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

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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, known for their architectural flexibility and large spans, are particularly vulnerable to progressive collapse due to the lack of beams that can redistribute loads when a column fails, unlike moment frame buildings. This study compares the progressive collapse behavior of multi-storey reinforced concrete flat slab buildings with regular framed structures under prescribed gravity load combinations by the General Services Administration. The effects of removing typical columns from an intermediate floor of the multistorey both statically and dynamically are also examined. Additionally, the study evaluates perimeter beams as a strengthening technique in flat slab structures to prevent progressive collapse, assessing their effectiveness in reducing demand capacity ratio, joint displacement, and chord rotation.

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. Static analysis showed greater DCR and vertical displacement values compared to dynamic analysis. Additionally, conventional framed structures outperformed flat slab models, benefiting from a more effective load redistribution mechanism. The simulations further demonstrated that incorporating edge perimeter beams significantly reduced the risk of progressive collapse in flat slab structures. Moreover, the analysed flat slab building models, both with and without perimeter beams, showed no signs of progressive collapse during typical column removal on the ground and intermediate storeys, as the critical columns' DCR values stayed within the acceptable range of 2.0. In conclusion, buildings engineered to withstand seismic loads based on the IS 1893:2016 code demonstrate a robust resistance to significant damage from 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 civil engineering structures, initial local failure of a certain structural member (columns, retaining walls etc.) can arise due to the adoption of incorrect materials or system models, construction errors, or excessive loading. They can also be caused by malicious or unfortunate incidents such as automobile, ship, or aero plane collisions, explosions caused by gas leaks, terrorist strikes, or missile impact and explosions. Local damage may also result from natural environmental factors such as floods, storms, or fire accidents [1]. Following the occurrence of an initial local failure, the structure will attempt to attain a state of equilibrium relative to its altered loading and support conditions, resulting in a partial or entire redistribution of loads. If the load and deformation capacity of adjoining structural members and connections are inadequate in this new state, they are going to fail. Progression of that damage up to a point where a state of equilibrium is satisfied is commonly referred to as progressive collapse [2]. The term "progressive" signifies the incremental and often rapid spread of damage, where each failure increases the load on remaining members, potentially leading to further collapses. This phenomenon is a critical consideration in structural engineering, requiring designs that mitigate the risk of progressive collapse through measures such as redundancy and alternate load paths.

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. Among these, the DoD and GSA design guidelines offer the most detailed and extensive specifications that are practically most enforceable, to prevent progressive collapse. [3] These guidelines specifically outline measures such as redundancy in structural elements, robust connection details, and alternative load paths to ensure that structures can withstand localized failures maintaining overall stability.

The U.S. General Services Administration (GSA) developed the "Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects" to ensure that potential progressive collapse risks are addressed in the design, construction, and planning phases of new and renovated structures. These guidelines adopt an indirect design approach known as the Alternate Path Method (APM), which involves simulating the sudden removal of load-bearing components like columns to assess their impact on the entire structure. Current U.S. building design standards, including those by GSA (2003) and DoD (2005), emphasize the use of the alternate load path approach to mitigate the risk of progressive collapse. This study utilizes the APM to investigate the likelihood of progressive collapse

By providing different load pathways, the APM is able to prevent significant collapse despite of occurring of local failure. When a vertical structural member fails, loads are transmitted to a member within proximity of the damaged member or component, causing a change in the load direction. If the adjacent members have sufficient strength and ductility, then alternative load paths are established by the structural system. By eliminating a load-bearing element from the structure and assessing the ability of the remaining structure to withstand additional failure, the potential of a building to prevent progressive collapse is determined using this method. The benefit of this approach is that it is independent of the initial load, which implies that it may be utilized for any kind of possibility that causes member loss [5].

The suggested positions for the removal of columns are summarised as follows: 'an exterior column at the outer edges close to the middle of the either side of the building; a column situated in a corner of the structure; a column in the interior to the column lines which form the perimeter for facilities which consist underground parking or unregulated public ground floor areas. [4]. As per the guidelines provided by the GSA (2003), the building's potential collapse areas must be determined by analysing the outcomes of the progressive collapse analysis in order to determine 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 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. [5]

2.LITERATURE REVIEW

Park et al. (2013) conducted a thorough investigation into the collapse of the Sampoong Department Store in Seoul, South Korea. The study involved assessing the collapsed structure, analysing ground conditions, conducting strength tests on concrete and steel samples, and performing structural analyses to determine the collapse mechanism. The investigation aimed to understand the factors contributing to the collapse of the department store, which utilized a flat slab structural system without beams. This system was found to be more vulnerable to progressive collapse compared to traditional 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]

Sharma *et al*. (2013) conducted dynamic studies on reinforced concrete columns with the objective of assessing two key aspects: the shear demand generated by a vehicle impact and the dynamic shear capacity of the columns. The objective of the research was to establish a comprehensive framework for the performance-based analysis and design of reinforced concrete columns under the effect of vehicle impacts. The framework aimed to minimize the extent of damage and achieve an economically efficient design. By analyzing these factors, they were able to improve the estimation of the probability of column loss. The findings indicated that the response of RC structures to an explosion is heavily influenced by the reinforcement detailing of the columns. This suggested that the outcome of an explosion on RC structures, specifically whether it would result in the loss of a column, was highly dependent on the specific reinforcement configuration and design details employed in the construction. [8]

Russell *et al.* (2015) investigated the behavior of in situ reinforced concrete (RC) flat slab structures using seven 1/3 scale simplified substructures. Two types of tests were conducted: static load increases and sudden dynamic column removal. In the static tests, the column at the study location was removed, and the slab was loaded with sand and gravel bags. Measurements included support reactions, deflections, strains, and cracking patterns. The study found flexural cracking in sagging areas and regions above adjacent columns but these did not cause ultimate failure. Instead, failures were primarily due to punching shear, occurring mostly at corner locations where columns punched through the slab. Structural integrity was compromised at these locations. Additionally, a decrease in slab stiffness was observed at peak deflections between 0.1 to 0.15 times the slab's depth, indicating reduced resistance to deformation. [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]

Hegde *et al.* (2018) discussed the seismic analysis of conventional slab, flat slab, and grid slab systems for RC framed structures. In this study, a G+14 storey building is investigated to carry out design and analysis in order to compare the flat, grid, and standard slab systems. Models were analyzed in Etabs 2015 using IS-456-2000 parameters. The equivalent static technique as used to analyze and design structures in accordance with IS-1893-2002. After analyzing the fidings, it was determined that the grid slab structure's seismic performance was superior to that of flat slab and conventional slab, and that grid and flat slab storey drift was 10% less than that of conventional slab. Moreover, it was found that when compared to a grid and a conventional slab, a flat slab's base shear was found lower. [10]

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 following the removal of the column and the resulting unbalanced moments induced additional punching-like cracks around adjacent edge columns. This highlighted the potential risk of progressive collapse due to the removal of an interior column. [11]

Attia et al. (2017) in their study numerically evaluated the resistance to progressive collapse of medium-rise reinforced concrete flat slab structures using the Alternate Path Method (APM). Their study focused on 7-bay structures with 6m spans and 31m height, adhering to ACI 318 and UFC criteria. It highlighted that upper floors in flat slab systems are more susceptible to vertical support failures, leading to increased deflections and potential partial collapse. The primary alternate load paths identified were Vierendeel action from upper slabs and columns, and slab catenary action. Edge shear wall loss on higher floors was identified as a critical scenario causing partial collapse. Additionally, despite it not resulting in collapse, the study noted that failure of an interior column near the structural periphery induced significant rotations exceeding UFC limits. [12]

Reichmann et al. (2018) carried out research on "Improved Design of Concrete Flat Slab Buildings for Seismic Effectiveness," analysing the structural system's ability to withstand seismic excitation and prevent a possibility of progressive collapse at the onset of a first floor column failure brought on by an explosion in a 20-storey flat slab office building. 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. [13]

Khattab et al. (2019) In this study, recommendations for reducing the potential for progressive collapse in structural systems consisting flat slab were discussed, focusing on the prevalent failure mechanisms in such constructions. Continuous and adequately anchored reinforcement, with slabs extending beyond columns using bottom reinforcing bars, is essential. Incorporating edge beams along the outer periphery was identified as an effective measure to enhance performance by stiffening the floor edges and facilitating two-way membrane action, crucial for load distribution and preventing punching shear failure. Ensuring continuity, proper lap splicing, and adequate anchorage of bottom reinforcement throughout the slab was accounted as an effective way to mitigate progressive collapse. The reinforcement was recommended to be properly connected to the slab edges or the spandrel beam to maintain integrity within the column and contribute to overall structural stability. [14]

Naradwar et al. (2021) investigated punching shear in a system containing a flat slab which was subjected to seismic load by examining the effect of factors which affect the behavior of connections under punching shear such as concrete strength, column aspect ratio, slab thickness, and gravity loading. The influence of depth-to-span ratio and column aspect ratio on punching shear capacity of column connections was also investigated using equivalent static analysis, which proved to be the governing criteria to prescribe drift limits for flat plate systems in seismic zones. Their research indicated that the aspect ratio and span-to-depth ratio had a substantial impact on the punching shear capacity of the flat plate at intermediate and corner column connections. The shear strength around the flat plate column connections decreased as column aspect ratio increased. While the shear capacity for both intermediate and corner connections rose as the overall depth to span ratio increased. [15]

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. The model was subjected to alternate, simultaneous and sequential removal of columns in the first storey. 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 for its vulnerability to progressive collapse by utilising the GSA's acceptance criteria for DCR. Specifically, 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 code 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 this 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. [16]

Pujari et al. (2023) conducted a study which examined the influence of geometrical (horizontal and vertical) irregularities on the Progressive Collapse Analysis (PCA) of reinforced concrete structures with flat slabs. Using the Equivalent frame method, the current analytical study evaluated the progressive collapse behaviour of a ten-story reinforced concrete slab building. Five models were taken into consideration: a rectangular RCC flat slab, a flat slab with an excessive opening, a re-entrant corner, mass irregularity, and vertical geometrical irregularity. Numerical results demonstrated that the static analysis yields 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. They ultimately arrived at the conclusion that structures with sufficient degree of continuity, redundancy, and ductility in their design and detailing might create alternate load routes thus preventing the loss of individual members and mitigating progressive collapse. [17]

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. Out of the two models that were examined, the one created in accordance with IS 1893 (part 1) - 2016 was found to have a lower DCR value, indicating a higher degree of resistance to progressive collapse and a larger margin of safety. According to IS 1893 (part 1) - 2016 and PSHA analysis, the DCR values for the columns were determined to be almost identical. Moreover, indicating that the structure was able to offer a different load path, the robustness indicator had a value of 1. [18]

Cardoni et al. (2024) analysed the Champlain Tower South Condo collapse in Surfside, Florida, using the Applied Element Method (AEM) to explore various speculative causes. The study considered deterioration scenarios and column failures, suggesting the eastern wing collapse resulted from deep beam failures at the pool deck level attached to perimeter columns. 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. [19]

Cheng et al (2024) The purpose of this study was to gain an understanding of the dynamic behaviour of reinforced concrete frames in the event of progressive collapse caused by the removal of corner columns for which LS-DYNA software was used. To investigate the dynamic performance of structures after abrupt removal of corner columns, a parametric analysis was carried out. Additionally, a comparison was conducted between the quasi-static and dynamic regimes for the RC frames' load resistance and load transfer mechanisms. It was addressed how important elements like strain rate, damping ratio, slab thickness affects, and upper story of the frame limits affect the system. The results showed that the damping ratio was important since it decreased vibrations' amplitude, peak displacement, while the effects were minimal on variation in rate of strain. The thickness of the slab had a significant impact on the dynamic responses. Additionally, the constraints provided by the uppermost floor of the structure were found to lessen the dynamic reactions considerably. [20]

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, meeting the DOD's minimum three-story criteria for resistance to progressive collapse. Each model featured a 4-meter first story height and 3-meter heights for the remaining floors. Column removal locations followed GSA guidelines (2016). Furthermore, the method of column removal plays a vital role in this study. Columns were removed both statically, using linear static analysis, and dynamically, employing a time step function to simulate instantaneous column removal.

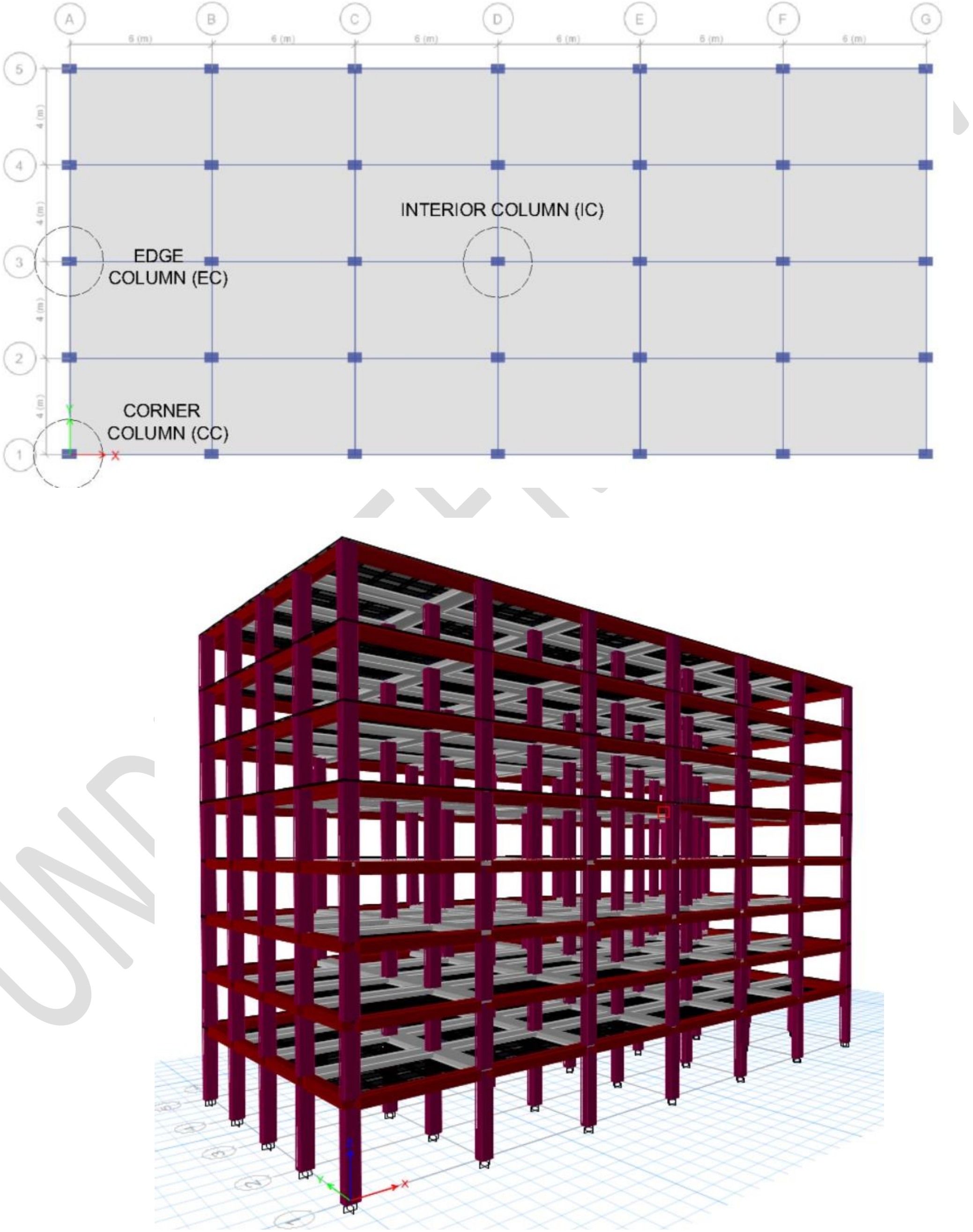


Fig. 1 Building Plan and configuration

3.1 DETAILED DATA OF BUILDING

Table 1 The properties adopted for the buildings are as shown

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

3.2 MODEL SPECIFICATIONS OF FLAT SLAB & REGULAR FRAMED STRUCTURES WITH DIFFERENT POSITIONS OF COLUMN REMOVAL ON MIDDLE FLOOR

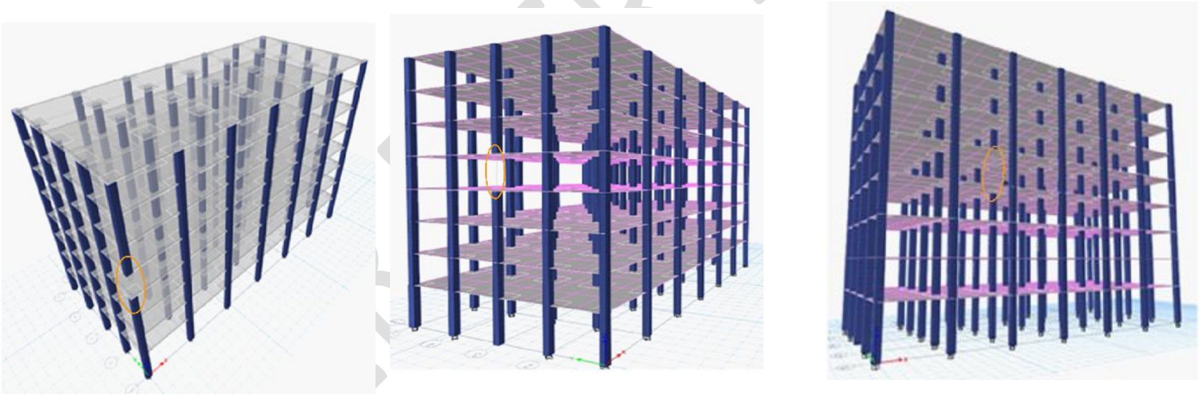
Table 2 Details of the different Models

S.No.	**Building type**	**Analytical Method 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	Corner column	D4
11.			Edge column	D5

12.		time step function	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. 2 Details of the Model with Static column removal for Regular Framed Building



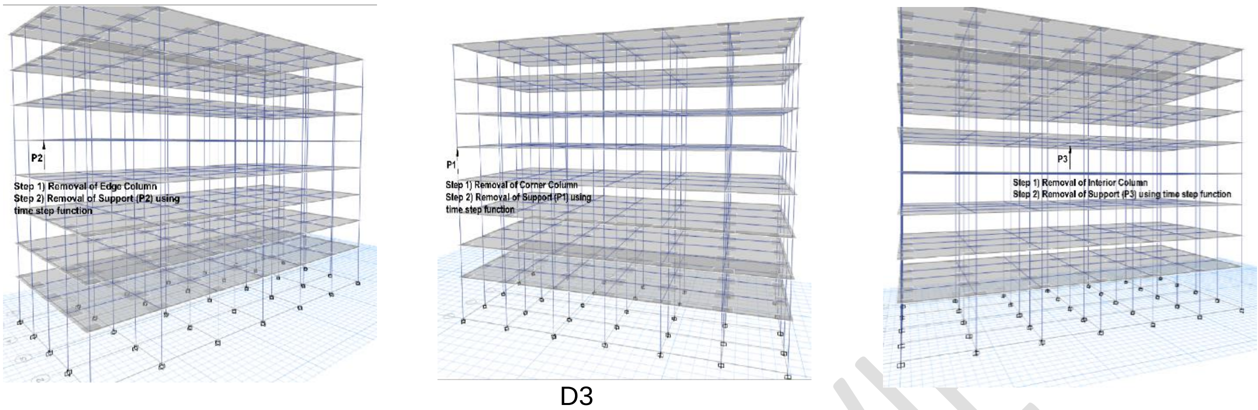
S7 S8 S9

Fig. 3 Details of the Model with Static column removal for Flat Slab with Drop Panel Building

S13 S14 S15

Fig. 4 Details of the Model with Static column removal for Flat Slab with Drop Panel and edge Beams Building

D1 D2



D3

Fig. 5 Details of the Model with Dynamic column removal for Flat Slab with Drop Panel and edge Beams Building

4 RESULT & DISCUSSION

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

4.1 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.

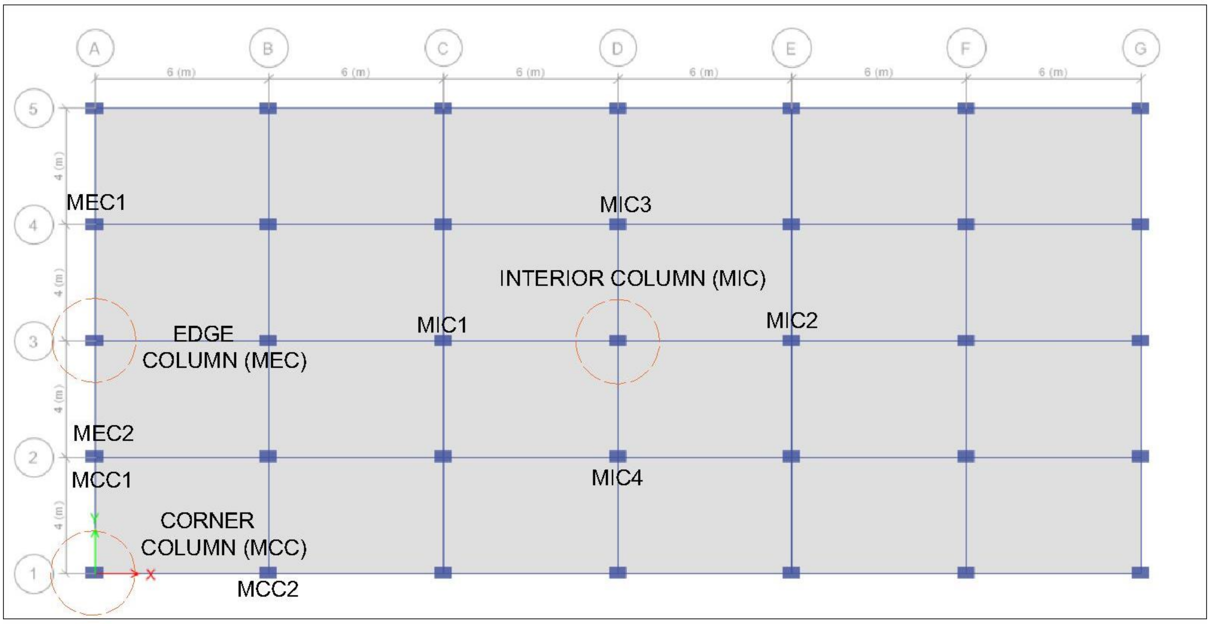


Fig. 6 Location of column removal and the corresponding critical columns for measuring of D/C ratio for intermediate (middle) floor columns

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

The study analyzed DCR values of axial and biaxial moment sectional forces for critical column MCC1 across three structural models, both under static and dynamic scenarios involving removal of corner column MCC. Results indicate that in all models, including flat slab structures with and without perimeter beams, and framed structures, DCR values remained below the safety limit 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.

Fig 7 and 8, 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 Fig. 21 and 22. 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.

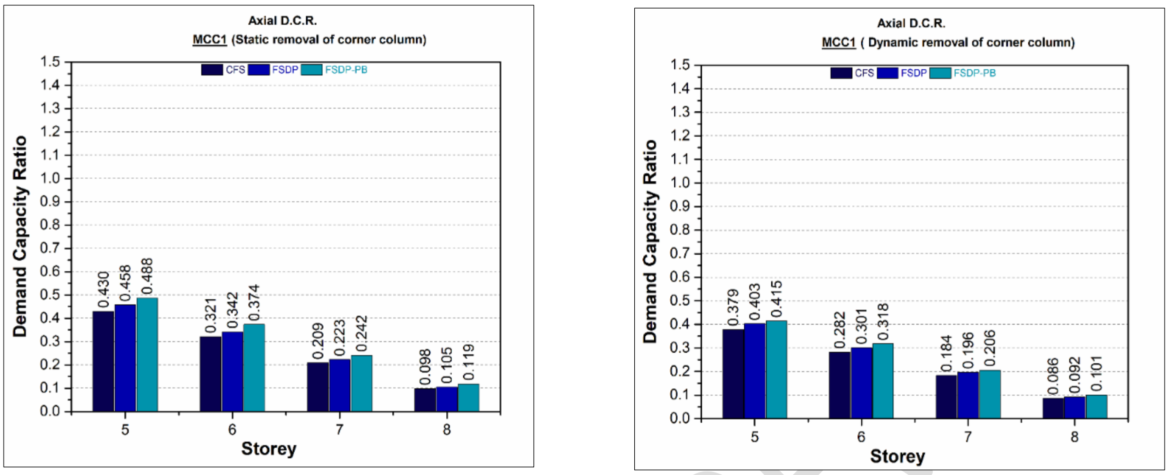


Fig. 7 DCR for axial forces of column MCC1 on the removal of middle floor corner column (a) static removal (b) dynamic removal

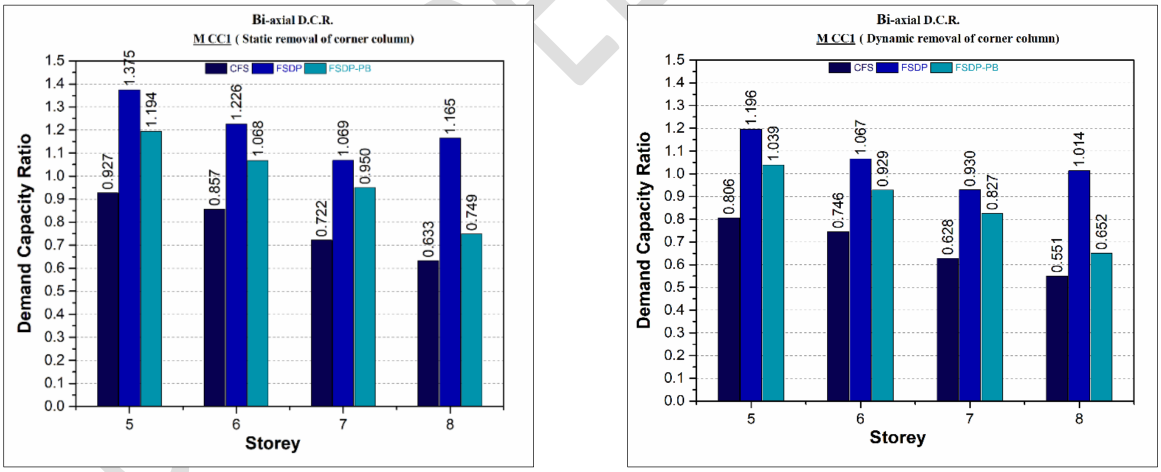


Fig. 8 DCR for biaxial forces of column MCC1 on the removal of middle floor corner column(a) static removal (b) dynamic removal

Fig. 9 and 10 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.

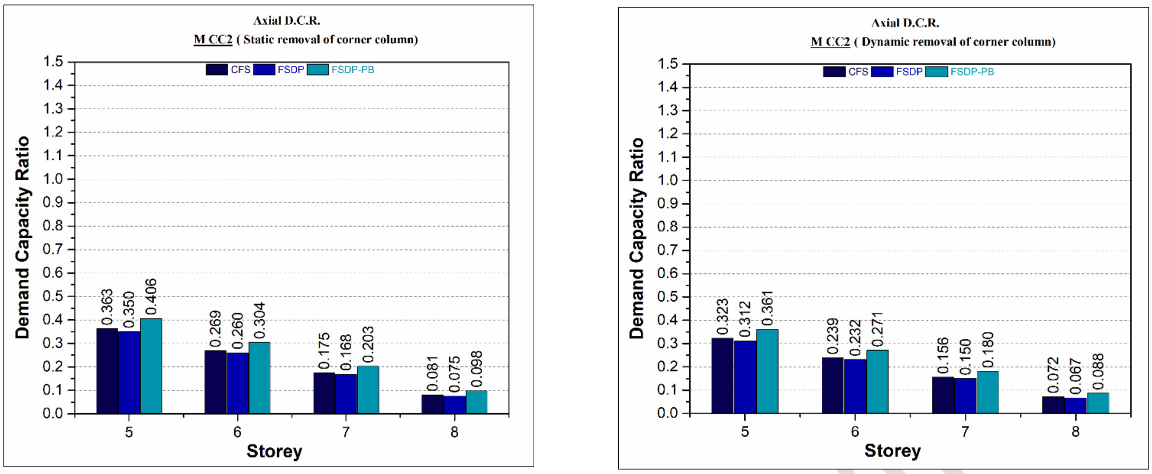


Fig. 9 DCR for axial forces of column MCC2 on the removal of middle floor corner column (a) static removal (b) dynamic removal

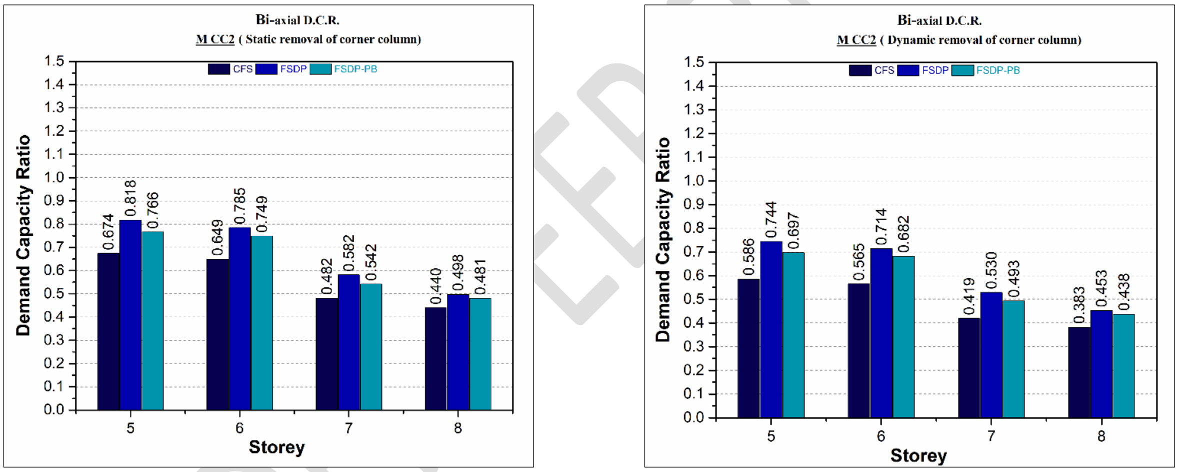


Fig. 10 DCR for axial forces of column MCC2 on the removal of middle floor corner column (a) static removal (b) dynamic removal

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

Fig. 11 & 12 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.

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.

As stated previously in ground storey column removal cases, 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

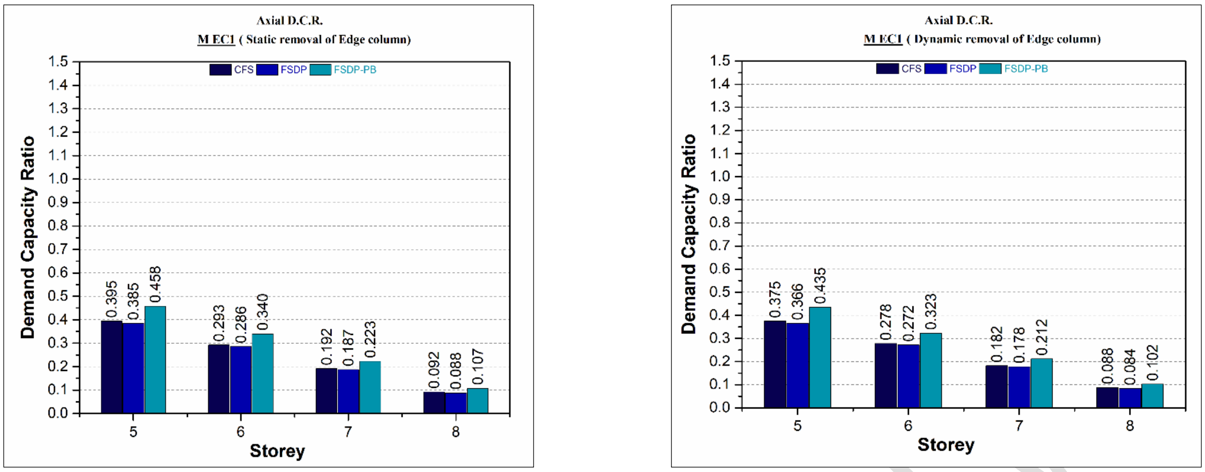


Fig 11 DCR for axial forces of column MEC1 on the removal of middle floor edge column (a) static removal (b) dynamic removal

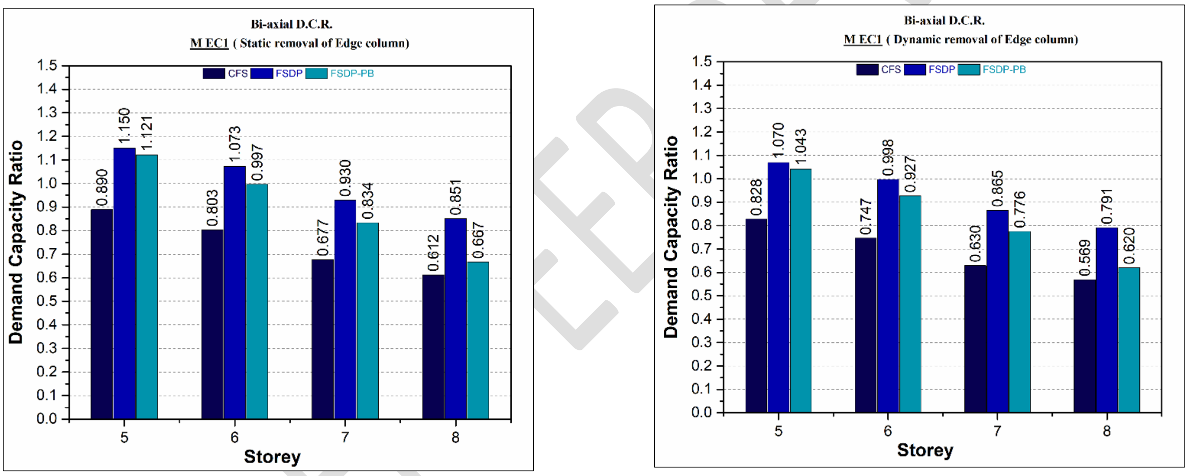


Fig 12 DCR for biaxial forces of column MEC1 on the removal of middle floor edge column (a) static removal (b) dynamic removal

Fig. 13 and 14 show the DCR values for axial and biaxial moments of the critical column MEC2 after static and dynamic removal of an edge column on the middle storey (MEC). Dynamic removal results in a 6.0% to 10.0% average reduction in DCR for the biaxial moment compared to static removal.

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.

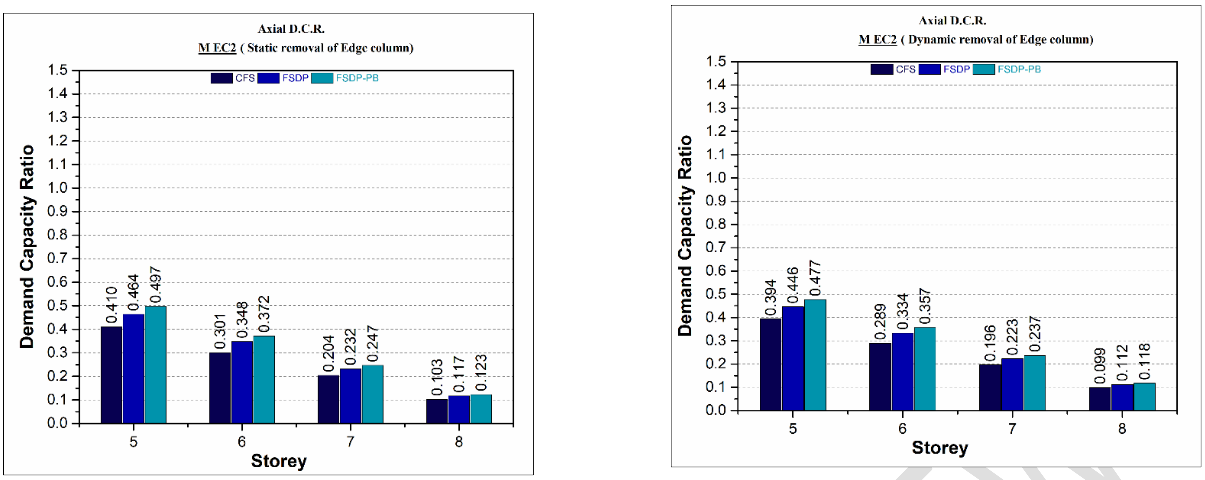


Fig. 13 DCR for axial forces of column MEC2 on the removal of middle floor edge column (a) static removal (b) dynamic removal

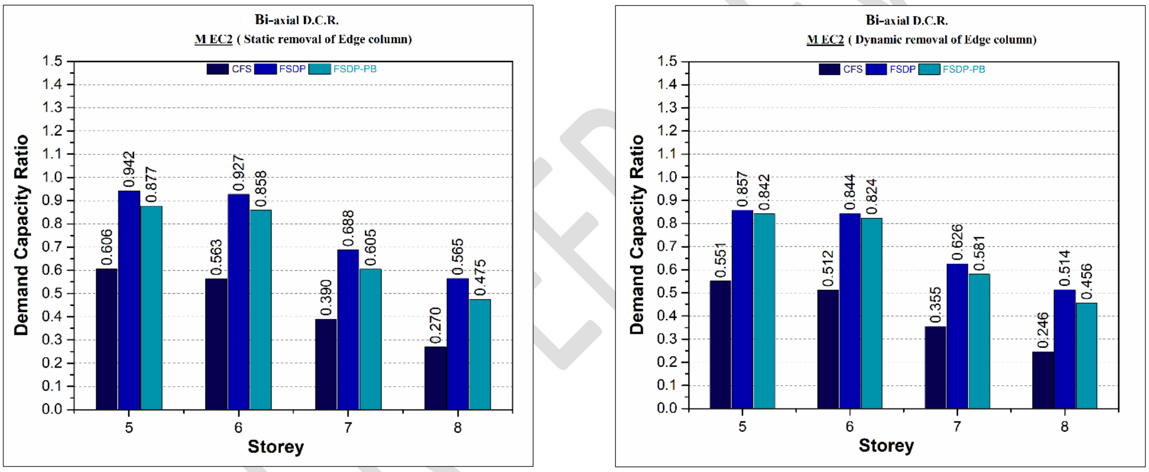


Fig. 14 DCR for biaxial moments of column MEC2 on the removal of middle floor edge column (a) static removal (b) dynamic removal

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

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.

Fig. 15 and 16 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.

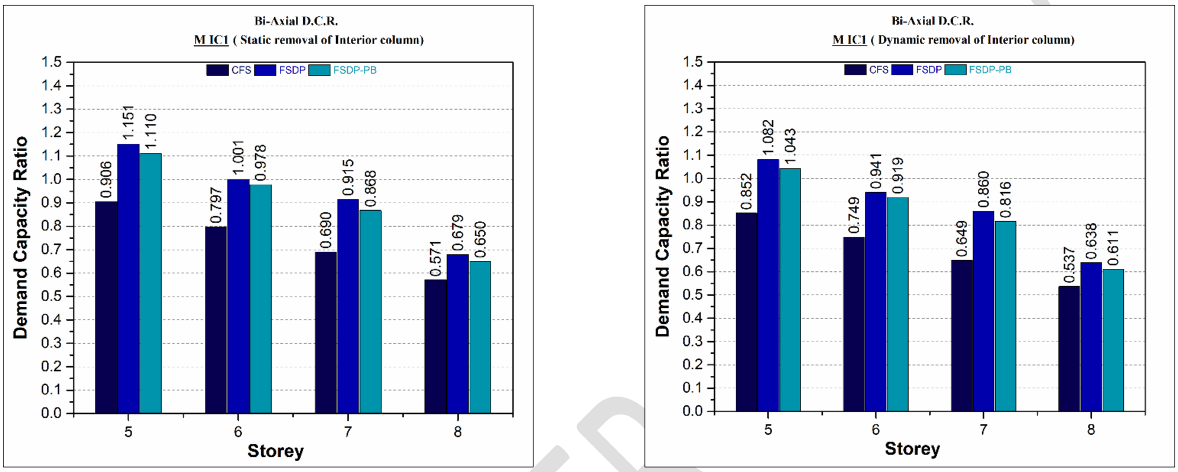


Fig. 15 DCR for axial forces of column MIC1 on the removal of middle floor interior column (a) static removal (b) dynamic removal

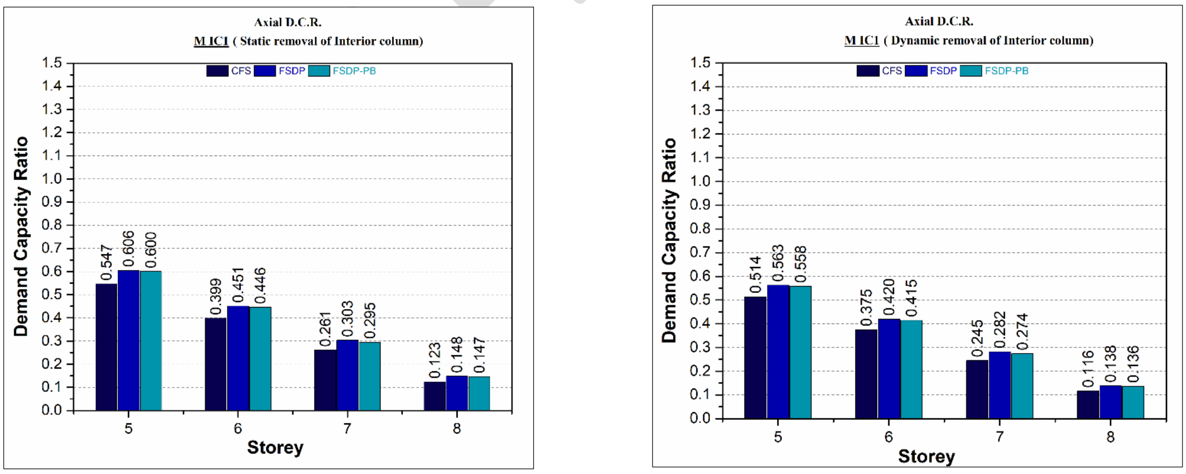


Fig. 16 DCR for biaxial moments of column MIC1 on the removal of middle floor interior column (a) static removal (b) dynamic removal

Fig. 17 & 18, 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.

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.

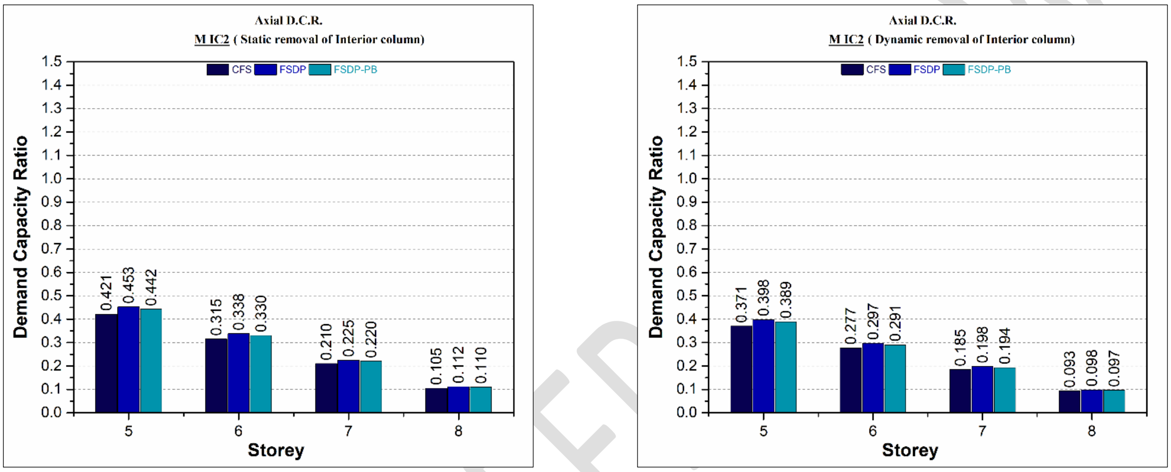


Fig. 17 DCR for axial forces of column MIC3 on the removal of middle floor interior column (a) static removal (b) dynamic removal

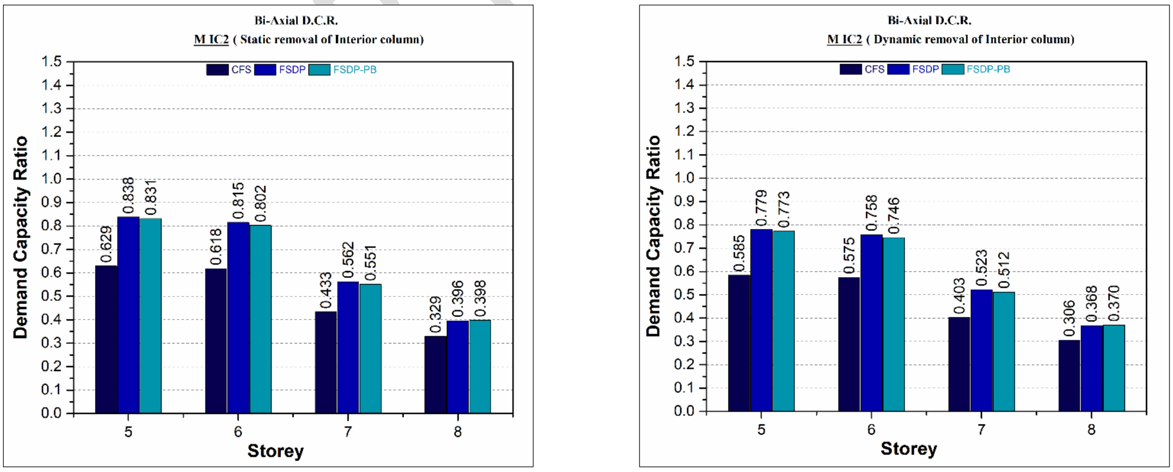


Fig. 18 DCR for biaxial forces of column MIC3 on the removal of middle floor interior column (a) static removal (b) dynamic removal

4.2 JOINT DISPLACEMENT

Joint displacement is a crucial indicator of a structure's susceptibility to progressive collapse. In performance-based design, maintaining joint displacement within a reasonable range ensures the structure's strength and stiffness. When a vertical member is lost due to natural or man-made hazards, controlling joint displacement is essential. The following section will compare joint displacements at three column removal locations across different structures to evaluate their performance in potential progressive collapse scenarios.

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. Figures 19, 20, and 21 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

Fig. 19 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.

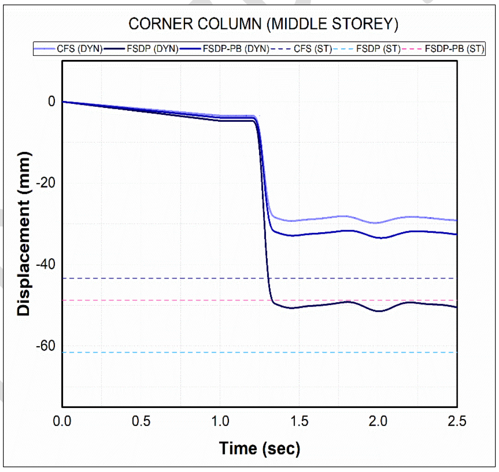


Fig. 19 Time history response of vertical displacement when CC is instantaneously removed at t = 1.25 s for buildings CFS, FSDP, and FSDP-PB along with static displacement response on intermediate storey

4.2.2 Joint Displacement for Edge column removal

Fig. 20 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.

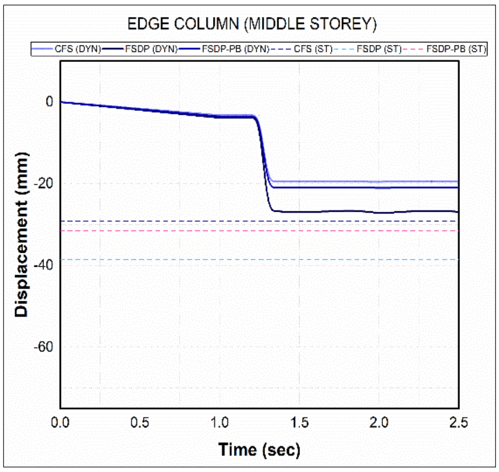


Fig. 20 Time history response of vertical displacement when EC is instantaneously removed at t = 1.25 s for buildings CFS, FSDP, and FSDP-PB along with static displacement response on intermediate storey

4.2.2 Joint Displacement for Interior column removal

Fig. 21 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.

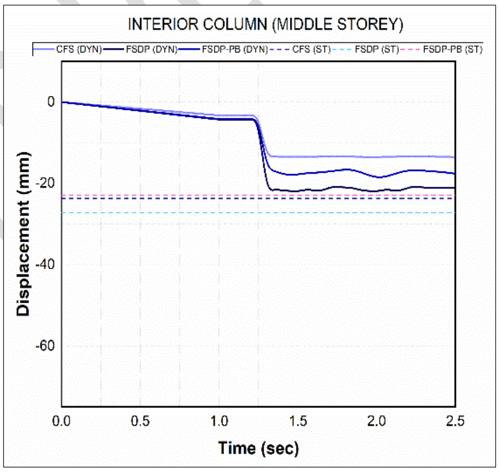


Fig. 21 Time history response of vertical displacement when IC is instantaneously removed at t = 1.25 s for buildings CFS, FSDP, and FSDP-PB along with static displacement response on intermediate storey

4.3 CHORD ROTATION

To comprehend the progressive collapse behaviour of a flat slab building, one important parameter that is determined is the vertical joint displacement at the removed column position, which is ascertained following the completion of a linear static progressive collapse analysis for each occurrence 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.

4.3.1 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 **Fig. 22, 23, and 24**, 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 22, 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.

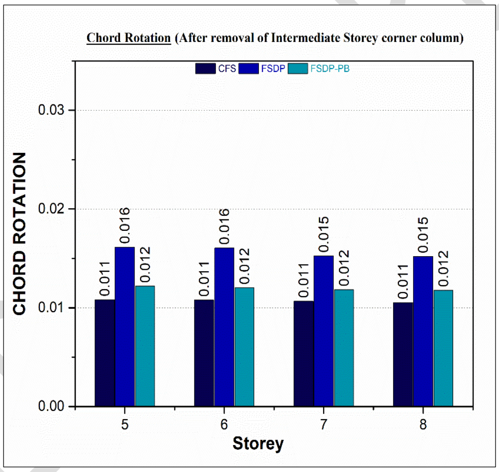


Fig. 22 Chord Rotation when Corner column is statically removed for buildings CFS, FSDP, and FSDP-PB on intermediate storey

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

In Fig. 23, 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.

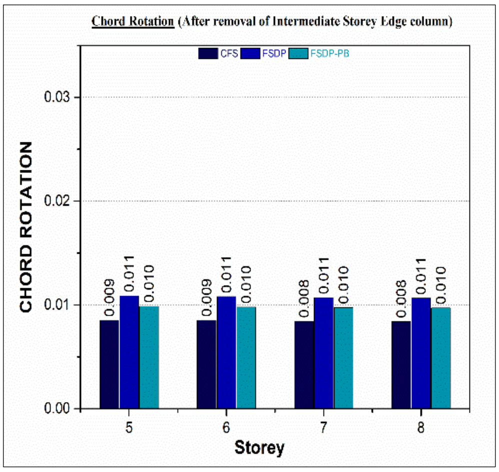


Fig. 23 Chord Rotation when Edge column is statically removed for buildings CFS, FSDP, and FSDP-PB on intermediate storey

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

In Fig. 24, the removal of an Interior Column shows an insignificant reduction in joint displacement and hence chord rotation with the addition of perimeter beams. When the Interior column was removed, perimeter beams did not effectively support any of the four connecting slab beams, resulting in negligible change in chord rotation values in both the flat slab structure with and without perimeter beams. Consequently, the perimeter beams were insufficient to significantly affect chord rotation values in the flat slab structure with or without perimeter beams.

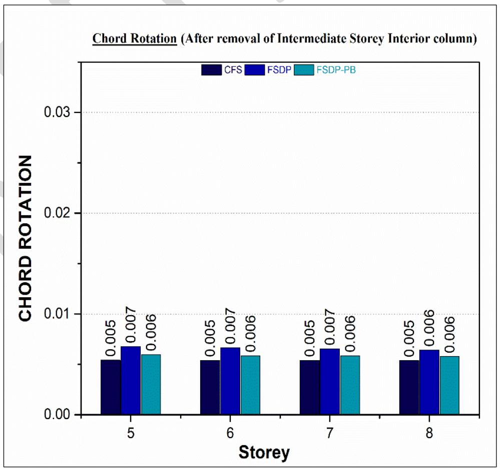


Fig. 24 Chord Rotation when Interior column is statically removed for buildings CFS, FSDP, and FSDP-PB on intermediate storey

5. CONCLUSION

This study examines the potential for progressive collapse under certain combinations of gravity loads prescribed by GSA guidelines (2003) in two buildings: a standard beam slab building and an eight-story flat slab building (36 m x 16 m), both designed for seismic zone III as per IS 1893-2016 provisions. The study also aims to understand how the three building structures (CFS, FSDP & FSDP-PB) respond to progressive collapse caused by vertical member failure, in terms of joint displacement and chord rotation at column removal locations, as well as Demand Capacity Ratio (DCR) at adjacent critical columns. This analysis is conducted through both linear static and dynamic methods, the latter utilizing a time-step function for column removal simulations. In addition, it examines the effectiveness of enhancing progressive collapse resistance in flat slab buildings by adding perimeter beams to different model simulations in the ETABS 2018 program.

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 gives more conservative results.
- Joint displacements and DCR values typically decrease when columns are removed from intermediate storeys compared to ground storeys, suggesting greater resistance to progressive collapse as we move from lower to upper storeys.
- A flat slab building simulation is more susceptible to progressive collapse compared to a regular framed structure due to higher DCR values, joint displacements, and chord rotation at column removal locations. This is because a beam slab structure can bridge, redistribute, and withstand additional loads through its floor beams.
- 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.

REFERENCES

[1] Kakhki, S.A.E., Kheyroddin, A. & Mortezaei, A. Evaluation of the Progressive Collapse of the Reinforced Concrete Frames Considering the Soil–Structure Interaction. International Journal of Concrete Structures and Materials. 2022; 16: 38-51.

[2] Paripour, M.B., Budak, A. & Düzgün, O.A. Investigation of Progressive Collapse Resistance Mechanism in Reinforced Concrete Beam-Column Assembly. Iranian Journal of Science and Technology. 2021; 45: 505–512

[3] Humay FK, Baldridge SM. & Ghosh SK. Prevention of progressive collapse in multi-storey concrete buildings. Structures and Codes Institute (SCI). 2006; 8: 73-79

[4] GSA. Progressive collapse analysis and design guidelines for new federal office buildings and major modernizations projects. General Services Administration (GSA). Washington DC, USA 2003

[5] Garg, S., Agrawal, V., and Nagar, R. Progressive collapse behavior of reinforced concrete flat slab buildings subject to column failures in different storeys. Materials Today. 2020**;** 43:1031-1037

[6] Park, T.W. Inspection of collapse cause of Sampoong Departmental Store. Forensic Science International. 2013; 217:119-126.

[7] Qian, K., & Li, B. Experimental study of drop-panel effects on response of reinforced concrete flat slabs after loss of corner column. ACI Structural Journal. 2013; 110: 319-330.

[8] Sharma, H., Hurlebaus, S. and Gardoni, P. Performance-based response evaluation of reinforced concrete columns subject to vehicle impact. International Journal of Impact Engineering. 2013; 43: 52-62.

[9] Russell, J.M., and Owen, J.S. Experimental investigation on the dynamic response of RC flat slabs after a sudden column loss. Engineering Structures. 2015; 99: 28-41

[10] Divya, N., Gururaja, B. and Sridhar, R. Comparative study of progressive collapse analysis of flat slab building with and without shear wall. International Journal of Research in Engineering and Technology. 2016; 20: 301-306.

[11] Hegde, R., Chethana, R., and Kumar, V. Comparative study on seismic analysis of conventional slab, grid slab system for a RC framed structures. IRJET. 2018; 5: 395-407

[12] Attia, F., Salem, H., and Yehia, N. Progressive collapse assessment of mid-rise reinforced concrete flat slab structures. Structural Concrete Journal of the Fib. 2017;18: 409-420.

[13] Reichman, Y., and Adan, M. Improved design of concrete flat slab buildings for seismic effectiveness and prevention of blast induced progressive collapse. US National Conference on Earthquake Engineering. 2018; 10: 114-124

[14] Khattab, R., Mohamed, O., Mishra, A., and Isam, F. Recommendations for Reducing Progressive Collapse Potential in Flat Slab Structural Systems. Materials Science and Engineering. 2019; 471: 52-69

[15] Naradwar, A. Study of Punching Shear in Flat Slab System Subjected to Seismic Load. International Journal of Scientific & Engineering Research. 2021; 9: 135-147

[16] Anandakrishnan, G. and Antony, J. Progressive Collapse Analysis of a Multistoried Building with Flat Slab. Proceedings of SECON 21, Lecture Notes in Civil Engineering. 2022; 171: 235-248

[17] Pujari, A. and Girme, S. Progressive collapse analysis of reinforced concrete structures with flat slab considering effects of geometrical irregularities. International Research Journal of Engineering and Technology. 2023; 10:1-11

[18] Raja, D. and Rani, N. Analysis of progressive collapse of building using ETABS. Materials Today. 2023; 93: 278-286

[19] Cheng, J., Qian, G., and Kai, Q. Dynamic behaviour of RC frames against the progressive collapse subjected to loss of a corner column scenario. Journal of Building Engineering. 2024; 86: 108-121

[20] Cardoni, A., Pellecchia, C., Cimellaro, C.P. & Domaneschi, M. Progressive Collapse Analysis of the Champlain Towers South in Surfside, Florida. Journal of Structural Engineering. 2024; 150. 1061-1078