reinforced concrete structures. Once the DCR values of the structural elements surpass the specified limits, there will be no additional capacity for effective redistribution of loads in structural members and hence they will be considered as failed. Consequently, this will eventually lead to the collapse of the entire structure.

The acceptance value according to the guidelines by GSA 2003 is given as

- DCR < 2 for regular configuration building plans.
- DCR < 1.5 for irregular configuration building plans.

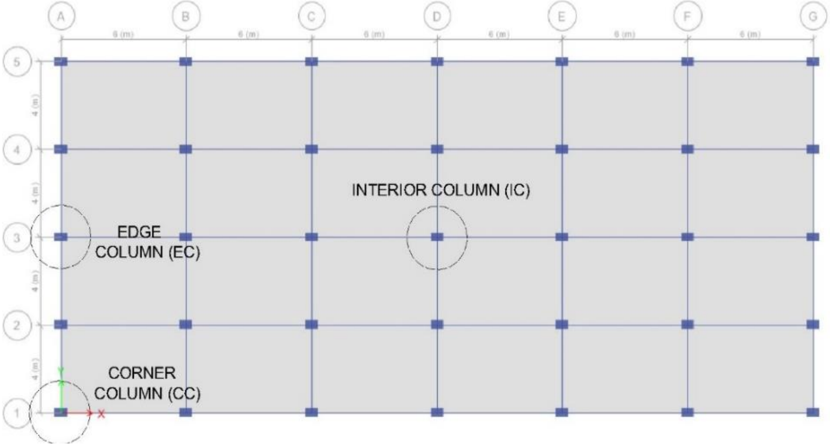


Fig. 1. Plan of the 8-storey building

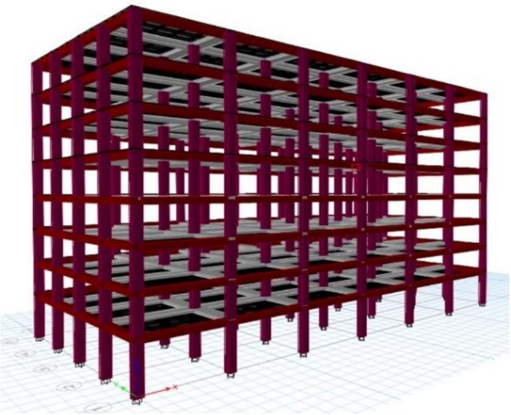


Fig. 2. Three dimensional geometry of the 8-storey Building

Table 1. The properties adopted for the buildings

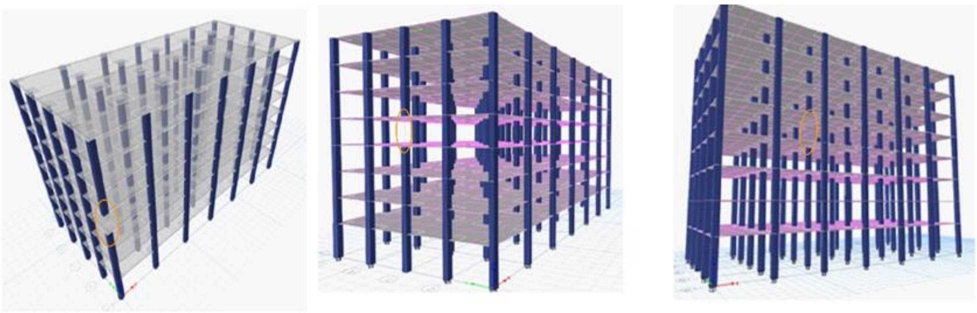
Properties	
Total stories	8 (G+7)
Plan Size	36mX24m
Bottom Storey height	4m
Remaining Storey height	3m
Spacing in X direction	6m
Spacing in Y direction	4m
Seismic zone	Zone III
Soil type	Medium Soil
Concrete grade	M25
Steel grade	Fe500
Young's modulus of M25 concrete, E	2.5x104 MPa
Poisson's ratio of concrete	0.2
Density of concrete	25 KN/m3
Properties of Structural Members (in millimetres)	
Slab thickness for framed structure	150
Flat slab thickness	200
RCC Beam size	400 x 450 mm
RCC Column size	400 x 600 mm
Super imposed Dead Load	
Floor finishes	1.0 KN/m3
9" thick Wall Load	13.15 KN/m3
Live Load	
Terrace	1.5 KN/m3
Floor	3 KN/m3
Response reduction factor	5
Damping ratio	5%(IS 1893:2016)
Importance factor	1.5
Poisson ratio	0.2
Seismic zone factor	0.16
Column reinforcement %	1.83

Table 2. Details of the different Models

S.No.	**Building Type**	**Analytical Methods of Column Removal**	**Position of Column Removal**	**Model Name**
1.	Conventional Framed Structure	Linear Static	Corner column	S1
2.			Edge column	S2
3.			Interior column	S3
4.		Dynamic (Instantaneous removal) using time step function	Corner column	D1
5.			Edge column	D2
6.			Interior column	D3
7.	Flat slab building with drop panel only	Linear Static	Corner column	S4
8.			Edge column	S5
9.			Interior column	S6
10.		Dynamic (Instantaneous removal) using time step function	Corner column	D4
11.			Edge column	D5
12.			Interior column	D6
13.	Flat slab building with drop panel and perimeter beam both	Linear Static	Corner column	S7
14.			Edge column	S8
15.			Interior column	S9
16.		Dynamic (Instantaneous removal) using time step function	Corner column	D7
17.			Edge column	D8
18.			Interior column	D9

S1 S2 S3

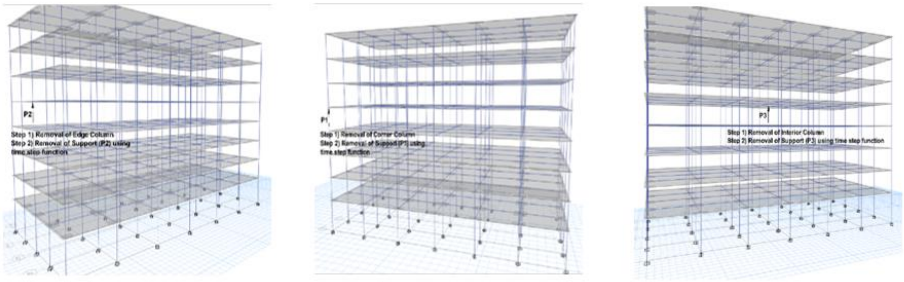
Fig. 3. Details of the model with static column removal for regular framed building



S7 S8 S9

Fig. 4. Details of the model with static column removal for flat slab with drop panel building

Fig. 5. Details of the model with static column removal for flat slab with drop panel and edge beams building



D1 D2 D3

Fig. 6. Details of the Model with dynamic column removal for Flat Slab with drop panel and edge Beams (FSDP-PB) building

Table 3. Notations for the different types of building structures considered

Building Notation	Type of Building Structure
CFS	Conventional framed structure with beams and slab
FSDP	Flat slab building with drop panel only
FSDP-PB	Flat slab building with drop panel and outer perimeter beams

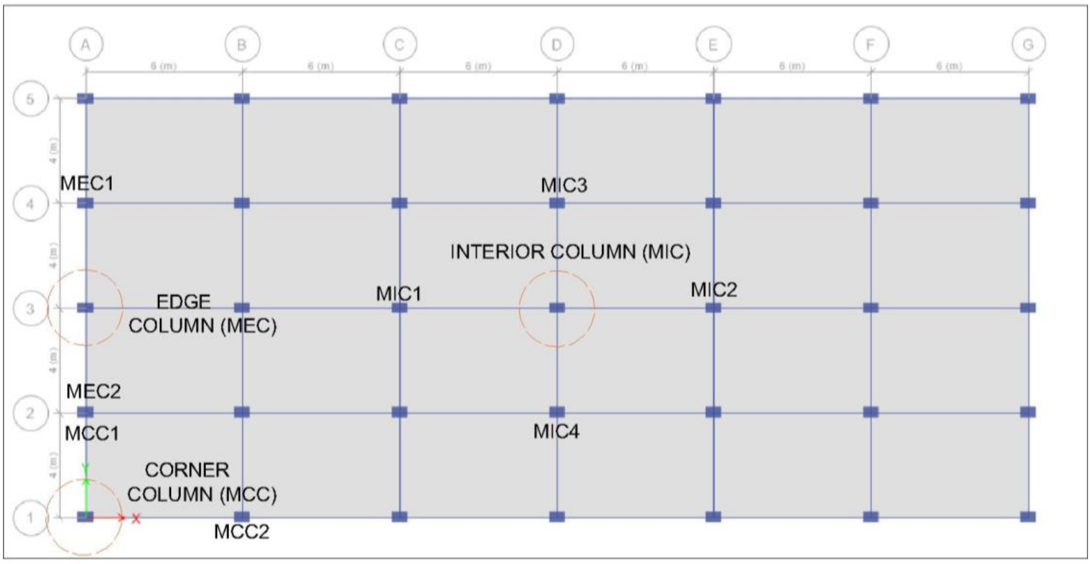


Fig. 7. Location of column removal and the corresponding critical columns for measuring of D/C ratio for intermediate (middle) floor columns

3.2.2 Joint Displacement

The degree to which a structure is susceptible to progressive collapse can be determined by its joint displacement. In performance-based design, the strength and stiffness of the structure is preserved by keeping joint displacement within a suitable range. When a vertical member is lost due to natural or man-made hazards, controlling joint displacement is essential. The following study will compare joint displacements at three column removal locations, across different structures to evaluate their performance, in potential progressive collapse scenarios.

3.2.3 Chord Rotation

The vertical joint displacement at the removed column position is a crucial parameter that is determined in order to understand the progressive collapse behaviour of a flat slab building. This parameter is determined for a linear static progressive collapse analysis, for each instance of column removal. However, another important parameter which is used to evaluate the performance of a structure in a progressive collapse scenario is called chord rotation and the ratio of the vertical joint displacement and the length of the vertical member (which is taken to be 4000 mm in this study) is defined as the chord rotation (in radians) at each column removal site. The DoD (Department of Defence, USA) guidelines' mandated plastic rotation angle of 0.05 rad at the appropriate joint for flat slab structures is then compared to the chord rotation values obtained in this study to ascertain whether there is a possibility of progressive collapse.

4. RESULTS AND DISCUSSION

4.1 Demand Capacity Ratio (DCR)

4.1.1 DCR for critical column MCC1 and MCC2, on removal of corner column MCC

Subsection 4.1.1 discusses results obtained by evaluating model simulations (S1, S4, S7, D1, D4 and D7). All of these are models which elaborate removal of corner column across the three distinct building structures, analyzing both static and dynamic elimination of columns. For critical column MCC1, the study examined DCR values of sectional forces (axial and biaxial moment), for both static and dynamic column removal scenarios. The results indicate that in all three models, framed and flat slab buildings with and without perimeter beams; the DCR values remained below the safety threshold of 2.0. This suggests that even with static or dynamic removal of MCC, the critical columns are stable and not at risk of gradual collapse. Moreover, Static analysis showed higher DCR values compared to dynamic analysis and upon instantaneous (dynamic) removal of the corner column (MCC), the DCR of the sectional forces of the critical column CC2 experiences an average reduction of 14 to 16 % in comparison to the static removal scenario.

Figs 8 and 9, the maximum DCR values for the critical column MCC1 during static analysis are 0.488 (Axial) and 1.315 (Moment) for FSDP and FSDP-PB models. For dynamic analysis, the maximum DCR values are 0.415 (Axial) and 1.196 (Moment). The lowest DCR values for the critical column MCC1 are observed in the CFS building, with 0.43 (Axial) and 0.927 (Moment) for static analysis, and 0.379 (Axial) and 0.806 (Moment) for dynamic analysis. These values are all below the critical threshold, indicating a lower vulnerability to progressive collapse. The conventional beam slab structural system is identified as the safest option, even for middle floor column removal scenarios.

The DCR values for the axial force of critical columns have generally increased in corner and edge column removal scenarios due to the added dead weights from the perimeter beams, as illustrated in Figs. 8 and 9. This has caused an average increase in DCR values for axial force by 4.0 to 6.0% when corner columns (CC), edge columns (EC), and interior columns (IC) are sequentially removed. Additionally, there is a slight decrease in the DCR values of the column moments for each column removal scenario.

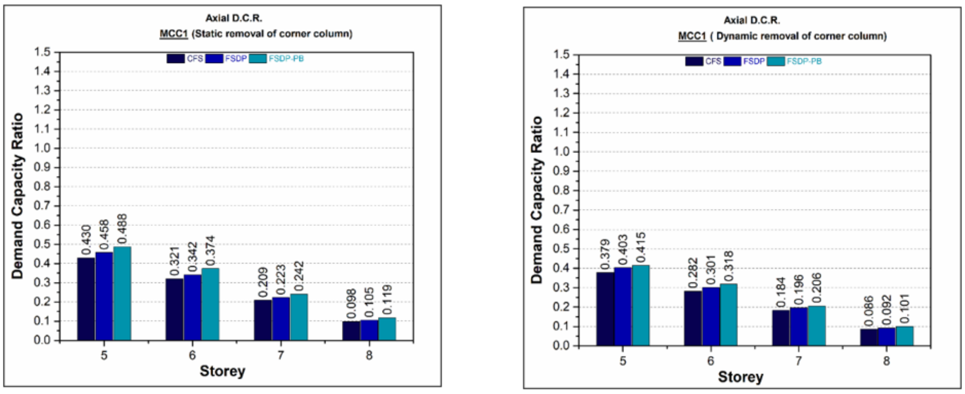


Fig. 8. DCR for axial forces of column MCC1 on the removal of middle floor corner column (a) static removal (b) dynamic removal

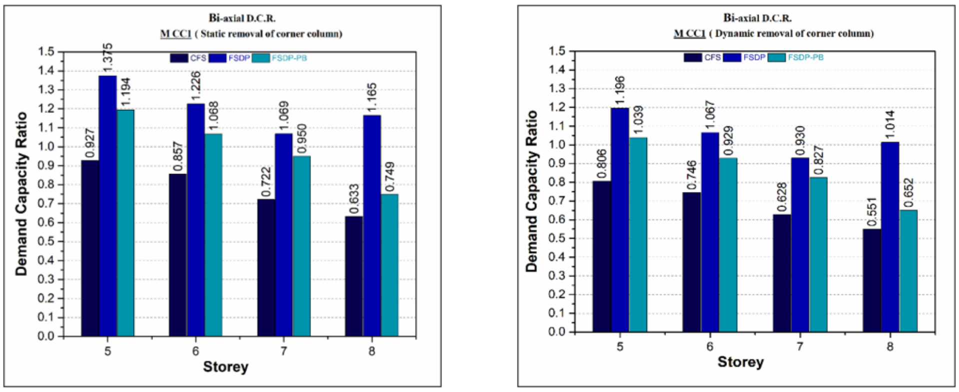


Fig. 9. DCR for biaxial forces of column MCC1 on the removal of middle floor corner column(a) static removal (b) dynamic removal

Figs. 10 and 11 illustrate the DCR values for axial and biaxial moments of the critical corner column MCC2, under static and dynamic removal scenarios. The highest DCR values are observed in the critical column MCC2 during MCC removal in the FSDP and FSDP-PB models, with values of 0.406 (Axial) and 0.766 (Moment) for static analysis, and 0.361 (Axial) and 0.744 (Moment) for dynamic analysis. This indicates that the flat slab model is more vulnerable to progressive collapse. However, the lowest DCR values are found in the critical column MCC2 for building CFS, with 0.35 (Axial) and 0.674 (Moment) for static, and 0.323 (Axial) and 0.566 (Moment) for dynamic analysis. Column MCC2 shows less vulnerability to progressive collapse compared to column MCC1, as it withstands the maximum loads from failed vertical members due to load sharing along a shorter path.

4.1.2 DCR for critical columns MEC1 and MEC2 after removing edge column MEC

Subsection 4.1.2 summarises the outcomes obtained by analysing model simulations (S2, S5, S8, D2, D5, and D8). All of these models elaborate on the removal of edge columns across three different building structures, studying both static and dynamic column elimination.

Figs. 12 & 13, the DCR values of the sectional forces (axial and biaxial moment) for the critical column MEC1 (edge column) for each of the models under examination that were subjected to the static and dynamic removal of the edge column MEC are depicted. The maximum value of DCR is observed as 0.458 (Axial) for FSDP-PB and 1.121 (Moment) for FSDP in the critical column MEC1 in case of EC (edge) removal in static analysis and 0.435 (Axial) for FSDP-PB and 1.07 (Moment) for FSDP for dynamic analysis in the critical column. This again demonstrates that flat slab buildings without edge beams are more vulnerable to progressive collapse (biaxial moment) in comparison to the flat slab structures with perimeter beams since the perimeter beams efficiently bridge the widened span generated by column removal.

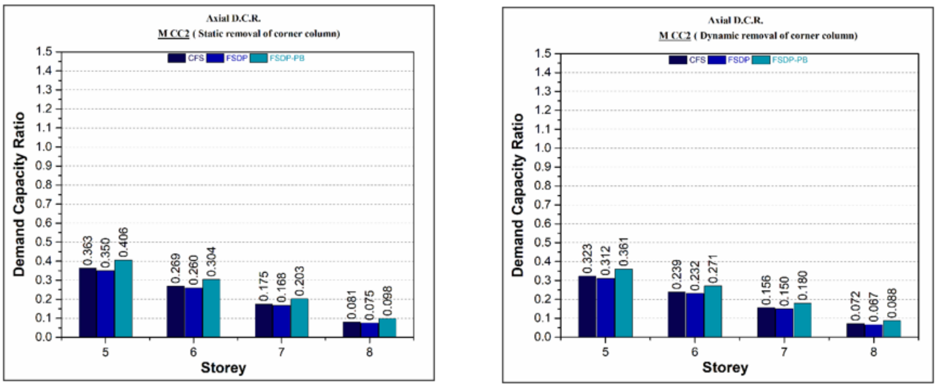


Fig. 10. DCR for axial forces of column MCC2 on the removal of middle floor corner column (a) static removal (b) dynamic removal

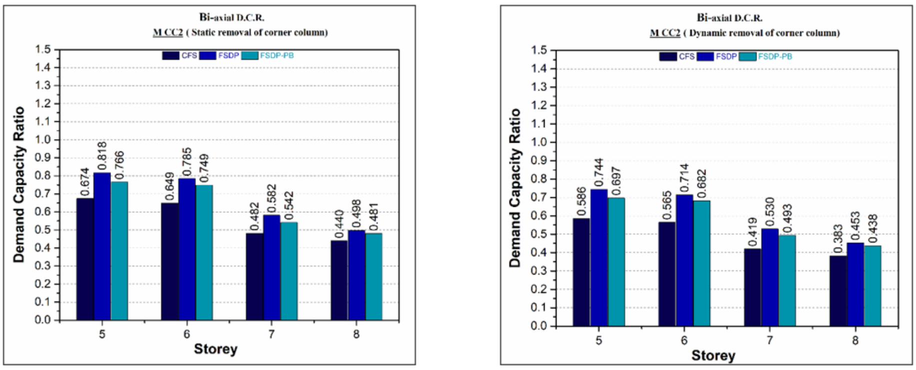


Fig. 11. DCR for axial forces of column MCC2 on the removal of middle floor corner column (a) static removal (b) dynamic removal

However, the least DCR values are observed for the critical column MEC1 for building CFS, noted as 0.395 (Axial) and 0.89 (Moment) for static and 0.375 (Axial) and 0.828 (Moment) for dynamic analysis.

Moreover, DCR values for edge column removal are less than the corner column failure owing to the fact that edge column can redistribute additional loads to three columns in its vicinity but the corner column has only two adjacent columns.

The DCR values for the axial and biaxial moments of the critical column MEC2, following the static and dynamic removal of an edge column on the middle storey (MEC), are displayed in Figs. 14 and 15 Compared to static removal, dynamic removal reduces the DCR for the biaxial moment by an average of 6.0% to 10.0%.

The highest DCR values in static analysis are 0.497 (Axial) for FSDP-PB and 0.942 (Moment) for FSDP. In dynamic analysis, they are 0.477 (Axial) for FSDP-PB and 0.857 (Moment) for FSDP, indicating nearly similar performance for FSDP and FSDP-PB. But the lowest DCR values are in regular framed structures, with 0.41 (Axial) and 0.616 (Moment) in static analysis, and 0.394 (Axial) and 0.551 (Moment) in dynamic analysis, indicating the best performance. Moreover, when MEC is removed from all the three building simulations, the critical column MEC3 has the lowest DCR value compared to other cases of corner and interior column removal.

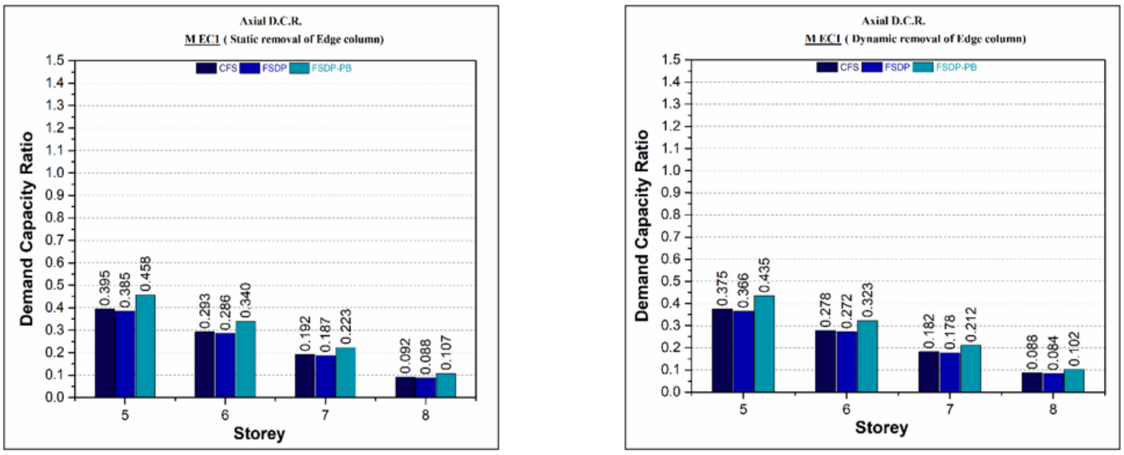


Fig. 12. DCR for axial forces of column MEC1 on the removal of middle floor edge column (a) static removal (b) dynamic removal

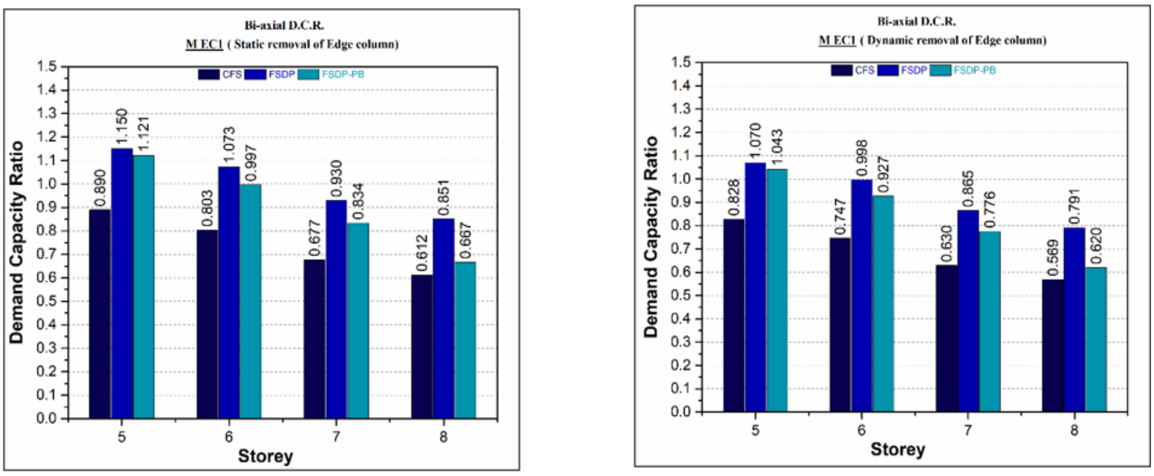


Fig. 13. DCR for biaxial forces of column MEC1 on the removal of middle floor edge column (a) static removal (b) dynamic removal

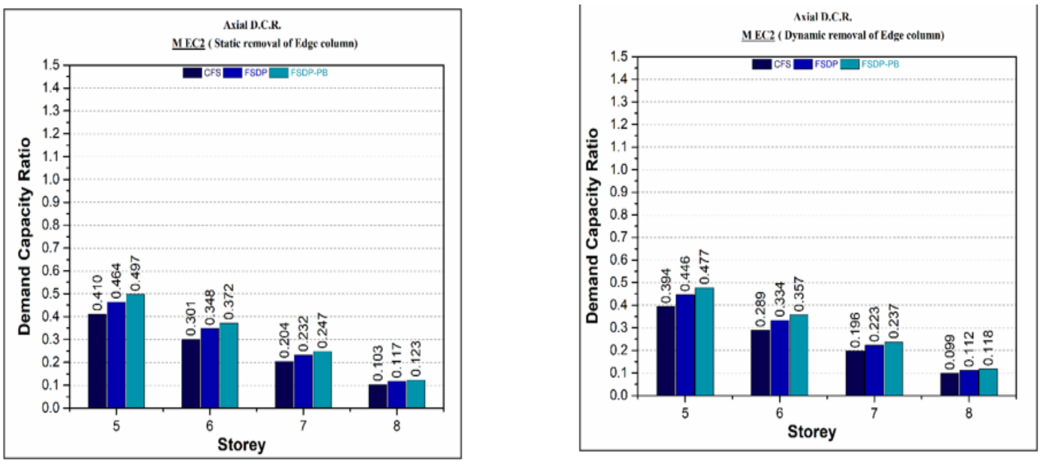


Fig. 14. DCR for axial forces of column MEC2 on the removal of middle floor edge column (a) static removal (b) dynamic removal

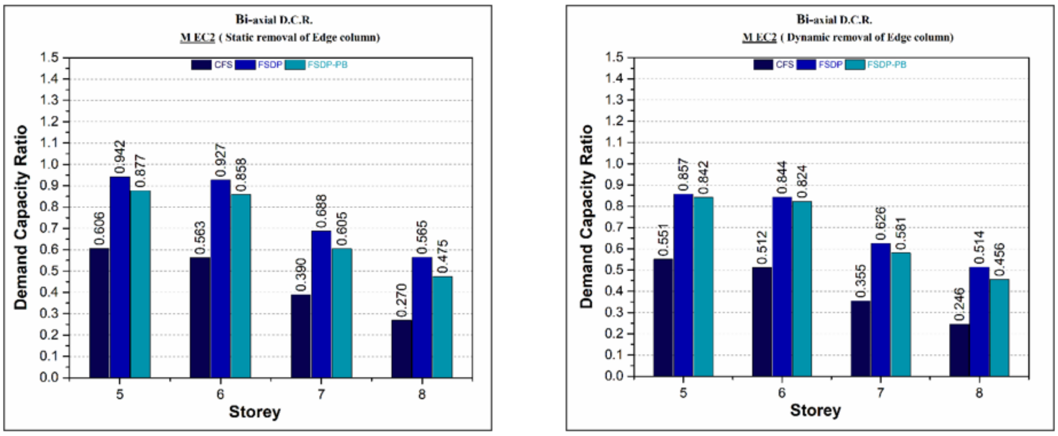


Fig. 15. DCR for biaxial moments of column MEC2 on the removal of middle floor edge column (a) static removal (b) dynamic removal

4.1.3 DCR for critical column MIC1 and MIC3, on removal of interior column MIC

Subsection 4.1.3 summarises the outcomes of analysing model simulations (S3, S6, S9, D3, D6, and D9). All of these models elaborate on the removal of interior columns across three different building structures, studying both static and dynamic column elimination.

The DCR of the sectional forces of the critical column MIC1 experiences an average reduction of 5.0% to 8.0% in comparison to the static removal scenario for biaxial moment upon instantaneous (dynamic) removal of the interior column (MIC). This is because, in contrast to dynamic analysis, the static analysis produced larger DCR values for sectional forces at removed columns. Furthermore, as no building model simulation for either static or dynamic analysis exceeded the DCR threshold of 2.0 mandated by GSA, no column displayed any indications of catastrophic failure, or gradual collapse.

Figs. 16 and 17 depict the DCR values for axial and biaxial moments of the critical column MIC1 on the middle storey after static and dynamic removal of the interior column MIC. In static removal from FSDP, the maximum DCR values are 0.606 (Axial) and 1.151 (Moment). For dynamic removal, they are 0.563 (Axial) and 1.082 (Moment). Both flat slab models show similar DCR values, while the conventional frame structure (CFS) exhibits better resistance to progressive collapse, with the lowest DCR values for MIC1 being 0.547 (Axial) and 0.906 (Moment) in static, and 0.514 (Axial) and 0.852 (Moment) in dynamic analysis. This indicates the conventional beam-slab structure has better progressive collapse resistance compared to flat slab structures. Moreover, on comparing interior and edge columns with corner column removal across different models, shows that removing a corner column makes the RC structure more susceptible to progressive collapse than removing interior, long edge, or short edge columns.

Also, the DCR values of adjacent column MIC1 are less than IC3 since more redistribution of additional loads takes place at the shorter bays, since the shorter bays in all column removal cases are the most affected from progressive collapse.

Figs. 18 & 19, when interior column (MIC) is removed from FSDP in static fashion, the maximum value of DCR is observed as 0.453 (Axial) and 0.838 (Moment) in the critical column MIC2, and 0.398 (Axial) and 0.779 (Moment) in the critical column MIC2 when MIC is removed from FSDP for dynamic analysis.

As noticed in previous case, here too both the flat slab models with and without perimeter show nearly same values of DCR while conventional frames structure displays slightly better resistance to progressive collapse then both the flat slab structures owing to lesser DCR values. So when MIC is removed from the building CFS, the critical column MIC2 has the lowest DCR value, which is 0.421 (Axial) and 0.629 (Biaxial) for static analysis whereas for dynamic(instantaneous) column removal DCR values obtained are 0.371 (Axial) and 0.565 (Biaxial) respectively thus indicating better progressive collapse resistance of a conventional beam-slab structure in contrast to a flat slab structure.

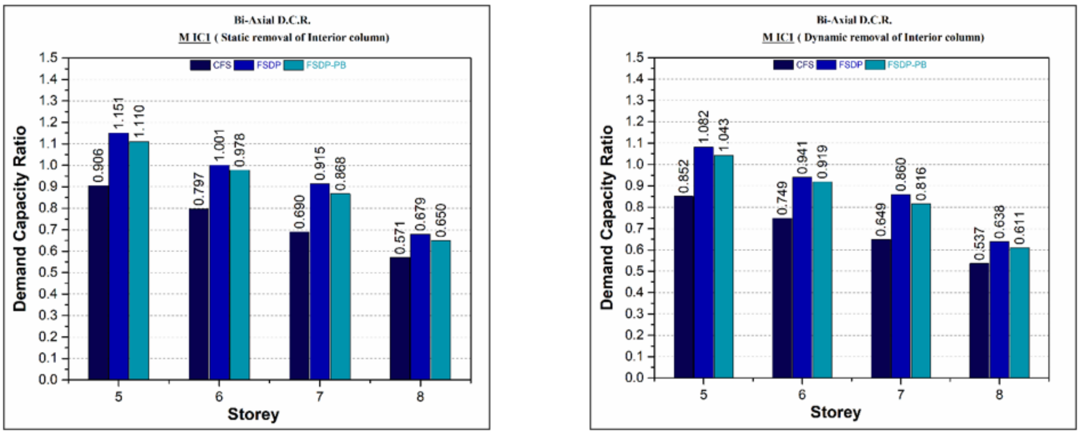


Fig. 16. DCR for axial forces of column MIC1 on the removal of middle floor interior column (a) static removal (b) dynamic removal

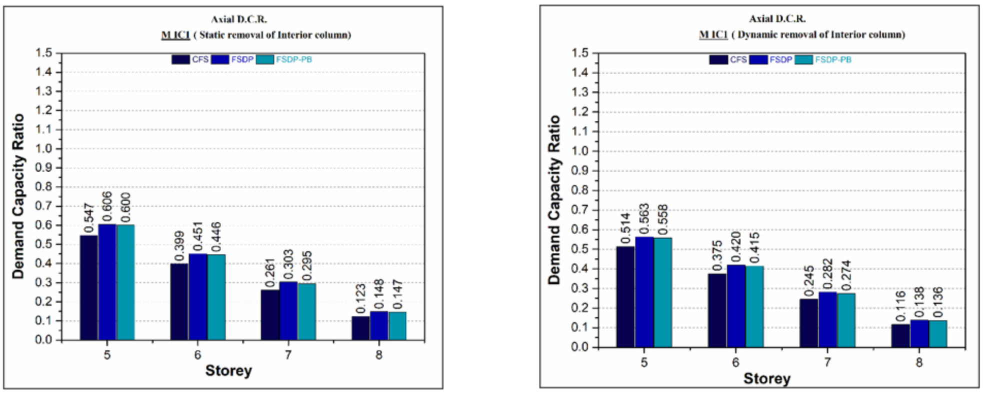


Fig. 17. DCR for biaxial moments of column MIC1 on the removal of middle floor interior column (a) static removal (b) dynamic removal

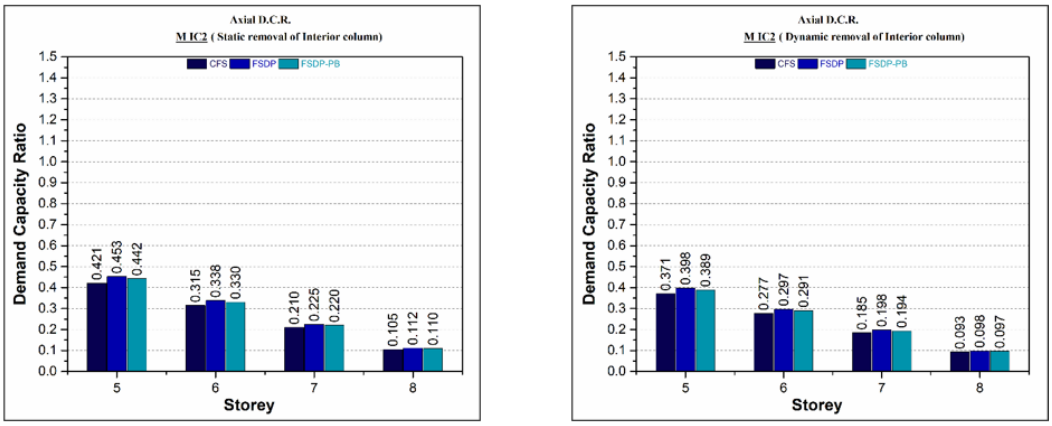


Fig. 18. DCR for axial forces of column MIC3 on the removal of middle floor interior column (a) static removal (b) dynamic removal

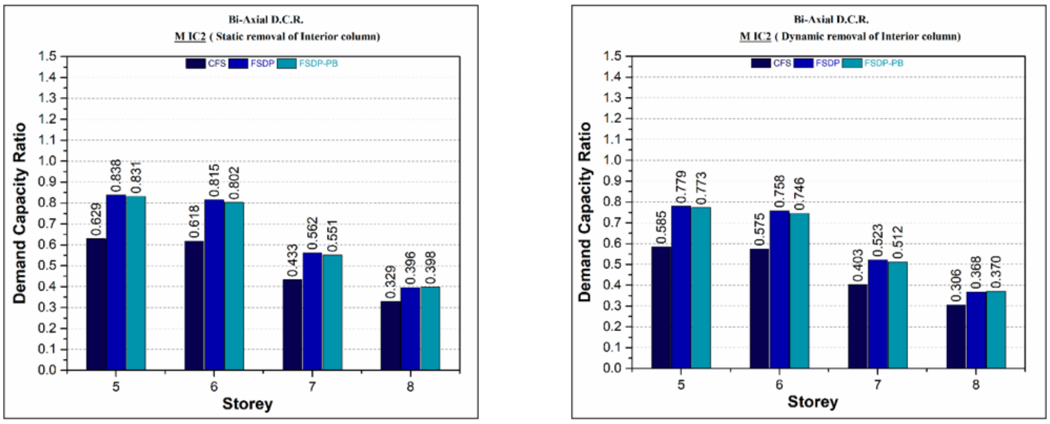


Fig. 19. DCR for biaxial forces of column MIC3 on the removal of middle floor interior column (a) static removal (b) dynamic removal

Also in the case of interior column removal. However, both the flat slab models with and without perimeter beams show nearly same values of DCR which indicates that the addition of outer periphery beams does not enhance a flat slab structure's progressive collapse resistance when an interior column is removed. This is because an interior column is not connected to an external perimeter beams by the means of other slab beams, so no redistribution of additional loads from failed vertical members takes place.

4.2 Joint Displacement

This section presents a dynamic analysis using a time step function to assess joint displacements on intermediate storeys for three building structures: CFS, FSDP, and FSDP-PB. Figs. 20, 21 and 22, display the vertical displacement time history for these models when columns CC, EC, and IC are removed instantly at t = 1.25 s. The time history response, from t = 0.0 s to t = 1.25 s, shows the timeframe for reaching static equilibrium. The columns are eliminated successively at t = 1.25 s in 0.005 s to simulate instantaneous removal.

4.2.1 Joint displacement for corner column removal

Section 4.2.1 presents the results, gathered from analysing model simulations (S1, S4, S7, D1, D4, and D7), that focus on the removal of corner columns, dynamically as well as statically, for all building configurations included in this study.

Fig. 20 depicts the vertical displacement time history for the building models CFS, FSDP, and FSDP-PB when the column MCC (corner column) is immediately removed at t = 1.25 s. Compared to static column removal, instantaneous column removal results on an average 25 to 30 % reduction in absolute maximum vertical displacement (ΔCC). Furthermore, we may conclude that even in dynamic column removal, model FSDP exhibits the greatest amount of displacement due to its susceptibility to progressive collapse caused by column failure, whereas CFS, i.e. beam slab building, is the least affected since due to the presence of floor beams, its redistribution capacity helps it in withstanding additional loads due to failure of vertical members.

In addition, corner column removal case for intermediate storey indicates the maximum amount of joint displacement which is in accordance to research conducted by which concluded that the displacement values are maximum for corner column removal and as we travel up, storeys from the first to the ultimate floor, the resistance against progressive collapse increases as vertical joint displacement, chord rotation at column removal positions decrease.

4.2.2 Joint Displacement for Edge column removal

Sub-section 4.2.2 presents the results found from analysing model simulations (S2, S5, S8, D2, D5, and D8) that elaborate on the removal of edge columns dynamically as well as statically for all building configurations included in the research.

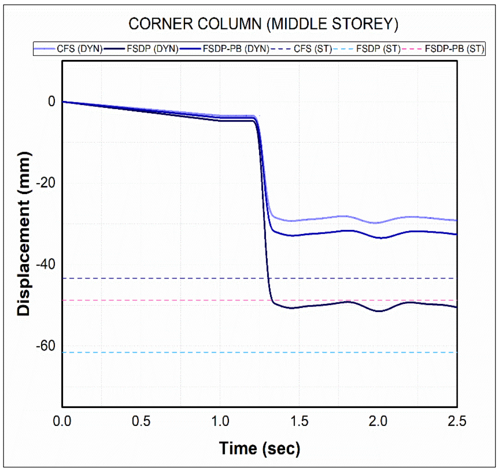


Fig. 20. Time history response of vertical displacement when CC is instantaneously removed at t = 1.25 s for buildings CFS, FSDP, and FSDP-PB along with static displacement response on intermediate storey

Fig. 21 depicts the vertical displacement time history for the building models CFS, FSDP, and FSDP-PB when the column EC is immediately removed at t = 1.25 s. Compared to static column removal, instantaneous column removal results in an average 30% reduction in absolute maximum vertical displacement (ΔCC). Furthermore, we may conclude that even in dynamic column removal, model FSDP exhibits the greatest amount of displacement due to its susceptibility to progressive collapse caused by column failure, whereas CFS, i.e. beam slab building, is the least affected. In addition to that, the displacement of edge column is lesser than the corner column removal case due to availability of more number of adjacent columns to redistribute additional loads occurring due to the failure of a vertical member.

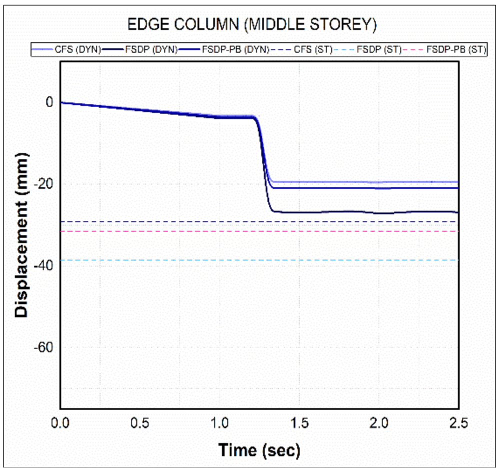


Fig. 21. Time history response of vertical displacement when EC is instantaneously removed at t = 1.25 s for buildings CFS, FSDP, and FSDP-PB along with static displacement response on intermediate storey

4.2.3 Joint Displacement for Interior column removal

Sub-section 4.2.3 presents the results found from analysing model simulations (S3, S6, S9, D3, D6, and D9) which focus on the removal of interior columns dynamically as well as statically for all building configurations included in the research.

Fig. 22 depicts the vertical displacement time history for the building models CFS, FSDP, and FSDP-PB when the column IC is immediately removed at t = 1.25 s. Compared to static column removal, instantaneous column removal results in an average 20 to 25% reduction in absolute maximum vertical displacement. Moreover, we may deduce that, even in the case of dynamic column removal, the model FSDP shows the most displacement because of its vulnerability to progressive collapse brought on by column failure, while the model CFS, or beam slab building, experiences the least amount of displacement.

Also compared to other column removal cases, the displacement values are lowest for the interior column removal scenario.

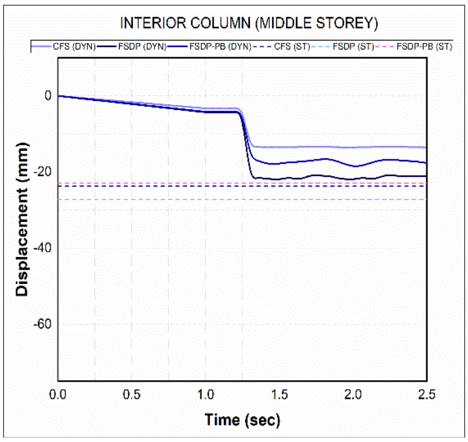


Fig. 22. Time history response of vertical displacement when IC is instantaneously removed at t = 1.25 s for buildings CFS, FSDP, and FSDP-PB along with static displacement response on intermediate storey

4.3 Chord Rotation

4.3.1 Chord rotation for corner column removal at specified locations on Intermediate Floor

The progressive collapse resistance of the three building model simulations under GSA mandated load combinations is investigated for each of the three column removal scenarios (CC, EC, and IC) on intermediate storey. The results of the progressive collapse study, as shown in Figs. 23, 24 and 25, do not indicate the emergence of a progressive collapse of the building because the chord rotation values never exceed the 0.05 threshold. Moreover, the maximum chord rotation is found for model FSDP i.e. flat slab building model without perimeter beams owing to the maximum amount of joint displacement at column removal locations. However, the trend of maximum chord rotation at corner column removal position persists on intermediate storey as well which indicates that removal of corner column is the most susceptible to progressive collapse while the interior column removal on intermediate storey shows the least possibility of a gradual collapse.

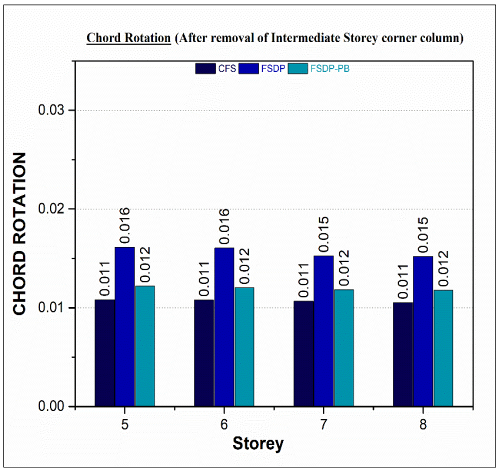


Fig. 23 Chord rotation when corner column is statically removed for buildings CFS, FSDP, and FSDP-PB on intermediate storey

Fig. 23, which is corner column removal case, for all building simulations, it was found that the addition of perimeter beams decreased joint displacement and hence chord rotation by 25.0% which is the most in all three column removal cases. It is due to the fact that, in the event of corner column removal, perimeter beams stiffen both connecting slab beams, but in the event of edge column removal, perimeter beams only stiffen two of the three connecting slab beams.

4.3.2 Chord rotation for edge column removal at specified locations on Intermediate Floor

In Fig. 24, which examines an edge column removal scenario across all building simulations, it was observed that incorporating perimeter beams did not decrease joint displacement and chord rotation significantly. The presence of perimeter beams stiffens the connecting slab beams, which explains this decrease. However, as previously determined, the beam-slab structure exhibits the highest resistance to progressive collapse, evidenced by the lowest chord rotation among the building simulations studied.

4.3.3 Chord rotation for interior column removal at specified locations on Intermediate Floor

In Fig. 25, the removal of an Interior Column shows an insignificant reduction in joint displacement and hence chord rotation with the addition of perimeter beams. There was not much variation in the chord rotation values of the flat slab structure with and without perimeter beams when the Interior column was removed, since the perimeter beams were unable to support any of the four connecting slab beams. Therefore, regardless of the presence of perimeter beams, the flat slab structure's chord rotation values were not considerably impacted because of it.

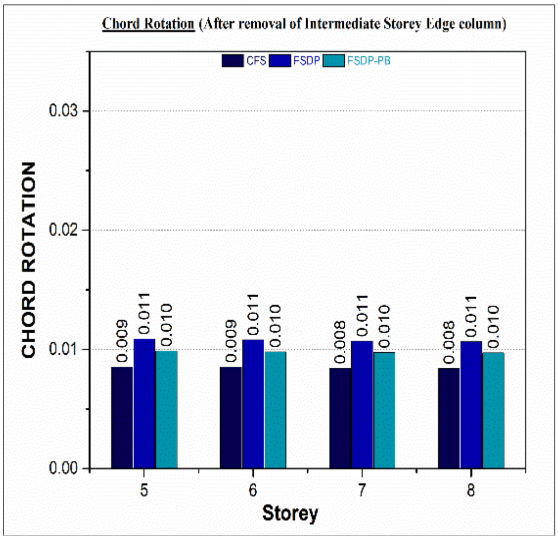


Fig. 24. Chord rotation when Edge column is statically removed for buildings CFS, FSDP, and FSDP-PB on intermediate storey

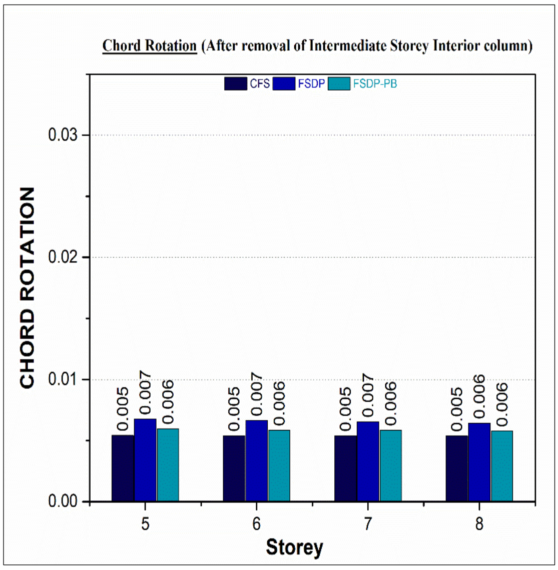


Fig. 25. Chord Rotation when Interior column is statically removed for buildings CFS, FSDP, and FSDP-PB on intermediate storey

5. CONCLUSION

The current research evaluates the potential for progressive collapse in an eight-story flat slab and beam slab building with size (36 m x 16 m), designed for seismic zone III, in compliance with IS 1893-2016 and GSA guidelines (2003). In addition, it analyses chord rotation and joint displacement, at points of column removal, and the DCR at adjoining critical columns, to investigate how different configurations respond to vertical member failure. Moreover, it investigates how effectively perimeter beams when incorporated to various flat slab simulations, might improve progressive collapse resistance in flat slab buildings.

Based on the results obtained, we can draw the following conclusions.

- Removing a corner column in the three building structure models led to the highest DCR values compared to edge and interior column removal. This was because there were fewer adjacent columns available, to redistribute additional loads.
- The analysis shows that statically removing a column, results in higher DCR and joint displacements, compared to dynamic removal, which indicates that static analysis produces conservative results.
- Joint displacements and DCR values regularly decrease, when columns are eliminated from intermediate floors as opposed to ground floors. This indicates a trend of increasing capacity to resist disproportionate collapse, when moving from bottom to top storeys.
- In comparison to a typical framed structure, a flat slab simulation is more prone to progressive collapse, because of increased DCR values, joint displacements, and chord rotation at locations of column removal.
- Perimeter beams significantly control vertical displacements at the top of removed corner and edge columns in an alternate column removal scenario. Also, perimeter beams reduce progressive collapse risk by spanning the increased gap and reinforcing the slab's edges, facilitating load redistribution.

- When interior columns are removed from either storey in a flat slab structure, the addition of perimeter beams does not lead to a significant decrease in joint displacement because the external beams do not offer rigidity to the connecting slab beams near the interior columns.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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