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Study on the Progressive Collapse Behaviour of Steel and RCC Moment Resisting Frames

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Abstract: **One of the key requirements for any major construction is the structural safety of the building along with the ability to resist partial or total collapse. One or more structural elements fail due to abnormal loading leading to the collapse of the entire structure progressively. This phenomenon is referred to as Progressive Collapse. Seismic loading may also cause progressive collapse of the structure due to repeated lateral loading on a critical load bearing element in a building in seismically prone regions. The capacity of a building has been analysed to resist collapse of a 15 storey 3D Steel and RCC moment resisting frames. They have been modelled and designed for seismic zone 5 as per Indian Standards using ETABS. Three scenarios of column removal namely middle, corner and interior has been studied by the linear method of analysis to arrive at the most critical location of column loss. The Demand Capacity Ratio (DCR) has been assessed in the critical regions as per the provisions of GSA guidelines. Further, the variation in the maximum vertical displacement values for both the steel and RCC structures has been compared. The study concludes that the loss of column in the corner location proved more susceptible to collapse by comparing the DCR values. It has also been observed that a steel building has the ability to resist collapse following the loss of a column when compared to an RCC building.**

***Keywords*:-- DCR, linear static analysis, moment resisting frames, Progressive collapse, seismic**

I. INTRODUCTION

An earthquake is a sudden and violent shaking of the ground causing great damage to life and property due to movements within the earth's crust thereby releasing energy in the form of seismic waves. An earthquake resistant design has therefore become a basic requirement of every multi-storey structure. Most lateral loads are live loads whose main component is a horizontal force acting on the structure. Typical lateral loads are considered as wind and earthquake loads.

There are various structural forms for ensuring adequate safety and stability against lateral loading. The most commonly adopted structural systems are the Moment Resisting Frame (MRF) structures [1]and the Braced Framed structures [2]. MRFs are a rectilinear arrangement of beam and column elements with the beams rigidly fixed to the columns. Lateral loads can be resisted by developing bending moment and shear force at the joints and members. The connection between the beams and columns are necessarily rigid in a moment resisting frame structure. A braced frame consists of diagonal members used to resist the lateral loading such as X braced frame, K braced frame or Knee Braced Framed. The braces are designed to take compressive and tensile forces thereby being effective in resisting the lateral loads. These structural systems are generally adopted in areas of high seismic risk. The system can be either concentrically braces or eccentrically braced. [2]

II. PROGRESSIVE COLLAPSE

One of the means of structural failure that has been gaining importance over the years is the progressive collapse of multi-story buildings subjected to abnormal loading conditions like blast, fire, seismic waves, aircraft impact, construction error etc. Although the occurrence of an abnormal loading condition is very rare, the result of this loading may be catastrophic. It involves a series of failures that ultimately leads to the total collapse of the structure. When one of the major vertical load bearing element fails, the load gets redistributed to the adjacent elements thereby increasing the load on these elements more than their capacity ultimately leading to its failure. However this mode of failure is usually not considered and analysed while designing any multi-story building.

ASCE defines Progressive Collapse 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." [3]

The United States General Services Administration defines Progressive Collapse as "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." [4]

Song, et.al., [5] investigated the progressive collapse potential of an existing steel frame building by eliminating four first storey columns from 2D as well 3D buildings modelled in SAP2000 using linear static and nonlinear static analysis. Mohamed [6] studied the load increase factor required for a progressive collapse resistant design of steel building structures. Further the ductility of the individual components were taken into account after the initiation of collapse.

III. GSA GUIDELINES

The aim of the GSA (General Services Administration) [4]is to provide guidelines to evaluate the possibility of progressive collapse in new and existing federal buildings. There are different locations of critical element removal as specified by the GSA based on whether the elements being considered are internal or external. As per the guidelines it is required to remove the columns near the middle of the short side, near the middle of the long side, the corner of the building and adjacent to the corner of the building. For structures with underground parking or areas of uncontrolled public access, remove internal columns near the middle of the short side, near the middle of the long side and at the corner of the uncontrolled space.

According to the GSA Guidelines, an increased gravity loading should be applied to all regions immediately adjacent to the element removed at all floor levels as given by the equation below as shown in Figure 3-1

GLD=ΩLD (1.2DL+0.5LL)

In areas other than those loaded by the above the following gravity loading should be applied

G=1.2DL+ 0.5LL

where DL refers to Dead Loading and LL refers to Live Loading and ΩLD refers to a dynamic load increase factor

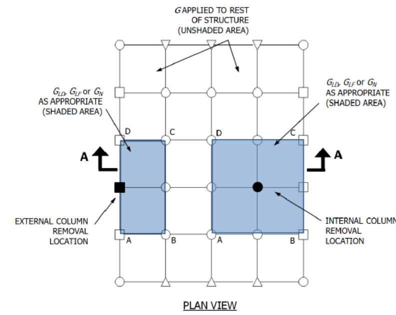

Figure 3-1 Increased Gravity Loads as per GSA Guidelines [4]

IV. LINEAR STATIC PROCEDURE (LSP)

Linear Static analysis is the most basic type of analysis carried out on any structure where the material as well as geometric non linearity after the load has been applied will be ignored.

The Demand Capacity Ratios (DCR) will be evaluated as follows in order to assess whether the structure will remain stable or collapse considering the acceptance criteria.

$$DCR = \frac{Acting\ Force}{Capacity}$$

4.1 Acceptance Criteria

The Demand Capacity Ratio shall not exceed 2 for all beam and column elements to ensure resistance against collapse. [4]

V. METHODOLOGY

A 15 story 3D steel and RCC moment resisting frame is modelled using the Extended 3D Analysis of Building System (ETABS) software. The lateral dimensions of the MRF are 30x30m with bays of 5m in each direction a concrete slab of 150mm thick of grade M30 as shown in **Error! Reference source not found.**

The building models have been designed to resist seismic loading corresponding to Zone 5 [7] and the live loads are applied as per IS 875 Part 2 [8]and taken as 3kN/m2. The load combinations are as per IS800:2007 [9]and IS456:2000. [10]

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I Data used for analysis models

Building Type	Steel	RCC
Column Size	Story 1&2-Box 450x450x15mm Story 3 to 15- Box 400x400x15mm	Story 1&2-600x600mm Story 3 to 15-450x450mm
Beam Size	ISMB500	300x450mm
Slab	150mm	150mm
Grade	Fe250	M30
Seismic Zone	5	5
Response Reduction Factor	5	5
Importance Factor	1	1
Time Period	1.476 seconds	1.303 seconds

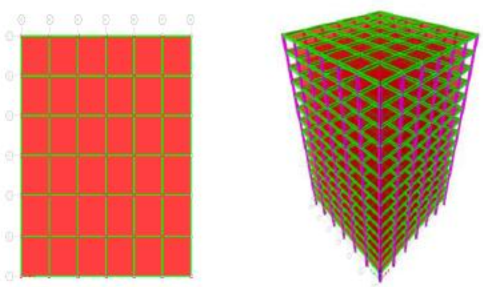

Figure 5-1 Isometric View and Plan View of Building Model

5.1 Column Removal Locations

As per GSA 2003 [4] guidelines a column should be eliminated at the corner as well as middle of the long and short side of the building as shown in Figure 5.1-1

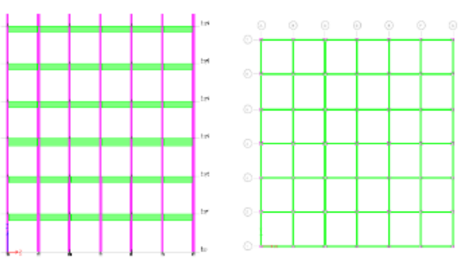

Figure 5.1-1 Column Elimination Location , exterior and interior columns

The 3D model has been prepared and the analysis was done for the load combinations as per the design codes for RCC and Steel to be safe against seismic loading.

5.2 RCC Frame

- The reinforcement to be provided in the members is determined.
- The members in the corner, middle and interior locations are eliminated separately and the gravity loads in the bays adjacent to the removed column is increased as below

$$GLD=\Omega LD\ (1.2DL+0.5LL)$$

- Based on several references the value of ΩLD was taken 2 [11]
- A linear static analysis is carried out and the Bending moments in the
- members adjacent to the eliminated column location are calculated.
- From the reinforcement obtained prior to column elimination the allowable Bending moment in the members are computed.
- The DCR for these members is obtained as the ratio of the Bending moment following the elimination of the column to the Allowable Bending moment.

5.3 Steel Frame

- The Allowable bending moment of the section provided using the equation M=fyxZ [9]where fy is the yield strength of the material and Z is the section modulus is calculated.
- The members in the corner, middle and interior locations are eliminated separately and the gravity loads in the bays adjacent to the column removed is increased.
- A linear static analysis is carried out and the Bending moments in the members adjacent to the eliminated column location are calculated.
- The DCR for these members is obtained as the ratio of the Bending moment following the elimination of the column to the Allowable Bending moment.

VI. RESULTS AND DISCUSSIONS

The Linear static analysis carried out to obtains the bending moment diagrams as below.

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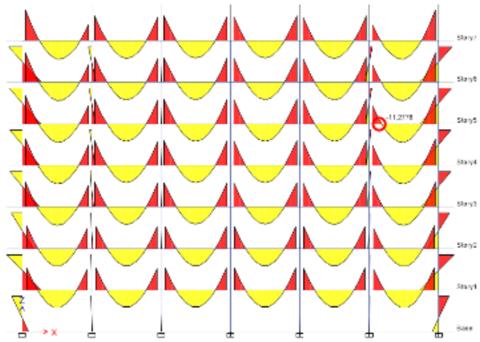

Figure 6-1 Bending Moment Capacity of the building

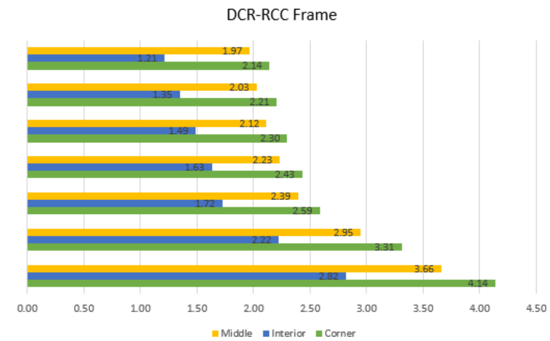

Figure 6.1-2 DCR Comparison for Beam element adjacent to column removal location

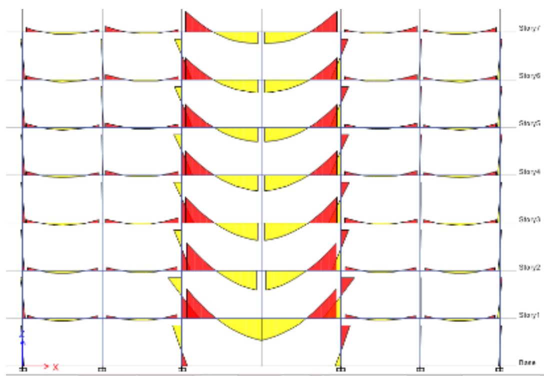

Figure 6-2 Bending Moment Demand after column elimination

After the column has been eliminated an increase in the values of bending moment is observed as in the case of a middle column elimination scenario. This is due to the increase in the span length from 5m to 10m after the column has been removed leading to moment distribution as shown in Figure 6-2

The maximum vertical deflection is observed as 18mm for the intact structure which is less than the allowable of 20mm, however after the column has been eliminated the maximum value has been exceeded especially in case of the corner location with a value of 34mm.

Further observing the DCR values of the beam elements the corner location resulted in values more than 2 indicating that the members have failed as per the GSA guidelines.

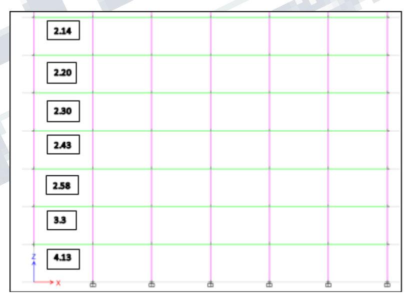

Figure 6.1-3 DCR Values for RCC MRF with corner column elimination

6.1 RCC Frame

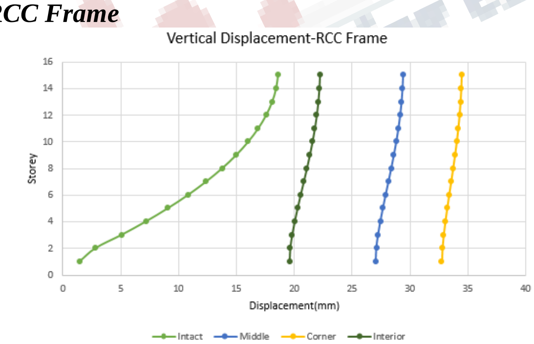

Figure 6.1-1 Vertical Displacement comparison

6.2 Steel Frame

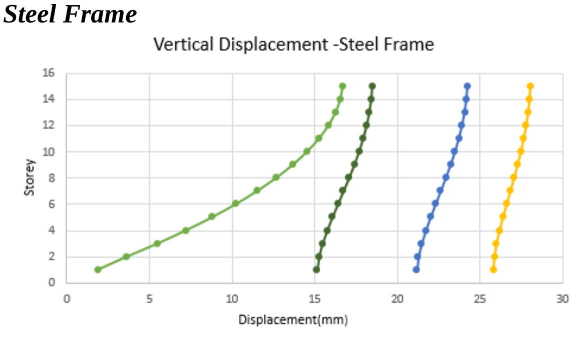

Figure 6-2-1 Vertical Displacement comparison

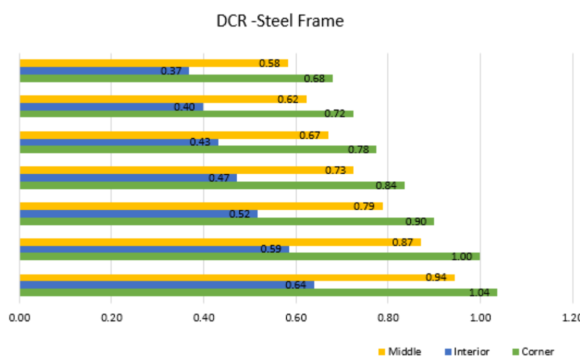

Figure 6.2-2 DCR Comparison for Beam element adjacent to column removal location

Similar variation in the vertical displacement values are observed in case of a steel moment resisting frame , however with marginally lower values when compared to the RCC frame. The DCR values are all found to be less than 1 indicating no failure in the case of a steel MRF. The column loss at the interior location shows less susceptibility to failure when compared to the external locations.

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