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Progressive Collapse Analysis of Reinforced Concrete Framed Structure

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Abstract: **Progressive collapse is a chain reaction of failures that propagates either throughout or a portion of the structure disproportionate to the original local failure. The progressive collapse of building structure is initiated when one or more vertical load carrying members are removed. Once a column is removed or made weak, due to man-made or natural hazards, load carried by column removed is transferred to neighbouring columns in the structure, if the neighbouring column is incapable of withstanding the extra load, leads to the progressive failure of adjoining members and finally to the failure of partial or whole structure. The collapsing system continually seeks alternative load paths in order to survive. One of the important characteristics of progressive collapse is that the final damage is not proportional to the initial damage. The research material available for progressive collapse failure of structures suggests that buildings designed to resist seismic actions have good robustness against progressive collapse. However, no detailed investigations have been conducted so far to assess this robustness. Hence this study is made to examine the potential ability of seismically designed building against progressive collapse.**

A twelve storey reinforced concrete framed structure was considered in the study to evaluate the Demand Capacity Ratio (DCR), the ratio of the member force and the member strength as per U.S. General Services Administration (GSA) guidelines. The Linear static analysis is carried out using software, ETABS according to Indian Standard codes. Analysis and design is carried out to get the final output of design details. To study the collapse, typical columns are removed one at a time, and continued with analysis and design. Many such columns are removed in different trials to know the effects of progressive analysis. Member forces and reinforcement details are calculated. From the analysis, DCR values of columns and beams are calculated.

Keywords: **Progressive Collapse, Demand Capacity ratio (DCR), U. S. General services administration (GSA) Guidelines, ETABS.**

I. INTRODUCTION

The robustness of the structure is the ability of the structure to withstand local damages that may arise due to accidental actions without disproportional failure that is disproportional to the original cause, progressive collapse is such a disproportional failure which refers to the condition when the failure of a local component (or localized region) leads to global system failure and the final failure state of the structure is disproportionate to the original cause. Progressive collapse can be defined as “the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it”. After the event of 11 September 2001, more and more researchers have started to refocus on the causes of progressive collapse in building structures, seeking ultimately the establishment of rational methods for the assessment and enhancement of structural robustness under extreme accidental events.

When the structural elements are loaded beyond their ultimate capacities, the structure has its loading pattern or boundary conditions changed and hence the progressive collapse occurs and the structure fails. When any element fails, the remaining elements of the structure seek alternative load paths to redistribute the load applied to it. As a result, other elements may fail due to insufficient resistance capacity causing partial or total failure mechanism. It is a dynamic process, usually accompanied by large deformations, in which the collapsing system continually seeks alternative load paths in order to survive. One of the important characteristics of progressive collapse is that the final damage is not proportional to the initial damage.

The attention of structural engineers was first drawn after the accidental collapse of the Ronan Point tower in Canning Town, UK on May 1968. The cause of the collapse was a human error gas explosion that knocked out the precast concrete panels near the 18th floor causing the floors above to collapse.

Structural progressive collapse has been the focus of extensive research during the past few years because of the increasing rate of victims resulting from natural disasters (e.g., earthquakes and hurricanes) or human-made disasters (Example: bomb blasts, fires and vehicular impacts). Structural designers have traditionally focused on optimizing the cost of constructed facilities while meeting code requirements. Unfortunately, most of the structures have been designed to resist gravity loads and lateral loads resulting from wind or moderate earthquakes. The structural behavior of a constructed facility when subjected to loads beyond conventional design is not typically addressed.

1.1 Analysis

Linear Static analysis is used to analyse the potential for progressive collapse, coupled with the following criteria: Criteria for assessing the analysis results, a suite of analysis cases, Specific loading criteria.

1.1.1 Analysis Loading

For static analysis purposes the following vertical load shall be applied downward to the structure under investigation:

Load = 2DL + 0.5LL

Where,

DL = dead load

LL = live load

1.1.2 Acceptance Criteria

An examination of the linear elastic analysis results shall be performed to identify the magnitudes and distribution of potential demands on both the primary and secondary structural elements for quantifying potential collapse areas. The magnitude and distribution of these demands will be indicated by Demand-Capacity Ratios (DCR).

Acceptance criteria for the primary and secondary structural components shall be determined as:

$$DCR = \frac{Q_{UD}}{Q_{CE}}$$

Where,

$\mathbf{Q_{UD}}$= Acting force (demand) determined in component or connection/joint moment, axial force, shear, and possible combined forces).

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

Using the *DCR* criteria of the linear elastic approach, structural elements and connections that have *DCR* values that exceed the following allowable values are considered to be severely damaged or collapsed.

The allowable *DCR* values for primary and secondary structural elements are:

DCR < 2.0 for typical structural configurations

1.1.3 Software Used

Extended Three Dimensional Analysis of Buildings Systems (ETABS), the Structural Analysis finite element program that works with complex geometry and monitors deformation at all hinges to determine ultimate deformation. It has builtin defaults for ACI 318 material properties and ATC-40, FEMA 273 hinge properties and also includes Indian Standard codes. ETABS9.7 deals with the buildings only. The analysis in ETABS 9.7 involves the following steps:

1. Modelling,
2. Analysis,
3. Designing.

II. METHODOLOGY

For the analysis, a typical frame of height 37.5 m is considered. The longer plan dimension is taken as the X direction, the shorter one as Y direction and Z direction is taken in the vertical direction.

The ground storey height is taken as 3.4 m and the rest of the storey are taken to be 3.1 m high. The column cross section is taken as 0.60m x 0.30m. Beam size is taken for twelve stories as 0.3m x 0.45 m. The floor slabs are modelled as plates of 0.15m thickness. Wall having 115 mm thickness is considered on all the beams. All the supports are modelled as fixed supports. Linear analysis is conducted on each of these models.

Fig 1: 3D model of a 12 storey building considered for present study

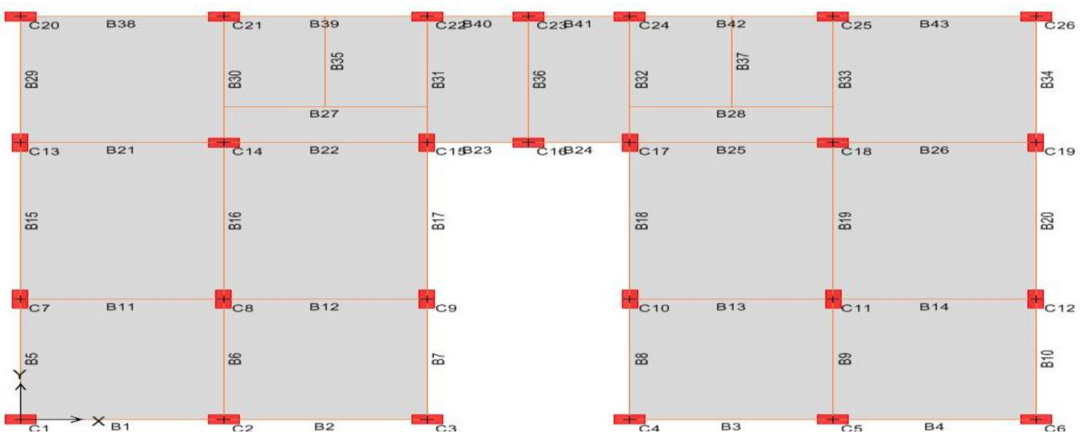

Fig 2: Plan of RC Framed Structure

2.1 Analysis Procedure

To evaluate the potential for progressive collapse of a twelve storey symmetrical reinforced concrete building using the linear static analysis four column removal conditions is considered. First building is designed in ETABS v9.7 for the IS 1893 load combinations. Then separate linear static analysis is performed for each case of column removal. Demand capacity ratio for flexure at all storeys is calculated for different cases of column failure.

2.2 Linear Static Analysis

In the linear static analysis column is removed from the location being considered and linear static analysis with the gravity load imposed on the structure has been carried out. From the analysis results demand at critical locations are obtained and from the original seismically designed section the capacity of the member is determined. Check for the DCR in each structural member is carried out. If the DCR of a member exceeds the acceptance criteria, the member is considered as failed. The demand capacity ratio calculated from linear static procedure helps to determine the potential for progressive collapse of building.

2.2.1 Dead Load

The dead load is obtained from IS 875(part1). The unit weight of concrete is taken as 25 kN/m3. Self-weight of the structural elements.

Floor finish = 1.5 kN/m^2 and

Wall load on all beams is 11.16 kN/m

2.2.2 Live Load

The live load is obtained from IS 875(part2).

On roof 1.5 kN/m^2

On floor 3 kN/m^2

2.2.3 Earthquake Load

The structure is designed in all zones (2, 3, 4 and 5) as per IS 1893-2002. Zone factor is taken as 0.10, 0.16, 0.24, and 0.36 as in code for zone 2, zone 3, zone 4 and zone 5 respectively. For all zones Soil type II, Response Reduction Factor= 3, Importance Factor = 1 is considered.

2.2.4 Wind Load

The wind load is assigned as per IS 875 (part 3) code. The characteristic compressive strength of concrete (f_{ck}) is 30 N/mm2 and yield strength of reinforcing steel (f_y) is 415 N/mm^2.

2.3 Progressive Collapse Analysis

The reinforced framed structure in the earthquake zones 2, 3, 4 and 5 is designed using ETABS program for dead, live, wind and seismic loads. For progressive collapse analysis columns C1, C16, C23, C8, C14, C9, C15 and C20 are removed. The specified GSA load combination was applied and the forces are calculated for all members using ETABS program.

The Demand Capacity Ratio (DCR), the ratio of the member force and the member strength is calculated. The member strength is calculated from Area of Steel obtained in the design results of ETABS program according to IS 456-2000 code. The member force is taken directly from obtained design forces values of ETABS program.

III. RESULTS AND DISCUSSIONS

The bending moment diagram obtained by ETABS software for loadings assigned as per GSA is drawn to know behavior of columns and beams in the structure.

The removal of column C1 caused moment reversal in the beams B1 and B5 intersecting at the removed support. Fig 3 shows the distribution of moments in different elevation after the removal of the column. The figures show that values of the reversed moment diminish in the upper floors and for beams away from the vicinity of removed column.

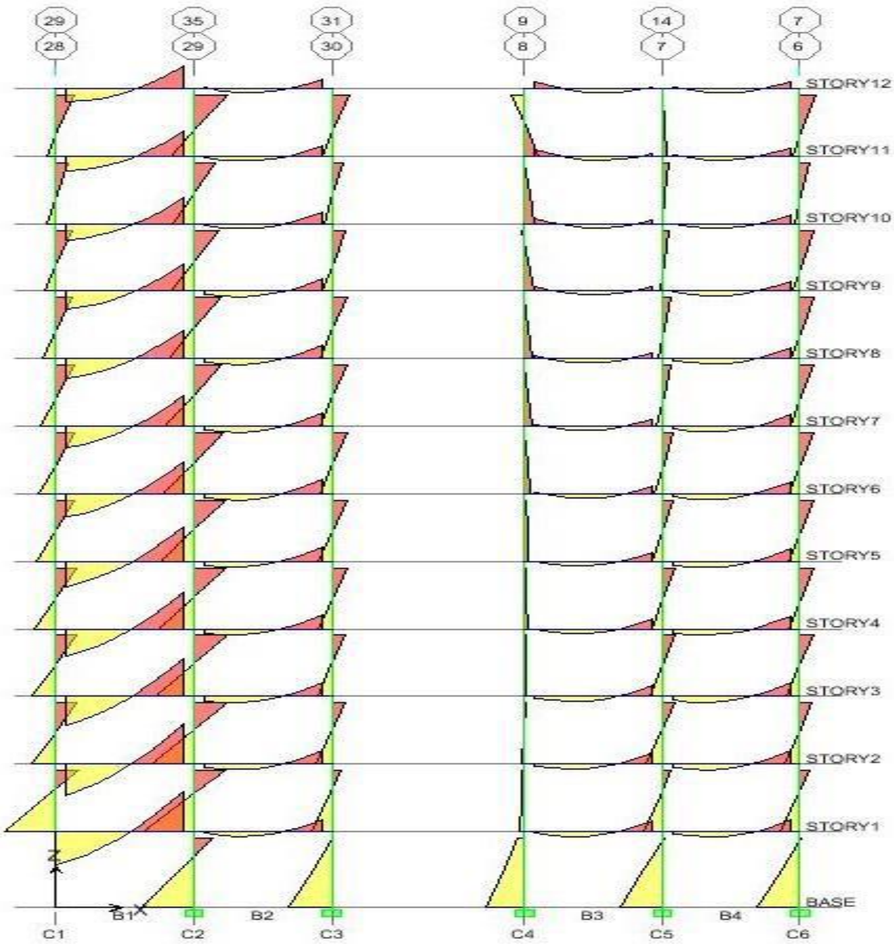

Fig 3: Moments in elevation view when C1 is removed

Similarly all the columns were removed and analysed by linear static method.

3.1 Summary of Column DCR for Zone 2

The Demand Capacity Ratios for all the columns removed were calculated and the values were less than 2 which suggests that all columns have the potential to resist progressive collapse. When the particular column removed the DCR value of that column in all the other stories was very less. These values indicate that the major load is transferred to the connecting beams. When the C1 column was removed adjacent columns C2, C7 and C8 of first storeys DCR values were greater than 1. The DCR of columns for remaining stories was lesser than 1. Columns exhibit descending pattern in DCR values when moved to higher stories. The same trend was observed in all the cases of removed column.

3.2 Summary of Column DCR for Zone 3

The Demand Capacity Ratios for all the columns removed were calculated and the values were less than 2 which suggests that all columns have the potential to resist progressive collapse. When the particular column removed the DCR value of that column in all the other stories was very less. These values indicate that the major load is transferred to the connecting beams. When the corner column was removed adjacent columns of first storey had DCR values greater than 1. The DCR of columns for remaining stories was lesser than 1. Columns exhibit descending pattern in DCR values when moved to higher stories. The same trend was observed in all the cases of removed column.

3.3 Summary of Column DCR for Zone 4

The Demand Capacity Ratios for all the columns removed were calculated and the values were less than 2 which indicates that all columns have the potential to resist progressive collapse. When the particular column removed the DCR value of that column in all the other stories was very less. These values indicate that the major load is transferred to the connecting beams. When the middle column was removed all adjacent columns of first storey DCR values were greater than 1. The DCR of columns for remaining stories was lesser than 1. Columns exhibit descending pattern in DCR values when moved to higher stories. The same trend was observed in all the cases of removed column.

3.4 Summary of Column DCR for Zone 5

The DCR values for building designed for zone 5 exhibit the same fashion as in remaining zones. The demand capacity ratios for all the columns were less than 2 as in the rest of zones. This indicates that all columns have the potential to resist progressive collapse in all four earthquake zones. The DCR values were slightly increased compared to rest of zones. The columns which are adjacent to removed column exhibit DCR values more. But the values are decreased in upper stories. As DCR is less than 2 in all the columns, they are safe and can avoid the progressive collapse which leads failure of structure when single vertical load carrying member is removed.

IV. CONCLUSIONS

Since the DCR values of columns are less than 2 in all the cases studied, the columns are adequate and do not need additional reinforcement to meet GSA criteria. Columns designed for seismic forces in all Zones have inherent ability to resist Progressive Collapse.

1. When column was removed, among the intersecting beams the shorter span beams tend to take the extra burden load and DCR values that beams were more compared to longer span beams.
2. For removed column C1, DCR values of B1 beams exceed 2. Decreasing pattern of DCR values is observed has storey increases. B5 beams below storey 7 have DCR values more than 2 and others are less than 2.
3. For C16 column removed, DCR of 1 B25 beams and 1 - storey 9 B24 beams exceed 2.Including adjacent B32 beams other are well within 2.
4. For C23 column removed, DCR of 1 B40 beams and B41 beams of all stories exceed 2.Including adjacent B32 beams other are well within 2.
5. For C8 column removed, DCR of B11, B12, B6 beams of all stories exceed 2. Adjacent B16 beams have DCR less than 2.
6. For C18 column removed, DCR of B25 and B26 beams of all stories exceed 2. B19 and B34 adjacent beams have DCR less than 2.
7. For C9 column removed, DCR of B7, B12 and B17 beams of all stories exceed 2.
8. For C17 column removed, DCR of B24 and B25 beams of all stories exceed 2. B18 and B33 adjacent beams have DCR less than 2.
9. For C26 column removed, DCR of 1 B35 beams and B43 beams of all stories exceed 2 other beams have DCR less than 2.
10. To avoid the progressive failure of beams and columns, caused by failure of particular column, adequate reinforcement is required to limit the DCR within the acceptance criteria.

The adequate reinforcement provided in extra to beams which are unsafe can develop alternative load paths and prevent progressive collapse due to the loss of an individual member.

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