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Progressive Collapse Analysis of RC Buildings using Linear Static and Linear Dynamic Method

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***Abstract*—To study the effect of failure of load carrying elements i.e. columns on the entire structure; 15 storey moment resistant RC buildings is considered. The buildings are modeled and analyzed for progressive collapse using the structural analysis and design software SAP2000. There are total four analysis procedures namely linear static, linear dynamic, nonlinear static and nonlinear dynamic analysis. In this we discuss linear static and linear dynamic analysis to evaluate the potential for progressive collapse of RC buildings.**

***Keywords*— Progressive Collapse; RC Building; Linear Static; Linear dynamic; SAP2000.**

I. INTRODUCTION

Progressive collapse can be defined as widespread propagation of structural member failures in which the resulting damage is disproportionate to the original cause. Failure of one or more primary load carrying members cause overloading of nearby other structural member due to change of load pattern which ultimately leads to failure of the members. As a result, total or partial collapse of the structure occurs, which is termed as progressive collapse. It is not always feasible to design the structures for absolute safety, nor it economical to design for accidental events unless they have a reasonable chance of occurrence. Events like gas explosions, bombs, vehicle impacts, foundation failures, failures due to construction or design errors etc. are not usually considered in normal design practices. Considering these aspects, many government authorities and local bodies have worked on developing some design guidelines to prevent progressive collapse. Out of these guidelines, US General Services Administration (GSA) has illustrated step wise procedure to minimize the progressive collapse, issued in 2000 and revised in 2003. According to GSA guidelines, Progressive Collapse is “a situation where local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse. Hence, the total damage is disproportionate to the original cause.

Progressive collapse is a situation where local failure of a primary structural component leads to the collapse of adjoining members, which in turn leads to additional collapse. Progressive collapse occurs when a structure has its loading pattern or boundary conditions changed such that structural elements are loaded beyond their capacity and fail. Progressive collapse of building structures is initiated when one or more vertical load carrying members (typically columns) are collapsed. Once a column is failed the building's weight (gravity load) transfers to neighboring members in the structure. If these members are not properly designed to resist and redistribute the additional load that part of the structure fails. The vertical load carrying elements of the structure continue to fail until the additional loading is stabilized. As a result, a substantial part of the structure may collapse, causing greater damage to the structure than the initial impact.

II. BUILDING CONFIGURATION

To study the effect of column removal condition on the structure, hypothetical case of 15 storey RC building is considered. Progressive collapse analysis is based on the GSA guidelines. Structure considered in this analysis is assumed to be a residential building, which is designed for an importance factor 1 (IS code 1893-2002). Bay size is taken as 6m in one direction and 4m in other direction. Building size in plan is 30m x 24m. Height of base to plinth is taken as 2m, Plinth to ground floor as 4 m, which is considered as hollow plinth and height of typical floor as 3.5m. 230mm thick walls are assumed to be on all beams Figure shows typical floor plan and 3D view of regular building.

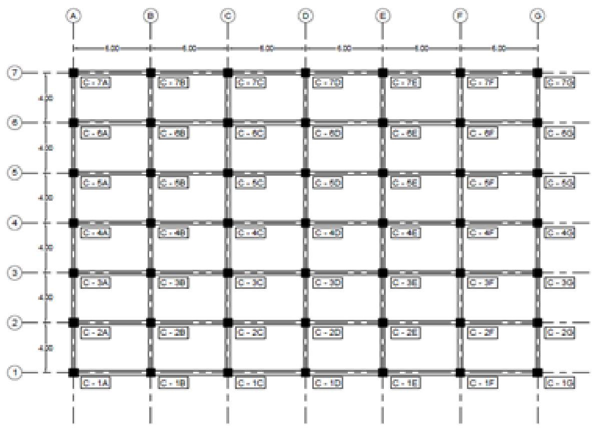


Fig. 1 Typical floor plan of regular building

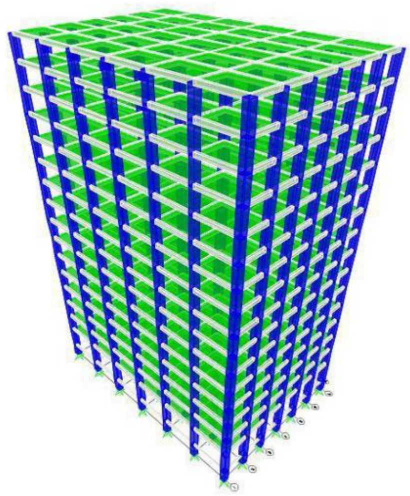


Fig. 2 3D view of regular building

LOADING DATA

Live load at typical floor = 2 kN/m2
Live load at roof =1.5 kN/m2
Floor finish at typical floor = 1 kN/m2
Parapet wall load at terrace (230mm thick) = 4.6 kN/m
Water proofing roof = 1 kN/m
Wall load at typical floor (230mm thick) = 13.685 kN/m
Self weight of slab (150mm thick slab) = 3.75 kN/m2

Material Properties:

Concrete grade = M25
Steel grade = Fe415
Seismic Parameters:
Seismic Zone = 3
Zone factor = 0.16
Soil Type = Type II
Importance Factor = 1
Response Reduction factor = 5

Load Combinations:

Following primary load cases are considered for design of building.

1. Dead Load (DL)
2. Live Load (LL)
3. Floor Finish (FF)
4. Wall Load (Wall) and Parapet Wall Load
5. Earthquake Load along X direction (EQX)
6. Earthquake Load along Y direction (EQY)

Along with the above cases, following load combinations are considered for design of structural elements as per IS 1893-2002.

1. 1.5 (DL+LL)
2. 1.2 (DL+LL±EQX)
3. 1.2 (DL+LL±EQZ)
4. 1.5 (DL±EQX)
5. 1.5 (DL±EQZ)
6. 0.9 DL ± 1.5 EQX
7. 0.9 DL ± 1.5 EQZ

Building design

Building design and progressive collapse analysis is carried out using computer program. Final member sizes of the G+15 building, after analysis and design are as below. Beam size: 300mm × 600mm Column size: 800mm × 800mm. Slab thickness: 150mm RC design is carried out and percentage steel is provided accordingly. Steel design for this building is governed by the earthquake load combination envelope.

III. PROGRESSIVE COLLAPSE ANALYSIS

Progressive collapse analysis is performed by instantly removing one or several columns and analyzing the building's remaining capability to absorb the damage. The key issue in progressive collapse is in understanding that it is a dynamic event, and that the motion is initiated by a release of internal energy due to the instantaneous loss of a structural member. This member loss disturbs the initial load equilibrium of external loads and internal forces, and the structure then vibrates until a new equilibrium position is found or until the structure collapses. Four column removal cases for progressive collapse analysis are considered.

For case-1 middle column from long side of the building (C – 1D) is removed, for case-2 column of shorter side of the building (C – 4A) is removed, for case-3 corner column (C – 1A) is removed, for case-4 interior column (C – 4D) is removed. Fig. 3 shows the column removal locations. SAP2000 software is used to understand the behaviour of structure under different "failed column" scenarios.

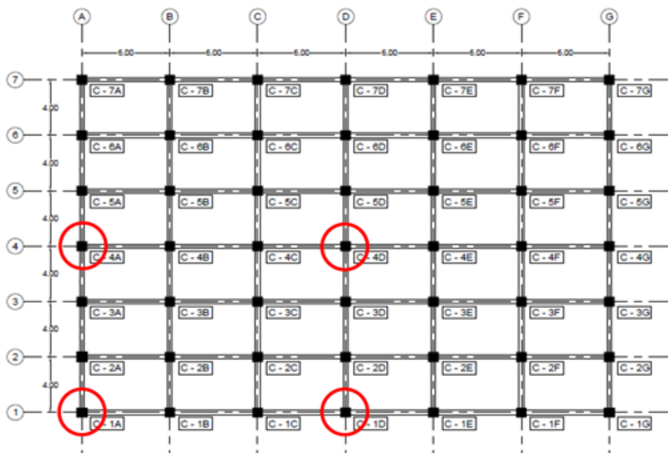


Fig. 3 Column removal locations are shown by red circles

A. Linear Static Analysis

GSA guideline has provided following stepwise procedure to carry out linear static analysis.

Step 1: Prepare three dimensional model in Computer. Perform concrete design and determine the reinforcement to be provided in members.

Step 2: Based on the reinforcement provided, calculate the capacity of the member in flexure and shear, considering "strength increase factor" to take in to account high strain rate during progressive collapse.

Step 3: Create column loss scenario by removing ground floor column from the specified location one at a time as mentioned in GSA guidelines.

Step 4: Perform the static linear analysis and determine the demand for the specific column removal case.

Step 5: Calculate the "demand to capacity ratio (DCR)" and evaluate the results as per the acceptance criteria provided in GSA guidelines.

GSA guidelines have specified the following load case for static analysis procedure.

Loading = 2 (DL + 0.25LL) Where, DL = Dead Load, LL = Live Load The factor '2' in Static analysis is provided to function as dynamic magnification factor to simulate the dynamic response. The performance of structure is evaluated by demand to capacity ratios (DCR), which should not exceed 2 for regular structures and 1.5 for irregular structures or else they are considered as severely damaged or failed. GSA has defined DCR as below.

DCR = QUD / QCE

Where, QUD = Acting force (demand) determined in component or connection/joint (moment, axial force, shear, and possible combined forces), QCE = Expected ultimate, un-factored capacity of the component.

B. Linear dynamic analysis

The failure of vertical members under abnormal loading is a highly dynamic phenomenon. So it is necessary to study the response of building structure by performing dynamic analysis. Dynamic analysis procedures (either linear or nonlinear) are usually avoided, as they are perceived to be excessively complex. But compared to static analysis procedures, their accuracy is much higher since dynamic procedures incorporate dynamic amplification factors, inertia, and damping forces. It is more appropriate to refer to this method of analysis as a time history analysis. Time-history analysis is a step-by-step analysis of the dynamic response of a structure to a specified loading that may vary with time. Time- history analysis is used to determine the dynamic response of a structure to arbitrary loading.

Loading: As per GSA guideline, Load = (DL + 0.25 LL)

Step 1: Build a computer model

Step 2: Remove a column from the model

Step3: Apply the dynamic load combinations as per GSA guidelines. In SAP2000, there are two analysis options: direct integration and modal superposition. But it is found that the direct integration procedure runs much faster and hence analysis is performed using direct integration method.

Step4: Perform time history analysis with zero initial conditions, a standard analysis procedure in SAP2000.

Step5: Evaluate the results based on demand-to-capacity ratio (DCR), where demand is taken as the peak value of response from the calculated time-history response.

Advantages of this analysis procedure include its accuracy, which derives from its ability to account for internal dynamic loading effects coupled with the effects of higher modes of vibration. The disadvantage of this methodology is its inability to account for material and geometric nonlinearity, which could be significant in complex structures where structure yield patterns cannot be easily identified. Linear dynamic analysis case has been defined in SAP2000 for GSA is shown in Figure.

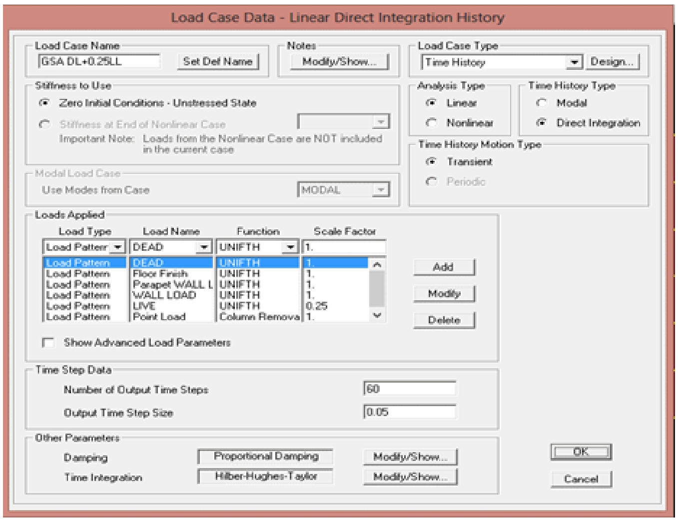


Fig.4 Linear dynamic analysis in sap2000

IV. CALCULATION OF DCR (DEMAND CAPACITY RATIO)

Local damage scenario is created by removing the external long bay column C - 1D and Linear Static Analysis and Linear Dynamic Analysis are performed. After performing the progressive collapse analysis, flexure and shear demand of the beams are found. Figure shows the bending moment and shear force diagram of before column removal condition and after column removal condition for static linear analysis. These analysis should carried out for all four column removal cases.

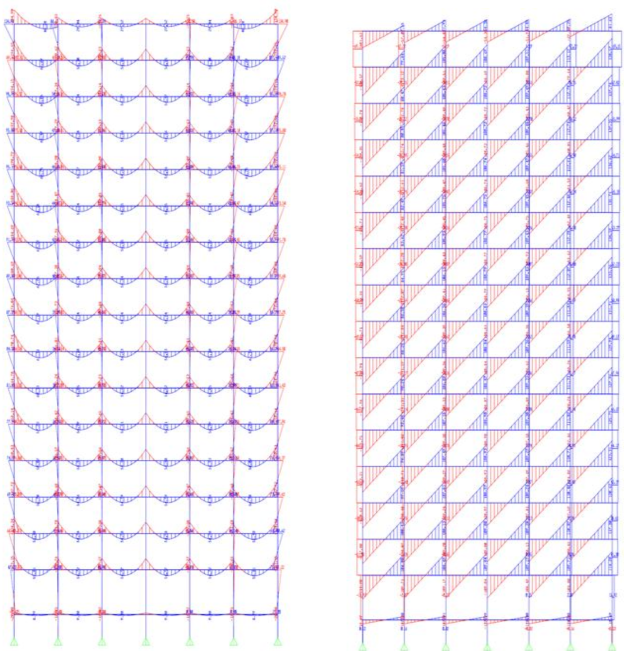


Fig.5 BM and SM diagram before column removal condition

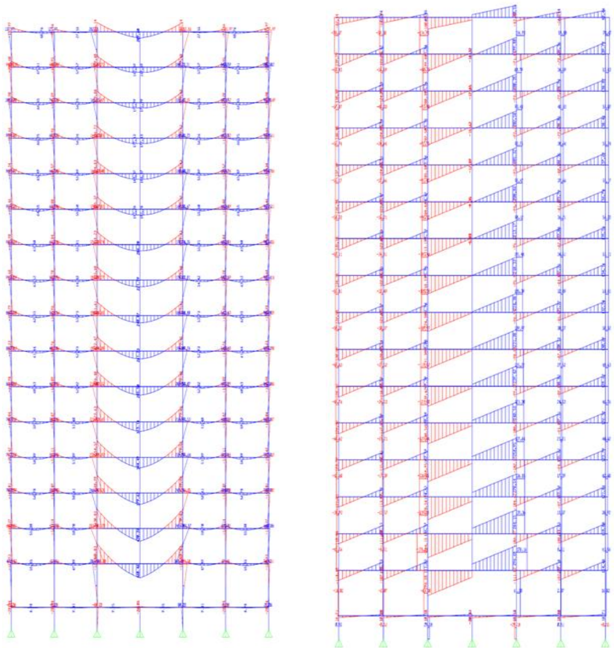
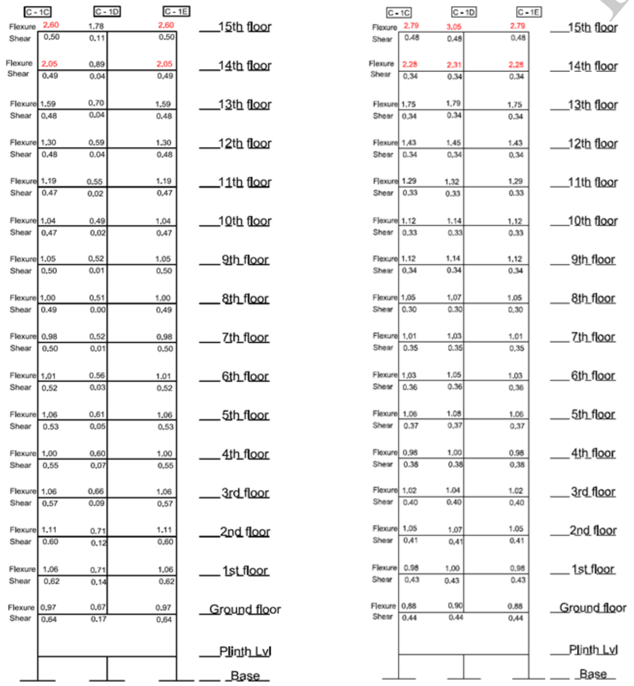


Fig.6 BM and SF diagram after column removal condition

DCR For Flexure = Demand Moments / Flexure Capacity of Member

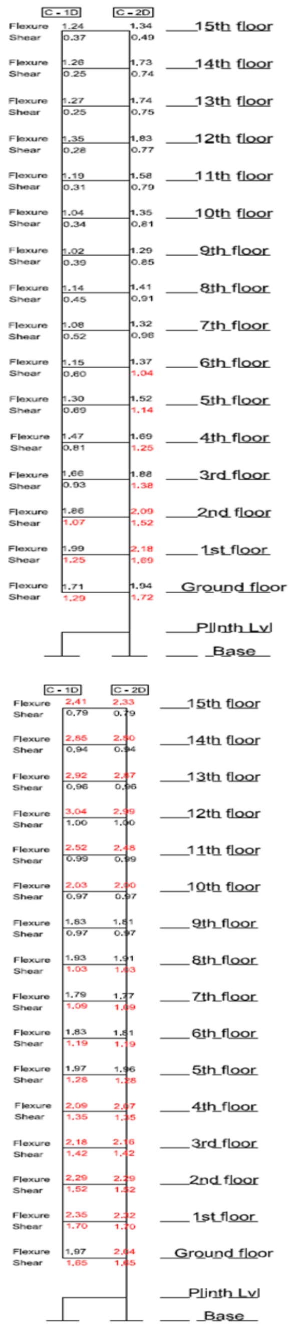
DCR For Shear = Demand Shear Force / Shear Capacity Of member

The value of DCR along the height in longitudinal and transverse direction frame is shown in following figures.



Linear Static (Long Bay) Linear Dynamic (Long Bay)

Fig.7 DCR for case 1 linear static and linear dynamic long bay



Linear Static (Transvers Direction) Linear Dynamic (Transvers Direction)

Fig.8 DCR for case 1 linear static and linear dynamic transvers bay

Likewise we can find DCR for all column removal cases.

A. *Comparison of displacements for linear static and linear dynamic analysis (column removal location)*

Table -1: Comparison of results

Column Removal Cases	Linear Static Analysis	Linear Dynamic Analysis
Long Bay Column (1D)	24.78 mm	25.42 mm
Short Bay Column (4A)	17.81 mm	14.79 mm
Corner Column (1A)	20.6 mm	19.37mm
Central Column (4D)	22.60 mm	25.33 mm

V. RESULTS AND DISCUSSION

In this chapter linear static and linear dynamic analysis procedures are carried out for progressive collapse analysis of 15-storey moment resistant RC buildings. DCR are found out for beams and highly stressed nearby columns at all storey for four column removal cases. Study of the vertical displacement under the column removal locations is carried out for all the column removal cases using linear static and dynamic analysis.

It is observed that DCR in flexure in beam exceeds permissible limit of 2 in all column removal cases of building. DCR calculated by linear dynamic analysis is having values nearer or higher to DCR calculated by linear static analysis. DCR calculated in flexure and shear for beams by linear static analysis is higher on left and right side of column removal points while on center generally linear dynamic analysis gives higher value. So for better results both the analysis methods should be followed for progressive collapse analysis. From the study it is observed that for all the four column removal cases, shorter bays in all column removal cases are most affected for collapse. The reason is that the shorter bays in all column removal cases act as cantilever after removal of column and heavy point load from the longer bays act on shorter bay. So it can be concluded that when the column is removed from the building, shorter bays will have high potential for progressive collapse for all column removal for type of building considered in this study. DCR values for flexure, shear and column increase as the height of the building increases. So potential for progressive collapse of the building increases as the height of the building increases. Displacements under the column removal locations found from linear static analysis are compared with displacements obtained by linear dynamic analysis for all the four column removal cases and it is very close to each other so it can concluded that the Dynamic Amplification factor 2 for Linear Static analysis is good estimated.

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