Progressive Collapse Analysis of RC Structure with Shear Walls

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Abstract - *When a structure is exposed to natural hazards such as earthquakes, high winds, Tsunamis, and so on, or man-made hazards such as fire, gas explosions, vehicle collisions, terrorist attacks, and so on, its stability is compromised. Progressive Collapse refers to the process of local failure leading to global failure. In this study, an RCC structure with "S" shaped plan with shear walls is used for Progressive Collapse analysis. According to General Service Administration (G.S.A.) guidelines, the columns are removed one by one at the interior, exterior, and corner regions. Linear dynamic analysis is performed using the ETABS software version 15.2. In the critical region of the structure associated with the column removal, the Demand Capacity Ratio (DCR) and Interaction Ratio are calculated. According to the literature review, the most critical case for progressive failure is interior column removal at the base, and the least critical case is corner column removal at the base.*

Key Words: Progressive Collapse, Column Removal, Demand Capacity Ratio, ETABS, GSA Guidelines, DOD Guidelines, Interaction Ratio, Linear static Analysis

1.INTRODUCTION

Structures are built to withstand extreme forces and stresses. However, when the load acting on an element exceeds its ultimate value, a member fails. When a load-bearing structural member in a building fails, it causes the failure of some other adjacent members, and the failure of those adjacent members causes the failure of some more adjacent or higher storey members, and so on until the entire structure fails. This is known as Progressive-Collapse or Progressive Failure.

The analysis can be performed by removing one or more vertical load carrying elements. Extreme loading of normal and abnormal loads causes progressive failure. The main cause of progressive failure is abnormal loads, which include gas explosion loads, wind overpressure loads, blast loads, earthquake loads, and so on. When a building is subjected to abnormal loads, the structural elements are the first to be damaged. When a vertical member, such as a column, is damaged due to a sudden impact of load, the load is distributed to other adjacent or neighboring elements. If the adjacent members are strong enough to withstand the additional load There will be no failure, but if they cannot, a member will fail.

1.1 Prevention of Progressive collapse

1. The structure should be designed as a redundant structure, so that if any of the columns fails, there is another way to distribute the loads effectively and the structure can withstand the loss of any member.

2. Providing local resistance, which entails using some extra elements to connect the structural elements so that the structure can effectively transfer or redistribute forces.

3. The members should be effectively interconnected so that forces can transfer without causing any damage. This is nothing more than increasing redundancy or local resistance.

1.2 General Service Administration (GSA) Guidelines

The main goal of this guideline is to ensure that the failure occurs at the beginning, which is referred to as a local failure, and that this local failure is limited to some damage less point so that the global failure, or whole structure failure, can be stopped. First, this guidance provides an analysis procedure to determine whether or not the building is safe based on building usage, load, and other parameters. If the structure passes the analysis, it is referred to as safe; otherwise, columns are removed at specific locations and the results are evaluated to ensure the structure's resistance to progressive collapse.

GSA specifies column removal locations as

1. exterior column removal in buildings in both the longer and shorter directions.

2. Building interior column removal.

3. Building corner column removal

1.3 Load Combinations as per GSA Guidelines

1. Before column removal the load combination to be considered is DL+LL
2. After column removal for linear static analysis the load combination to be considered is 2(DL+0.25LL)
3. After column removal for linear dynamic analysis the load combination to be considered is DL+0.25LL

1.4 Linear Dynamic analysis

1. It is appropriate for structures subjected to abnormal loads because it is a dynamic phenomenon. As a result, dynamic analysis becomes necessary.
2. Even though dynamic analyses are avoided because they are complex and time consuming, they have a higher accuracy level than static analyses because they account for amplification factors, inertia, and damping forces
3. It is also known as Time History analysis and is a step-by-step procedure for determining the dynamic response of a structure to specific loading that may vary over time.
4. In this analysis the load combination is (DL + 0.25LL)
5. The D-C Ratio of structural members is used to differentiate results.
6. The disadvantage is that the non-linearity of geometry and material is not taken into account.

1.5 Steps in brief for software

1. Create a computer model with the necessary configuration.
2. Remove the columns from the designated locations.
3. Run the analysis using the dynamic load combination specified by G.S.A
4. The time history function is used with a zero-starting condition.
5. Determine the D-C ratio of the structural members based on the peak value calculated from the time history response.

1.6 Demand Capacity Ratio (DCR)

The G.S.A classifies structural members as safe or unsafe based solely on D-C Ratio values. If the D-C Ratio value is within the acceptable range, it is safe; otherwise, it is unsafe. It is defined as the ratio of "force acting on the structural member to the member's ultimate capacity".

D-C Ratio = $P_{ULTIMATE}$ / P_{ACTING}
Where, P_{ACTING} denotes the force acting on the element. It could be any kind of force, such as a bending moment, shear force, or axial load.

$P_{ULTIMATE}$ = The member's ultimate force or capacity in terms of Shear force or axial load. G.S.A limits the permissible value of G.S.A

For typical structures to D-C Ratio= 2.0.
For atypical structures, D-C Ratio=1.5
The linear analysis D-C Ratio is used to determine member safety against collapse as well as for nonlinear analysis. The rotation of the plastic hinge and the displacement ductility ratio are used.

1.7 Interaction Ratio

As the analysis is a three-dimensional frame analysis, the columns in this case are subjected to axial load and biaxial moment. Bi-axial bending is more prevalent in the building's corner columns. Even though the exact design is difficult, these columns are designed using the Interaction ratio. The design should be done for the respective load combinations, such as (DL +LL) before column removal and 2(DL + 0.25 LL) after column removal. The flexure details, such as rebar percentage, Axial-load, and moments, are then recorded.

[MUX / MUX1] n + [MUY / MUY1] n 1.00 is the interaction formula.
Where, MUX and MUY are the moments about the x and y axes caused by the design load.
MUX1 and MUY1 are the maximum uniaxial moments for axial loads about the x and y axes, respectively.
0.45 fck Ac + 0.75 fy = Puz Asc
Where, fck and fy are the concrete and steel characteristic strengths, respectively.
Ac and Asc represent the concrete and steel areas, respectively.

2.1 Methodology

To grasp the concept of progressive failure, different columns are removed from various locations, and variations in Bending-moment, Axial-load, and interaction ratio are observed from floor to floor.

The structure is in the shape of an "S" with basement floor, ground floor, and 20 storeys, with bay sizes of 5 meters in the X direction and 4 meters in the Y direction. The height of typical storey are 3.2 meters, and the height of Base storey is 3.1 meters. The dimensions of the beams remain constant across all storeys, but the dimensions of the columns decrease as the floor rises, giving the building geometric irregularity.

The load combinations are taken according to G.S.A guidelines, which are (DL +LL) for before column removal cases and 2(DL + 0.25 LL) for the case after column removal.

The model was created using ETAB software

The Details of the building are as follows

1. Material Information
   a. Grade of Concrete –M30 and M25
   b. Grade of steel – Fe 550 and Fe415
   c. Poisson's ratio – 0.20
2. Beam Dimension – 230mm X 450mm
3. Slab thickness – 150mm
4. Wall thickness – 230mm
5. Column dimensions
   a. 300mm X 1000mm for 1st to 2nd Storey
   b. 300mm X 900mm for 3rd to 4th Storey
   c. 300mm X 750mm for 5th to 16th Storey
   d. 300mmX450mm for 17th to 23rd Storey
6. Load considerations
   a. Dead Load – Self weight of the member
   b. Live load – 3 KN/m
   c. Floor finish – 1 KN/m
   d. Wall load for 230mm AAC Block– 3.86 KN/m
   e. Parapet wall load – 1.72 KN/m

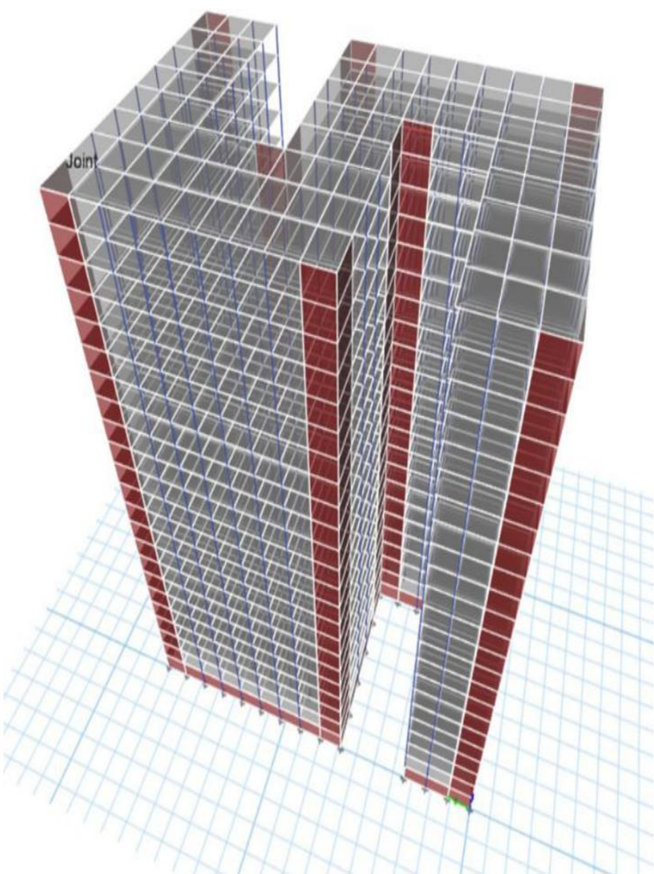

Fig -1: 3D Model of 22 Storey "S" shaped building

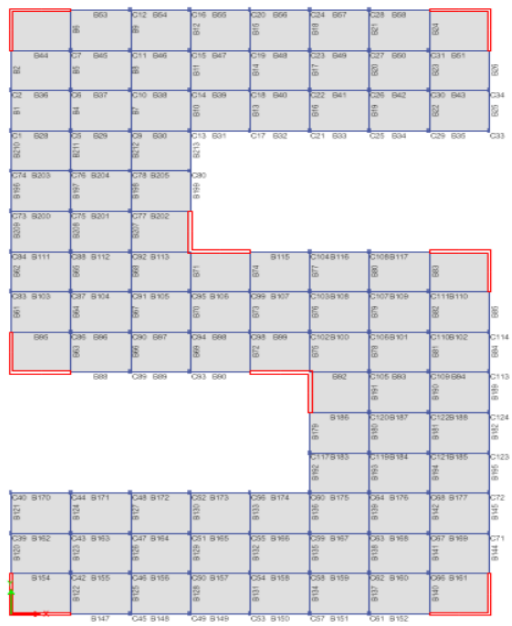

Fig -2: Plan of S shaped building

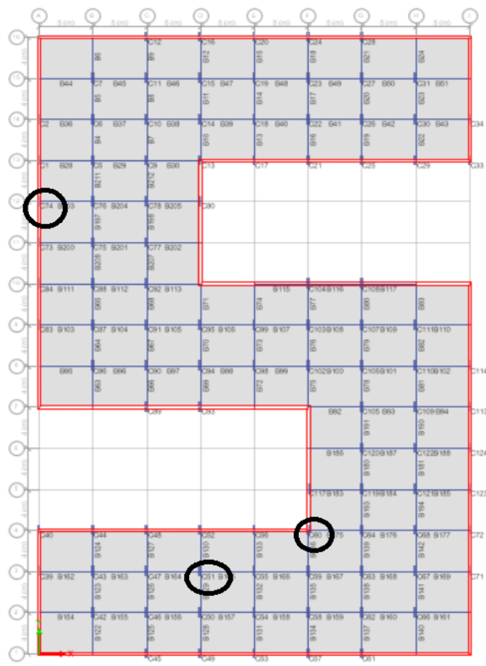

Fig -3: Plan showing locations of column removal

2.2 Results and Discussions

Case 1: Removal of Exterior column C74 at Storey 2

For this case DCR of beams B203, B196, B210 and Interaction ratio of columns C73, C76, C1 needs to be considered.

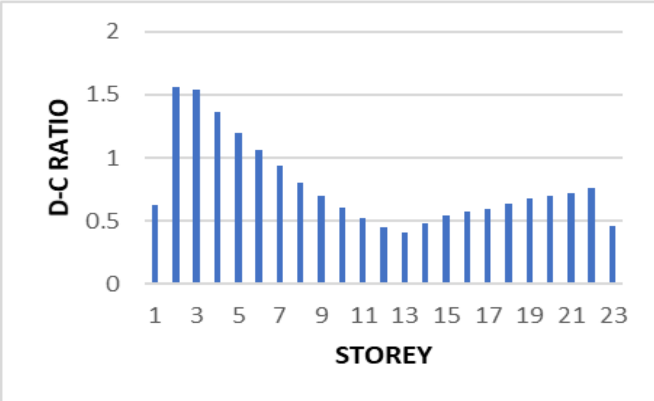

Chart -1: D-C Ratio v/s Storey for Beam B203

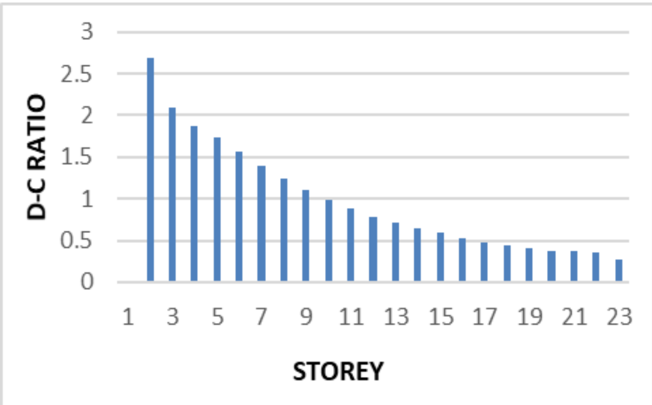

Chart -2: D-C Ratio v/s Storey for Beam B196

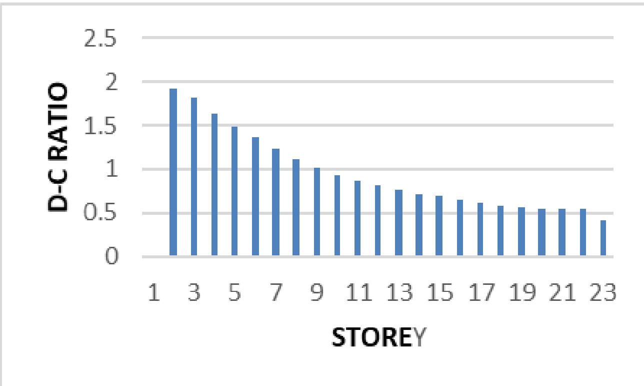

Chart -3: D-C Ratio v/s Storey for Beam 210

Table -1: Interaction Ratio after removal of column C 74

INTERACTION RATIO AFTER REMOVAL OF COLUMN C74				
Storey	Dimension in (mm)	I.R for Column C 73	I.R for Column C1	I.R for Column C 76
1	300X1000	0.99	0.99	0.99
2	300X1000	0.99	0.99	0.99
3	300X900	0.99	0.99	0.99
4	300X900	1.05	0.99	1.05
5	300X750	1.04	1.05	0.104
6	300X750	1	1.04	1
7	300X750	0.99	1	0.99
8	300X750	0.99	0.99	1
9	300X750	0.99	1	0.99
10	300X750	0.99	0.99	1
11	300X750	0.99	1	0.99
12	300X750	0.99	0.99	0.99
13	300X750	0.99	0.99	1
14	300X750	0.99	0.99	0.99
15	300X750	0.99	0.99	1
16	300X750	0.99	0.99	0.99
17	300X450	0.99	0.99	0.99
18	300X450	0.99	0.99	0.99
19	300X450	0.99	0.99	0.9
20	300X450	0.98	0.98	0.74
21	300X450	0.96	0.97	0.46
22	300X450	0.96	0.98	0.295
23	300X450	0.95	0.98	0.176

In this case, the DCR value of beam 209 is exceeding the permissible value 1.5 in storeys 2 to 3except other stories, the DCR value of Beam 196 and 210 is exceeding the permissible value 1.5 in storeys 2 to 6 and lies within limits for remaining storeys. From table 1 we can observe that the interaction ratio of columns adjacent to the removed column lies within the permissible value 1.0

Case 2: Removal of Corner column C 60 at storey 2

For this case DCR of beams B174, B175, B136, B192 and Interaction ratio of columns C56, C64, C59, C117 needs to be considered.

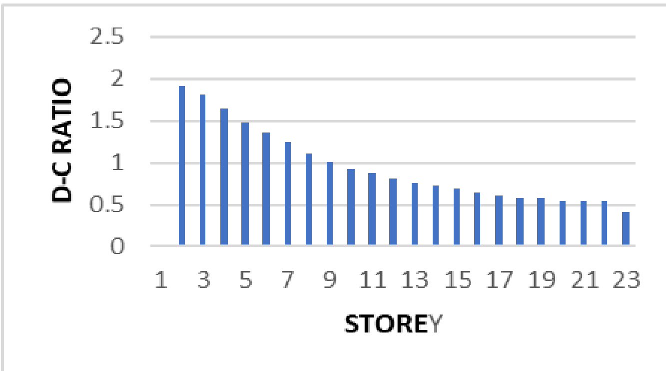

Chart-4 : D-C Ratio V/S Storey for Beam 175

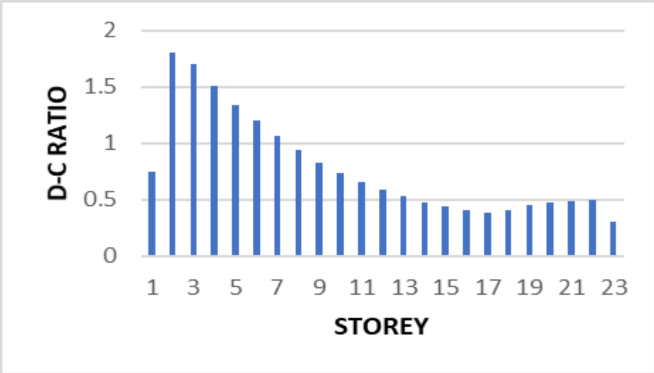

Chart -5: D-C Ratio v/s Storey for Beam B174

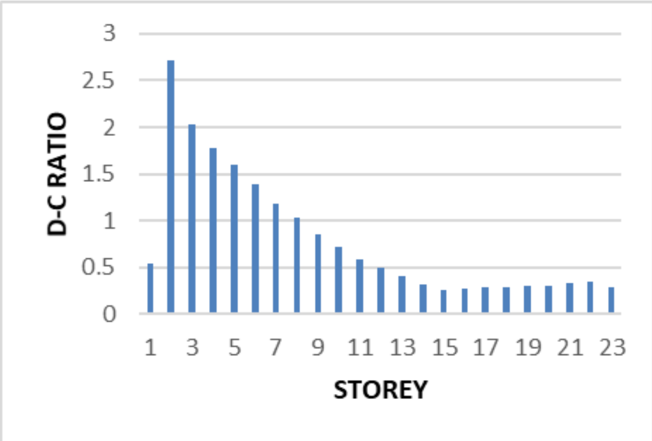

Chart-6 : D-C Ratio V/S Storey for Beam 136

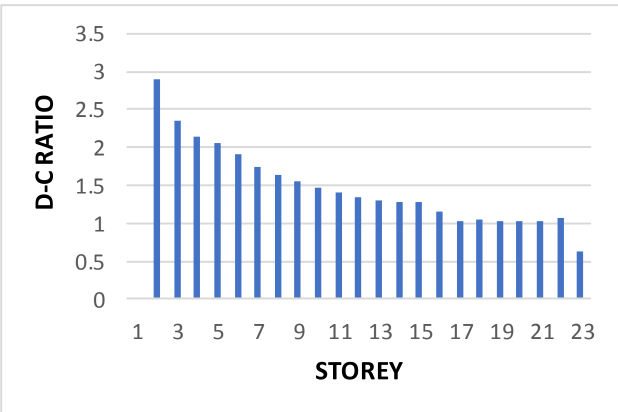

Chart-7 : D-C Ratio V/S Storey for Beam 192

Table -2: Interaction Ratio after removal of column C 60

INTERACTION RATIO AFTER REMOVAL OF COLUMN C60					
Storey	Dimension in (mm)	I.R for Column C 56	I.R for Column C64	I.R for Column C 59	I.R for Column C 117
1	300X1000	0.99	0.99	0.99	0.91
2	300X1000	0.99	0.99	0.99	0.99
3	300X900	0.99	0.99	0.99	0.99
4	300X900	0.99	1	1.03	1.05
5	300X750	1	1.032	1.04	1.04
6	300X750	1.03	1	1.04	1
7	300X750	1	0.99	0.99	0.99
8	300X750	0.99	1.03	1.04	1
9	300X750	1.03	0.99	1	0.99
10	300X750	0.99	0.99	0.99	0.99
11	300X750	0.99	1	0.99	0.99
12	300X750	0.99	0.99	0.99	0.99
13	300X750	1	0.99	0.99	0.99
14	300X750	0.98	0.99	0.99	0.99
15	300X750	0.99	0.99	0.99	0.99
16	300X750	0.96	0.99	0.99	0.99
17	300X450	0.99	0.99	1	0.99
18	300X450	0.93	.99.99	0.99	0.99
19	300X450	0.88	0.92	0.89	0.99
20	300X450	0.64	0.64	0.62	0.99
21	300X450	0.55	0.55	0.45	0.99
22	300X450	0.45	0.3	0.28	0.99
23	300X450	0.76	0.14	0.16	0.98

In this case, the DCR value of beam B174 and B175,B136,ffff are exceeding the permissible value 1.5 in storeys 2,3,4,5 except other storey, DCR value of beam 192 is exceeding the permissible value 1.5 in storeys 1 to 9 and lies within limits for remaining storeys.

From Table 2 we can observe that the Interaction ratio of columns adjacent to the removed column lies within the permissible value 1.0

Case 3: Removal of interior column C 51 at storey

For this case DCR of beams B164, B165, B129, B130 and Interaction ratio of columns C47, C55, C50, C52 needs to be considered.

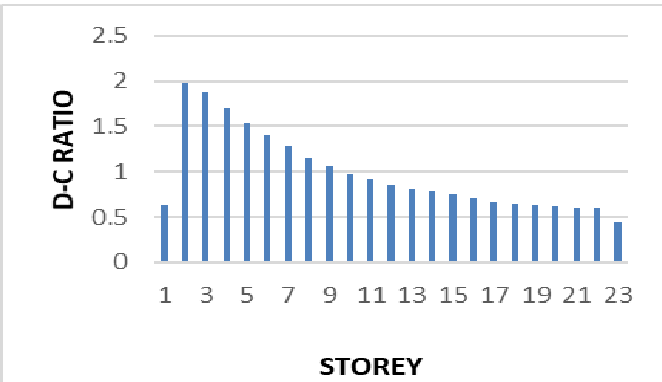

Chart -8: D-C Ratio v/s Storey for Beam B164

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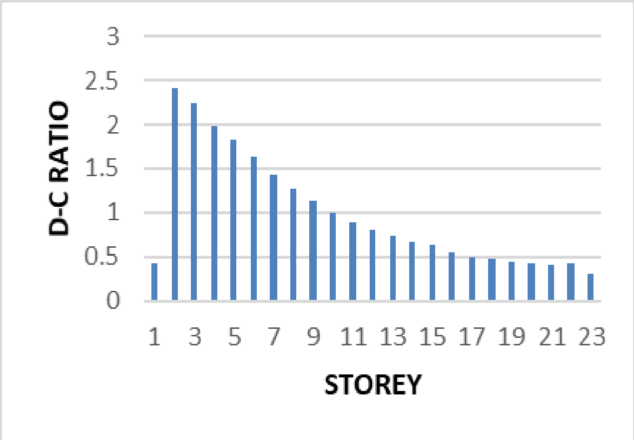

Chart -9: D-C Ratio v/s Storey for Beam B165

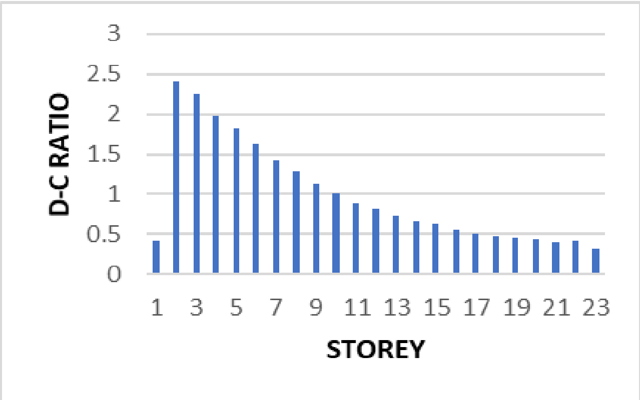

Chart -10: D-C Ratio v/s Storey for Beam B129

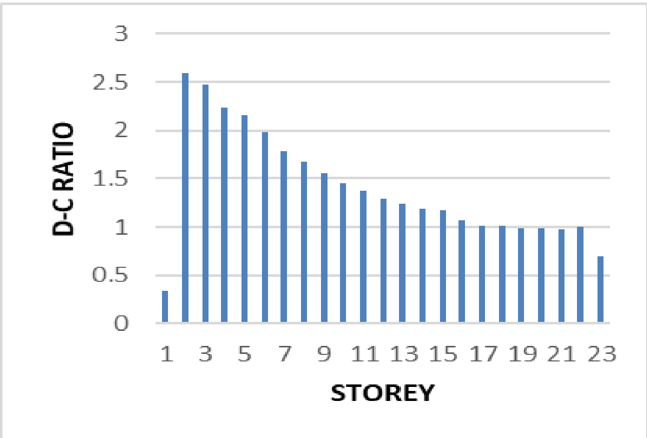

Chart -11: D-C Ratio v/s Storey for Beam B130

Table -3: Interaction Ratio after removal of column C 51

INTERACTION RATIO AFTER REMOVAL OF COLUMN C51					
Storey	Dimension in (mm)	I.R for Column C 47	I.R for Column 55	I.R for Column C 50	I.R for Column C 52
1	300X1000	0.99	0.99	0.99	0.99
2	300X1000	0.99	0.99	0.99	0.99
3	300X900	0.99	0.99	0.99	0.99
4	300X900	0.99	1	1.04	0.99
5	300X750	1.04	1.03	1.04	1
6	300X750	0.99	1	1.04	1
7	300X750	0.99	0.99	0.99	0.99
8	300X750	1	1.04	1.04	1
9	300X750	0.99	0.99	1	1
10	300X750	1	0.99	0.99	0.99
11	300X750	0.99	0.99	0.99	0.99
12	300X750	0.99	0.99	0.99	0.99
13	300X750	0.99	1	0.99	0.99
14	300X750	0.99	0.99	0.99	0.99
15	300X750	0.99	0.99	0.99	0.99
16	300X750	0.94	0.99	0.99	0.99
17	300X450	0.96	0.99	0.99	0.99
18	300X450	0.92	0.99	0.99	0.99
19	300X450	0.85	0.93	0.99	0.99
20	300X450	0.63	0.62	0.68	0.67
21	300X450	0.51	0.45	0.54	0.57
22	300X450	0.55	0.33	0.41	0.44
23	300X450	0.56	0.39	0.6	0.79

In this case, the DCR value of all beam B164, B165, B129, are exceeding the permissible value 1.5 in storeys 2 to 5 and lies within the limit for other storeys, DCR value of beam 130 is exceeding the permissible value 1.5 in storeys 2 to 9 and lies within limits for remaining storeys

From Table 3 we can observe that the Interaction ratio of columns adjacent to the removed column lies within the permissible value 1.0

3. CONCLUSIONS

1. Vertical structural element failure is more dangerous than horizontal structural element failure.

2. The axial force at the base is greater in the column-removed case than in the normal case, and we can conclude from the comparison of the results of axial force with and without considering dynamic factor that it is better to design the building without considering dynamic factor as that case is more critical.

3. considering dynamic factor that it is better to design the building without considering dynamic factor as that case is more critical.

4. The interior column removal case at the base is discovered to be the most critical case for progressive failure.

5. For the structure under consideration in this paper, the D - C Ratio for beam exceeds the limit only for the upper 2-6 floors; the values for the remaining storeys are within the limit.

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