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Progressive Collapse Analysis of Moment Resisting RCC Frame Structure using ETABS

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Progressive collapse is an occurrence in the frame structures due to which the structural members (for eg. columns) unexpectedly fall out due to impact load. The problem of progressive collapse seized the attention of many researchers succeeding the fall out of Ronan Point Apartment in London (UK) in the year 1968. Later, the fall down of World Trade Center (WTC) towers in USA, many professionals started working on development of various guidelines for structural design that includes progressive collapse resistant structures. In the present work, linear method analysis i.e., linear static method and linear dynamic method analysis is performed and comparison is made in 18-storey RCC frame building. The progressive collapse analysis (PCA) is based on US government's General Services Administration (GSA) guidelines. The analysis was performed using structural analysis software, ETABS.

The matter of progressive collapse is not talked about in the standards of India till now. Therefore, the main objective of the current work is to give a clear ideal gradual elucidation of static procedures for PCA by performing suitable sample analyses using ETABS. The main aim of this current work is to explain & generate consciousness about the progressive collapse of the building in an easy way among practicing professionals.

Keywords: *RC frame building, Progressive Collapse Analysis (PCA), GSA guidelines, Linear Dynamic Analysis, Linear Static Analysis, World Trade Center, Ronan Point Apartment, Demand and Capacity Ratio (DCR).*

1. Introduction

Progressive collapse is defined as the action that results from the failure of any structural element that leads to the failure of further elements in consecutive manner, finally resulting in entire structural failure in some cases (ASCE, 2005). Progressive collapse is a series of reaction of failures that transmit all over the structure not in proportion to the initial local failure. When it is triggered, may cause an unforeseen loss of utmost structural load carrying members (for e.g. columns) because of localized damage. This results in either limited or complete collapse of the structure. One of the first observed failed structures due to progressive collapse, which got the attention of various engineers was the 22-storey apartment building in Ronan Point, London (UK) in 1968(Cynthia Pearson and Norbert Delatte)[1]. Numerous government authorities and local agencies have worked in developing the guidelines for designing of progressive collapse-resistant structures after the fall out of USA's WTC towers because of terrorist attacks in September 2001. In the list of these guidelines, GSA and DoD (Department of Defense, 2005) guidelines both developed by United States of America are extensively. These guidelines have provided the analysis approach as well as the design qualification of the buildings to hold on the progressive collapse.

2. This Study

In this study, PCA is executed by removing single or more vertical members i.e., columns at once and then exploring the structure's remanent ability to withstand collapse. The prime concern within this failure mechanism is the cognizance that it is a dynamic happening. As the compression member, column in this case, is removed from different locations, the equilibrium of the building is disturbed and motion in the building is commenced by the emancipation of internal energy. Then, the structure undulates till a new balanced position is established or until it fall out.

Here 18-storied moment-resistant RC frame is considered to conduct the analysis using ETABS software. The main objective of this work is to simplify the progressive collapse phenomenon and explain it conceptually by performing static analysis. Also to formulate a procedure with more valid and conventional results by using GSA guidelines. Although both the procedures may be performed separately but they complement each other very well, and therefore it is advocated that combined results must be taken into consideration. Progressive collapse analysis needs software which is capable in making changes in the stiffness matrix and also in the geometry instantaneously.

2.1 GSA Guidelines[2]

The USA's GSA has contributed "The Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects" to calculate the capacity of progressive collapse for existing RC and steel frame buildings. These guidelines are based on method of rotating load path and removal of vertical load carrying members.

2.2 Description of Assumed RC Framed Building

- To examine the consequence of removal of column over the building, a symmetrical plan having size 36m x 24m is considered.
- It has 6 bays in both longitudinal (long bay) as well as transverse direction (short bay).
- Each bay is of 6m and 4m in longitudinal and transverse direction respectively.
- The assumed building in this study is 18 storeyed RC residential building having 3.5m storey height making 63.3m as the overall height of the building.
- The height of base to plinth is assumed to be 3 m while that between ground floor and Plinth is 3.35 m considering plinth to be hollow.
- The assumed thickness of outer walls is 230mm and that of inner walls is 150 mm.
- The importance factor for the building as per IS 1893-2002 is considered to be 1.

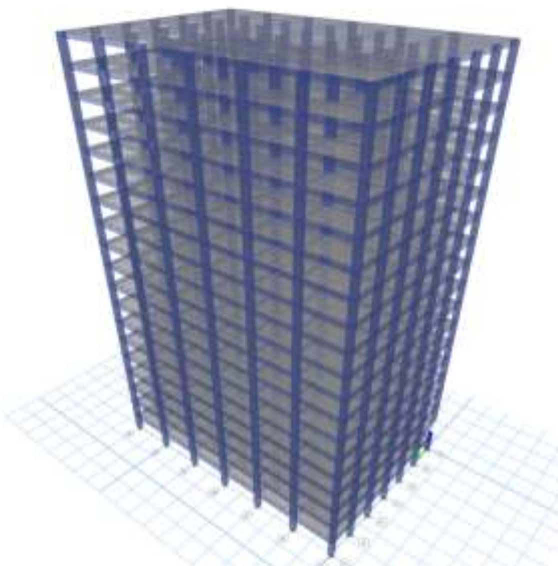

Figure 1 3D View of the Building Model

Loading Data:

i	External wall load (230 mm)	12.65 kN/m
ii	Internal wall load (150 mm)	8.25 kN/m
iii	Parapet wall load (230 mm)	6.9 kN/m
iv	Floor finish	1.0 kN/m^2
v	Water proofing roof	1.5 kN/m^2
vi	Live load on each floor	3.0 kN/m^2
vii	Live load on roof only	1.5 kN/m^2
viii	Self-weight of slab (200 mm)	5.0 kN/m^2

Properties of Construction Materials used:

i	Grade of Concrete	M35
ii	Grade of Steel	Fe500

Earthquake Parameters:

i	Seismic Zone of building	IV
ii	Zone factor	0.24
iii	Soil Type	Type II
iv	Importance Factor	1
v	Response Reduction factor	3

Load Cases:

The loading cases which are taken into consideration for the design of building in present study are as follows:

- Dead Load inclusive of self weight (DL)
- Live or Imposed Load (LL)
- Load due to Partition Wall
- Floor Finish (FF)
- Load of Wall at Parapet
- Seismic Load in longitudinal direction (EQ_X)
- Seismic Load in transverse direction (EQ_Y)

Load Combinations:

Besides the above mentioned cases, given below are the load combinations that are considered for design of structural elements as per Indian Standard, IS: 1893(2002).

- 1.5 (DL+LL)
- 1.2 (DL+LL± EQ_X)
- 1.2 (DL+LL± EQ_Y)
- 1.5 (DL± EQ_X)
- 1.5 (DL± EQ_Y)
- 0.9 DL ± 1.5 EQ_X
- 0.9 DL ± 1.5 EQ_Y

Building Design:

The final dimensions of the members of G+18 building, after analysis and design is given below:

- Beam = 400mm × 600 mm
- Column = 800mm × 600 mm
- Slab thickness = 200 mm

Reinforcement design for the given structure is administered by the earthquake load combination envelope.

Progressive Collapse Analysis

In the present work, four columns are considered that will be removed from different locations. The all four columns are removed from first storey which are labeled as D1, D4, A4 and A1, and beams are labeled as DE1, D12, D4, D45, A45, AB4, AB1 and A12 as shown in Fig. 2.

In order to exhibit and elucidate progressive collapse analysis steps in clearer manner, certain assumptions have been made:

1. In order to avoid the potential complexity in analysis, a symmetric building with a symmetric loss situation is used introduced by asymmetry;
2. To ascertain that they do not stagnant progressive collapse, stiffness of out-of-plane bending of floor slabs was minimized;
3. SMRF frames are used in which joints are vigorous than beams that will force plastic hinges to form into the beam and not in the joints or columns;
4. Analyses are performed with the exception of large deflections effects;
5. To report the strain-rate effect and material over-strength, the properties of the materials used are modified by Strength increase factors; and
6. The damping coefficient of 5% is assumed for RC building in the dynamic analysis.

Linear Static Procedure

1. In the static analysis, the removal of column is from its location and the building is analyzed under gravity load given in Eq.1 imposed on the structure is carried out. In accordance with the following equation, the linear static analysis was evaluated by the Demand to Capacity Ratio (DCR), for all beams in shear or moment.

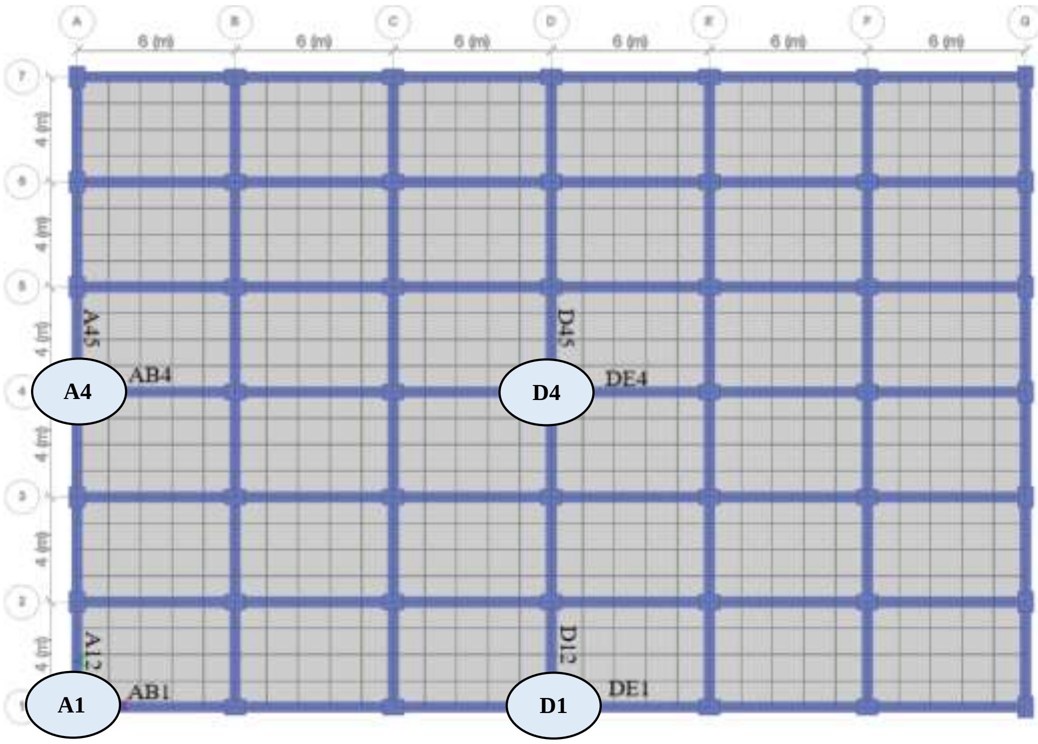

Figure 2 Building plan along with beams and columns considered in the study

$$Loading = 2\,(Dead\ Load + 0.25 Live\ Load) \quad (1)$$

$$DCR = \frac{Q_{UD}}{Q_{CD}} \quad (2)$$

$$DCR_M = \frac{M_{max}}{M_p} \quad (3)$$

$$DCR_V = \frac{M_{max}}{V_p} \quad (4)$$

Q_{UD} = Load (demand) in the building components or connection/joint (BM, axial force, SF, and other possible forces combination),
Q_{CE} = Maximum Shear capacity or Maximum Moment Capacity
The DCR indicates the possible progressive collapse of building. The idea of DCR comes from static linear procedure and it set down the limit values of DCR, based on the dimensions of the cross-section and on the materials used in the construction (Menchel et al., 2009).
In Equation 2, Q_{UD} and Q_{CE} are the capacities of force whether it is BM, axial force and SF in a component or the connection that are determined in the analysis. Q_{UD} is the maximum SF or BM in the concrete beam induced by suggested loading combination in the GSA or DOD guidelines. In evaluation of Q_{CE}, to account the strain rate effect and material over-strength, the material properties are modified by Strength increase factors. For RC frame structure, this factor is 1.25.
In Equation 3 and 4, M_{max} and V_{max} are demands in bending moment and shear force estimated through linear analysis in ETABS and M_p and V_u are the maximum BM (plastic moment) and maximum SF, respectively. Both can be evaluated for all structural members of the building. Based on above two values, the DCR value is computed. The structural members and joints exceeding DCR_V or DCR_M values by 2 are assumed to be severely impaired or disintegrated. Hence, it is unexpected that the structural member or joints will have sufficient stored ductility for functionally reallocating loads.
According to the GSA guidelines, the procedure to conduct linear static analysis is as follows.
Step 1: A 3D structure is prepared using computer software (ETABS used in this study).
Step 2: The members of the building are designed and the reinforcement requirement is found out.

Step 3: On the basis of the reinforcement provided in the members, the capacity in bending and shear are calculated. Note that the "strength increase factor" is considered to calculate the targeted material strength to determine the capacities and strain rate effect.

Step 4: Column failure condition is the generated by removal of column from the ground floor from the mentioned place but one at a time.

Step 5: The structure is analyzed for static analysis and for that particular removed column the demand is calculated.

Step 6: The capacity and the demand of the members are obtained from above analysis performed. It is been used in calculating the "demand to capacity ratio (DCR)" and their outcomes are evaluated.

The loading used in Equation 1 is used for static analysis.

The scale factor for different loads as defined in ETABS is taken equal to 2 as shown in figure 3. This load combination is used in Static analysis. The scale factor used here is to account the dynamic effect of the different loads. The functioning of the building is then evaluated using **Demand and Capacity Ratio** (DCR)**, and as per GSA guidelines this should not exceed by the magnitude of 2 for symmetrical structures and 1.5 for asymmetrical structures**. If this exceeds by prescribed value they are considered to be severely damaged or failed members or structure.

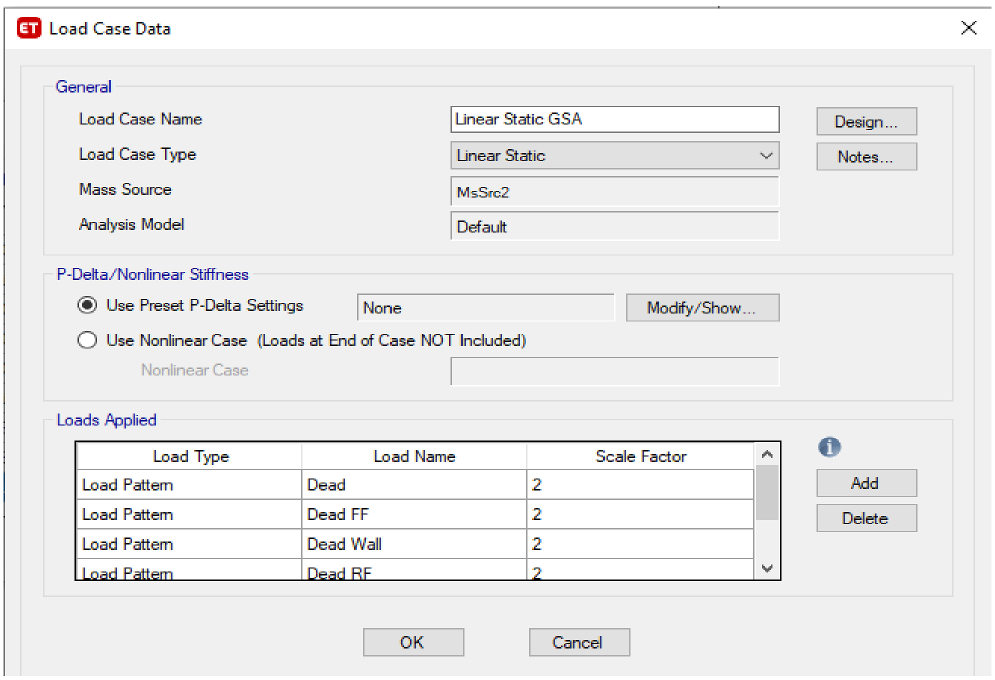

Figure 3 Linear static analysis in ETABS as per GSA

CALCULATION OF DCR (DEMAND CAPACITY RATIO)

Local collapse condition occurs due to removal of the columns D1, D4, A1 AND A4 as shown in figure 2 and Static Analysis is performed on the structure. After successful analysis on the building, the shear demand and flexure demand of the beams in the building are calculated. Fig. 4 and 5 shows BMD & SFD of the building for before and after column removal cases. The analysis was for all four column removal cases.

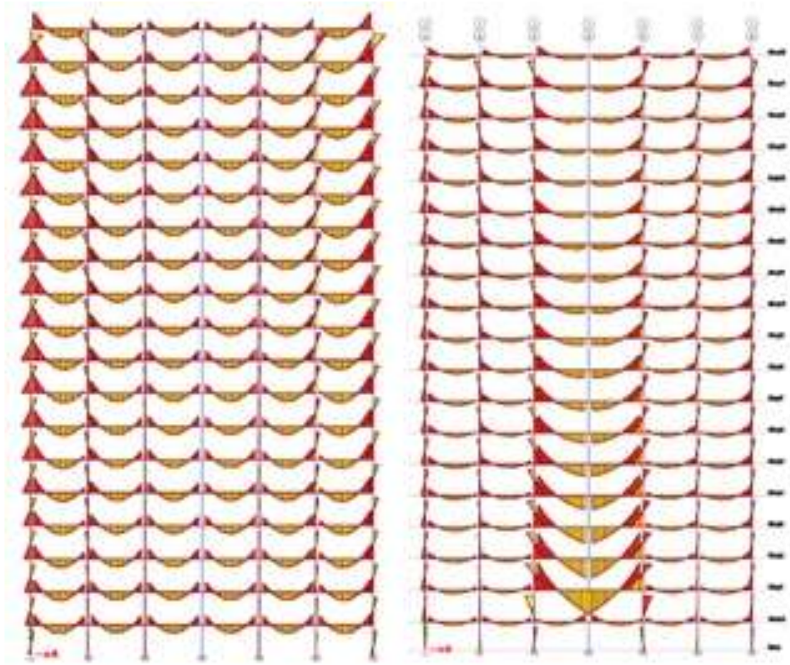

Figure 4 BMD for before and after column removal cases.

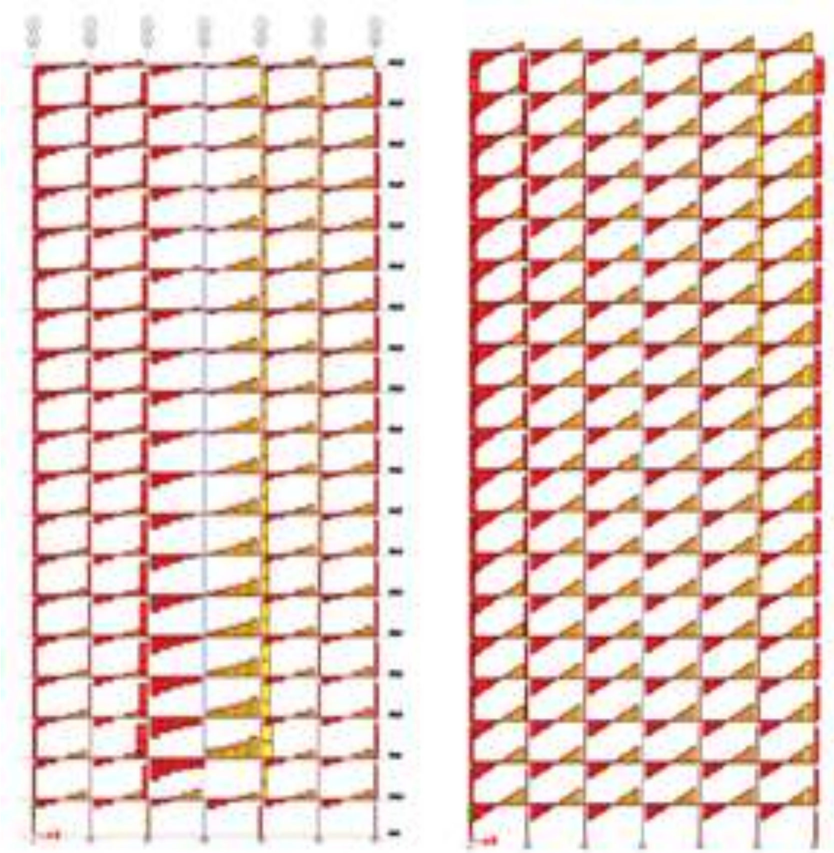

Figure 5 SFD for before and after column removal cases.

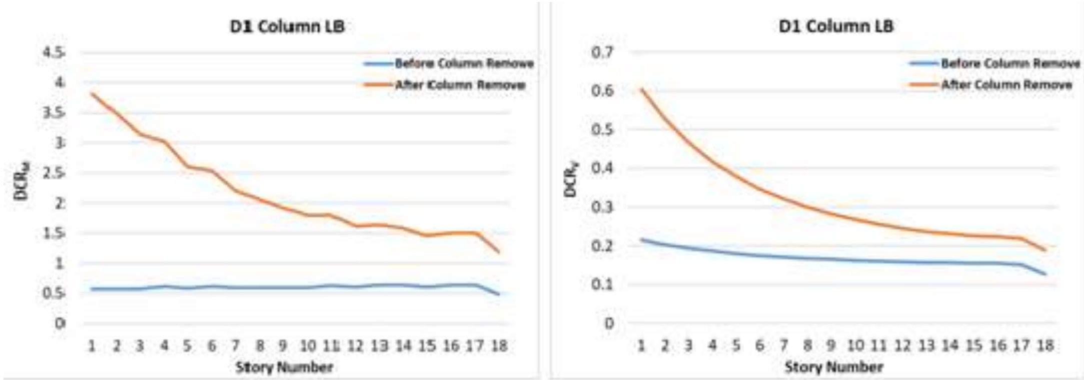

Figure 6 DCR_M vs DCR_V for Long Bay beam D1 column removal

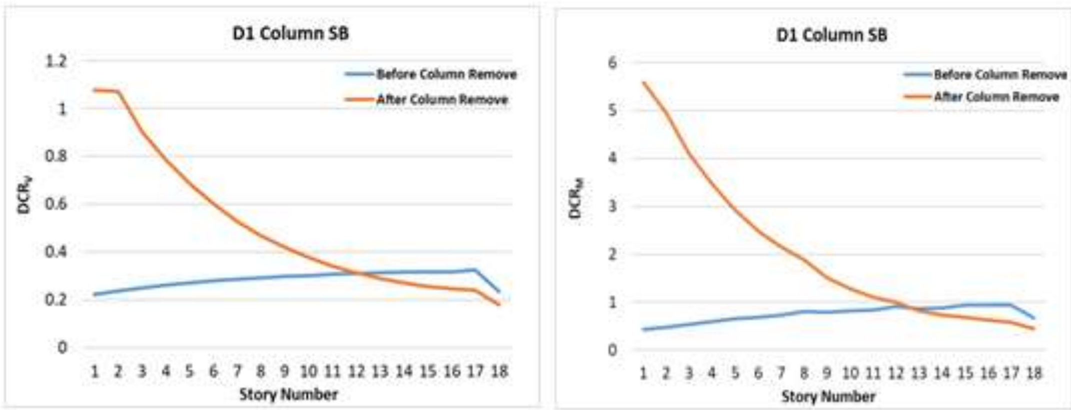

Figure 7 DCR_M vs DCR_V for short Bay beam D1 column removal

Linear Dynamic Procedure

The failure of columns under abrupt loads is an extremely powerful in nature. Therefore, it is essential to review the behavior of the building under dynamic loading.

Dynamic analyses (that may be linear or nonlinear in nature) are usually avoided because they are assumed to be highly complex and involve number of uncertain parameters. But in comparison to static analysis procedures, they have pretty high accuracy; reason being them incorporate inertial force, dynamic amplification factors and damping forces. This method is also referred as a time history analysis (THA). THA analyses the dynamic response of the building under any specific load that might change with time.

The benefits of this analysis include its precision in the result it provides, which comes from its ability to consider various complex parameters such as effects of dynamic loads from inside along with the effects of higher modes of vibration.

The drawbacks include its inability to consider the nonlinearity of the material used and that of geometry, which may contribute remarkable complexity in the structures (RC frame building in this case). Therefore, the structure's collapse pattern is not easy to predict.

In the present study, linear dynamic analysis was done for mentioned four column removal cases.

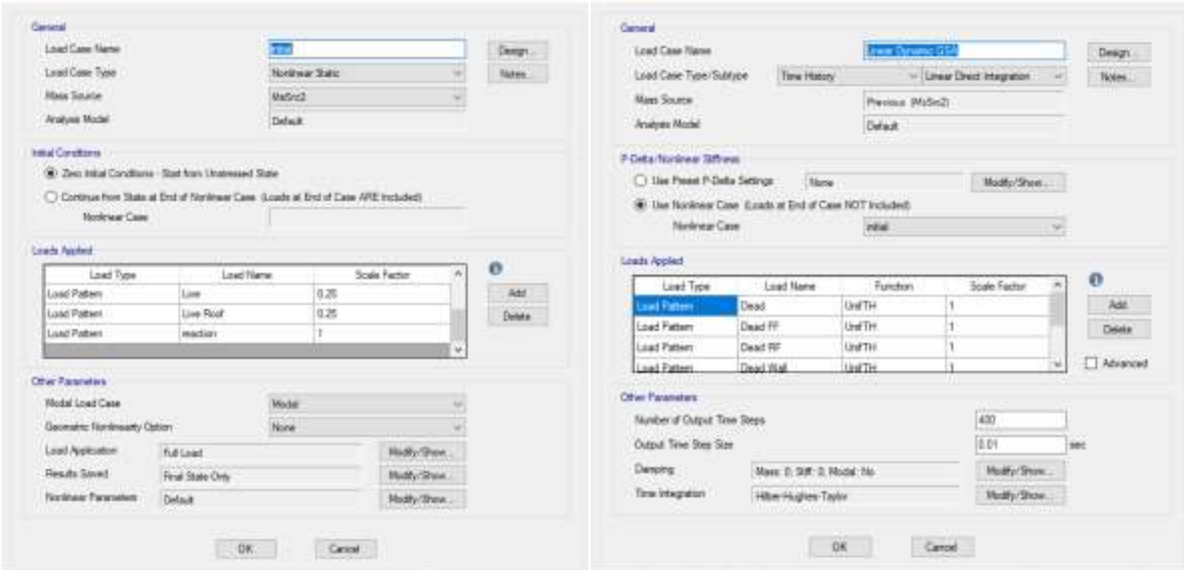

Figure 8 Definition of initial condition and column removal case according to GSA Guideline

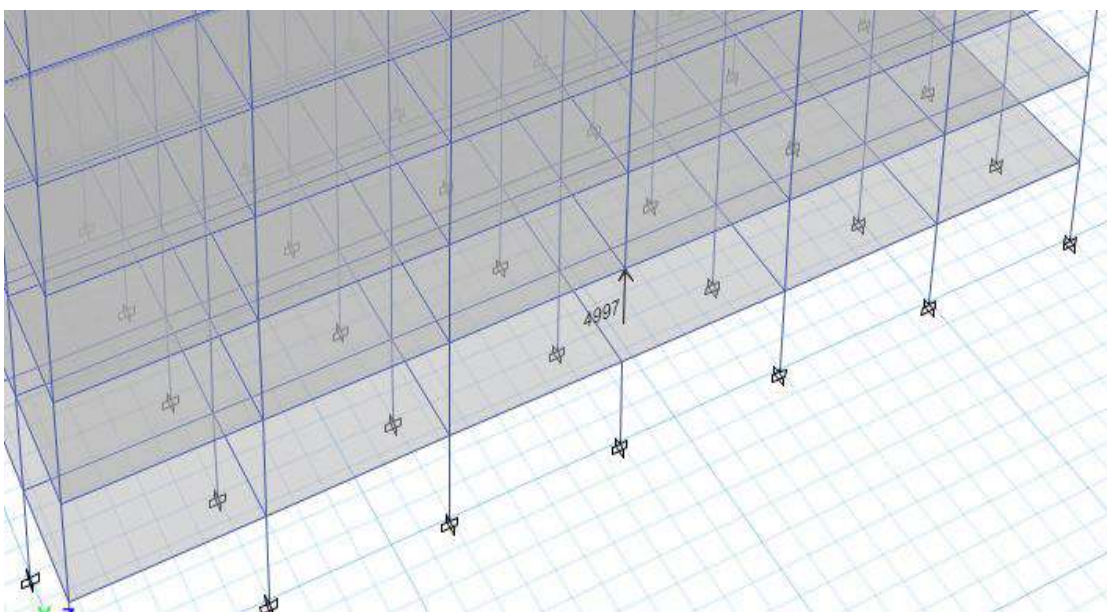

Figure 9 Column load applied to the building.

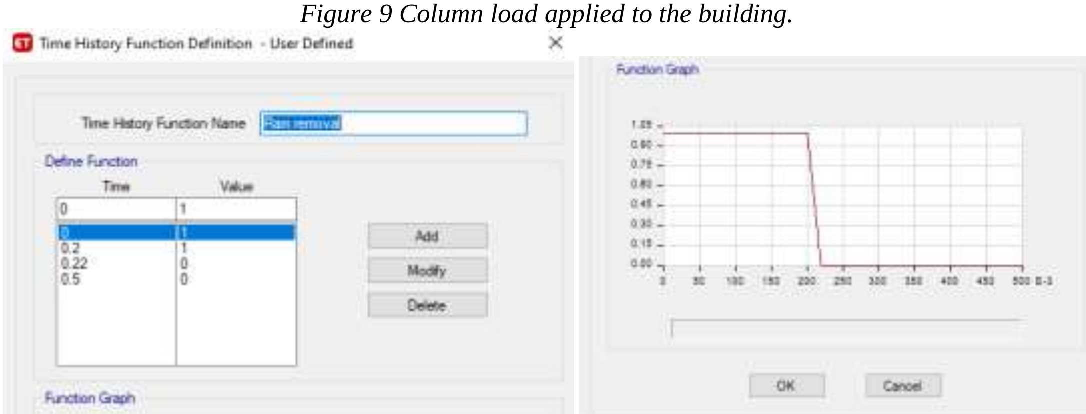

Figure 10 Time history function for removal

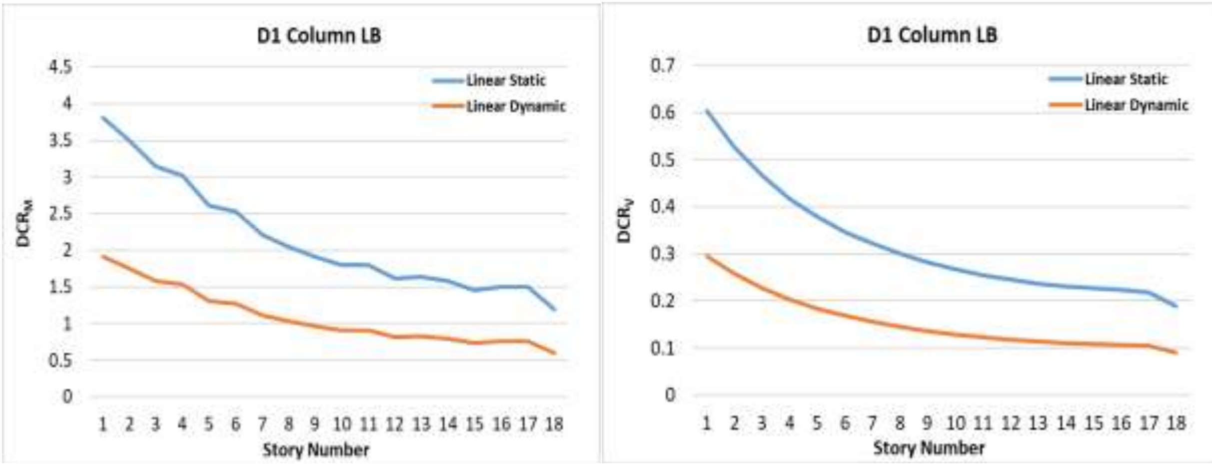

Figure 11 DCR_M vs DCR_V after D1 column removal for long bay beam.

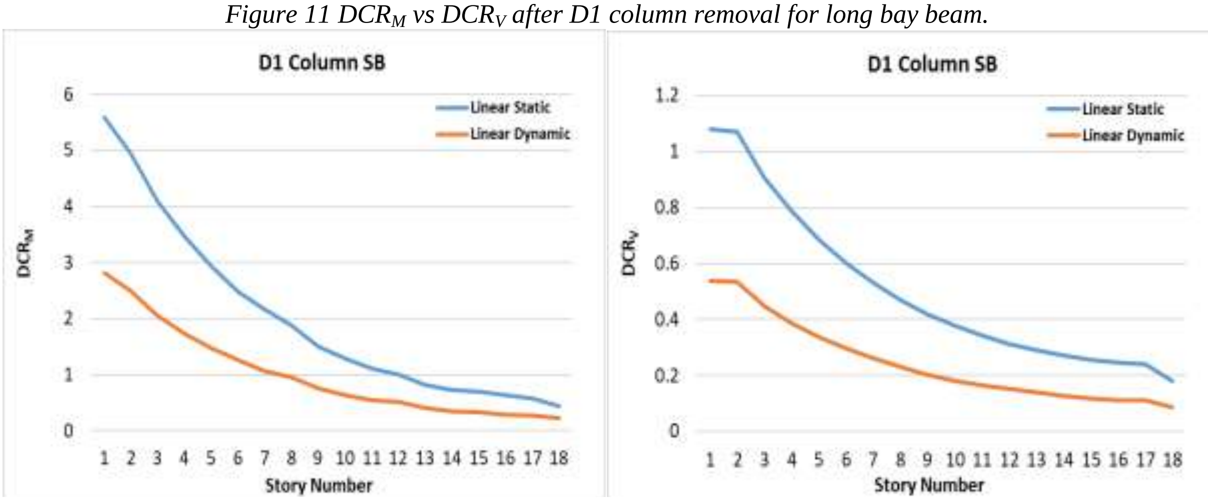

Figure 12 DCR_M vs DCR_V after D1 column removal for short bay beam.

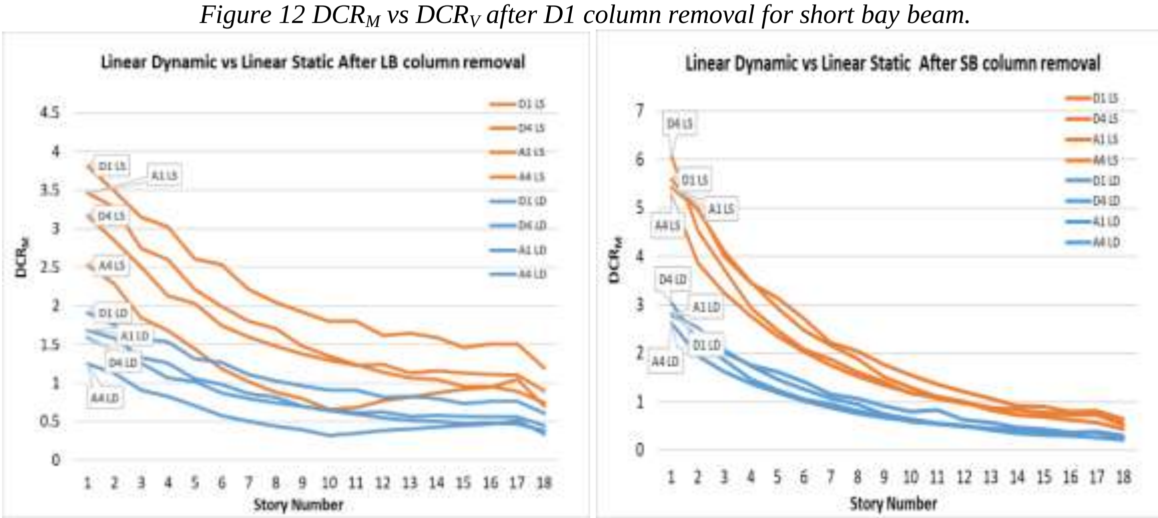

Figure 13 DCR_M for all column removal for long bay and short bay beam.

Conclusions and Recommendations

After the analyses which were performed on the building under different column removal cases, following conclusions are observed:

- From the results obtained from linear analysis i.e., both static (linear) and dynamic (linear) analysis, the column removed in the lower storeys create a more fragile state in the building as the DCR due to column removal in the lower storeys is more. But according to GSA regulations, if the DCR for any member is exceeding 2, the structure will collapse by developing plastic hinge and severe damage will at two ends of the beam.
- From figure 13, it is clearly observed that short bay beam is more sensitive to the damages in comparison with long bay beams for all column removal cases.
- On comparing the results of DCR_M and DCR_V for all 4 cases of column removal, it was observed that every beam whether in long bay or short bay, it is more sensitive in flexure as their DCR value is much greater than the acceptance criteria, where in DCR in shear is not reaching to the acceptance criteria. So according to that it can be predicted that beam will fail in flexure but not in shear especially in the present case model.
- The maximum static and dynamic deflections are obtained from factored load combinations and compared with the results from the linear static analysis.
- DCR obtain for linear dynamic analysis is less critical in compare to linear static. For long bay beam the DCR_M hardly reach to failure criteria but for short bay beam, DCR_M exceeding the failure criteria.
- After evaluating the column loss scenario for all four columns either by static or dynamic procedure, it is in account that column could be more or less susceptible to damage which completely depends on the position of any column location.
- As per the acceptance criteria, adequate steel reinforcement area is required at the end to limit the DCR. The beam must be designed with an adequate percentage of reinforcement in lower storeys. To prevent progressive collapse and maintain their serviceability, the alternative load paths could be developed. This will further transfer the load of each member to ground if failure or local collapse of structures occurs.

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