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RESEARCH ARTICLE OPEN ACCESS

Progressive Collapse Assessment of a Multi-Storey RC Framed Structure Using Non-Linear Static Analysis Technique

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ABSTRACT
Progressive collapse is the process of extensive failure initiated by local structural damage, or a chain reaction of failures. Local damage that initiates progressive collapse is called initiating damage. The main focus of this research paper is to assess the vulnerability to progressive collapse of atypical RC framed structures under column removal scenario using ETABS software having version v16.2.1. A G+9 RCC hotel building (finite element model) has been considered and designed as per Indian Building Code and Pushover analysis (nonlinear static analysis) was carried out. Then the removal process of the identified critical columns is initiated for progressive collapse to happen and the various parameters like Demand capacity ratio and Robustness indicator are calculated and then checked against the acceptance criteria as provided in GSA 2003. Thus the influence of removal of critical elements has been discussed here by comparing the parameters before and after the progressive collapse.

Keywords - Pushover analysis; DCR; Damping; Target Displacement; Robustness Indicator; ETABS

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I. INTRODUCTION

The local failure of one or many structural elements creates the additional load in surrounding elements that leads to steady progressive collapse initially and then to the total failure. Therefore the remaining portion of the building is required to redistribute the loads applied to it through the alternate load paths provided for the purpose. This process may continue further till the equilibrium condition of the structure is reached either by provision of load-bearing bracing, or by stable alternative load paths. Progressive collapse is a natural non-linear event, in which structural components are stressed beyond their elastic limit to occur the failure.

The progressive collapse of the building has started gaining attention after the partial collapse in London (Roman point apartment building structure) and the collapse of the Alfred p. Murrah Federal Building structure (Oklahoma City, 1995) and the structure collapse of the World Trade Centre Towers, caused due to the terrorist attacks.

In the nonlinear static analysis, the final displacement depends on the damping and the loss of energy that took place due to inelastic deformation. There are Software available to perform nonlinear static (pushover analysis) analysis and they are SAP, Extended Three Dimensional Analysis of Buildings Systems (ETABS), SC-Push3D etc. Through these softwares, monitoring of the deformation at all hinges becomes possible to determine further the final or ultimate deformation. It has in-built default arrangement for ACI 318 material properties and ATC40 and FEMA 273 hinge properties. It is quite possible to import or input any material or hinge property through this software. Here the four steps Modeling, Static analysis, Designing and Nonlinear Static analysis are used to perform the analysis in ETABS 16.2.1.

II. EARLIER RESEARCH

S. Mohan Kumar, R. Jeyanthi have studied in July-August, 2016, a G+8 structure of a Multi-storey RC building structure and analysed it with the gravity load, Wind load and Seismic load to conduct pushover analysis to obtain the demand at critical locations. Thereafter they determined the capacity of the structure member from the original seismically designed section by considering the three cases and concluded that in the RCC building that has been considered by them, has minimum potential for the progressive collapse of the building when the corner column is removed. It was also found that the beams adjacent to removed column have maximum Bending Moment compared to the beams that are away from the damaged column.

Srinivasu. A and Dr. Panduranga Rao. B they did “Non-Linear Static Analysis of Multi-Storied Building” in the year of October, 2013. In this, a method for the determination of the parameters of plastic hinge properties (PHP) for structure containing R.C.C framed structures in the pushover analysis is proposed. The analysis is carried out by the linear static procedure and nonlinear static procedure (pushover) by using ETABS software. The nonlinear relationship between the lateral shear and lateral deformation of RC framed G+5 storey structure is calculated. They concluded that as the deflection increases the load increment at base of decreases. The frame behaves linearly elastic up to certain limit and thereafter it behaves nonlinear in behavior.

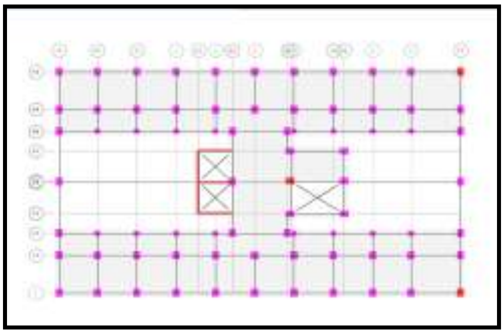
III. PROVISIONS FOR DESIGN

1) IS 1893:2002 (Part 1): Criteria for Earthquake Resistant Design of Structures, Part 1: General Provisions and Buildings (Fifth Revision).
2) IS 875 Code of Practice for Design Loads (Other than Earthquake) For Buildings and Structures {(Part 1 for Dead Loads, Part-2 for Imposed load, Part-3 for wind load and Part-5 for special loads and load combinations)}
3) IS 4326: Earthquake Resistant Design and Construction of Buildings Code of Practice (Second Revision).
4) IS 456:2000: Plain and Reinforced Concrete - Code of Practice.
5) BVN: 2012 – Bhumi vikash niyam (M.P.)

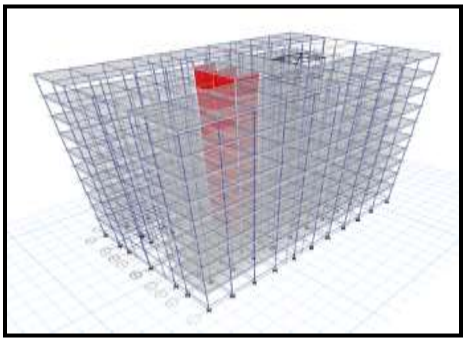
IV. MODEL DESCRIPTION

A finite element model of 10-story RC (Reinforced concrete) multi-story hotel building from Zone-II with height 33 m as defined in BVN: 2012 part-1 clause no. 2 has been developed with overall dimensions of 22.5m X 36m to study the progressive collapse mechanism. The structure is then designed for the Seismic loads as per IS: 1893:2002. The gravity load and wind load acting on building structure is carried out as per IS 875 part 1&2 and IS 875 Part3.

The 2D model of building will be generated in the AutoCAD software and 3D model of structure is proposed to be designed using ETABS v16.2.1 software.



(a) Building Floor Plan



(b) 3D model in ETABS software

Fig.1 2D planning and 3D model of a G+9 story building considered for present study

V. DETAILED DATA OF THE BUILDING

Span in X direction (22.5 m), Span in Y direction (36 m), GF Height (4 m), FF Height (3.4 m), SF to TF Height (3.2m), Beam of GF and FF (600 mm x 350 mm), Beam on SF onwards (500 mm x 300 mm), Column size on GF/FF (800 mm x 650 mm), column size on SF and above (800 mm x 350 mm), Corridor column (500 mm x 350 mm), support conditions as fixed, slab thickness of 125 mm, seismic zone-II, M 30 Concrete, Shear and Brick wall thickness of 200 mm, Steel (Fe 500 and Fe 250), Unit weight of RCC (25 KN/m3), Unit weight of bricks (20 KN/m3).

VI. METHODOLOGY

A G+9 RC framed structure with the gravity load and Seismic load has been analyzed in this Pushover analysis. Initially the identified critical elements (Columns) are removed from the respective locations and the Nonlinear static analysis is carried for all the critical cases under consideration. In this research work, the value of the applied loads has been increased gradually until an extreme load is attained (load controlled) or extreme displacement is reached (displacement controlled) so as to see nonlinear behavior of structural members. The advantage of this pushover analysis is that it engages many structural elements at a time and generally ensures balanced design. Therefore, here the Displacement controlled method has been used as the magnitude of seismic loads is not known.

It allows getting the DCR value in each structural member which is then checked against the acceptance criteria as provided in GSA 2003. If the DCR of a structural member exceeds the acceptable criteria, then the elements is considered to be failed. In addition, the robustness indicators are also obtained.

In this analysis, the alternative load path (ALP) method as mentioned in GSA, IS and FEMA guidelines is used for analysis which allows for the transfer of load to the surrounding elements of failed member thus permitting for the redistribution of moments.

Procedure for Non-Linear Static Analysis in ETABS Software:

1. Establish the finite element model.
2. Define and apply the loads and load combinations: According to IS 1893.
3. Perform Static analysis: For performing the static analysis first to set the load cases and then run the analysis.
4. Design: In Designing of structure, the Structure Design as Concrete Frame Structure where define Rebar selection rules for column and beam and select design load combination for designing the building structure and finally Start Design.
5. As the static analysis is performed, evaluate the damage of the structural components, if an element is shown to fail, redistribute the element's loads and restart the analysis.
6. Perform Pushover analysis.

Pushover Analysis:

Step:- 1 Define and apply the non-linear load cases (Push X and Push Y).
Step:- 2 Define Auto plastic hinges to Beams for Push X and Push Y load cases.
Step:- 3 Define Auto plastic hinges to Columns for Push X and Push Y load cases.
Step:- 4 Set to Load cases such as Dead load, Live load, Push X load and Push Y load.
Step:- 5 Run Analysis.
Step:- 6 Compare the DCR values with allowable limit to predict the failure of an element.
Step:- 7 If DCR value exceeds its acceptance criteria (specified by GSA2003) then will leads to progressive collapse.

VII. ANALYSIS LOADING

Table No.1 Loading for the analysis as per IS are given below,

Gravity Loads as per IS 875 part 1
Dead Load
• Self-Weight – 1 KN/mm^2 • Wall load on all beams – a) Ground Floor (Exterior wall)-14.8 KN/m^2 For Interior wall – 7.4 KN/m^2 b) First Floor (Exterior wall)- 12.4 KN/m^2 For Interior wall – 6.2 KN/m^2 c) 2nd-10th Floor (Exterior wall) 11.6 KN/m^2 For Interior wall – 5.8 KN/m^2 • Floor + Floor finish load – 5 KN/m^2
Live Load
a) On Floor – 3 KN/m^2 b) On Roof – 1.5 KN/m^2
Other Loads
Wind Load as per IS 875 Part 2
• Wind load criteria for Bhopal, Madhya Pradesh (India) are:- Wind Speed – 39 m/s Terrain Category – II Importance Factor (I) – 1 Response Reduction (R) – 5
Seismic Loads as per IS 1893:2002
seismic zone-II Zone Factor – 0.10

VIII. ANALYSIS LOAD COMBINATION

For seismic analysis of a building, following are the load combinations as per IS 1893:2002:
• 1.5(DL + LL) • 1.2(DL + LL ± EL) • 1.5(DL ± EL) • 0.9 DL ± 1.5 EL

IX. PERMISSIBLE CRITERIA AS PER GSA: 2003

Demand-Capacity Ratios (DCR):

The magnitudes and distribution of potential demands on both the primary and secondary structural elements have been identified through linear elastic analysis to quantify the potential collapse areas. These magnitude and distribution of demands are being indicated by Demand-Capacity Ratios (DCR).

An acceptance criterion for the primary and secondary structural components is determined as:

D.C.R= Q_{UD} / Q_{CE}
Where,
Q_{UD} = Demand force (acting) such as bending moment, axial force, shear force)

Q_{CE} = Expected ultimate, un-factored capacity of the component and/or connection/joint (moment, axial force, shear and possible combined forces)

The load bearing structural elements are considered to be severely damaged or collapsed if their DCR values through linear elastic approach, exceeds the allowable values. These, the allowable values of DCR are:

DCR < 1.5 for atypical structural configurations (GSA 2003 Section 4.1.2.3.2)

Robustness Indicator:

Robustness indicator (R) is defined as the ability of building to survive the local failure to withstand the loading and does not cause any disproportionate damage.

$R = V_d / V_i$
Where,

V_d is the Base shear of damaged building,
V_i is the Base shear of intact building.
The limiting value of Robustness indicator is 1, to allow for an alternative load path.

X. ANALYSIS

Initially, the plan of the building is developed using AutoCAD which has been then incorporated in ETABS v16.2.1 software along with the provisions of IS 1893 for design and load combinations. Then the Non-linear static analysis is carried out separately for each case of column removal and check the structure for progressive collapse potential.

Identification Of Critical Columns:

Three column removal conditions have been considered as mentioned in GSA 2003 guidelines to evaluate the potential for progressive collapse of G+9 atypical reinforced concrete structure and the method of analysis used here is Non-linear static analysis techniques.

Thus, there are four cases under consideration. 1. Removal of C-31 on GF situated at the long side corner of the building; 2. Removal of a column C-12 on GF situated at the Short side corner of the building; 3. Removal of column C-76 on GF situated at the interior of the building; 4. Removal of all three critical columns (C-31, C-12, and C-76) on GF together. The building analysis is carried out according to the load combination of IS 1893:2002. In all these four cases, the behaviour of bending moments and the load transfer through alternative load paths are studied and checked for the vulnerability through DCR values and Robustness indicator values.

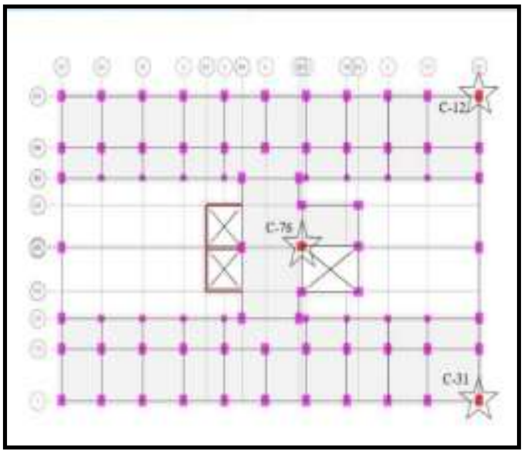


Fig.2 Plan of atypical G+9 Storey RC building showing removed column location cases (C-31, C-12, and C-76)

XI. RESULTS AND DISCUSSIONS

Table No.2 Maximum Story Displacement for Each Cases are:

Case No.	+X Direction	-X Direction	+Y Direction	-Y Direction
1	12.879 mm	75.981 mm	12.488 mm	24.563 mm
2	12.973 mm	80.670 mm	12.542 mm	25.000 mm
3	12.000 mm	85.409 mm	01.000 mm	25.191 mm
4	15.000 mm	77.271 mm	01.000 mm	23.839 mm

Table No.3 Comparison of the Values of the Axial Load (AL), Bending Moment (BM), and Shear Force (SF) Results for the case of removal of critical column C-31 (case 1).

Building Parameters related to column No. C-32			
Building Parameters	Value in Damaged cond.	Value in Intact cond.	Increment in Percentage
AL (kN)	4601.6609	3543.764	30%
BM (kN-m)	1606.2360	1143.819	40%
SF (kN)	37.8344	27.1186	39.5%
Building Parameters related to column No. C-48			
Building Parameters	**Value in Damaged cond.**	**Value in Intact cond.**	**Increment in Percentage**
AL (kN)	4654.0862	2991.416	55.5%
BM (kN-m)	345.2153	2170.282	59.6%
SF (kN)	17.7328	16.050	14%

Table No.4 Comparison of the Values of the Axial Load (AL), Bending Moment (BM), and Shear Force (SF) Results for the case of removal of critical column C-12 (case 2).

Building Parameters related to column No. C-11			
Building Parameters	Value in Damaged cond.	Value in Intact cond.	Increment in Percentage
AL (kN)	4601.6810	3543.7226	30%
BM (kN-m)	1606.2430	1143.8670	40.5%
SF (kN)	37.8443	27.1258	39.5%
Building Parameters related to column No. C-23			
Building Parameters	**Value in Damaged cond.**	**Value in Intact cond.**	**Increment in Percentage**
AL (kN)	4632.3875	2989.5737	55%
BM (kN-m)	3463.9505	2168.9276	60%
SF (kN)	17.7317	16.0481	10.5%

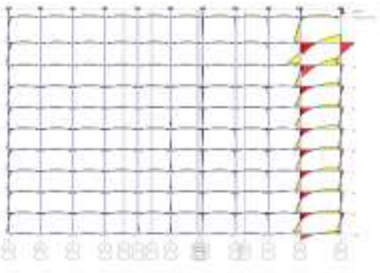
Table No.5 Comparison of the Values of the Axial Load (AL), Bending Moment (BM), and Shear Force (SF) Results for the case of removal of critical column C-76 (case 3).

Building Parameters related to column No. C-74			
Building Parameters	**Value in Damaged cond.**	**Value in Intact cond.**	**Increment in Percentage**
AL (kN)	4554.5074	2943.6537	55%
BM (kN-m)	18.8722	15.3076	23%
SF (kN)	10.7413	7.9774	35%
Building Parameters related to column No. C-79			
Building Parameters	**Value in Damaged cond.**	**Value in Intact cond.**	**Increment in Percentage**
AL (kN)	3724.9933	2594.2129	43.5%
BM (kN-m)	12.1066	11.5601	5%
SF (kN)	5.0479	3.7565	34%

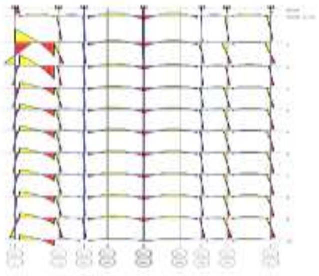
Table No.6 Comparison of the Values of the Axial Load (AL), Bending Moment (BM), and Shear Force (SF) Results for the case of removal of critical column C-31, C-12, C-76 (case 4).

Building Parameters related to column No. C-32			
Building Parameters	**Value in Damaged cond.**	**Value in Intact cond.**	**Increment in Percentage**
AL (kN)	4551.5413	3543.7649	30%
BM (kN-m)	1588.7415	1143.8194	40%
SF (kN)	36.581	27.1186	35%
Building Parameters related to column No. C-48			
Building Parameters	**Value in Damaged cond.**	**Value in Intact cond.**	**Increment in Percentage**
AL (kN)	4600.7666	2991.4167	54%
BM (kN-m)	3425.5160	2170.2828	58%
SF (kN)	17.8574	16.050	11%
Building Parameters related to column No. C-11			
Building Parameters	**Value in Damaged cond.**	**Value in Intact cond.**	**Increment in Percentage**
AL (kN)	4541.4184	3543.7226	30%
BM (kN-m)	1585.208	1143.8670	40%
SF (kN)	36.3783	27.1258	34%
Building Parameters related to column No. C-23			
Building Parameters	**Value in Damaged cond.**	**Value in Intact cond.**	**Increment in Percentage**
AL (kN)	4587.2088	2989.5737	54%
BM (kN-m)	3415.4215	2168.9276	57%
SF (kN)	17.8856	16.0481	11.5 %
Building Parameters related to column No. C-74			
Building Parameters	**Value in Damaged cond.**	**Value in Intact cond.**	**Increment in Percentage**
AL (kN)	4544.3184	2943.6537	54%
BM (kN-m)	24.6995	15.3076	61%
SF (kN)	10.5618	7.9774	32%
Building Parameters related to column No. C-79			
Building Parameters	**Value in Damaged cond.**	**Value in Intact cond.**	**Increment in Percentage**
AL (kN)	3719.3286	2594.2129	43.5 %
BM (kN-m)	15.9647	11.5601	38%
SF (kN)	5.9027	3.7565	57%

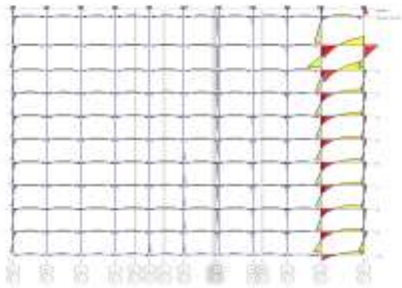
BENDING MOMENT DIAGRAMS:



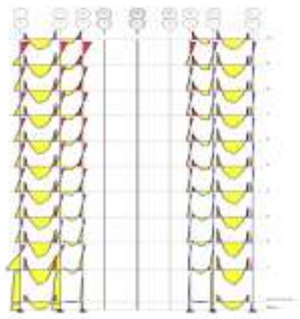
(a) case 1 (Removal of critical column C-31 in x direction)



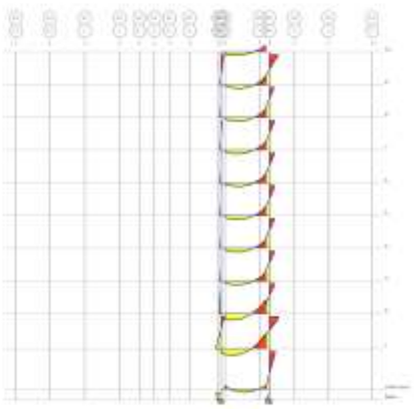
(b) case 1 (Removal of critical column C-31 in y direction)



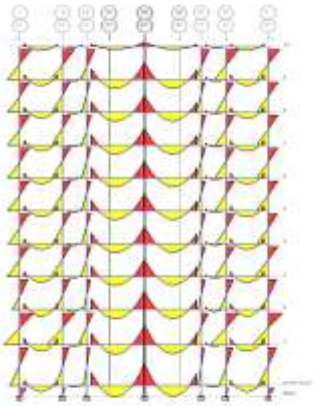
(c) case 2 (Removal of critical column C-12 in x direction)



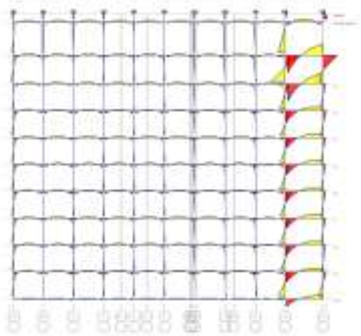
(d) case 2 (Removal of critical column C-21 in y direction)



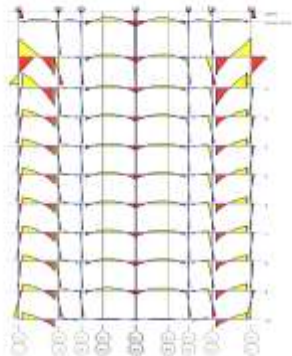
(e) case 3 (Removal of critical column C-76 in x direction)



(f) case 3 (Removal of critical column C-76 in y direction)



(g) case 4 (Removal of critical column C-31, C-12, C-76 in x direction)



(h) case 4 (Removal of critical column C-31, C-12 C-76 in y direction)

Fig.3 Bending moment diagrams for each case of removal of critical column

DEMAND CAPACITY OF THE STRUCTURE ELEMENTS:

Table No.7 Demand Capacity Ratio of the Adjacent Member of the Critical Columns for Each Case:

Case No.	Damaged column No. and Beam No.	DCR Value
1	C-32	1.400
	C-48	1.600
	B-10	2.030
	B-11	1.900
2	C-11	1.763
	C-23	1.597
	B-76	1.980
	B-77	2.028
3	C-74	1.550
	C-79	1.500
	B-58	0.571
	B-57	0.667
4	C-32	1.380
	C-48	1.570
	B-10	1.997
	B-11	2.001
	C-11	1.385
	C-23	1.570
	B-76	0.695
	B-77	1.990
	C-74	1.540
	C-79	1.500
	B-58	0.568
	B-57	0.697

ROBUSTNESS OF THE STRUCTURE:

Table No.8 Base Shear values of damaged and intact building in each cases,

Case No.	Base Shear (damaged building)	Base Shear (intact building)	Robustness value
1	7115.2042	8544.6598	0.833 < 1
2	7565.6301	8544.6598	0.885 < 1
3	7973.2430	8544.6598	0.933 < 1
4	7193.6971	8544.6598	0.842 < 1

Here since the robustness indicator is less than the acceptable limit 1, the structure is able to provide an alternative load path if the structure is damaged.

TARGET DISPLACEMENT FOR DIFFERENT – DIFFERENT DAMPING RATIO:

Table No.9 Target displacement and Damping Ratio values,

Damping Ratio	Target Displacement (mm)
1%	443.836
5%	317.701
8%	280.651
10%	263.626
20%	208.139

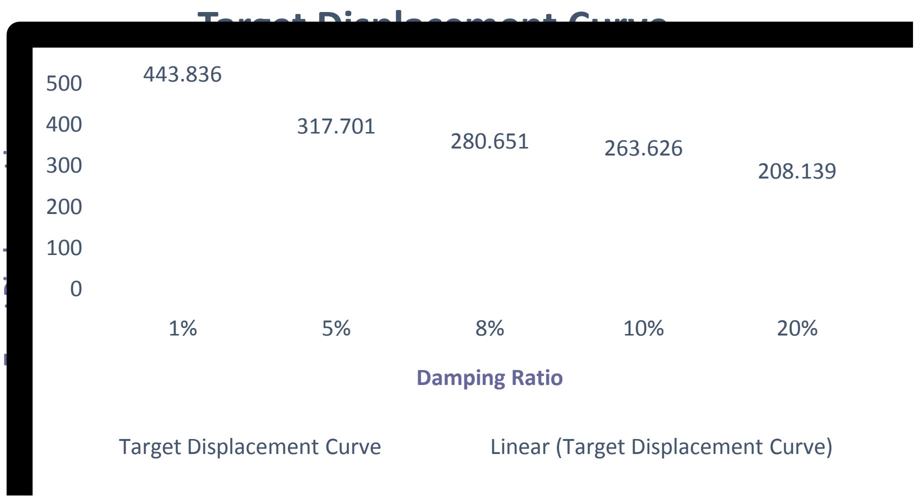


Fig.4 Graph between Damping ratio and Target Displacement

The above is the graphical representation of damping ratios against the target displacement and the equation of the curve obtained is given below:

$$y = -52.547x + 460.43$$

Where, y = Target displacement, x = Damping ratio value

XII. CONCLUSION

The behavior of the ten story RC building structure has been studied for its progressive collapse using Non-linear static analysis and Building parameters such as axial force, bending moments and shear force, demand capacity ratio, and robustness of the structure have been determined for these cases to draw the following conclusion:

1. In the nonlinear static analysis, it is found that the column number C31, C12 and C 76 are found to be critical as they fail in design criteria and thus leading to the four cases of column removal for analysis.
2. In Case 1, the column C-48, B-10 and B-11 adjacent to the critical column C-31 has been failed in axial loading, bending moment and shear force and has the DCR value as 1.60, 2.03 and 1.90 respectively which is greater than the acceptable limit of 1.5 as provided in GSA guidelines.
3. In Case 2, the column C-11, C-23, B-76 and B-77 adjacent to the critical column C-12 has been failed in axial, bending and shear and has the DCR value as 1.763, 1.597, 1.980 and 2.028 respectively, which is greater than the acceptable limit of 1.5 as provided in GSA guidelines.
4. In Case 3, the column C-79 and C-74 adjacent to the critical column C-76 has been failed in axial loading and has the DCR value as 1.55 and 1.50 respectively, which is greater than and equal to the acceptable limit of 1.5 as provided in GSA guidelines.
5. In Case 4, the column C-48, B-10, B-11, C-23, B-77, C-74 and C-79 adjacent to the critical column C-31, C-12 and C-76 respectively has been failed in axial loading bending and shear and has the DCR value as 1.57, 1.997, 2.001, 1.570, 1.990 and 1.54, 1.50 respectively, which is greater than the acceptable limit of 1.5 as provided in GSA guidelines.
6. The load transferring effect on the nearest member of the removed column is more and is negligible when moved away from the removed column.
7. In nonlinear static analysis, no beams (except B-10, B-11, B-77) in shear and no beams (except B-76) in bending moment are going to fail for any column removal case since their DCR ratio values are within acceptable limit which shows that Shear & bending moment in beam is not that critical in progressive collapse process of the building.
8. Since DCR ratio for most of the column (except ground floor column C-48, C-11, C-23, C-74, and C-79) is less than 1.5, these columns are not critical in progressive collapse process of the building.
9. The analysis of nonlinear static process revealed that removal of corner column on short side (C-12) is the most critical whereas the removal of interior column case is least critical.

10. As the robustness value of the structure is less than acceptable limit for all four cases studied so far, it is concluded that the structure will not collapse completely even if any part of the structure may get damaged partially. The reason for this is that there occurs the redistribution of loads through alternative load paths.

11. After observing the Collapse pattern, it is found that the demand capacity ratio (DCR) of the members/elements is maximum near the removed column and its value get decreases further away from it.

12. The collapse pattern suggests that there is increase the damping ratio with the decrease in target displacement value. In other words, the target displacement is indirectly proportional to the damping ratio and the graph represents a linear equation $y = -52.547x + 460.43$ (where y = Target displacement, x = Damping ratio value) for calculation of target displacement for the given building.

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