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RC Flat Slab Strengthening for Improved Structural Response under Static and Dynamic Column Removal

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ABSTRACT: This study is focused on investigating the response of the structures after the sudden column loss design scenarios. Critical columns are identified based on Demand Capacity Ratios (DCR). A reinforced concrete G+5 framed structure is analyzed for static and dynamic analysis according to General Services Administration (2016) guidelines. Based on the response of the structure after the sudden column loss design scenario, design parameter such as DCRs are determined. However, within reinforced concrete (RC) flat slab structures, there remains a significant gap in the investigation of progressive collapse when multiple columns are removed simultaneously or sequentially. Yet, there is a notable absence of research on evaluating the combined impact of perimeter beams and shear walls. Furthermore, there is a need to assess how varying the size of perimeter beams and the length of shear walls influence the enhancement of progressive collapse resistance in flat slab buildings, aiming to achieve structural robustness while optimizing the use of these strengthening measures. The various 3-D RC flat slab buildings are modelled and are constructed using ETABS software. In order to validate the proposed modelling process, the numerical results from the proposed model are compared to the analytical data from existing research. For study purpose 24 model considered they are RCC rectangular flat slab, flat slab having vertical geometrical irregularity by conducting Linear static progressive collapse analysis and dynamic PCA as per GSA guidelines (2016) and then result compared. Corner, edge and interior columns of each building model are analyzed by using static and dynamic PCA method. The results are analyzed for each case, in terms of demand capacity ratio (DCR).

KEYWORDS: Demand Capacity Ratio (DCR), Static and Dynamic Analysis, Reinforced Concrete (RC), Etabs Software.

I. INTRODUCTION

The collapse of load carrying structural element may lead to progressive collapse as a part or whole structure. According to GSA 2016 guidelines, progressive collapse is defined as extent of damage or collapse that is disproportionate to the magnitude of the initiating event. The progressive collapse initiates, when one or more load carrying members are removed. When one or more load carrying elements remove chain reaction structure failures start. The guidelines of the GSA and DoD suggested the Alternate Path Method (APM) for progressive collapse analysis where a single column in the ground level is assumed to be unexpectedly missing and analyses are carried out to assess the ability of the weakened structure to pass through the missing column. The APM focuses on the vertical deflection of the building after the column has been suddenly removed. The collapsing structure seeks for alternative load path continuously for prevent progressive attention collapse and survive. Traditional design work not considered extreme loading conditions. Previously some Experiences grab of structural engineer's attention Ronan point apartment building, Alfred P. Murrah building, skyline plaza, World Trade Centre. Based on the type of collapse occur, Progressive collapse divided into pancake-type, zipper-type, domino-type, section-type, Instability-type and mixed-type collapse. The purpose of this study is to analyze the effect of RC flat slabs for progressive collapse. Progressive collapse analysis where a single column in the ground level is assumed to be unexpectedly missing and analyses are carried out to assess the ability of the weakened structure to pass through the missing column. Progressive Collapse Analysis (PCA) is classified as Pressure load- Internal gas explosion, Blast load, Extreme wind pressure and another type is Impact Load- Aircraft impact, Vehicular collision, Earthquake in this study analyses behaviour of building under column loss at ground floor. Progressive collapse occurs in a matter of seconds in most cases.



a) Alfred P. Murrah Federal Building Collapse



b) World Trade Center Towers

1.1 OBJECTIVES OF WORK:

1. To study 6 storey RC rectangular flat slab building having vertical geometrical irregularity type structure models prepared to simulate a column loss event and check results in terms of DCR by using GSA and DoD guidelines.
2. To understand behaviour of building under critical column loss scenarios by using static and dynamic PCA Method is used.
3. To strengthen the RC flat slab buildings by using perimeter beams, shear walls and combination of both and also with the variation in the length of shear wall and size of perimeter beam for the improvement in the progressive collapse resistance of RC flat slab buildings.

II. RELATED WORK

2.1 PROBLEM STATEMENT:

24 3-D Models of 6 – Storey flat slab buildings having 3x3 Bays in the plan are constructed using Extreme Three – Dimensional Analysis of Building System (ETABS) Software. A Total of 24 building models are studied which are different from one another in respect to the strengthening technique used, i.e., one building without any strengthening measure (B-NR), three buildings with different sized perimeter beams (B-PB, B-PB1 and B-PB2), five buildings with shear walls of lengths 2m, 3m, 4m, 5m & 6m (B-SW2, B-SW3, B-SW4, B-SW5 & B-SW6) and fifteen buildings with both different sized perimeter beams and shear walls of lengths 2m, 3m, 4m, 5m & 6m (B-PBSW2, B-PBSW3, B-PBSW4, B-PBSW5, B-PBSW6, B-PB1SW2, B-PB1SW3, B-PB1SW4, B-PB1SW5, B-PB1SW6, B-PB2SW2, B-PB2SW3, B-PB2SW4, B-PB2SW5, B-PB2SW6). These models are created in such a way that B-NR is compared with B-PB, B-PB1, B-PB2, B-SW2, B-SW3, B-SW4, B-SW5, B-SW6, B-PBSW2, B-PBSW3, B-PBSW4, B-PBSW5, B-PBSW6, B-PB1SW2, B-PB1SW3, B-PB1SW4, B-PB1SW5, B-PB1SW6, B-PB2SW2, B-PB2SW3, B-PB2SW4, B-PB2SW5 & B-PB2SW6 and hence the effectiveness of strengthening measures is assessed separately and in combination. The buildings have the same plan throughout their entire height. The buildings are considered is 6 – Storey. The studied models have Bay spans of 6m in both directions.

2.2 PARAMETERS OF STUDY:

A number of models with different details are developed to examine the response of RC flat slab buildings to a column loss scenario. This section provides an overview of the variables considered in this study.

2.2.1 Type of column removed:

Removal of columns at critical locations for alternate load paths is determined by engineering judgment in accordance with the GSA (2016) standard. For the purposes of column removal, slab-to-slab continuity is assumed to be maintained across a removed column. The removed column extends from the bottom floor to the top floor (i.e., a one-storey height is removed). The loss of a corner, edge or interior column is simulated in all schemes. Since corner or edge columns are external components, they are often subjected to outside of the building accidents, whereas interior column loss is less frequent.

As per suggestions in GSA (2016) guidelines, the following columns have been removed from the first storey of the building:

1. Corner column CC (C7)

2. Edge column EC (C8)
3. Interior column IC (C5)

The critical cases are established by comparing the findings of each column removal case. That is the incident that causes the most structural damage.

2.2.2 Number of columns removed:

The number of columns removed in this research for alternate path method depends upon the specific column removal case:

Alternate column removal: In this research, the corner column (CC), edge column (EC) and interior column (IC) are statically or dynamically removed in an alternate manner, i.e., only one column is removed at one time. After each column removal, analysis is performed, and the results are evaluated.

Simultaneous column removal: In this study, the single or multiple columns are removed simultaneously, ignoring the time lag between removals. The simultaneous removal of columns is preceded in the following manner, and the results are assessed after each column removal:

1. Removal of first column (CC).
2. Simultaneous removal of first (CC) and second column (EC).
3. Simultaneous removal first (CC), second (EC) and third column (IC).

Sequential column removal: In this investigation, the single or multiple columns are removed sequentially, considering a reasonable time lag of 1.25 seconds between removals. The sequential removal of columns is preceded in the following manner, and the results are assessed after each column removal:

1. Removal of first column (CC) at time t_1 sec.
2. Removal of second column (EC) at time $t_2 = t_1 + 1.25$ sec.
3. Removal of third column (IC) at time $t_3 = t_2 + 1.25$ sec.

2.2.3 Method of column removal:

In this study, columns were removed under different conditions—statically or dynamically—depending on the timing of removal. In static analysis, columns are removed alternately and gradually. Conversely, dynamic analysis assumes a sudden loss scenario, where the column's support is removed instantaneously. Here, the column is replaced by a force (P) equal and opposite to its reaction force, mimicking the original scenario where the column remains intact and supports gravity loads. Subsequently, the force (P) is abruptly removed within 0.005 seconds using a time-history step function to simulate dynamic column removal conditions.

2.2.4 Strengthening measures:

In this study, different building simulation models with varying strengthening techniques are evaluated for progressive collapse resistance under static and dynamic column removal. The simulation models are chosen in such a way that the effectiveness of the strengthening measures is evaluated separately and in combination, i.e., the effectiveness of different sized perimeter beams, peripheral shear walls and the combination of perimeter beam and shear wall are evaluated separately in order to reduce the vulnerability of progressive collapse in flat slab buildings. The building model B-NR represents buildings with no strengthening technique, while B-PB, B-PB1, and B-PB2 exhibits buildings strengthened with the same or different sized perimeter beams. In addition, B-SW2, B-SW3, B-SW4, B-SW5 and B-SW6 illustrate buildings strengthened with different length peripheral shear walls. Several B-PBSW building models are analysed to assess different strengthening combinations further and eventually achieve the best alternative that uses minimum strengthening measures and simultaneously satisfies the progressive collapse code requirements.

III. METHODOLOGY

3.1 STATIC ANALYSIS PROCEDURE IS AS FOLLOWS:

1. As per GSA guidelines remove corner column, edge column and interior column alternately from the ground storey.

2. Two load combinations which follow the GSA guideline for the presentation of the gravity loads are used. A load combination of (1.2 DL + 0.5 LL) is used for gravity loads for floor spaces on the side from removed column and 2(1.2 DL + 0.5 LL) for additional gravity loads for floor spaces over the removed column. To account for dynamic effects, a factor of 2.0 is provided in the Static analysis as a dynamic magnification factor as per GSA guideline.
3. Perform static analysis as per GSA using the software ETABS.
4. Demand Capacity Ratio (DCR) of sectional forces of critical columns in the ground storey nearby removal column and vertical displacements at the top of removed columns are evaluated for the specific column removal case.
5. In case of the removal of columns in the ground storey, the responses of critical neighbouring columns are evaluated and results compare with guideline values.

3.2 DYNAMIC ANALYSIS PROCEDURE IS AS FOLLOWS:

In this process involves the removal of columns in real-time, which innately accommodates amplification factors, inertia and damping forces. This analysis has the key benefit of being able to account for the dynamic amplification effects. In this paper, the dynamic progressive collapse analysis procedure is as follows.

1. The gravity loading of 1.2 DL + 0.5 LL is uniformly applied in the entire span of the frame according to GSA guidelines.
2. Prior to the removal of the column, its reaction force is determined.
3. The column is removed and replaced by a force (P) equal and opposite to its reaction force. This reflects the original case where the column is still in place and carries the gravity loads.
4. To simulate the conditions of dynamic column removal, the member force (P) is suddenly removed using a time history step function.
5. The member force is applied till 1.25 sec. so that the structure reaches a stable condition, and finally, the force is suddenly removed. The total time of dynamic analysis is considered as 5.0 s, which is adequate to evaluate the maximum response and attain a steady-state under 5% of damping ratio. The gravity loads remain unchanged until the end of the analysis time.
6. The time over which a column is lost, in a real bomb explosion, is very short. The column removal time should be less than 1/10 of the natural period associated with vertical vibration as recommended by DoD. In this study, the column removal time is hence taken as 0.005 s, which indicates an instantaneous removal. The dynamic effects of the column removal time close to 0.005 s would result in adverse dynamic effects.
7. Perform dynamic analysis as per GSA using the software ETABS.
8. Evaluate the results in terms of DCR of sectional forces of critical columns and vertical displacements at the top of the removed column, where demands, as well as displacements, are taken as the peak values (absolute maximum) of responses from the calculated time history responses.

Loading Details	
Live Load	4.0 KN/m ²
Dead Load for internal partitions	2.0 KN/m ²
Grade of Concrete	M25
Grade of Steel	Fe500 (HSYD)
Designed as per	IS 456 (2000)
Thickness of Shear Wall for all buildings	230mm

IV. EXPERIMENTAL RESULTS

❖ COMPUTATIONAL ANALYSIS

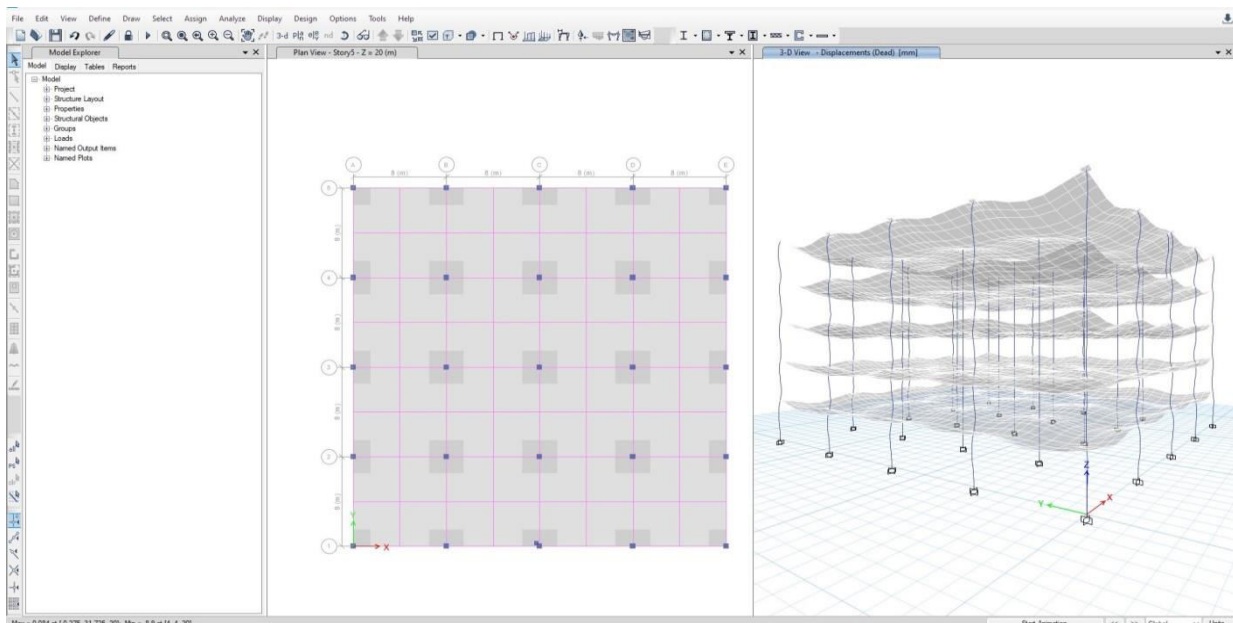
4.1 ANALYSIS AND DESIGN OF G+5 BUILDING IN ETABS SOFTWARE.

4.1.1 Plans and Structural Geometry in 3D

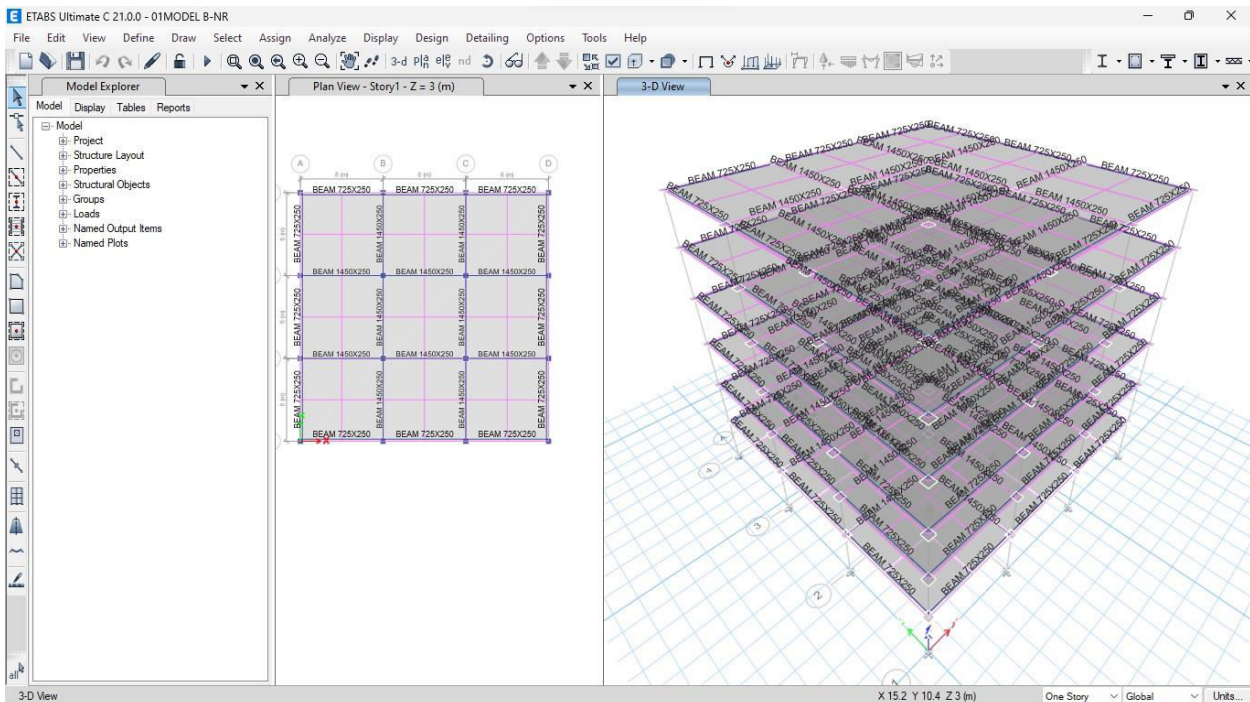
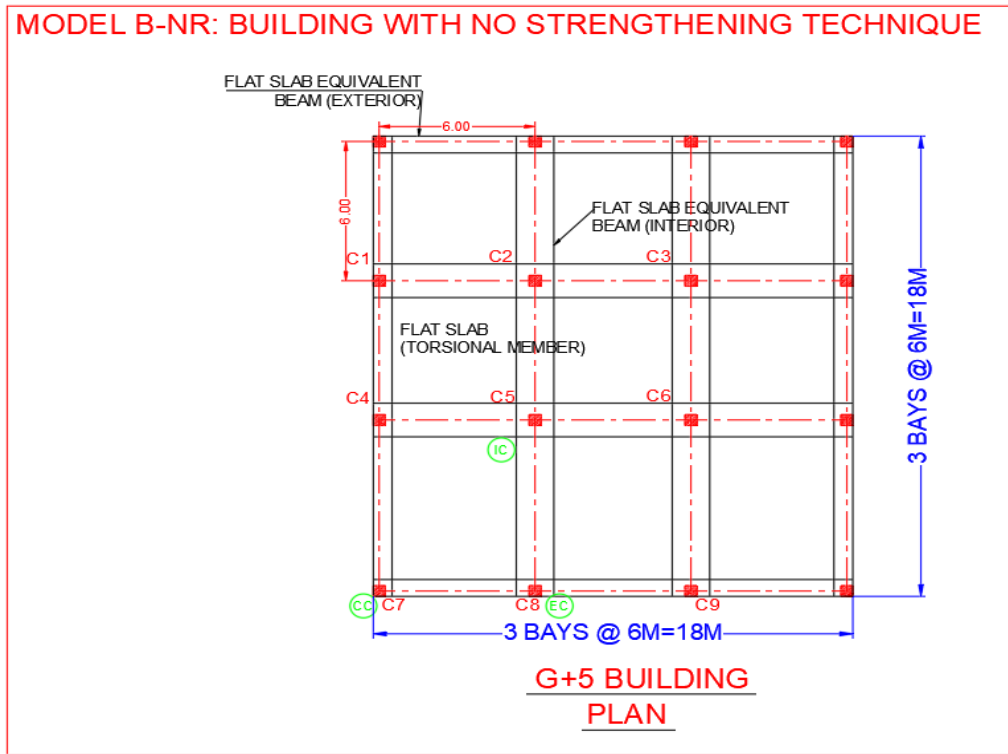
❖ Steps for Model B-PB1:

1. Model Initialization.
2. New Model Quick Template.
3. Structural Geometry and Properties for Flat Slab with Perimeter Beams.
4. Material Properties.
5. Define Materials.
6. Add New Material Property.
7. Material Property Data.
8. Add New Material Property.
9. Section Properties → Frame Sections.
10. Frame Properties.
11. Frame Property Shape Type.
12. Frame Section Property Data.
13. Property/ Stiffness Modification Factors for Beam.
14. Frame Section Property Reinforcement Data.
15. Frame Section Property Data.
16. Property/ Stiffness Modification Factors for Column.
17. Frame Section Property Reinforcement Data.
18. Properties of Object.
19. For the below View Press Control + W → Click on Object Assignment → Frame Assignment → Tick Sections → Apply.
20. Define Load Patterns.
21. Indian IS 1893:2016 Seismic Loading for X Direction.
22. Indian IS 1893:2016 Seismic Loading for Y Direction.
23. Preset P-Delta Options.
24. Define → Load Combinations.
25. Analyze → Run Analysis.

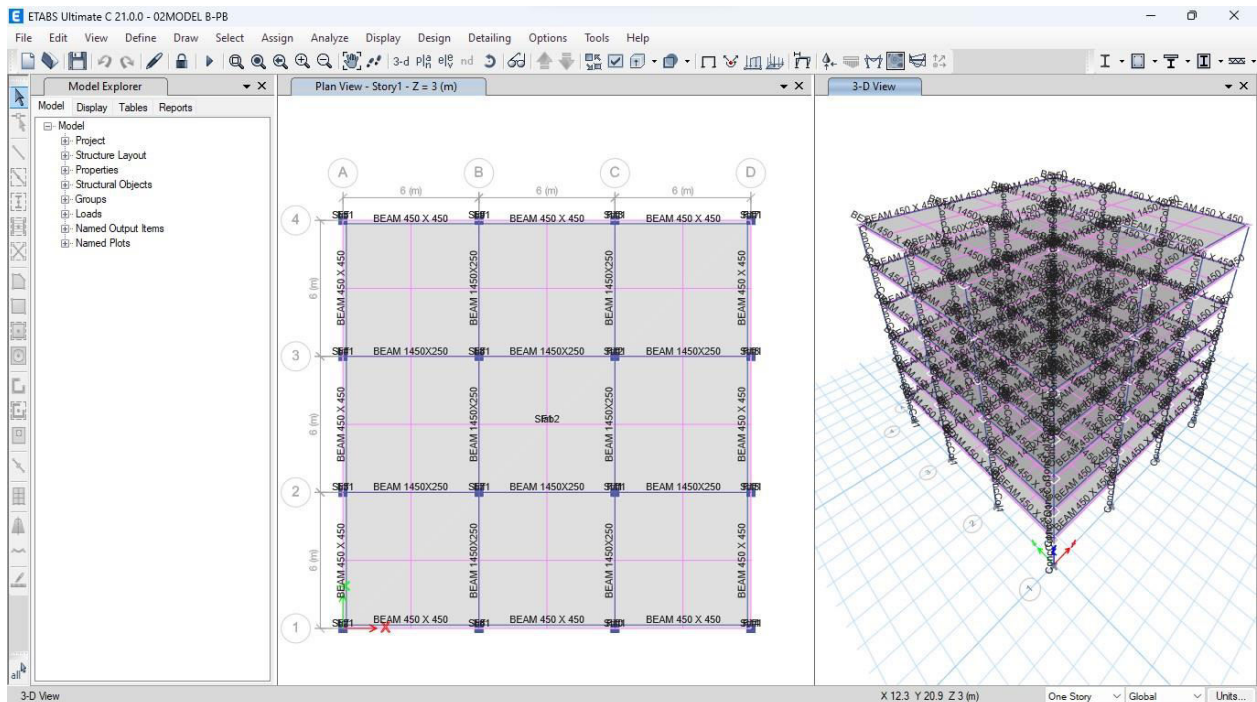
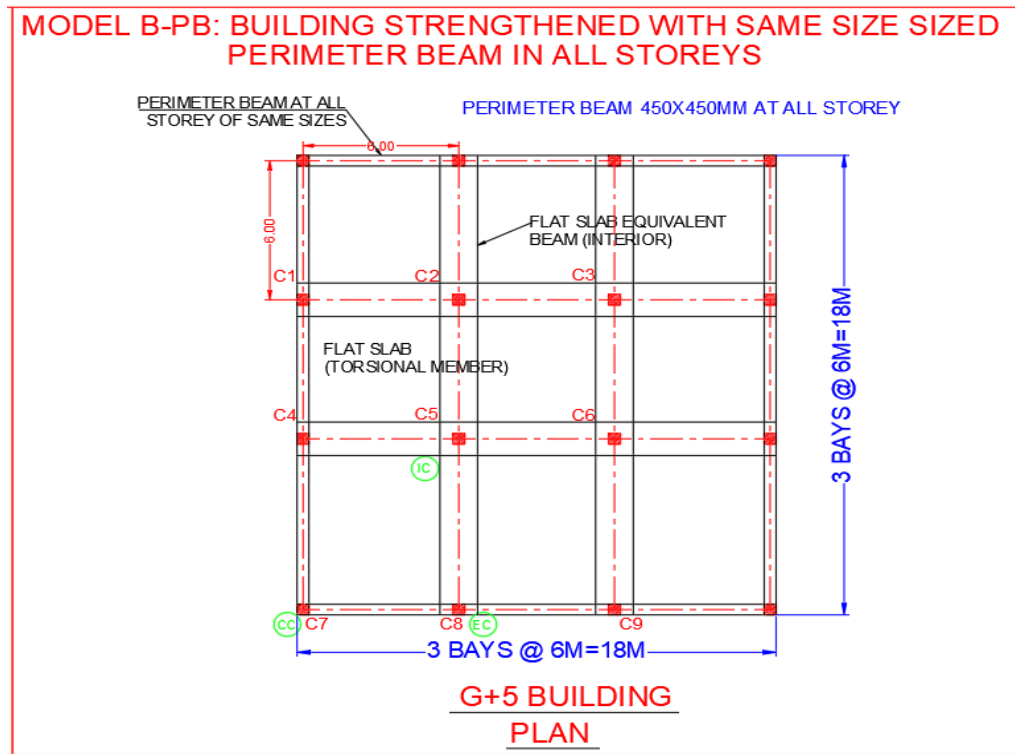
❖ For example Run Analysis of G+5 Building Model on ETABS Software:



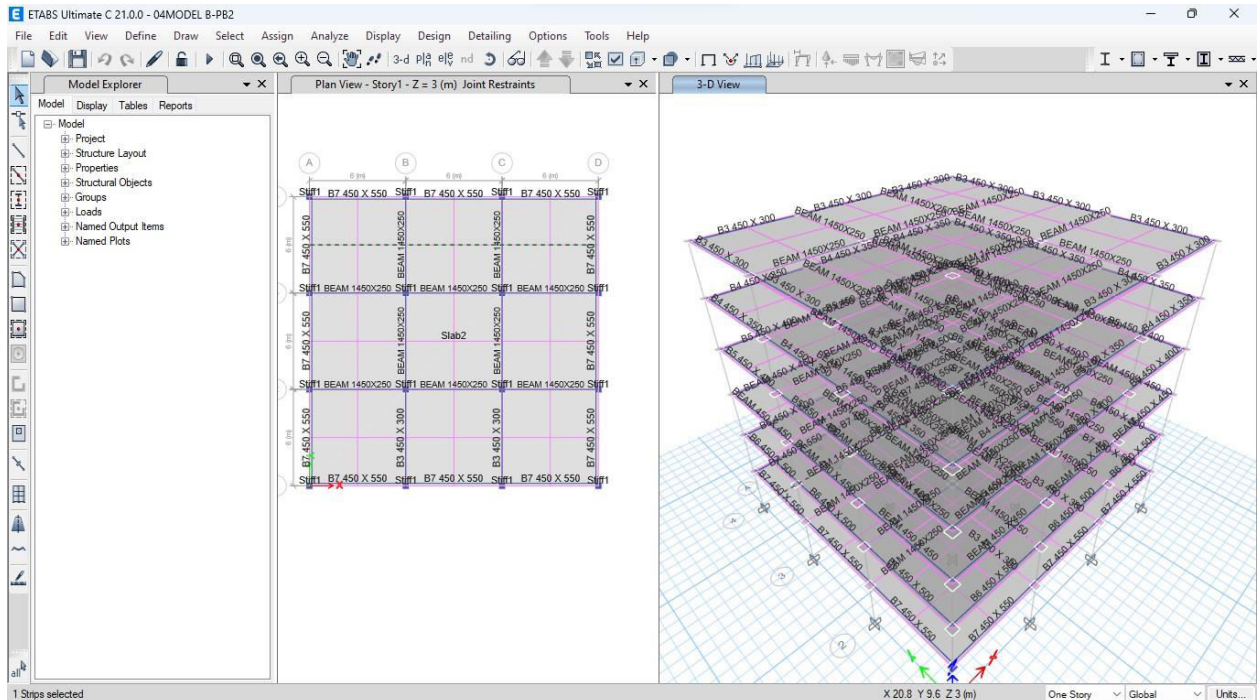
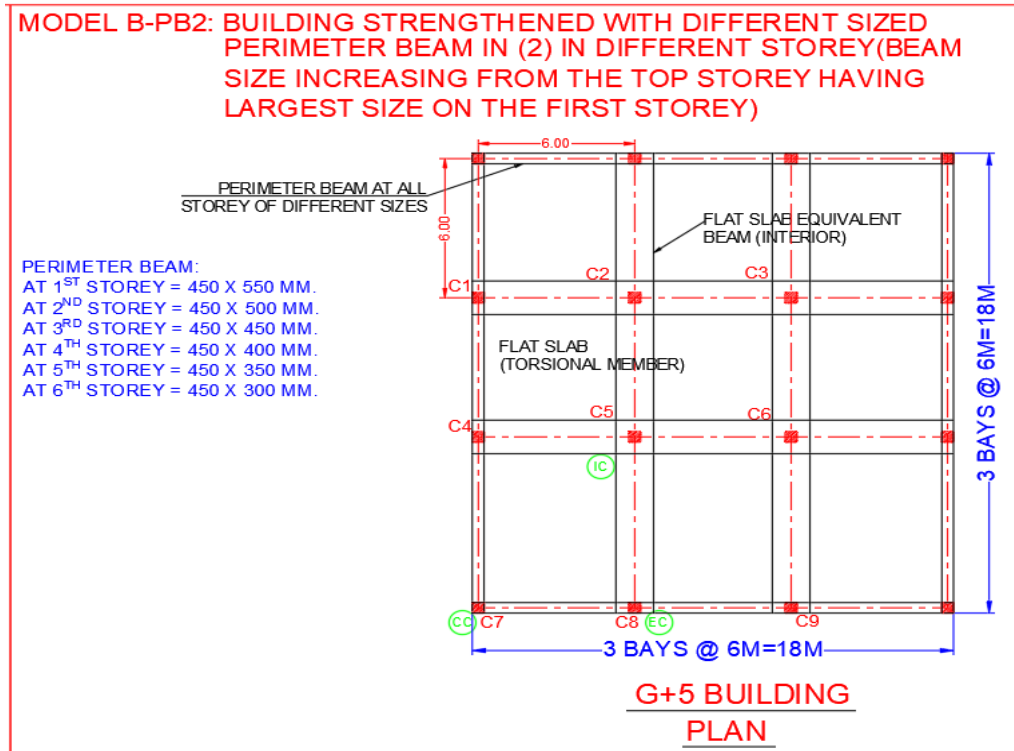
a) Analysis Plan and Model B-NR :



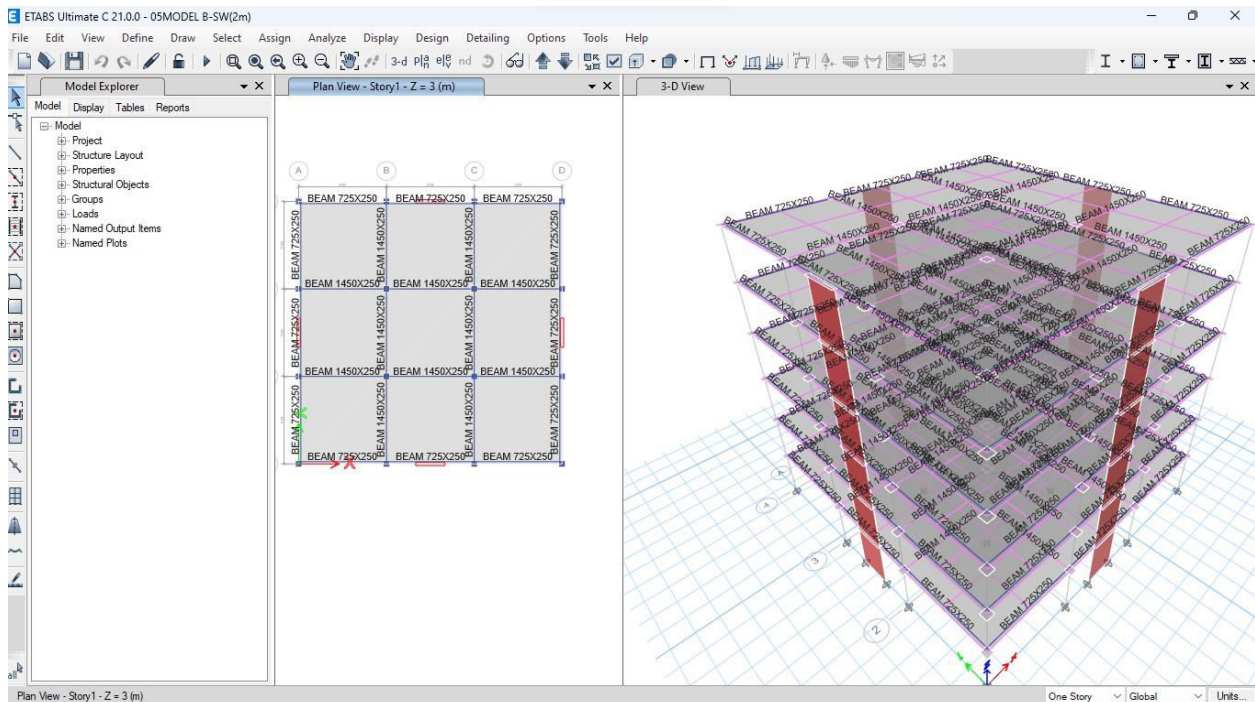
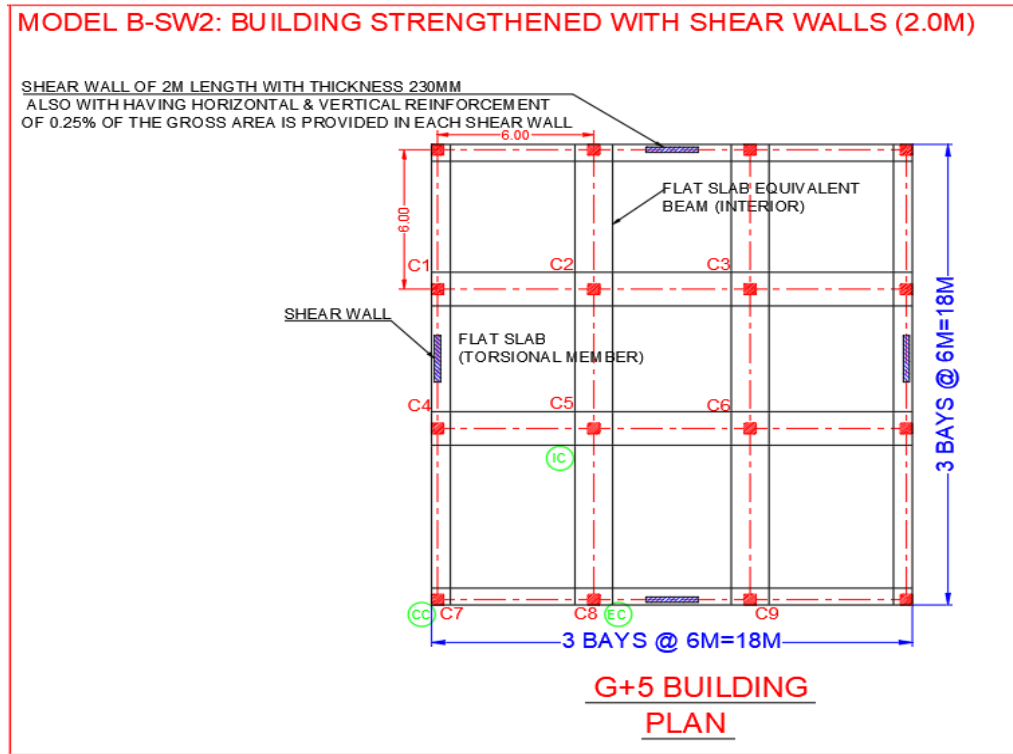
b) Analysis Plan and Model B-PB:



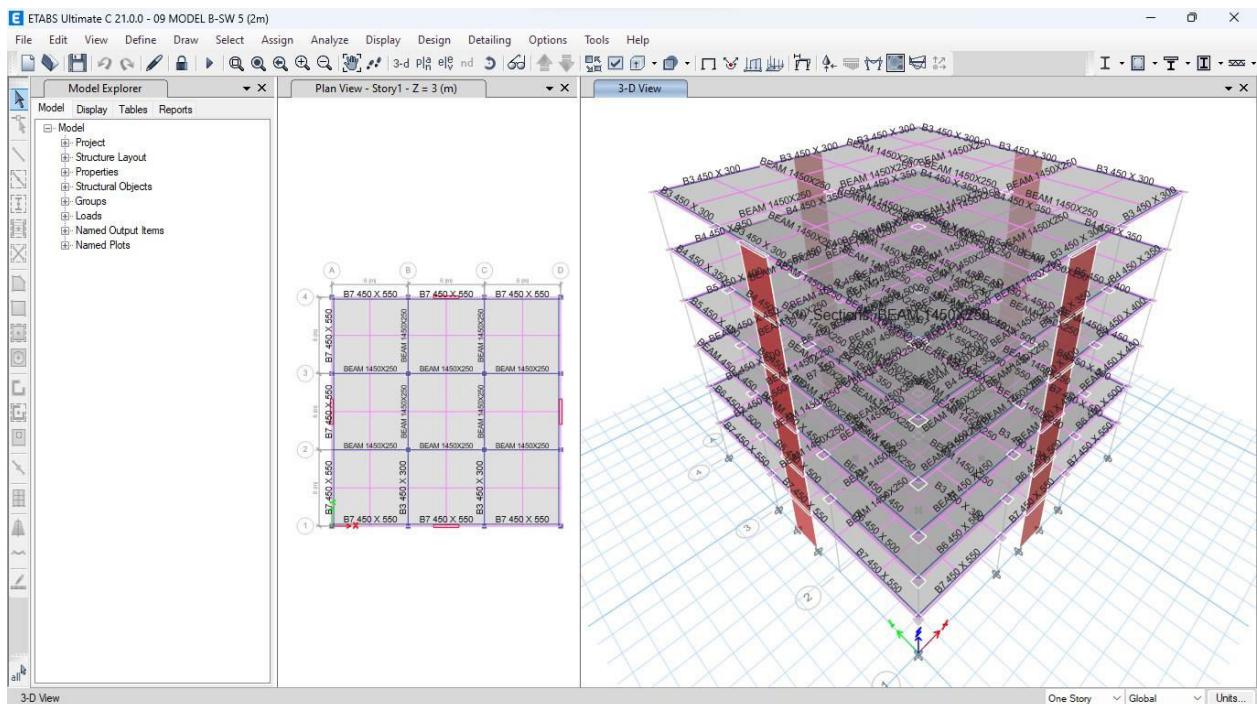
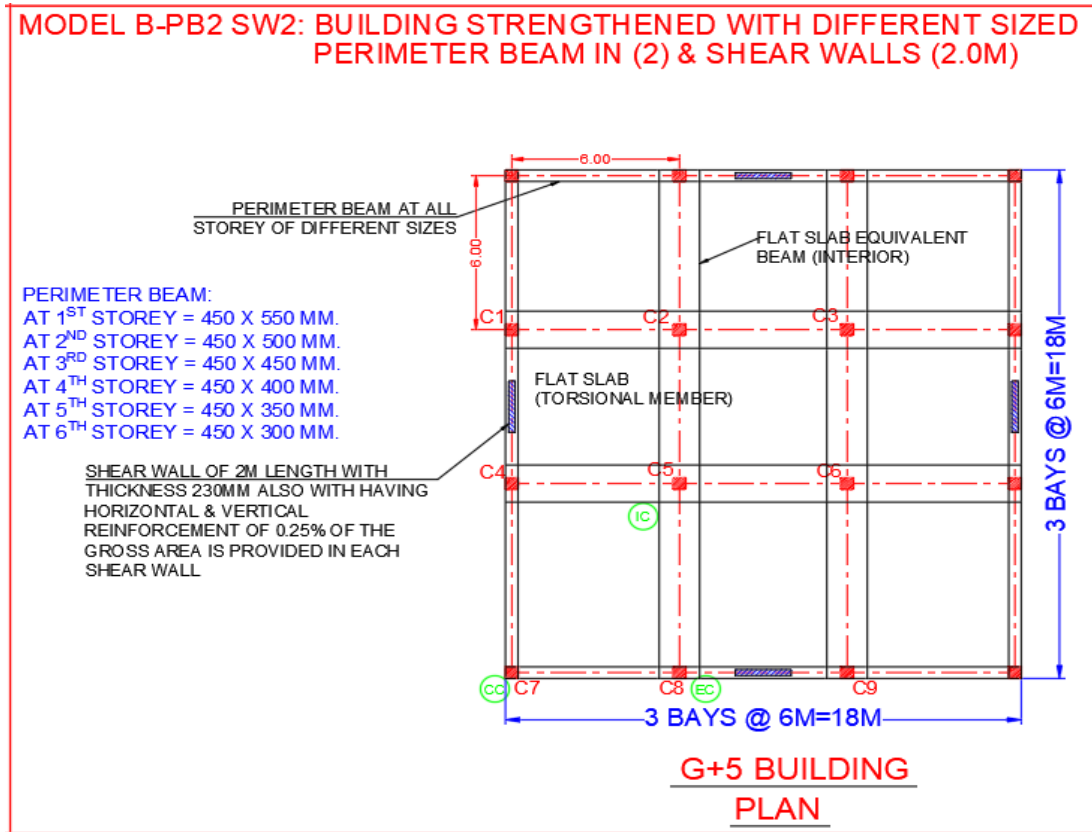
c) Analysis Plan and Model B-PB2:



d) Analysis Plan and Model B-SW2:



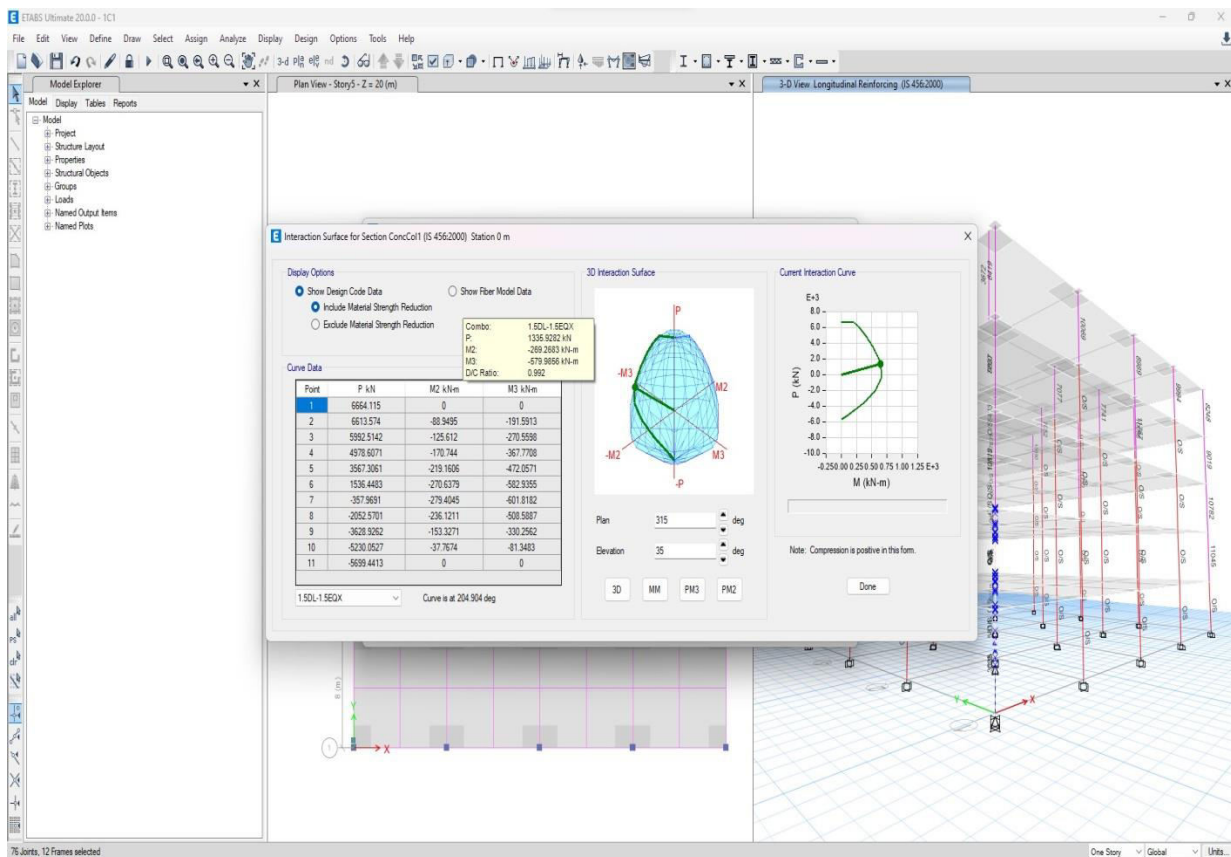
e) Analysis Plan and Model B-PB2SW2:



4.1.2 Steps to find DCR in ETABS:

1. Click on File then import file from ETABS.e2kText file.
2. Select Quick Draw Column then in property select Concrete Column.
3. Select Plan view and click once on column to be removed. Do same process in 3D View.
4. Now go into Assign to Select Joint → Restraints → Fixed → OK.
5. Again go into Assign to Select Joint Loads → Force → Force Global Z = -20KN (↓) → Moment Global XX = 10KNm (→).
6. Start Analysis Run then save the file with suitable file name.
7. Select Define → Load Combinations → 1.5 DL + 1.5 EQX → OK.
8. Click on Design → Concrete Frame Design → Design Combinations → 1.5 DL + 1.5 EQX → OK.
9. Again go in Design → Concrete Frame Design → Start Design Check.
10. Now Left Click on the column to be removed in 3D view. Select Appropriate Load then press on Interaction. Further Select Load Combination → 1.5 DL + 1.5 EQX → D/C Ratio flash on Desktop Screen.

❖ For example DCR Value of Corner Column (CC):



4.2 ASSESSMENT OF PROGRESSIVE COLLAPSE BEHAVIOR UNDER DIFFERENT COLUMN REMOVALS:

A] Comparison of results from Alternate Column Removal:

The aim of this section is to study the response of the simulated flat slab building models subject to static and dynamic (instantaneous) removal of columns.

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Table 4.1: DCR of Column C8 on the removal of CC (C7)

Sr. No.	Type of Building	Static (DCR)	Dynamic (DCR)
1.	B-NR	2.26	1.93
2.	B-PB	2.32	1.975
3.	B-PB2	2.30	1.955
4.	B-SW2	2.04	1.73
5.	B-PB2SW2	2.06	1.735

Table 4.2: DCR of Column C2 on the removal of IC (C5)

Sr. No.	Type of Building	Static (DCR)	Dynamic (DCR)
1.	B-NR	2.535	2.155
2.	B-PB	2.52	2.145
3.	B-PB2	2.5	2.125
4.	B-SW2	2.19	1.865
5.	B-PB2SW2	2.16	1.835

Table 4.3: DCR of Column C4 on the removal of IC (C5)

Sr. No.	Type of Building	Static (DCR)	Dynamic (DCR)
1.	B-NR	2.255	1.935
2.	B-PB	2.295	1.96
3.	B-PB2	2.275	1.94
4.	B-SW2	2.055	1.75
5.	B-PB2SW2	2.04	1.73

Table 4.4: DCR of Column C5 on the removal of EC (C8)

Sr. No.	Type of Building	Static (DCR)	Dynamic (DCR)
1.	B-NR	2.395	2.035
2.	B-PB	2.385	2.025
3.	B-PB2	2.365	2.005
4.	B-SW2	2.145	1.795
5.	B-PB2SW2	2.115	1.765

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Table 4.5: DCR of Column C7 on the removal of EC (C8)

Sr. No.	Type of Building	Static (DCR)	Dynamic (DCR)
1.	B-NR	2.305	1.995
2.	B-PB	2.37	2.035
3.	B-PB2	2.35	2.015
4.	B-SW2	2.08	1.76
5.	B-PB2SW2	2.065	1.74

Table 4.6: DCR of Column C9 on the removal of EC (C8)

Sr. No.	Type of Building	Static (DCR)	Dynamic (DCR)
1.	B-NR	2.125	1.86
2.	B-PB	2.205	1.91
3.	B-PB2	2.185	1.89
4.	B-SW2	1.045	1.035
5.	B-PB2SW2	1.04	1.025

B] Comparison of results from simultaneous and sequential column removal:

This section aims to investigate the effect of the removal sequence on the structural response of the building. Building models are exposed to simultaneous (at once) Dynamic column removals, ignoring the time lag between removals and sequential dynamic removal of columns, taking into account the time lag between removals.

Table 4.7: DCR of column C4 when CC, EC and IC are instantaneously removed in Simultaneous and Sequential manner

Sr. No.	Type of Building	Column removal	DCR of C4	
			Simultaneous	Sequential
1.	B-NR	CC	1.93	1.93
		CC, EC	2.38	2.57
		CC,EC,IC	3.665	3.99
2.	B-PB	CC	1.975	1.975
		CC, EC	2.465	2.69
		CC,EC,IC	3.76	4.075
3.	B-PB2	CC	1.955	1.955
		CC, EC	2.445	2.67
		CC,EC,IC	3.74	4.055
4.	B-SW2	CC	1.73	1.73
		CC, EC	1.91	2.02
		CC,EC,IC	2.555	2.745

5.	B-PB2SW2	CC	1.735	1.735
		CC, EC	1.905	2.045
		CC,EC,IC	2.57	2.74

Table 4.8: DCR of column C9 when CC, EC and IC are instantaneously removed in Simultaneous and Sequential manner

Sr. No.	Type of Building	Column removal	DCR of C9	
			Simultaneous	Sequential
1.	B-NR	CC	1	1
		CC, EC	2.245	2.515
		CC,EC,IC	2.825	3.215
2.	B-PB	CC	1	1
		CC, EC	2.345	2.57
		CC,EC,IC	2.905	3.305
3.	B-PB2	CC	1	1
		CC, EC	2.325	2.55
		CC,EC,IC	2.885	3.285
4.	B-SW2	CC	1	1
		CC, EC	1.025	1.025
		CC,EC,IC	1.05	1.05
5.	B-PB2SW2	CC	1	1
		CC, EC	1.02	1.02
		CC,EC,IC	1.045	1.045

Table 4.9: DCR of column C2 when CC, EC and IC are instantaneously removed in Simultaneous and Sequential manner

Sr. No.	Type of Building	Column removal	DCR of C2	
			Simultaneous	Sequential
1.	B-NR	CC	1	1
		CC, EC	1	1
		CC,EC,IC	1.86	1.89
2.	B-PB	CC	1	1
		CC, EC	1	1
		CC,EC,IC	1.85	1.88
3.	B-PB2	CC	1	1
		CC, EC	1	1
		CC,EC,IC	1.83	1.86
4.	B-SW2	CC	1	1
		CC, EC	1	1
		CC,EC,IC	1.64	1.67

5.	B-PB2SW2	CC	1	1
		CC, EC	1	1
		CC,EC,IC	1.61	1.64

Table 4.10: DCR of column C6 when CC, EC and IC are instantaneously removed in Simultaneous and Sequential manner

Sr. No.	Type of Building	Column removal	DCR of C6	
			Simultaneous	Sequential
1.	B-NR	CC	1	1
		CC, EC	1	1
		CC,EC,IC	2.06	2.1
2.	B-PB	CC	1	1
		CC, EC	1	1
		CC,EC,IC	2.05	2.09
3.	B-PB2	CC	1	1
		CC, EC	1	1
		CC,EC,IC	2.03	2.07
4.	B-SW2	CC	1	1
		CC, EC	1	1
		CC,EC,IC	1.85	1.89
5.	B-PB2SW2	CC	1	1
		CC, EC	1	1
		CC,EC,IC	1.82	1.86

V. CONCLUSION

1. The progressive collapse potential of simulated flat slab building models under static and dynamic (instantaneous) column removal is assessed and compared.
2. The static analysis results for the building without any strengthening measures, B-NR, showed the development of progressive collapse in the critical columns as their DCR values of sectional forces exceeded the limit of 2.0 in all the scenarios of column removal.
3. According to the analysis results, the DCR of sectional forces at the column removal locations are found to be greater for static analysis than for dynamic analysis.
4. The calculated DCR values of sectional forces for critical columns in all studied models subjected to simultaneous and sequential column removal are found to be quite large and exceeded the acceptance criteria.
5. The numerical results also showed that for sequential removal, the DCR of sectional forces at the column removal locations are greater than for simultaneous removal.

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