# Progressive Collapse Analysis of Reinforced Concrete Framed Structure

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**Abstract –** *When the structure is exposed to natural hazards like Tsunami, earthquake, over pressure of wind etc or due to manmade hazards like fire, gas explosion, impact of vehicles, terrorist attacks etc these affects the stability of the structure. The process in which local failure leading to global failure is called Progressive Collapse. In the present study a T shaped RCC structure with 11 storeys is considered for Progressive Collapse analysis. The columns are removed one by one at interior, exterior and corner regions as per the GSA guidelines. Linear static analysis is carried out using ETABS software Ver. 15.2. The Demand Capacity Ratio (DCR) and Interaction ratio is calculated in the critical region of the structure associated with the column removal. The study concluded that the most critical case for progressive failure is found to be interior column removal case at the base and least critical is found to be corner column removal case 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 designed to withstand some ultimate forces or stresses. But when load acting on an element increases beyond ultimate value failure of a member occurs. When a load carrying structural member in a building fails it causes the failure of some other adjacent members, and the failure of other member causes failure of some more adjacent or higher storey members, this goes on continuing causing failure o f whole structure. This phenomenon is called Progressive-Collapse or progressive failure. In short it may be defined as the process in which local failure becomes global failure.

The analysis may be carried out by removing one vertical load carrying element or more than one. The main cause of progressive failure is abnormal loads which may be listed as, loads due to gas explosion, vehicle impact loads, loads due to over pressure of wind, Blast loads, Earthquake loads etc.

When building is subjected to any abnormal loads, the structural elements are damaged first. The damage of Vertical structural member is more hazardous than damage of horizontal member. When any vertical member like column got damaged due to sudden impact of load it causes the load distribution to other adjacent or neighboring elements. If the adjacent members have sufficient capacity to withstand additional load then there will be no failure but when they cannot, then the failure of member occurs. When that member fails again its adjacent member should have capacity to withstand or else failure goes on increasing resulting in a chain action of failure causing structural collapse.

Any building has to withstand two types of loads. The load causing structural failure is type 1 and the additional load generated due to failure of one or more structural elements is type 2. The type 1 loads are externally applied or acting loads but type 2 loads are generated internally due to moment of structural elements.

The alternate path method is mainly suggested by G.S.A and DOD guidelines. Here a load carrying structural member is removed at specified locations and failure pattern is observed. The main aim is to ensure weather the adjacent members have sufficient capacity to take additional load and redistribute them accordingly or not.

### 1.1 GENERAL SERVICE ADMINISTRATIONS (GSA) GUIDELINES

The main aim of this guideline is to ensure that failure occurs at the beginning, which is referred as local failure and this local failure should be limited at some damage less point so that global failure i.e. whole structure failure can be stopped.

At first this guideline provides the analysis procedure to ensure weather the building is safe or not based on building usage, load and other parameters. If the building passes the analysis then it is referred as safe otherwise columns are removed at specified locations and results are evaluated to ensure the structure's resistivity against Progressive-Collapse.

GSA Specifies location for column removal as

a. Exterior column removal in buildings longer and shorter directions.
b. Interior column removal of the building.
c. Corner column removal of the building.

The analysis for Progressive-Collapse includes linear static, non linear static, linear dynamic and non linear dynamic analysis.

### 1.2 Load Combinations as per GSA Guidelines

G.S.A mainly uses alternate path method or redundant structure to ensure that Progressive- Collapse does not occur.

a. For linear static analysis, after column removal, the load combination is
   Load acting = 2(DL + 0.25 LL)
   Where,
   DL = Dead Load of structural member
   LL = Live Load acting
   2.0 = Dynamic Amplification factor

b. For linear Dynamic analysis and Non linear static analysis
   Load acting = DL + 0.25 LL
   Where,
   DL = Dead Load of structural member
   LL = Live Load acting

### 1.3 Linear Static analysis

Linear Static analysis is suitable for the materials which are linearly elastic that means materials with same dimension and elastic behavior. It is widely used because it is more simple method to understand and easy to execute. The Load combination used in this method for Progressive-Collapse is
Load acting = 2(DL + 0.25 LL)

The results are differentiated depends on demand capacity ratio which should be less than 2 for typical and 1.5 for atypical structures.

**Steps in Brief for software**

Step 1: Prepare the model with required configurations

Step 2: The model is analyzed with load combination (DL + LL) without removing any columns

Step 3: Now remove the column under consideration as per the GSA guidelines and analyze it with the load combination 2(DL + 0.25 LL)

Step 4: Further from the analysis results obtained, if the DCR for any member is exceeded the allowable limit based on moment and shear force, the member is expected as a failed member

Step 5: If the DCR value exceeds its limit then it will lead to Progressive Collapse

### 1.4 Demand Capacity Ratio (DCR)

G.S.A classifies a structural member as safe or unsafe depending on D-C Ratio values only. If the value of D-C Ratio is in the permissible limit then it is safe otherwise it is to be mentioned as unsafe.
It is defined as the ratio of “force acting on the structural member to ultimate capacity of the member”.

D-C Ratio = $P_{ACTING} / P_{ULTIMATE}$

Where,

$P_{ACTING}$ = Force acting on the element. It may be any type of force like Bending moment, Shear force, or axial load.

$P_{ULTIMATE}$ = Ultimate force or capacity of the member in terms of shear force or axial load.

According to G.S.A, the permissible value of G.S.A is limited to
D-C Ratio<= 2.0 for typical structures
D-C Ratio<=1.5 for atypical structures

For linear analysis the D-C Ratio is used find out member safety against collapse and for non linear analysis Plastic hinge rotation and displacement ductility ratio are used.

### 1.5 Interaction Ratio

The columns in the present case are the columns subjected to Axial-load and Bi-axial moment as the analysis is three dimensional frame analysis. In the corner columns of the building the Bi-axial bending is more predominant. Even though the exact design is difficult, the design of these columns is done with the help of Interaction ratio.

The design should be done for the respective load combinations like before removal of column it should be (DL +LL) and after removal of column it should be 2(DL + 0.25 LL).
Then the flexure details like rebar percentage, Axial-load and moments are taken for respective columns and checked for interaction formula.

The interaction formula is given by

$$[M_{UX} / M_{UX1}]^{\alpha n} + [M_{UY} / M_{UY1}]^{\alpha n} \leq 1.00$$

Where,
$M_{UX}$, $M_{UY}$ = Moments about x and y axis due to design load
$M_{UX1}$, $M_{UY1}$ = Maximum uniaxial moment for Axial-load about x and y axis respectively

Puz = 0.45 fck Ac + 0.75 fy Asc
Where,
fck and fy are the characteristic strength of concrete and steel respectively
Ac and Asc are area of concrete and area of steel

## 2. 1 Methodology

To understand the concept of progressive failure different columns are removed at different locations and variation of Bending-moment, Axial-load and interaction ratio is observed from floor to floor.

The structure considered for analysis is in " T " shape and consists of 11 storeys with bay size of 4 meters in X direction and 4 meters in Y direction. Height of bottom storey is taken as 3.5 meters and height of all remaining storeys is taken as 3.0 meters.

Beams dimensions are maintained constant in all storeys but the column dimensions are reduced with the increase in floor and hence the building can be considered to have geometric irregularity. The loading is taken as per G.S.A guidelines that is (DL +LL) for before removal case and 2(DL + 0.25 LL) for after removal case. The design has been done as per IS: 456 code using ETAB software.

The Details of the building are as follows

1. Material Information
   a. Grade of Concrete – M30
   b. Grade of steel – Fe 500
   c. Poisson's ratio – 0.20
2. Beam Dimension – 230mm X 450mm
3. Slab thickness – 150mm
4. Wall thickness – 230mm
5. Column dimensions
   a. 230mm X 750mm for 1st to 4th Storey
   b. 230mm X 600mm for 5th to 7th Storey
   c. 230mm X 450mm for 8th to 11th Storey
6. Load considerations
   a. Dead Load – Self weight of the member
   b. Live load – 3 KN/m
   c. Floor finish – 1.5 KN/m
   d. Wall load – 13.8 KN/m
   e. Parapet load – 6.9 KN/m

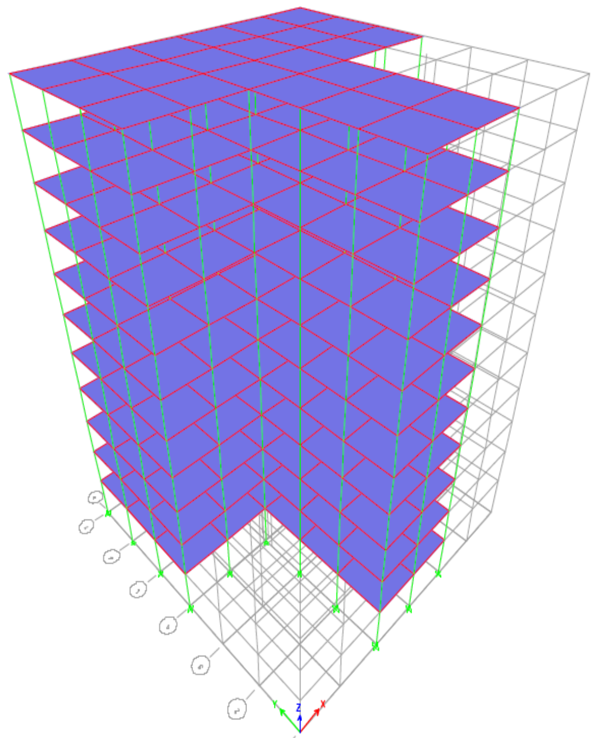

**Fig -1**: 3D Model of 11 Storey T shaped building

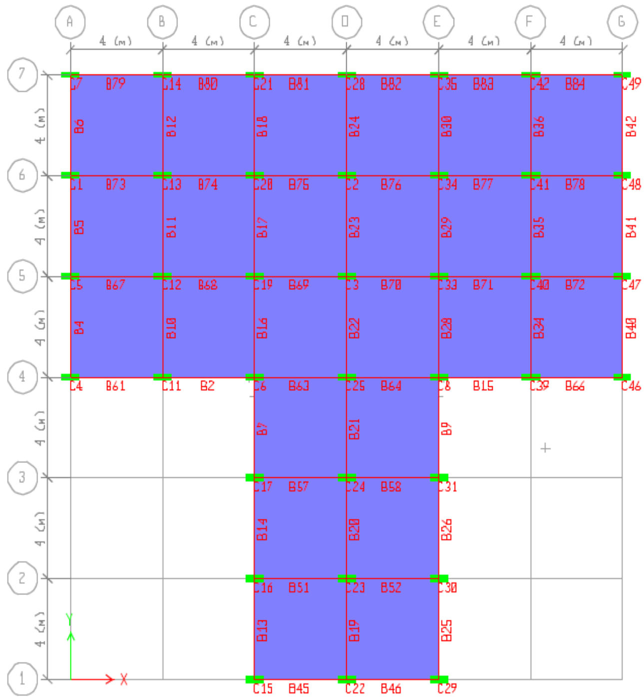


**Fig -2**: Plan of T shaped building

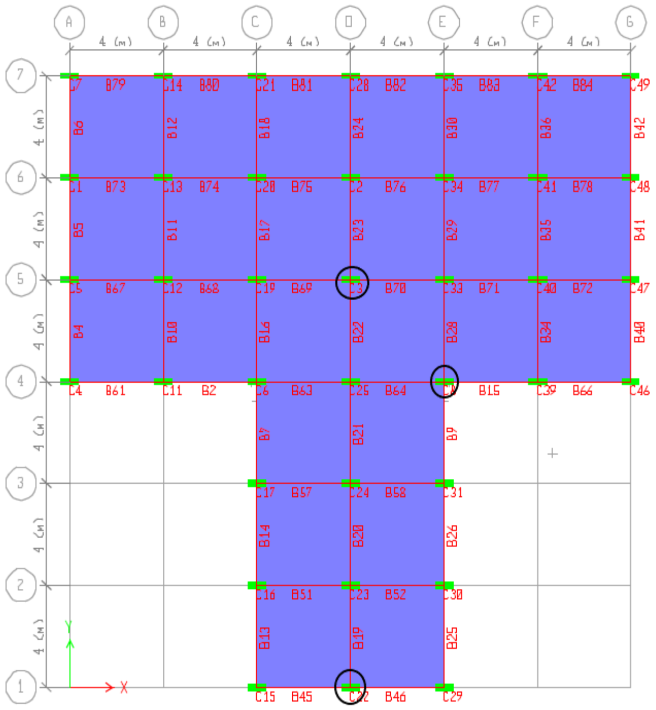

**Fig -3**: Plan showing locations of column removal

## 2. 2 Results and Discussions

### Case 1: Removal of Exterior column C22 at base

For this case DCR of beams B19, B45, B46 and Interaction ratio of columns C15, C23, C29 needs to be considered.

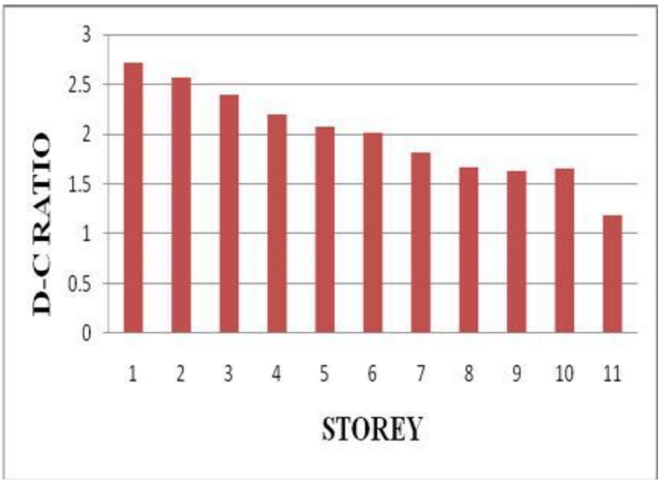


**Chart -1**: D-C Ratio v/s Storey for Beam B45

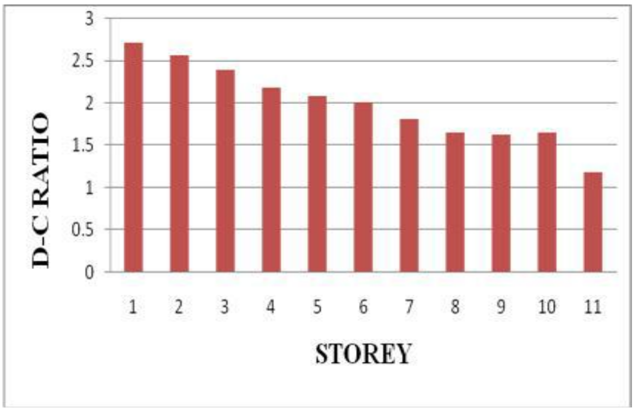


**Chart -2**: D-C Ratio v/s Storey for Beam B46


**Chart -3**: D-C Ratio v/s Storey for Beam B19

**Table -1:** Interaction Ratio after removal of column C 22

| Sl . No | Dimension In mm | I.R for Col C15 | I.R for Col C29 | I.R for Col C23 |
|---|---|---|---|---|
| 1 | 230 X 750 | 0.86 | 0.57 | 0.7 |
| 2 | 230 X 750 | 0.80 | 0.88 | 0.84 |
| 3 | 230 X 750 | 0.85 | 0.77 | 0.88 |
| 4 | 230 X 750 | 1.00 | 1.02 | 0.95 |
| 5 | 230 X 600 | 0.89 | 0.98 | 0.92 |
| 6 | 230 X 600 | 0.88 | 0.70 | 0.90 |
| 7 | 230 X 600 | 0.89 | 0.76 | 0.90 |
| 8 | 230 X 450 | 1.00 | 0.70 | 0.97 |
| 9 | 230 X 450 | 0.98 | 0.75 | 0.95 |
| 10 | 230 X 450 | 0.96 | 0.79 | 0.99 |
| 11 | 230 X 450 | 1.00 | 0.76 | 0.98 |

In this case, the DCR value of beam B45 and B46 is exceeding the permissible value 1.5 in all storeys except $11^{th}$ storey, DCR value of beam B19 is exceeding the permissible value 1.5 in storeys 1 to 4 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 8 at base**

For this case DCR of beams B64, B15, B9, B28 and Interaction ratio of columns C25, C39, C31, C33 needs to be considered.

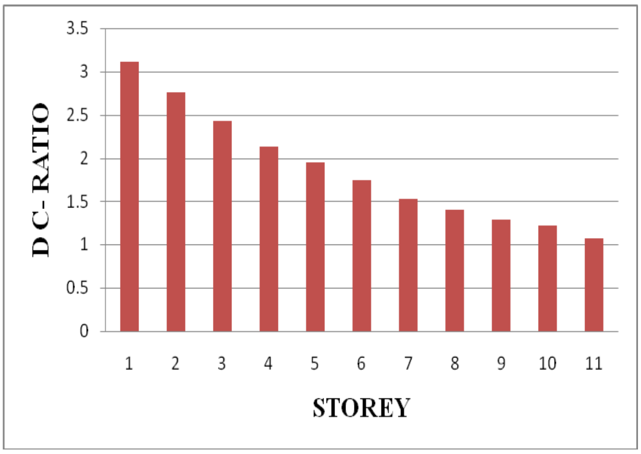


**Chart -4**: D-C Ratio v/s Storey for Beam B64

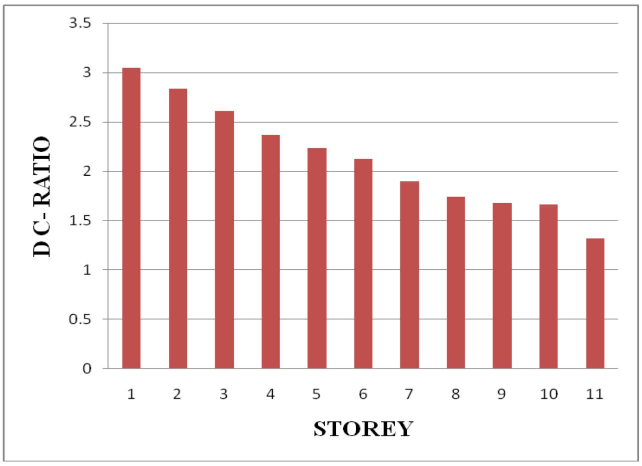


**Chart -5**: D-C Ratio v/s Storey for Beam B15

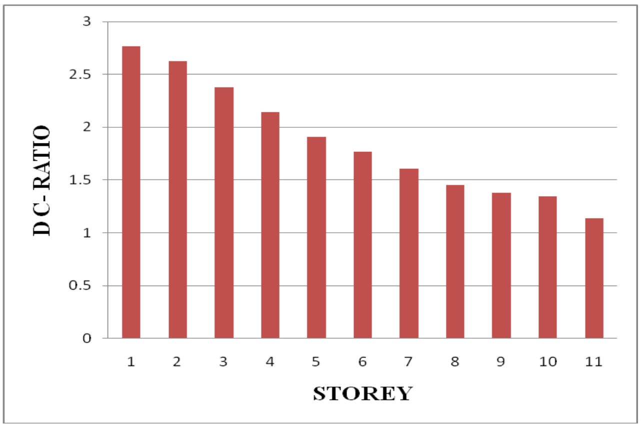


**Chart -6**: D-C Ratio v/s Storey for Beam B09

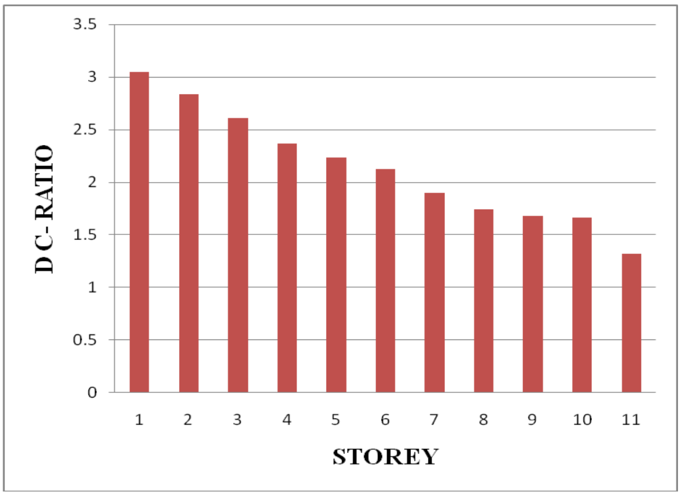


**Chart -7**: D-C Ratio v/s Storey for Beam B28

**Table -2:** Interaction Ratio after removal of column C 8

| Sl . No | Dimension In mm | I.R for Col C25 | I.R for Col C39 | I.R for Col C31 | I.R for Col C33 |
|---|---|---|---|---|---|
| 1 | 230 X 750 | 0.74 | 0.54 | 0.64 | 0.79 |
| 2 | 230 X 750 | 0.86 | 0.87 | 0.85 | 0.98 |
| 3 | 230 X 750 | 0.73 | 0.84 | 0.76 | 0.90 |
| 4 | 230 X 750 | 0.98 | 0.95 | 0.92 | 0.94 |
| 5 | 230 X 600 | 0.96 | 0.94 | 0.80 | 0.98 |
| 6 | 230 X 600 | 0.80 | 0.84 | 0.87 | 0.92 |
| 7 | 230 X 600 | 0.74 | 0.74 | 0.96 | 0.80 |
| 8 | 230 X 450 | 0.75 | 0.88 | 1.00 | 0.80 |
| 9 | 230 X 450 | 0.88 | 0.88 | 0.92 | 0.85 |
| 10 | 230 X 450 | 0.98 | 0.93 | 0.97 | 0.98 |
| 11 | 230 X 450 | 0.65 | 0.99 | 1.00 | 0.99 |

In this case, the DCR value of beam B15 and B28 are exceeding the permissible value 1.5 in all storeys except 11$^{th}$ storey, DCR value of beam B09 and B64 is exceeding the permissible value 1.5 in storeys 1 to 7 and lies within limits for remaining storeys

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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 Corner column C 02 at base**

For this case DCR of beams B75, B76, B23, B24 and Interaction ratio of columns C20, C34, C 3, C28 needs to be considered

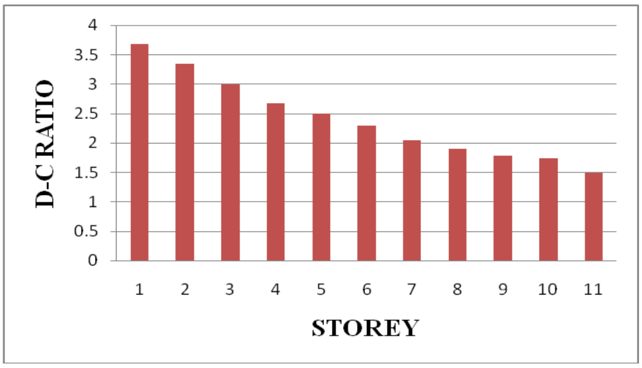


**Chart- 8**: D-C Ratio v/s Storey for Beam B75

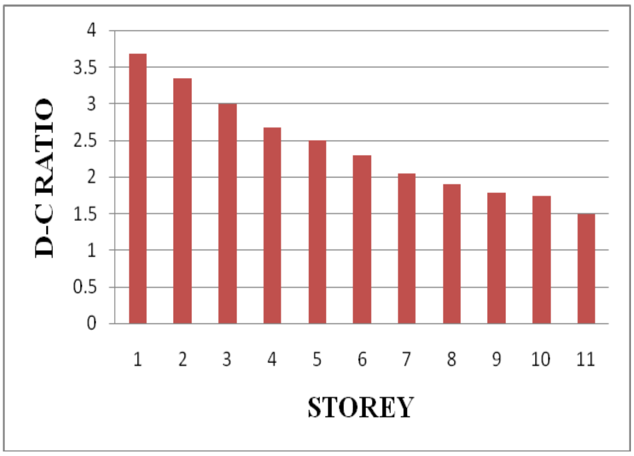


**Chart -9**: D-C Ratio v/s Storey for Beam B76

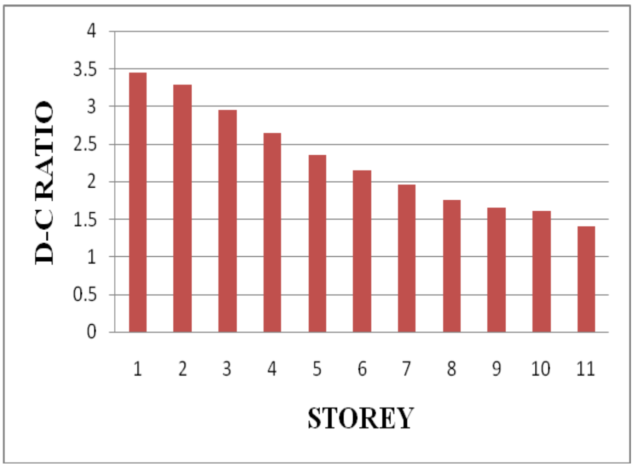


**Chart -10**: D-C Ratio v/s Storey for Beam B23

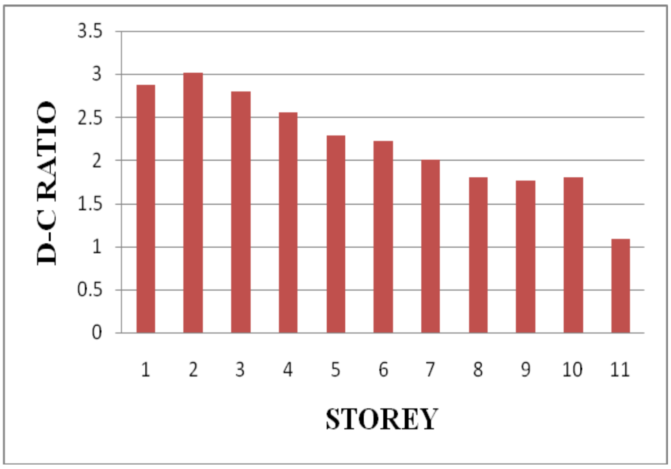


**Chart -11**: D-C Ratio v/s Storey for Beam B24

**Table -3:** Interaction Ratio after removal of column C 2

| Sl . No | Dimension In mm | I.R for Col C25 | I.R for Col C39 | I.R for Col C31 | I.R for Col C33 |
|---|---|---|---|---|---|
| 1 | 230 X 750 | 0.60 | 0.57 | 0.72 | 0.64 |
| 2 | 230 X 750 | 0.89 | 0.92 | 0.95 | 0.79 |
| 3 | 230 X 750 | 0.92 | 0.86 | 0.77 | 0.73 |
| 4 | 230 X 750 | 0.98 | 1.00 | 1.00 | 0.95 |
| 5 | 230 X 600 | 0.99 | 0.85 | 0.98 | 0.99 |
| 6 | 230 X 600 | 0.86 | 0.91 | 0.81 | 0.78 |
| 7 | 230 X 600 | 0.79 | 0.90 | 0.94 | 0.74 |
| 8 | 230 X 450 | 0.89 | 0.86 | 0.83 | 0.80 |
| 9 | 230 X 450 | 0.91 | 0.96 | 0.90 | 0.79 |
| 10 | 230 X 450 | 1.00 | 0.98 | 0.94 | 0.93 |
| 11 | 230 X 450 | 1.00 | 1.02 | 0.82 | 0.74 |

In this case, the DCR value of all beam B75, B76, B23, B24 are exceeding the permissible value 1.5 in all storeys except $11^{th}$ storey.

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. The most critical case for progressive failure is found to be interior column removal case at the base and least critical is found to be corner column removal case at the base.
2. Interaction ratio after removal is observed to be reaching the limiting value in few columns. It can be made safe either by increasing the reinforcement or by increasing dimension of column.
3. The failure of vertical structural element is more hazardous than failure of horizontal structural elements.
4. The axial force at the base is higher in column removed case compared to normal case and

from the comparison between the results of axial force with and without considering dynamic factor, we can conclude that it's better to design the building without considering dynamic factor as that case is more critical.
5. The DCR values are linearly varying from top to bottom floors.

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