RESEARCH ARTICLE OPEN ACCESS

Progressive Collapse Analysis of a RCC Structure as per GSA 2016

Mayank Sundriyal* Dr Vinaykumar C H**
**(M Tech Student, Structure Department, College Of Military Engineering, Pune -31)*
*** (Department Of Structures, College Of Military Engineering, Pune -31)*
Corresponding author: Mayank Sundriyal

ABSTRACT
Progressive collapse of a structure refers to local damage due to occasional and abnormal events such as gas explosions, bomb attacks and vehicular collisions. The local damage causes a subsequent chain reaction mechanism spreading throughout the entire structure, which in turn leads to a catastrophic collapse. Certain Landmark events in the history of Progressive Collapse includes the Collapse of Ronan Point apartment tower in London, the Alfred P. Murrah Federal Building collapse and the savage terrorist attack on the World Trade Centers in September 11, 2001. The structural engineers have now begun to refocus on the problem of progressive collapse. The design societies and researchers have shown a vast interest in the performance of the buildings under the situation of progressive collapse. There are a number of building codes, standards, and design guidelines to resist the phenomenon on progressive collapse. Out of these General Services Administration (GSA) addresses progressive collapse mitigation explicitly. An attempt has been made through this paper to check the resistance of a chosen building model to the phenomenon of Progressive Collapse as per the new GSA 2016 guidelines.

KEYWORDS: Deformation Controlled Actions,ETABS,Force Controlled Actions,GSA 2016,Linear Static Analysis,Progressive

---

Date of Submission: 25-02-2020 Date Of Acceptance: 05-03-2020

I. INTRODUCTION

As per ASCE 07-10 Progressive Collapse is defined as the spread of an initial local failure from element to element resulting eventually, in the collapse of an entire structure or a disproportionately large part of it. Progressive collapse is a failure sequence that relates local damage to large scale collapse in a structure, after redistribution structural components supports different loads and if any load exceeds the capacity of a member, it will cause local failure. If in such a sequence structure loses too many members it may cause progressive collapse. It is sometimes also called a disproportionate collapse, which is defined as a structural collapse disproportionate to the cause of the collapse.A good example of progressive collapse is a house of cards, if one card falls near the top or at the bottom, it causes multiple cards to fall below and above it due to the impact of the first card or removal of the bottom card. Around 15-20% building failures are due to progressive collapse. Noticeable events where this event came to public notice included the collapse of the 22-storey Ronan point apartment building in England 1968, Oklahoma city bombing in 1995, terrorists suicide attack using planes on World Trade Centre in New York on September 11, 2001.There are various Standards which have been developed over a period of time and are being used worldwide towards mitigation of the phenomenon of Progressive Collapse

Noticeable amongst them are ASCE 7-02, ACI 318-02, Euro codes, GSA and DOD Standards. Of all these standards the most favoured and followed approach is the General Services Administration Alternate path analysis & design guidelines for progressive collapse resistance.The alternate load path method is the most renowned method in the design of progressive collapse resistance. Its philosophy stipulates that the structure should tolerate the local damage and it should be able to achieve an equilibrium state after theoretically removing of the load-carrying element (bearing-walls or columns) one at a time and then analysing the structure.

II. OBJECTIVE

The Primary objective of this Research paper is to study the potential of Progressive Collapse of a RCC structure as per General Service Administration Alternate Path Analysis & Design Guidelines for Progressive Collapse Resistance 2016. The study investigates the potential of progressive collapse by performing Linear Static Analysis on the chosen RCC structure.

III. SCOPE OF WORK

The scope involves understanding GSA 2016 guidelines. Creating a computer model of the chosen RCC structure. Classifying Deformation and Force Controlled Actions. Calculation of M factors. Calculation of Load Increase Factors. Getting the Load Combinations. Performing a Linear Static Alternate Load Path Analysis and comparing the results to the Acceptance Criteria. Checking the model for Redundancy Requirements.

IV. GSA 2016

The intent of this document is to provide guidance to reduce and/or assess the potential for progressive collapse of Federal buildings for new or existing construction. It follows the analysis methodology and performance requirements of UFC 04-023-03 for Alternate Path. It also provides guidelines for incorporating redundancy into the progressive collapse resisting system to mitigate single points of failure and provide increased robustness for extreme loading scenarios not explicitly addressed in the design.

The design procedures employed by these Guidelines aim to reduce the potential for progressive collapse by bridging over the loss of a structural element, limiting the extent of damage to a localized area (Alternate Path) and providing a redundant and balanced structural system along the height of the building. The guidelines gives out the details and procedure for

- Load and Resistance factor design for alternate path method
- Classification of elements into primary and secondary components
- Classification of actions as either deformation-controlled or force-controlled
- Expected and lower bound strength
- Component capacities for the linear static procedure
- Allowable extents of collapse for different column removal cases
- Load case for deformation-controlled and force controlled actions
- Load increase factor
- Component and element acceptance criteria
- Redundancy requirements incorporating location, strength and stiffness.

V. MODEL STATEMENT

A G+5 storey RC building structure with bay width of 24 m along X and 15 m Y direction, with each floor height is 3.2m and slab thickness of 150mm is modelled in ETABS 2016 to check the potential of the building for progressive collapse analysis. Grade of concrete used is M30 for beams & columns & grade of rebar used in beams and columns is Fe 500 for main reinforcement and Fe250 for confinement reinforcement. All beams are 300 x 500 mm and all Columns Are 400 X 400 mm. The structure was subjected to Indian standard loading as per IS 875 & IS 1893.

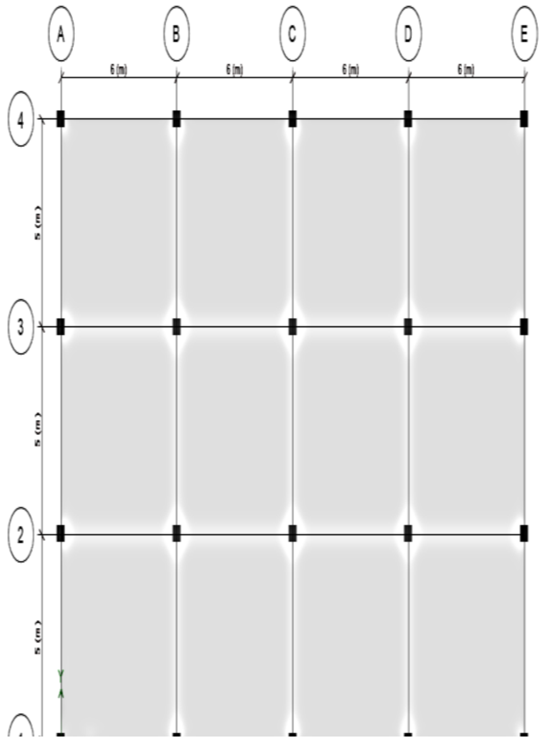

Fig 1 Plan Layout

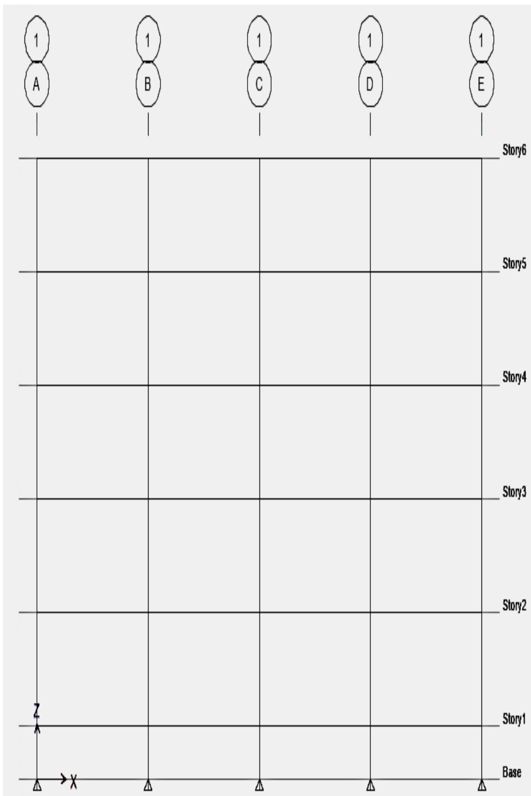

Fig 2 Elevation

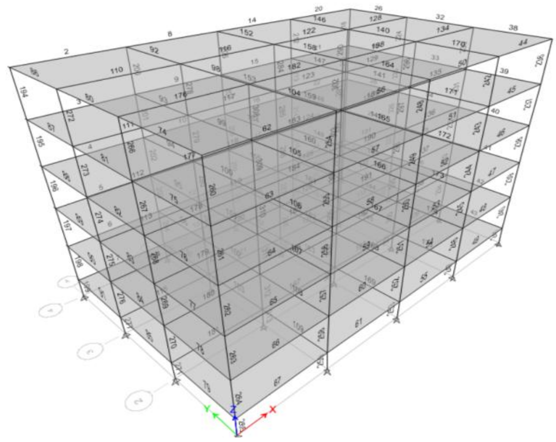

Fig 3 Isometric View

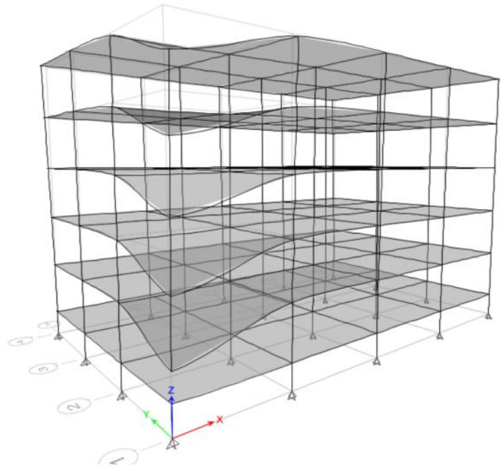

Fig 4 Edge Column Removed (Shorter Side)

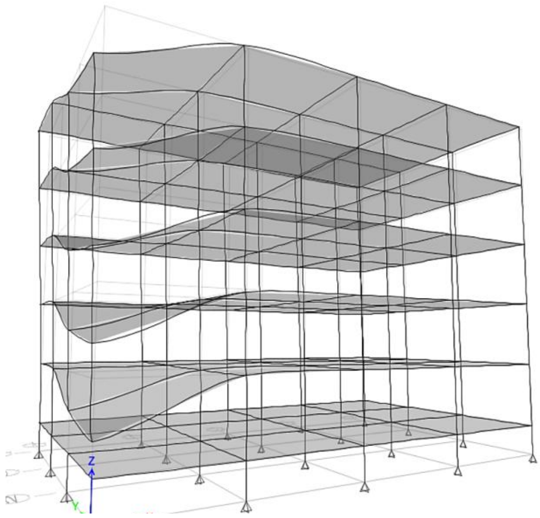

Fig 5 Edge & Centre Column Removed (Shorter Side)

VI. METHODOLOGY

The following methodology has been adopted for this research work,

Step-1 Selection of building geometry- G+5 storey.
Step-2 Define the material property of frame.
Step-3 Define the section property of frame- beam & column.
Step-4 Assign the joint pattern as fixed support.
Step-5 Define the load pattern- dead load, live load & EQ Loads.
Step -6 Perform a linear static analysis.
Step-7Get the analysis results.
Step- 8 Define load combination as per GSA 2016. Run Linear Static Analysis as per the new load combination after column removal.
Step-9 Evaluate Acceptance criteria for both Force & Deformation controlled actions.
Step-10 Check for Redundancy requirements.
Step-11Compare the Analysis results for different column removal case.

Table 1 Model Requirements for Deformation and Force-Controlled Actions

Design and/or Modeling Assumption	Deformation-Controlled	Force-Controlled
Design Strength	Expected (Q_{CE})	Lower Bound (Q_{CL})
Load Increase Factor	1.2 m_{LIF} + 0.8	2.0
Demand Modifier	m-factor	1.0

VII. CALCULATION OF m-FACTORS

Each component within the structure is assigned an m-factor, or demand modifier. The demand-modifier can be considered as the allowable Demand-Capacity-Ratio and is evaluated as the force or deformation controlled action divided by the design strength. The governing m-factor for each component is based on the smallest of the beam/girder elements. The m factor for a beam component is determined in accordance with Table 10-13 of ASCE 41 based on collapse prevention performance level and a primary component classification. The m factor is a function of the reinforcement ratio, transverse reinforcement and shear demand. The m-factor for column components is determined in accordance with Table 10-9 of ASCE 41 based on a Collapse Prevention performance level and a Primary component classification. The m-factor is a function of the shear demand, axial demand, and reinforcement ratio of the column.Correlating with the table of ASCE 41 and the value of m was found out as 16 for the beams.

VIII. LOAD COMBINATIONS USED

Increased Gravity Loads for Deformation Controlled Actions

ΩLD =1.2 m LIF + 0.8; ΩLD = (1.2x16) +0.8 = 20; GLD = ΩLD [1.2 D + 0.5 L]; GLD = 36(D) + 30(L)

Increased gravity Loads for Force Controlled Actions

ΩLF = 2;GLF = ΩLF [1.2 D + 0.5 L]; GLF = 2.4(D) + 3(L)

Gravity Loads for Areas away from removed Column Location

G=1.2D + 0.5L; G=1.8(D) + 1.5(L)

IX. RESULTS FOR DEFORMATION CONTROLLED ACTIONS FOR BEAMS

1. Limiting DCR is 16 for deformation controlled actions.On removal of a single edge column from the shorter side of the structure the maximum DCR achieved for beams is 14.6 which shows that the building is not susceptible to progressive collapse.
2. However On removal of two columns instantaneouslyfrom the shorter side of the structure (edge & Centre column) from first storey. DCR in 14 beams shot up above 16 and hence the building becomes susceptible to progressive collapse. The beams which fail under this criteria are 62,63,64,65,66,80,81,82,83,84,177,178,179 &180.
3. Graphs for DCR for Beams at different Stories for Deformation Controlled Action are produced below with Blue Colour indicating Original DCR for the beam before the Column was removed, Red Colour Line indicating DCR for beam on removal of Edge Column, Grey Colour Line indicating DCR for beam on removal of Edge & Centre Column simultaneously & Yellow Colour line indicating limiting DCR.

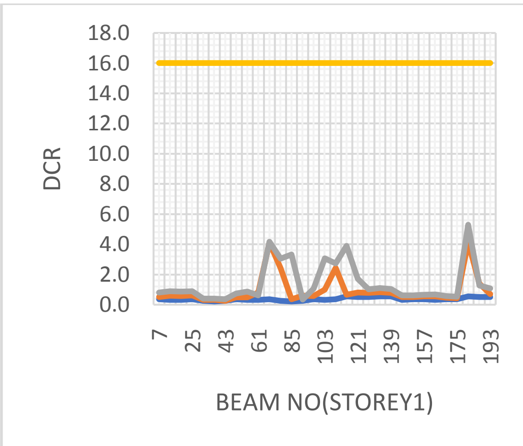

Fig 6 DCR for Beams of Storey 1

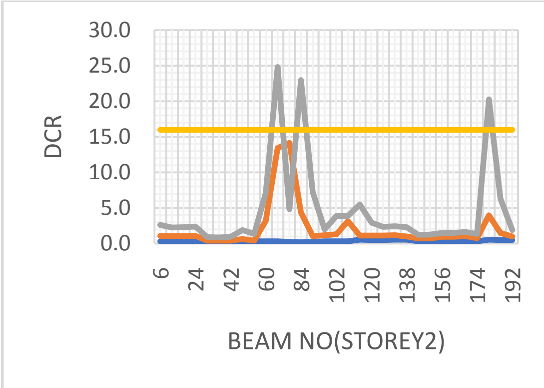

Fig 7DCR for Beams of Storey 2

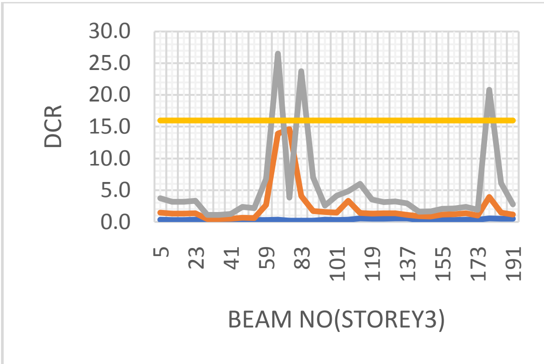

Fig 8 DCR for Beams of Storey 3

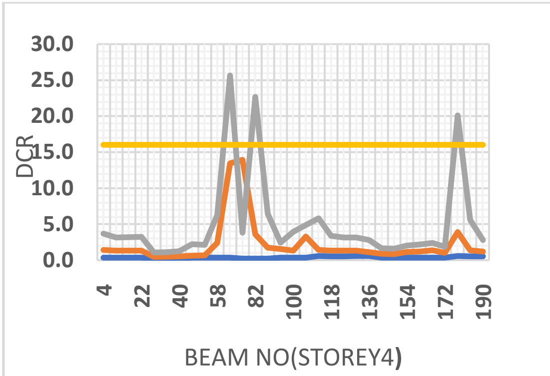

Fig 9 DCR for Beams of Storey 4

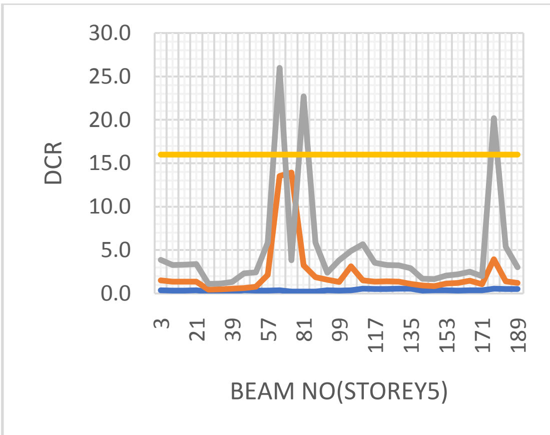

Fig 10 DCR for Beams of Storey 5

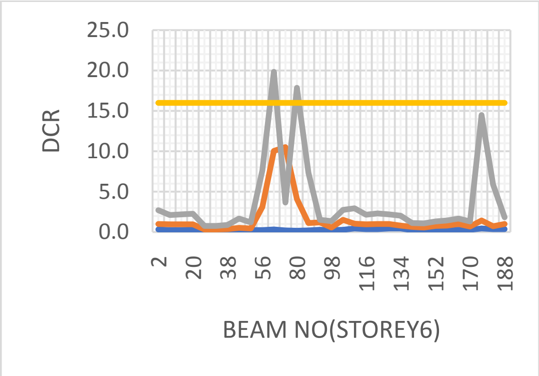

Fig 11 DCR for Beams of Storey 6

X. RESULTS FORCE CONTROLLED ACTIONS FOR COLUMNS

1. The Maximum Original DCR before Column removal was 0.41.The Limiting DCR for Columns for Force Controlled Actions is 1. On removal of edge column from the shorter side of the building 4 columns had their DCR crossing the limiting value 258,259,270 &271.
2. On removal of two columns (Edge & Centre Column) from the shorter side of the Structure instantaneously 11 columns had their DCR crossing the limiting value 257,258,259,274,275,276,277,310,311,312&313.
3. Graphs for DCR for Columns at different Stories for Force Controlled Action are produced below with Blue Colour line indicating Original DCR for the Column before the Column was removed, Red Colour Line indicating DCR for Columns on removal of the Edge Column, Grey Colour Line indicating DCR for Columns on removal of the Edge & Centre Column simultaneously & Yellow Colour line indicating limiting DCR for Columns for Force Controlled actions.

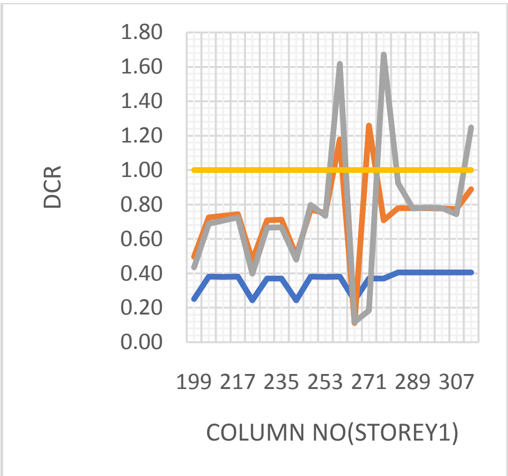

Fig 12 DCR for Columns of Storey 1

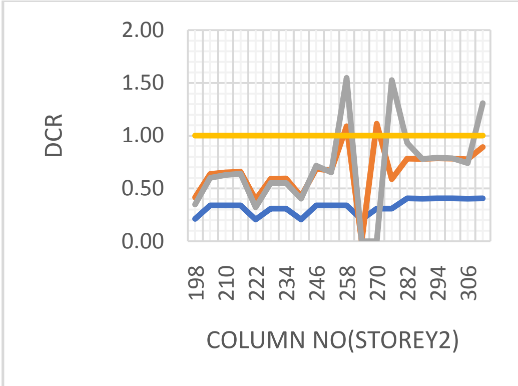

Fig 13 DCR for Columns of Storey 2

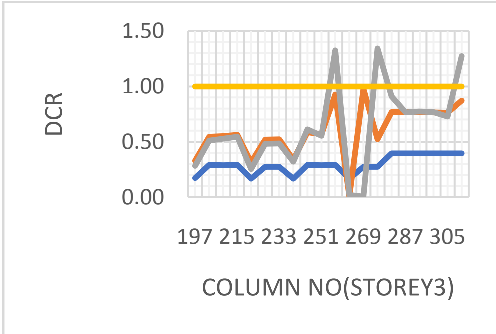

Fig 14 DCR for Columns of Storey 3

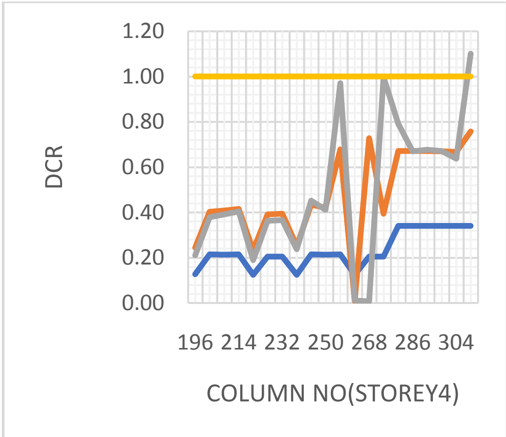

Fig 15 DCR for Columns of Storey 4

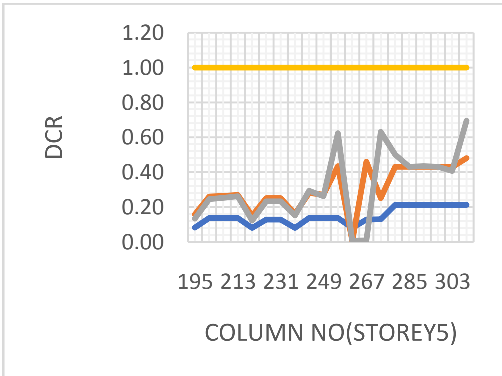

Fig 16 DCR for Columns of Storey 5

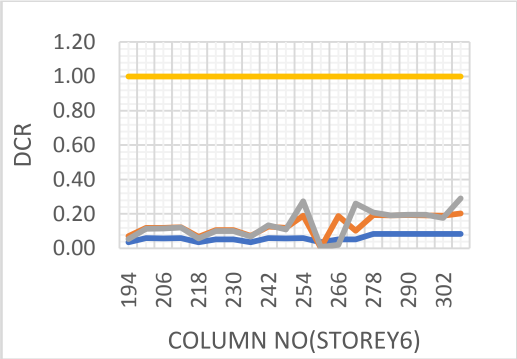

Fig 17 DCR for Columns of Storey 6

XI. REDUNDANCY REQUIREMENTS

The intent of redundancy requirements is to prevent structural designs where progressive collapse resistance is localized at one floor and to encourage balanced and redundant designs that distribute resistance up the height of the building. The edge column removal location has been considered for checking the redundancy requirements.

XII. LOCATION REQUIREMENTS

Load redistribution systems has to be spaced vertically along the height of the structure and the spacing between the systems should not exceed three floors. A redistribution system is defined as a structural system that has the capability to redistribute gravity loads to adjacent vertical structural elements under the loss of a column.The number of load redistribution systems in the structure; $n \geq N/3=2$& locating these systems at Level 2 and Level 4.

XIII. STRENGTH REQUIREMENTS

The strength of each vertical load redistribution system $=\left|\frac{QRi-\overline{QR}}{\overline{QR}}\right| \leq 0.3$.

Here $QRi = \sum \Phi QC$ = Design strength of a given load redistributing system at a single floor level associated with the exterior ground level column.QC = Expected strength of a component or element contributing to strength of a load redistribution system at a single floor level associated with the exterior ground level column.$\overline{QR} = \frac{\sum_{i=1}^{i=n} Q_{Ri}}{n}$= Average design strength of load redistributing systems up the height of the Building associated with the exterior ground level column. Φ = Strength reduction factor from the appropriate material specific code.The load redistribution system should include all primary horizontal members contributing to the redistribution of the gravity loads. The extent of the horizontal members included in the load redistribution system at a given plan location should be limited to a single structural bay perpendicular to and in either direction of the column removal location.The design strength of each horizontal element contributing to the vertical load distribution system at any Level is calculated as the minimum of the beam or its connections. For the moment frame elements the connection is assumed to be capable of developing the moment capacity of the beam; therefore the design strength of the element is governed by the beam section itself:

QC ==253.9 kN-m

$QRi = \sum QC$; $QR_2 = (Qc)_{66} + (Qc)_{78} = 507.8$ kN-m;$QR_4 = (Qc)_{64} + (Qc)_{76} = 507.8$ kN-m

$\overline{QR} = \frac{\sum_{i=1}^{i=n} Q_{Ri}}{n} = \frac{(507.8+507.8)}{2} = 507.8$ kN-m.The difference between the design strength at each floor and the average is calculated to verify it is within the 30% acceptable variance.

$\left|\frac{QRi-\overline{QR}}{\overline{QR}}\right| \leq 0.3$; For Level 2 $\left|\frac{507.8-507.8}{507.8}\right| \leq 0.0 \leq 0.3$; For Level 4 $\left|\frac{507.8-507.8}{507.8}\right| \leq 0.0 \leq 0.3$ Hence OK

XIV. STIFFNESS REQUIREMENTS

The strength of each vertical load redistribution system must meet the following equation:

$\left|\frac{KRi-\overline{KR}}{\overline{KR}}\right| \leq 0.3$hereKRi = ∑ KCE = Flexural stiffness of a given load redistributing system at a single floor level associated with the exterior ground level column. KCE = Flexural stiffness of a component or element contributing to strength of a load redistribution system at a single floor level associated with the exterior ground level column.$\overline{KR} = \frac{\sum_{i=1}^{i=n} K_{Ri}}{n}$= Average flexural stiffness of load redistributing systems up the height of thebuilding associated with the exterior ground level column. The same two horizontal members used to evaluate the strength of the vertical load redistribution system are used to evaluate the stiffness.The stiffness of each horizontal element contributing to the vertical load distribution system at Level 2 is calculated based on the boundary conditions of the element, prior to the column removal. Reinforcement continues through the connections such that support conditions can be assume to be fix-fix.

$K_{CE1} = \frac{384\ Ec\ Icr.B_{66}}{L^3} = 118.47$ kN/mm;

$K_{CE2} = \frac{384\ Ec\ Icr.B_{78}}{L^3} = 204.72$ kN/mm

The total stiffness for the vertical load redistribution system at Level 2 is the sum of all contributing elements:KR2 = ∑ KCE = KCE1 + KCE2 = 118.47+204.72=323.19 kN/mm.

Similarly, the stiffness of each horizontal element contributing to the vertical load distribution system at Level 4 is calculated as:

$K_{CE\,1}=\frac{384\ Ec\ Icr.B_{64}}{L^3}$ = 118.47 kN/mm;
$K_{CE\,2}=\frac{384\ Ec\ Icr.B_{76}}{L^3}$ = 204.72 kN/mm
The total stiffness for the vertical load redistribution system at Level 5 is the sum of all contributing elements:
KR4 = ∑ KCE = KCE1 + KCE2 = 118.47+204.72;KR4=323.19 kN/mm.
The average stiffness is that for all the vertical load redistribution systems for the column removal, which is Level 2and 4 only.
$\overline{KR} = \frac{\sum_{i=1}^{i=n} K_{Ri}}{n} = \frac{KR\,2 + KR\,4}{2}$=323.19kN/mm.
The difference between the stiffness at each floor and the average is calculated to verify it is within the 30% acceptable variance $\left|\frac{KR\,i-\overline{KR}}{\overline{KR}}\right| \le 0.3$
For level 2 $\left|\frac{323.29-\overline{323.19}}{323.19}\right| = 0 \le 0.3$;
For level 4 $\left|\frac{323.29-\overline{323.19}}{323.19}\right| = 0 \le 0.3$. Hence OK

The chosen model hence fulfils the criteria for redundancy requirements of location,strength and stiffness.

XV. RESULTS AND DISCUSSIONS

1. Under Edge Column Failure scenario all beam elements passed the checks for Deformation Controlled actions but 4 columns failed the force controlled actions thus leading to the conclusion that the building structure is susceptible to progressive collapse.
2. Under Edge & Central Column Failure scenario 14x beams failed under deformation control actions& 11x columns failed under force controlled action (shown as hashed in figure below).
3. The chosen model hence fulfils the criteria for redundancy requirements of location, strength and stiffness.

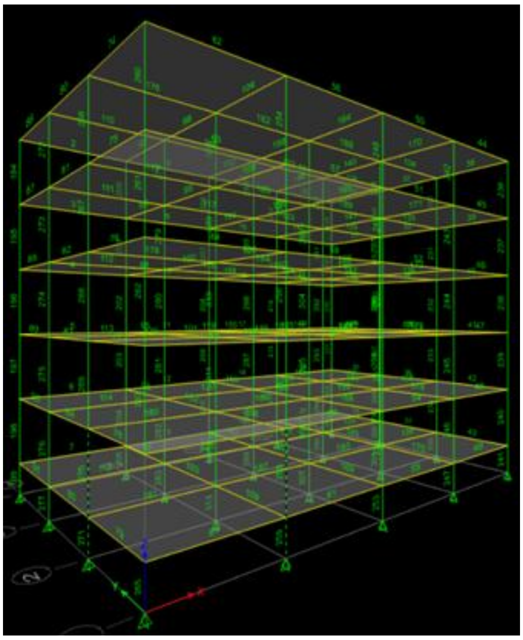

Fig 18 Failed elements Edge Column Removed

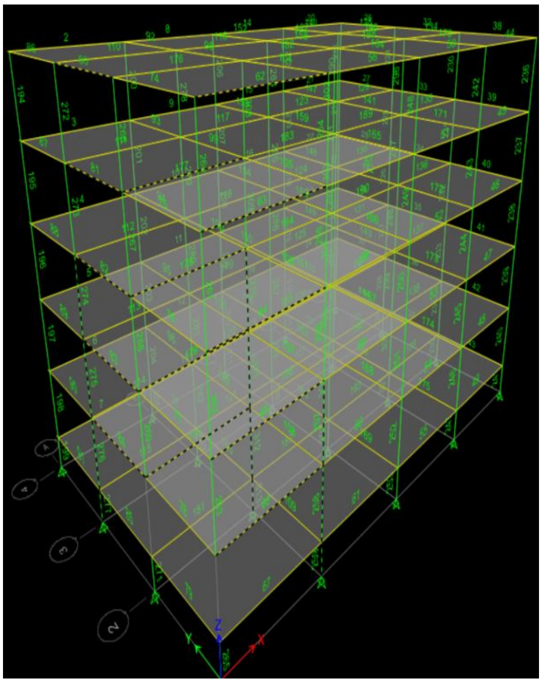

Fig 19 Failed elements 2 Column Removed

XVI. CONCLUSION

The Primary objective of this Research was to study the potential of Progressive Collapse of a RCC structure as per General Service Administration Alternate Path Analysis & Design Guidelines for Progressive Collapse Resistance 2016. The study investigated the potential of progressive collapse by performing Linear Static Analysis on the chosen RCC structure. The chosen structure was subjected to Indian Standard Loading as per IS 875 & IS 1893. Accordingly Alternate Load path Analysis was carried for the edge and both the central & edge column of the shorter side of the structure with the help of FEM software ETABS. The static analysis revealed the Resistance of the structure to Progressive Collapse. The structure has been checked for Force and Deformation Controlled actions as well as for the Redundancy requirements of location, strength and Stiffness. The methodology followed in this research can be used for checking other RCC structures for their potential for Progressive Collapse. Based on the analysis following conclusions can be drawn:

1. None of the beams are prone to progressive Collapse under a single column failure scenario. 14 x beams are prone to progressive Collapse under two column failure scenario.
2. For Deformation Controlled actions, removal of column from a particular location resulted in Moment Redistribution .The maximum moment being redistributed to the adjoining beams of the removed column location.
3. Damage after removal of a particular column was limited to the adjoining bay and the DCR on the beams in the damaged bay reduced as we moved to higher stories in the particular bay.
4. On removal of edge column 4 columns had their DCR crossing the limiting value. On removal of centre and edge columns instantaneously 11 columns had their DCR crossing the limiting value.
5. After removal of a particular column load redistribution took place within the structure with maximum Load redistributing to the adjacent columns and this redistribution of load decreases as we move up to higher stories.
6. Maximum load got redistributed to the column which was closest to the removed column. DCR for Columns decreases as we go higher storey wise. Damage due to progressive Collapse is localised and restricted to the bays immediately surrounding the removed column and varies across the height of the building for different cases.
7. The Structure full fills the redundancy requirements of location, strength and stiffness.
8. A building designed and detailed as per IS 1893 (Part1) : 2016 & IS 13920:2016 is less vulnerable to Progressive Collapse as compared to buildings Designed and Detailed as per old Codal provisions without considering seismic effects.
9. Designing for higher seismic Zones and with a greater importance factor makes a building less prone to Progressive Collapse.

REFERENCES

[1]. General Services Administration Alternate Path Analysis & Design Guidelinesfor Progressive Collapse Resistance (GSA 2016).

[2]. Progressive Analysis Procedure for Progressive Collapse S. M. Marjanishvili, P.E., M.ASCE1.

[3]. Unified Facilities Criteria (UFC). Design of building to resist progressive collapse, Department of Defence, 2009.

[4]. IS 875 (Part - 2). Code of practice for design loads (other than earthquake for buildings and structures), BIS, India, 1987.

[5]. IS 456-2000. Code of practice for plain and reinforced concrete, BIS, India, 2000.

[6]. IS 1893 Part 1(2016). Criteria for earthquake resistant design of structures, Bureau of Indian Standards, New Delhi.