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Non Linear Progressive Collapse Analysis of RC Frame Structure

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Abstract

The casualties due to collapse of buildings are enormous either through blast or vehicle strike which could have been reduced if the buildings have resisted progressive collapse after the accidental removal of vital load bearing elements. In this research, progressive collapse (PC) potential of an existing reinforced concrete (RC) building has been evaluated analytically using Nonlinear FEM software following General Services Administration guidelines. Linear static, non-linear static, linear dynamic and non-linear dynamic analyses have been carried out to explore PC potential. Building under consideration was designed for Earthquake Zone-2B and has potential for PC in linear static analysis while non-linear static and non-linear dynamic analysis results have shown that there is no potential for PC. Results of analysis have been compared by taking deflection under joint where the column is removed and is used as base for comparison. Results show that linear static procedure is conservative as compared to non-linear analysis. Non-linear static and non-linear dynamic analysis provides almost similar results. There is negligible effect of material strength and damping variations on PC. In linear static analysis decrease in deflection of joint at column removal location is approximately 7% for every 7MPa (≅1000psi) increase in fc' while 9% reduction is observed in non-linear dynamic analysis. Damping that can be achieved through installation of dampers has been found beneficial up to 10% value. Increase in damping ratio beyond 10% of critical damping has negligible effect on deflection and PC.

Key Words: Progressive Collapse; RC Frame Structure; Linear and Nonlinear Static and Dynamic Analysis

1. Introduction

American society of civil engineers defines progressive collapse (PC) as "spread of an initial local failure, from element to element resulting in the collapse of an entire structure or large part of it" [1]. The distinguishing characteristic of PC from other type of building collapses is that the cause of failure is local e.g., loss of a column, but the ultimate impact is global which may be collapse of an entire building. First notable PC took place on 14th July, 1902 when a bell tower "St. Mark's Campanile" collapsed in Venice city of Italy [2]. More than 3000 people lost their lives and over 7500 injured in only 14 notable events of PC [3]. Mentionable research on PC started after the collapse of Ronan Point apartments building in London (U.K) in 1968. After the collapse of world trade center which alone claimed over 2700 lives, research on this topic attracted special attention of researchers all over the world. Some countries have published detailed guidelines for PC and its mitigation. USA is leading the world in this field. General Services Administration (GSA) guidelines [4], Department of Defense (DOD) guidelines [5], Unified Facilities Criteria (UFC) guidelines [6], National Institute of Standards and Technology (NIST) guidelines [7] etc. have been published for analysis, design and mitigation of PC initiated by various causes including blast.

After 9/11 many researchers have studied various aspects of PC. In recent researches there are number of studies in which PC related aspects has been studied analytically/experimentally under column removal scenarios and information regarding prevention of PC has been presented. NIST, USA has furnished detailed introduction to PC. The acceptable risk basis for PC means risk reduction, indirect and direct PC resistant design approaches, comparison of design standards and some case studies involving PC of buildings. Uwe Starossek [8] has investigated various types of PC. Ronald Hamburger et al. [9]

carried out a performance study for WTC buildings after their collapse in USA. Matthew Giles [10] has explained the causes of collapse of the same buildings. Meng-Hao Tsai and Bing-Hui Lin [11] studied the PC potential of earthquake resistant reinforced concrete building following GSA [4] guidelines. They carried out two types of analysis: Non-linear static along with non-linear dynamic for estimation of PC potential under column removal scenarios. Feng Fu [12] investigated the behavior of a multistory composite frame structure experimentally as well as analytically under the column removal scenario. PC potential has been determined following GSA and DOD guidelines [4, 5]. Feng Fu [13] also performed PC analysis for high rise steel buildings by constructing 3-D FEM models using ABAQUS and ETABS software packages. Both geometry and material nonlinearity was considered in the research. Behavior of structures under sudden column loss scenarios was studied considering structural systems of different types following GSA and DOD guidelines. Elizabeth Agnew and Shalva Marjanishvili [14] carried out dynamic analysis for a 2D building using SAP-2000 following GSA guidelines. D.G. Lu et al. [15] performed a pushdown analysis for assessment of PC resistance of RC frame structure using Open Sees software. In this study the effect of instant column removal as well as column removal duration has been investigated. Taewan Kim et al. [16] evaluated the PC resisting capacity of steel frames using Pushdown method. Steven M. Baldridge and Francis K. Humay [17] evaluated a 12 storey RC building for PC using ETABS in Zone-4 following UBC-91 guidelines. While, column removal scenarios was investigated following GSA guidelines. Mehmet Inel and Hayri Baytan Ozmen [18] investigated the effects of user-defined plastic hinges. Jinkoo Kim and Taewan Kim (2008) [19] studied PC potential for steel frame buildings possessing different structural systems. Methodology of alternate path has been adopted as per DOD and GSA guidelines. M. Lupoae et al. [20] carried out nonlinear static and nonlinear dynamic analysis for PC potential of RC buildings containing infill walls. In this study a 3-D model of an existing building designed for mild seismicity is studied for PC potential. Furthermore, the effect of damping, concrete strength and steel grade on PC potential is also investigated.

2. FEM Modeling of the Building

An existing five storied RC frame structure is considered for this study (Fig. 1). First storey height is 4.90m while the remaining four stories are 3.70m high. The building is asymmetrical with varying grid spaces. It is designed for earthquake Zone 2B. Beams and slabs sections are given in Table-1 and are also marked in Figs. 2 and 3.

3. Progressive Collapse (PC) Analysis Techniques

PC analysis has been carried out in this study under column removal scenarios following GSA guidelines [4]. The main building is divided into three blocks separated by expansion joints (Fig. 4). Since blocks 1 and 3 are similar therefore, only blocks 1 and 2 are considered for the analysis. In total five column removal scenarios have been evaluated as encircled in Fig. 4 and for brevity of discussion only one column removal case is explained here and details can be seen in the reference [21]. Three column removal cases have been evaluated for block 1 and two for block 2. Since, the external columns are more vulnerable thus their removal is considered here. The methodology presented in section 4.2 of GSA [4] has been followed. Demand to Capacity Ratios (DCR) has been calculated to assess the extent and progression of damage when column at grid-1D is removed at ground floor level of block-1 (Fig. 5). For beams, nominal capacity has been calculated using $M_n=A_sf_y(d-a/2)$. The flexural moments of the building under column removal scenario are taken as demand. Strength increase factor of 1.25 has been used while calculating section capacities [4]. For columns, a simplified procedure has been used in this study assuming major force in the columns is the axial force under static loads. DCR for columns have been calculated by dividing axial force after column removal scenario to the axial force capacity of the column. DCR values for beams and columns are shown in Figs. 6 and 7 respectively. Analysis has been carried out for static load combination 2(DL+0.25LL) [4]. The elements that possess DCR$\geq$1.5 would be considered severely damaged or collapsed for atypical buildings [4]. Fig. 6 shows that DCRs at some beam ends in the bay where the column is removed have exceeded the limiting DCR so these ends are severely damaged. While, for

Table-1: Section Geometry and Size

Section Name	Section Type	Shape of the Section	Width (mm)	Depth (mm)
B1	Beam	Rectangular	225	450
B2	Beam	Rectangular	450	600
CB	Beam	Rectangular	450	225
C1	Column	Square	375	375
C2	Column	Square	600	600
C3	Column	Square	450	450
C4	Column	SD Rectangular	450	1400
C5	Column	Circular	450 (Diameter)	
C6	Column	Circular	600 (Diameter)	
Slab	Slab	Rectangular	150 (Thickness)	

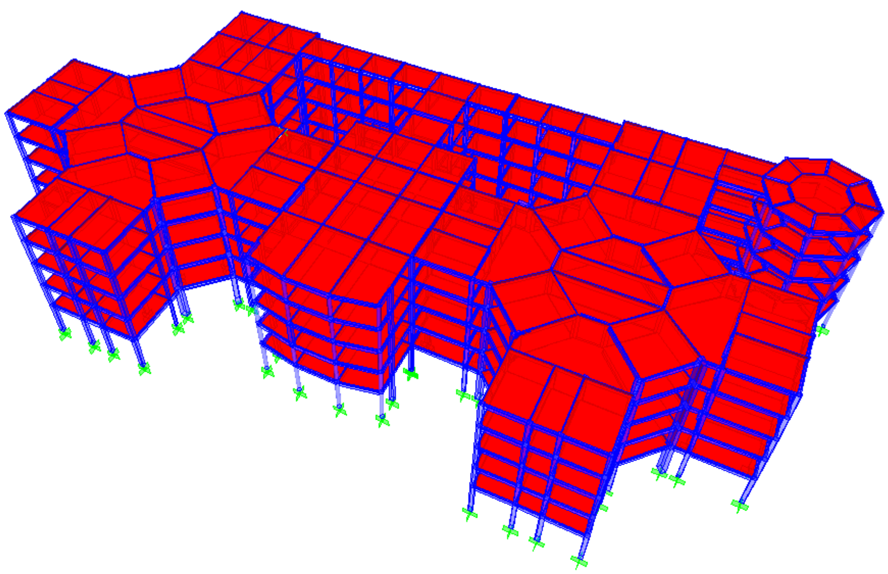

Fig. 1: FEM Model of the Building

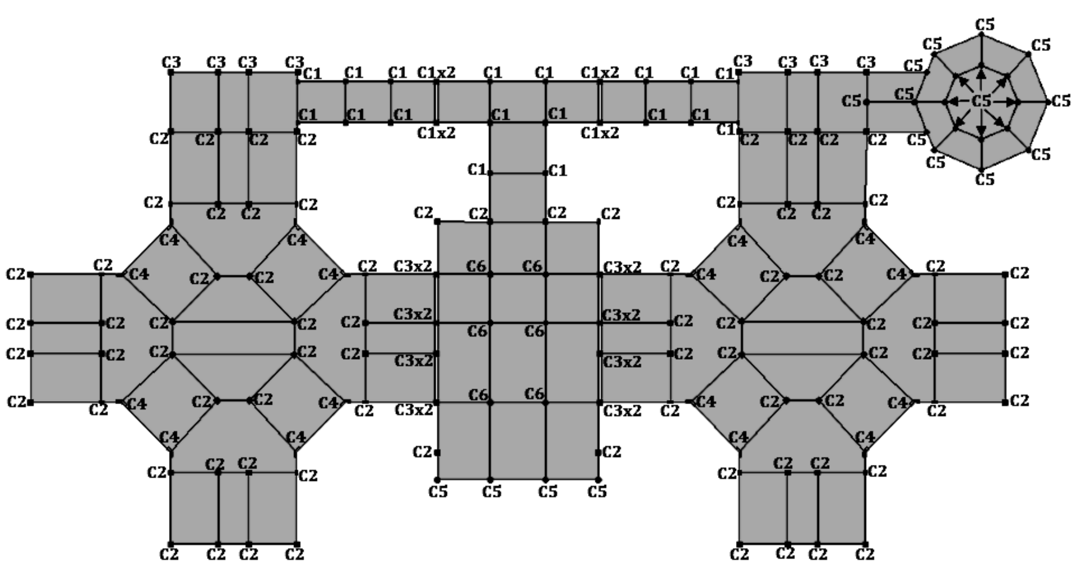

Fig. 2: Column Sections Locations in the Building

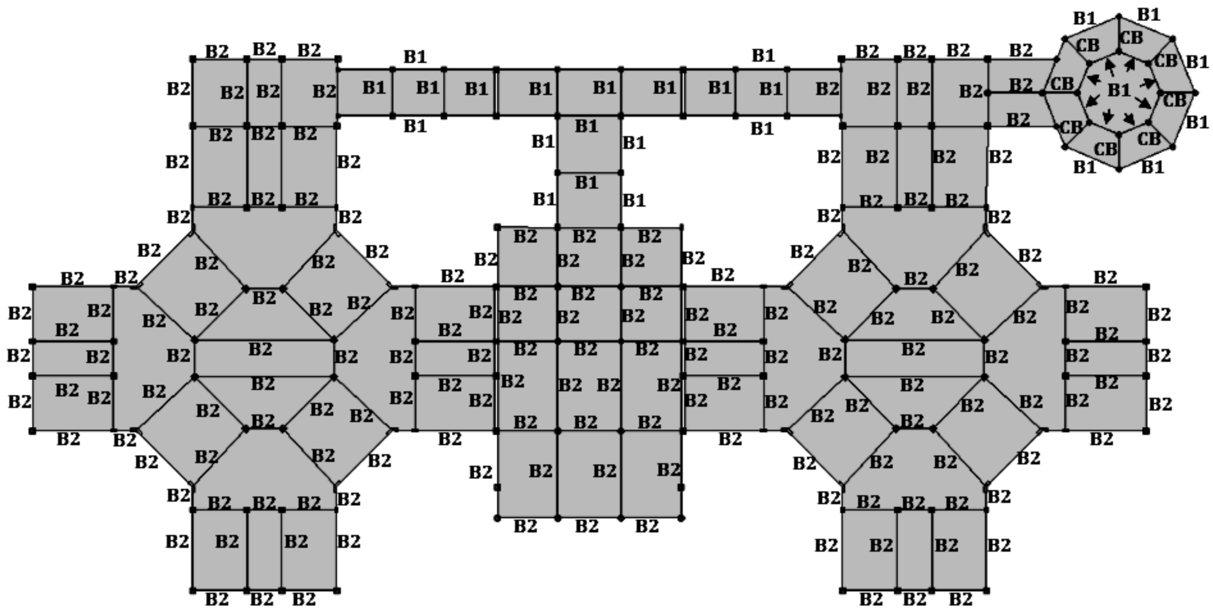

Fig. 3: Beam Sections Locations in the Building

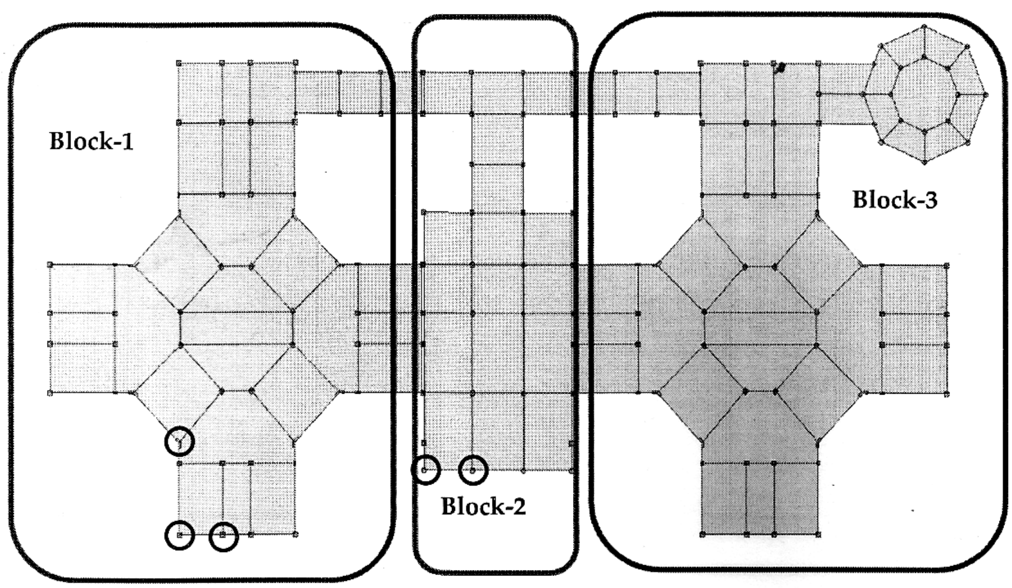

Fig. 4: Distribution of the Building into Sub-blocks

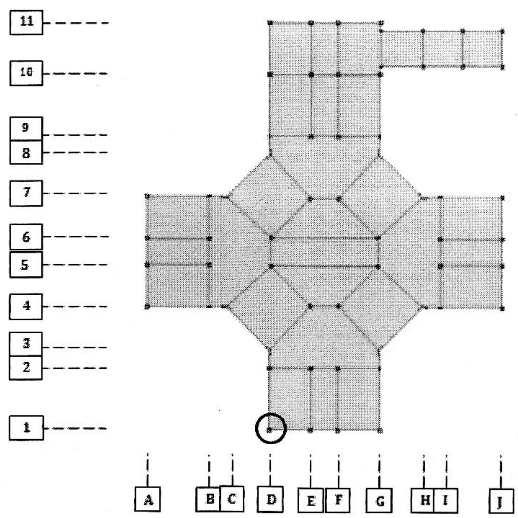

Fig. 5: Column Removal at Grid 1D of Block 1

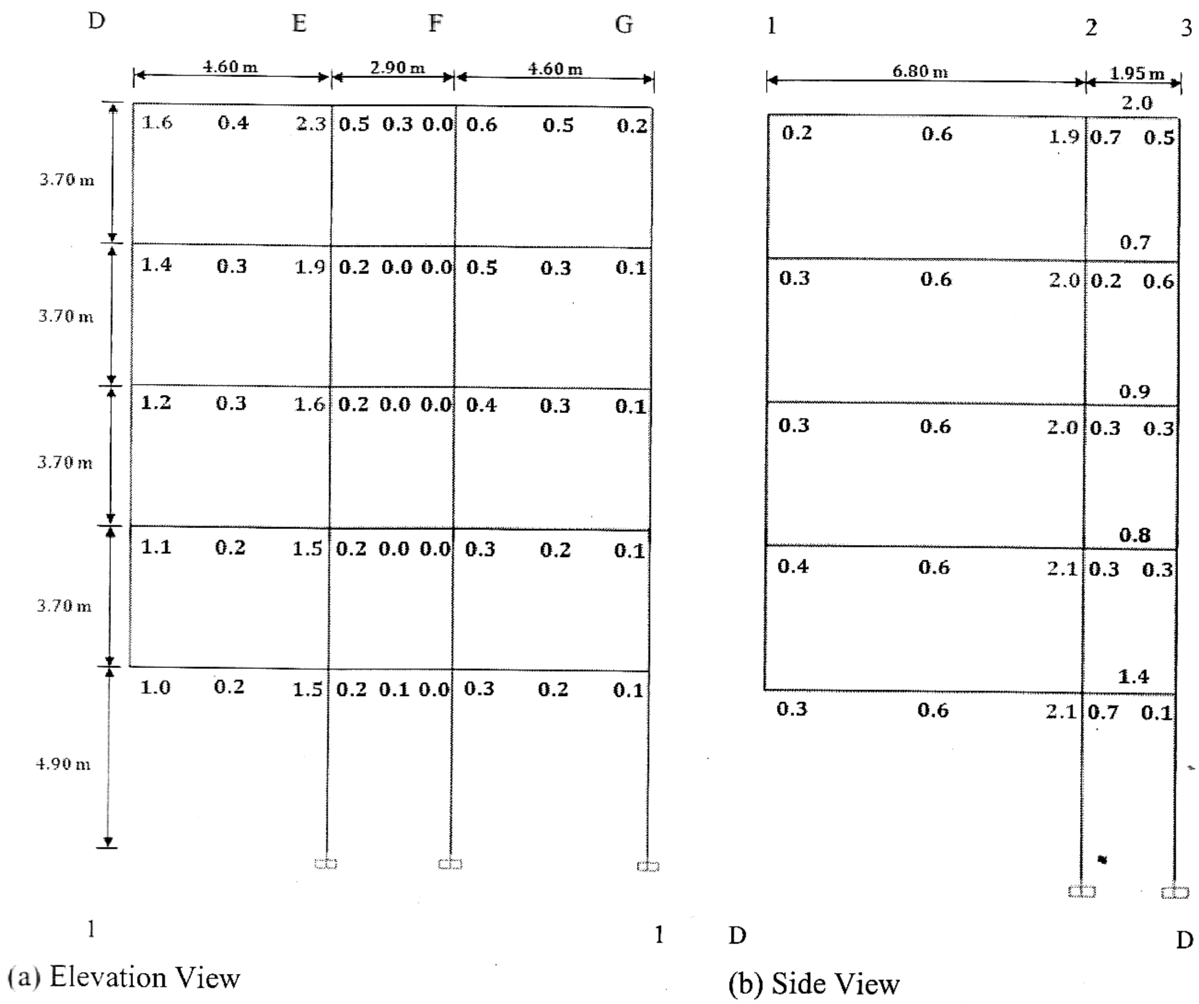

Fig. 6: DCR of Beams for Column Removal at Grid 1D of Block-1

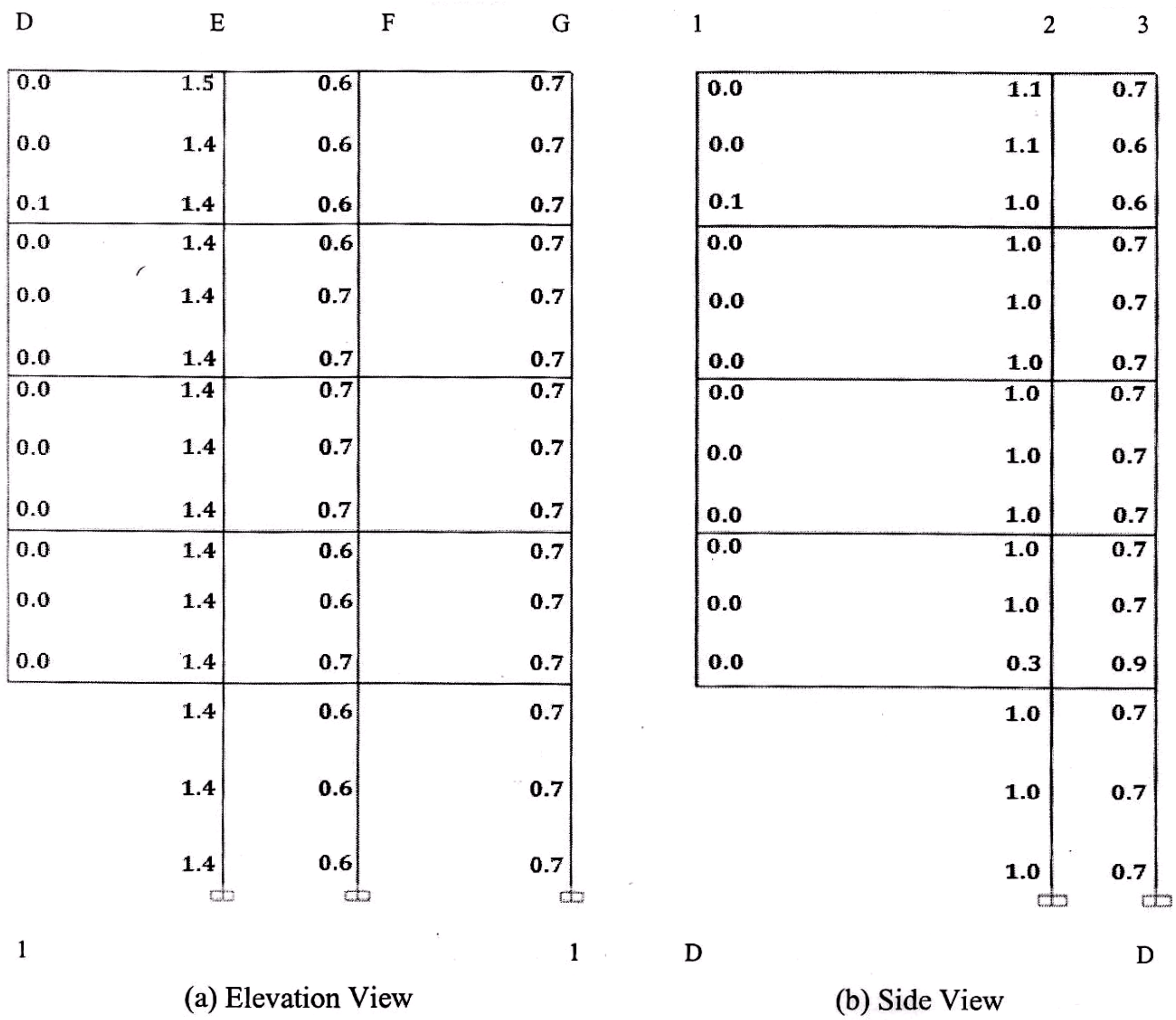

Fig. 7: DCR of Columns for Column Removal at Grid 1D of Block-1

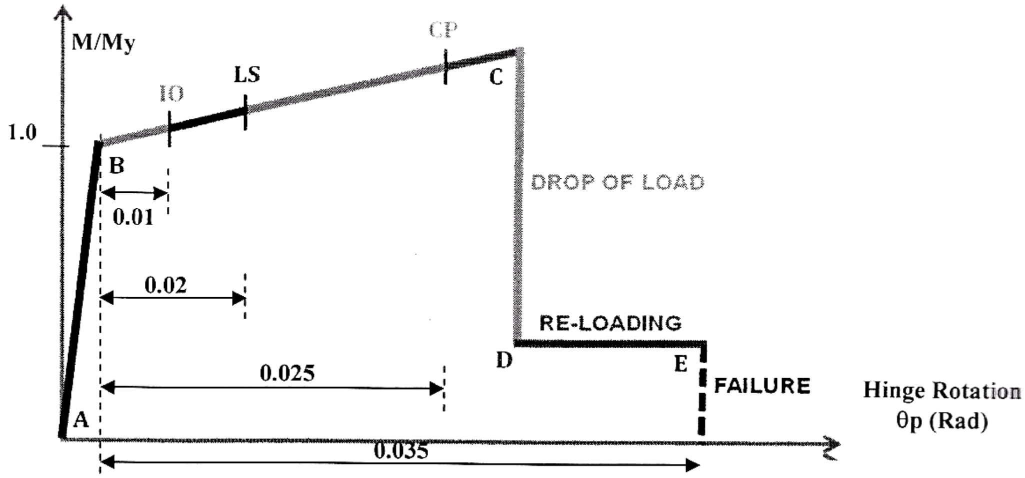

Fig. 8: Typical Plastic Hinge Backbone Curve

columns DCR limit is reached only in one section at roof level (Fig. 7). So, the probability of partial collapse exists only in corner bay for this particular column removal scenario and complete collapse of the building is not anticipated. Nonlinear analysis can simulate the damage more exactly. Three auto hinges have been assigned to each beam and column; two at the ends and one at center. Beam hinges are flexural hinges while column hinges are interaction hinges (Auto P-M_2-M_3). RC beam hinge properties from tables 6-7 and for RC column hinge properties from tables 6-8 of FEMA-356 are used [21]. All the elements are considered strong in shear and no shear hinge is assigned. The non-linear analysis has been carried out under "full load" application. To compare results of different analyses, deflection under the joint where the column is removed in LS analysis is considered as control deflection for comparison. The control deflection observed in the LS analysis at the column removal joint has been considered as target deflection in NLSA by varying GSA specified load, i.e., 2(DL+0. 25LL). The typical backbone curve for the plastic hinge is shown in Fig. 8. The result of the NLSA is shown in Fig. 9. NLDA is considered most accurate due to consideration of material non-linearity and dynamic effects which are observed during PC. Procedure for carrying out NLDA is similar to that of non-linear static analysis except the load case (DL+0.25LL). In NLDA damage is occurred at the same sections in NLSA (Fig. 9).

However, values of rotations are different in both the analyses. The similarity of results in NLSA and NLDA indicate that the acceleration component is not significant and material non-linearity alone can be considered for potential of PC. LDA has been performed to verify the Dynamic Amplification Factor (DAF) due to amplification of deformations in dynamic response [4]. A DAF factor of 2.4 has been achieved by comparison with NLDA load combination to achieve target deflection under the column removed joint. This value is close to DAF of 2.0 as specified by GSA [4].

4. Effect of Material Strength and Damping on Progressive Collapse Potential

Deflection under column removed joint is of primary concern to control the PC. Large deflection will generate more damages and ultimately increases the chances of PC. The effect of material strengths (concrete and reinforcing steel) and damping ratios on deflection of column removed joint has been investigated. The concrete design strength (f′c) is 21MPa for beams and slabs and 28MPa for columns. Concrete strength has been increased from design strength with an interval of 7MPa up to maximum of 35MPa keeping all other parameters as constant. Fig. 10 shows reduction of deflection of column removal at grid 1D, with increase in f′c. Reduction in deflection with increase in f′c is obvious due to increase in modulus of elasticity and flexural stiffness of the structure. Approximately 37% reduction in deflection is observed at 35 MPa f′c. In other words there is a decrease of 7.4% in deflection for each 7MPa increase in f′c.

The effect of increase in f′c on deflection has also been studied with NLDA. The vibrations of column removed joint at 1D with increase in f′c are shown in Fig. 11. Damping ratio has been considered zero for this analysis. Continuous reduction in deflection is observed with increase in f′c. Approximately, 45% reduction in deflection is observed at f′c =35 MPa. In other words 9.0% decrease in deflection is attained per 7MPa increase in f′c. The LSA and NLDA results with increase in f′c are compared in Fig. 12. Reduction in deflection is more in NLDA than in LSA.

Reduction in deflection with increase in f′c is apparent in both analyses due to increase in modulus of elasticity and flexural stiffness of the structure. Effect of steel strength (fy) is evaluated for three grades of steel i.e., 300, 420 and 520 MPa keeping all other parameters constant. Yield strength has been found to have no appreciable effect on reduction of deflection of column removed joint due to the fact that the flexural stiffness of RC members is not much affected by fy.

Damping reduces amplitude of a vibrating system. According to Unified Facilities Criteria (UFC), ignoring damping will increase deflection in structural members. Therefore, it is conservative to ignore damping in the structure. In this study effect of damping ratio on deflection of the column removed joint has been analyzed with NLDA at an interval of 1% and 5% up to maximum of 5% and 30% respectively. The result in Fig. 13 shows that there is reduction in deflection and amplitude of vibration.

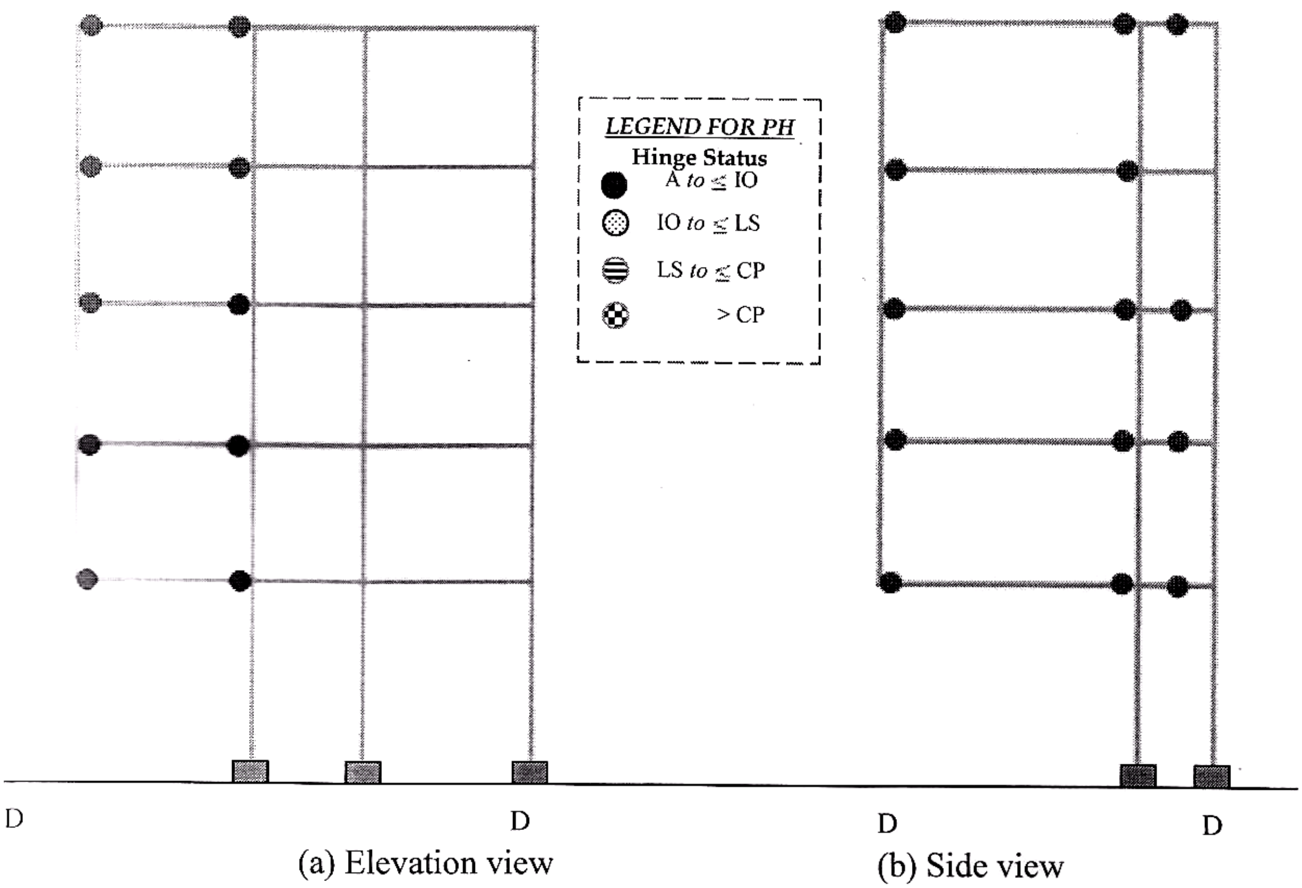

Fig. 9: Non-linear Plastic Hinges for Column Removal at Grid 1D of Block 1 under NLSA and NLDA

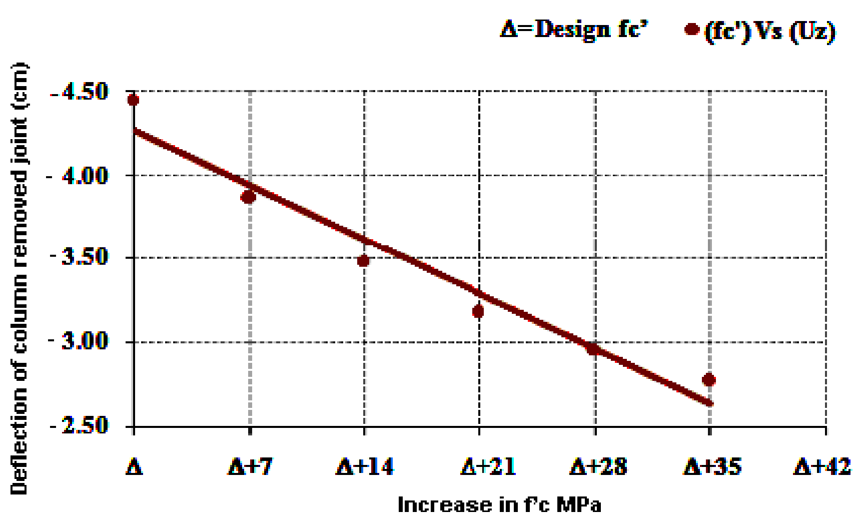

Fig. 10: Plot between f′c and Reduction of Deflection for Column Removal at Grid 1D

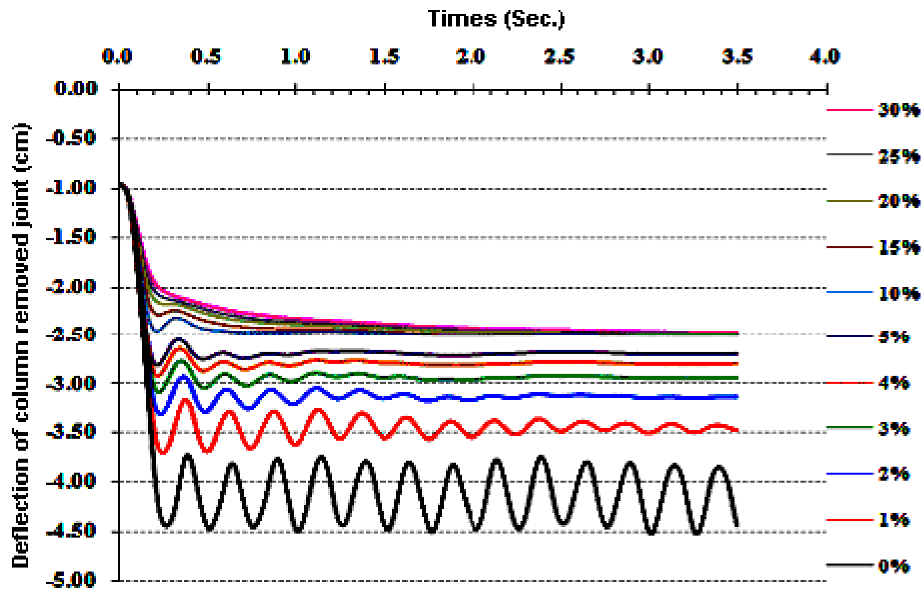

Fig. 11: Plot between f′c and Reduction of Deflection for Column Removal at Grid 1D

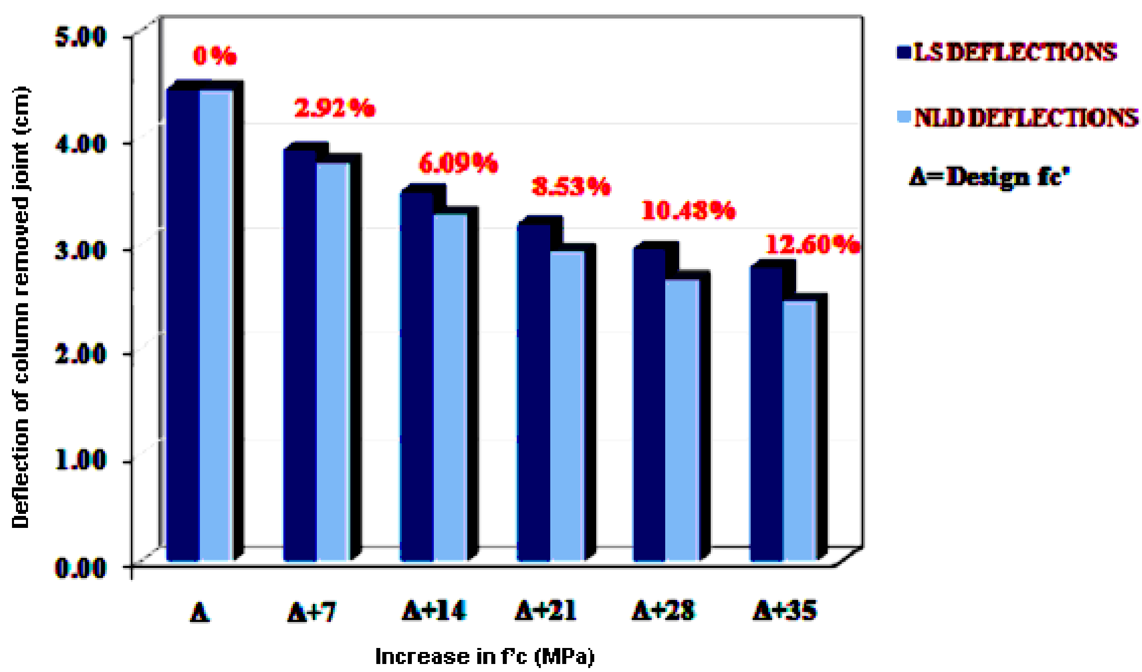

Fig. 12: Comparison of Linear Static and Non-linear Dynamic Deflections

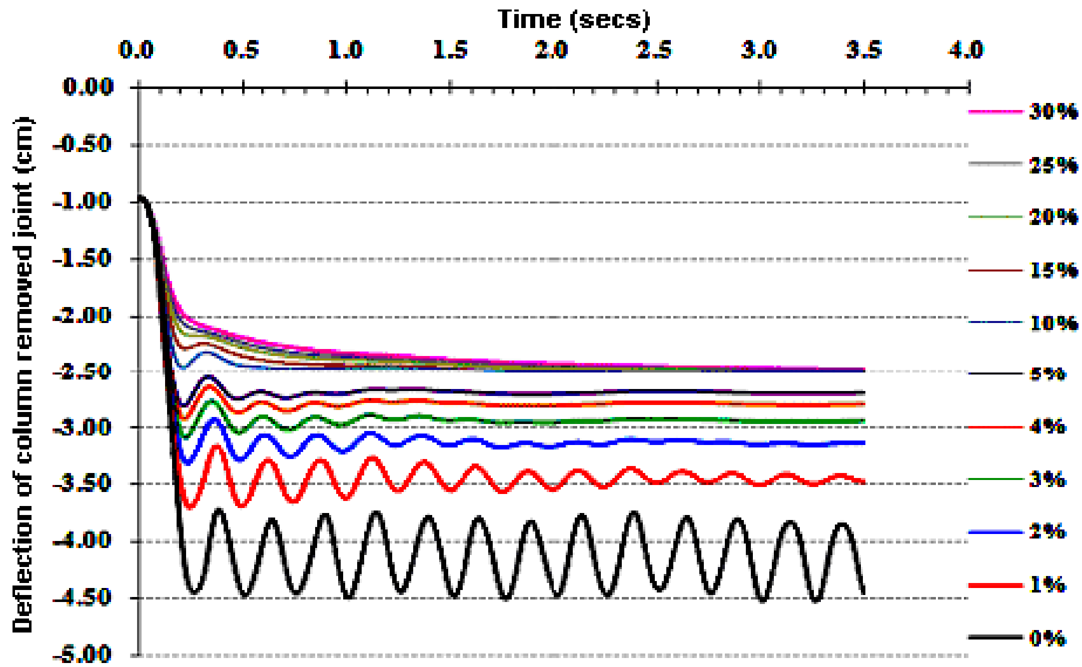

Fig. 13: Relationship between Damping Ratio and Deflection of Column Removed Joint at Grid 1D

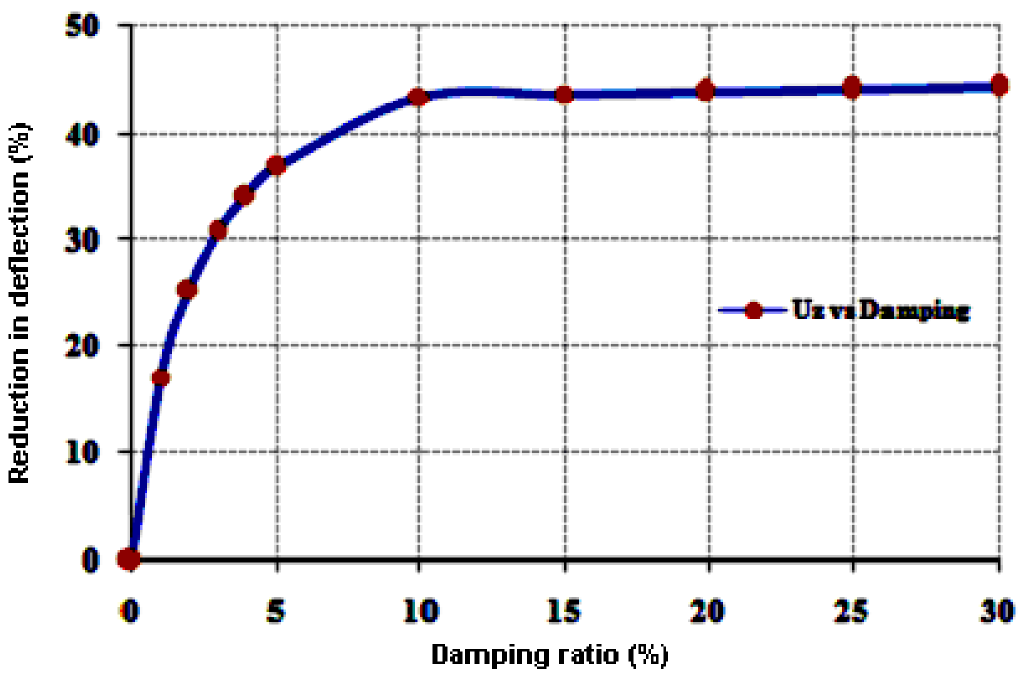

Fig. 14: Relationship between Damping Ratio and % Reduction in Deflection at Grid 1D

with the increase in damping ratio due to increase in stiffness of the system. Initially the impact of damping ratio on deflection of column removed joint is significant (Fig. 14). At 10% damping ratio, 43% reduction occurred. Increase in damping ratio beyond 10% is observed to have no significant impact on reduction of deflection. Therefore, 10% damping ratio may be considered an optimum value for this structure.

5. Conclusions

In this study Progressive Collapse analysis of an existing RC frame structure has been carried analytically under column removal scenario following GSA (2003) guidelines. The effect of variation in material strengths and damping ratio on progressive collapse potential has been investigated. Following are the conclusions:

1. Linear static analysis procedure of GSA (2003) guidelines is relatively more conservative than non-linear static and non-linear dynamic analyses.

2. In nonlinear dynamic analysis there is reduction in deflection of the column removed joint with the increase in compressive strength of concrete. However, steel strength (fy) has negligible effect on deflection.

3. Increase in damping ratio reduces deflection of the column removed joint. Up to 10% increase in damping ratio, reduction is prominent (approximately 43% reduction has been achieved with 10% damping ratio). Increase in damping ratio beyond 10%, has negligible influence on the reduction of deflection.

4. For atypical building due to its complex geometrical configuration and load re-distribution corner column removal case may not be considered critical directly. Moreover, for atypical building demand may exceed many times the available capacity.

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