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Assessment of Progressive Collapse in RC Buildings and Retrofit Strategy

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Abstract

Progressive collapse is the series of failures of load-carrying elements in the building caused by a local failure. The behavior of reinforced concrete buildings under the failure of such elements due to progressive collapse caused by abnormal loads and the techniques used for resisting this situation has been the subject of several studies. In this paper, the behavior of the reinforced concrete structure under the failure of edge column and how this issue can be withstood are studied and modeled using linear static analyses which are parts of the alternate path (A.P.) procedure, taking into consideration the guidance of the General Services Administration (GSA). An edge column loss in a 6-story building consisting of 5 bays on each side is modeled using the ETABS program. Multiple models are discussed to minimize the effect of the progressive collapse, including the addition of different types of steel bracing to identify the best model that reduces stresses generated due to the failure of an edge column. From the linear static model, it was found that removing an edge column will increase the moment and shear values in columns and beams, especially for those located on the exterior side of the building, so the amount of steel provided for them will also increase. Also, it is found that adding braces in the linear static model will reduce the moment and shear values in beams and columns, which will produce a more economical design. In the nonlinear static model, adding braces decreases the vertical displacement and rotation values significantly by about 75%, which will also produce a more economical design considering that the performance level reached was the Immediate Occupancy (IO) performance level.

Keywords: progressive collapse, moment resisting frames, linear analysis, braced frames.

1 Introduction

Progressive collapse is the series of failures of load-carrying elements in the building caused by a local failure. The behavior of reinforced concrete buildings under the failure of such elements due to progressive collapse caused by abnormal loads and the techniques used for resisting this situation has been the subject of several studies. In fact, the progressive collapse was given attention, starting from 1968 when London's Ronan Point apartment tower collapsed in the UK. [1].

The most recent code that discusses procedures to resist progressive collapse is the "GSA" [2], which discusses the analysis procedure using the alternate path method (AP) and provides the required reinforcement and guidelines for the elements to resist progressive collapse. ASCE/SEI 41-31 [3] has also provided some provisions that were used in the GSA code, in addition to the "UFC 4-023-03" [4], which also provides essential procedures to analyze and design buildings against progressive collapse.

The previous codes' procedures were based on redesigning the elements either by increasing sectional area or the reinforcement ratio to redistribute the applied load after the column loss. Many researchers covered important progressive collapse case studies to understand the behavior of structures under different scenarios. For example, Osama A. Mohamed [5] studied the progressive collapse behavior on an 8-story reinforced concrete building due to the loss of a corner column using 3D modeling. The authors highlighted the advantage of steel bracing on resisting induced moments produced due to corner column loss. S. M. Marjanishvili [6] summarized procedures used to analyze progressive collapse and the limitations of each. They concluded that simpler, static analyses could be used initially to validate the results and produce a correct cost-effective solution.

Digesh D. Joshi et al. [7] studied linear static and nonlinear static methods to analyze progressive collapse in buildings, while U. Al Sabouni et al. [8] studied the Performance and Progression of Collapse using Nonlinear Dynamic Analysis. They concluded that hinge formation would occur at locations where DCR (Demand to Capacity Ratio) exceeded. In addition, the authors pointed out the advantage of adding enough reinforcement to satisfy DCR requirements and detailing requirements as well.

Based on the literature, more studies are required to study the behavior of buildings under the progressive collapse of columns at different locations and explore viable retrofit strategies. Hence, analyses of buildings have been studied to assess the behavior against the removal of edge column scenarios.

2 Methods

Linear static analyses, a method prescribed in the (GSA) have been used to analyze six-story buildings consisting of 5 panels in both directions, 7 m by 7 m, under the scenario of the removal of the edge column. Buildings have been modelled using ETABS software [9]. The prototype building, model 1, is shown in Figure 1, while models 2 and 3 represent the column removal (D-1) without and with an inverted V bracing (W), respectively. Beams and columns are classified as deformation-controlled elements since the ratio of the shear demand over capacity using expected material properties V_p/V_o is less than 0.6. Figure 1 shows the original model without any column removal. Beams and columns are identified by the intersection of grids shown in Figure 1 (B).

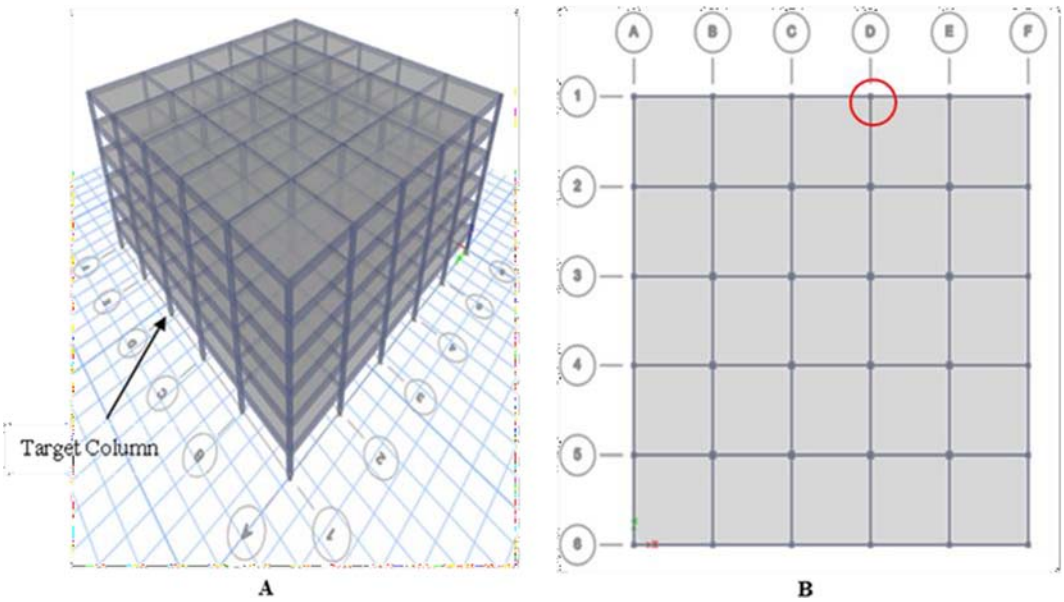

Figure 1: Building model in ETABS; (A) 3D view, (B) rooftop plan view showing the removed column.

The concrete compressive strength (fc') is assumed to be 40 MPa, and the steel yield strength (fy) is 420 MPa. The loads applied to the structure are summarized in Table 1.

Table 1. Applied loads

Dead Load	Concrete Self Weight (kN/m^3)	24
	Roof Floor (kN/m^2)	1.39
	Other Floors (kN/m^2)	3.39
Live Load	Roof Floor (kN/m^2)	0.96
	Other Floors (kN/m^2)	1.92

In the linear static method, which can be used for buildings less than ten stories and having acceptable limits of irregularities, a factor Ω=1.25 is assigned to the steel yield strength (fy), and a factor Ω=1.5 is assigned to the compressive strength of concrete (fc') as per ASCE/SEI 41-13 [3]. Other strength reduction factors for capacities (φ) of the moment, shear, and axial were used per ACI 318-14 [10].

Structural elements are classified either in deformation-controlled or force-controlled; in the deformation-controlled, the increased gravity load factor, G_{LD}, is defined as follows, excluding the snow loads effects:

$$G_{LD} = \Omega_{LD}\, [1.2\, D + 0.5\, L] \quad (1)$$

Where:

Ω_{LD}: Increase factor load for deformation-controlled action.

The previous load combinations are applied on the floors above the removed column, and for the rest of the structure, the following combination is used:

$$G = [1.2\, D + 0.5\, L] \quad (2)$$

Where:

G: Gravity loads.

After each analysis case converges, the demand-capacity ratio (DCR) of each component is evaluated and compared to the defined acceptance criteria, the m-factor, which represents the acceptance criteria in the linear static method prescribed in GSA [2].

3 Results

Analyses results of reactions for the three models are summarized in Figure 2 – Figure 4, where it is clear that the reactions increase after the column loss and increase more after adding braces due to the load redistribution. The m-factor that is obtained for each element affected by the column removal and the least m-factor is used to calculate the load increase factor (Ω_{LD}) by the following equation given in GSA [2]:

$\Omega_{LD} = 1.2\, m_{LIF} + 0.8$ (3)

Where:

Ω_{LD}: Load increase factor load for calculating deformation-controlled action.

m_{LIF}: The smallest m-factor.

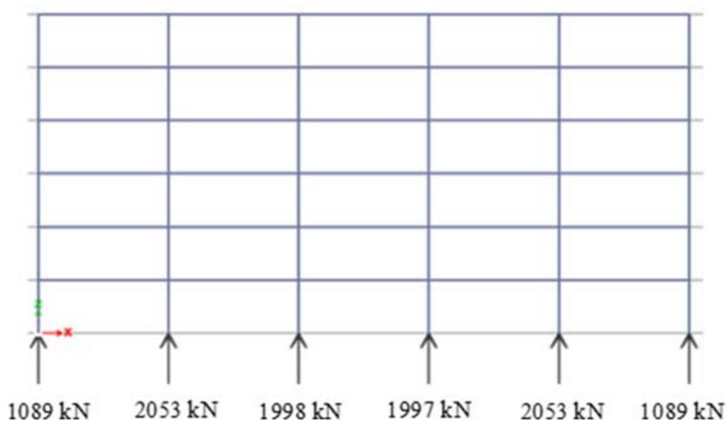

Figure 2: ETABS model 1 with reactions at elevation Grid (1)

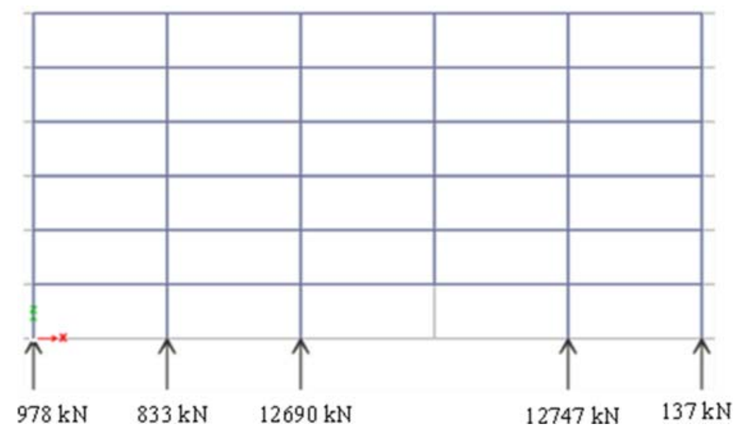

Figure 3: ETABS model 2 with reactions at elevation Grid (1)

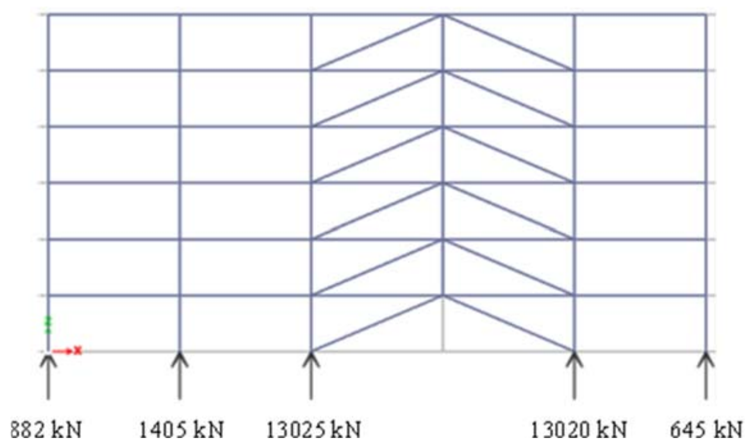

Figure 4. ETABS model 3 with reactions at elevation Grid (1)

Reinforcement is added to the sections in each model as shown in Table 2. Reinforcement in Sections of Model (2) and Model (3) is kept the same, so the effect of the bracing can be studied.

Table 2: Reinforcement

Element	**Position**	**Dimensions (mm)**	**Model (1) Reinforcement (mm^2)**	**Model (2) & (3) Reinforcement (mm^2)**
Beams	Exterior	600x300	510 (Top & Bottom)	510 (Bottom) 765 (Top)
	Interior	400x300	510 (Bottom) 765 (Top)	510 (Bottom) 765 (Top)
Columns	Interior	550x550	3,040	11,260
	Corner	400x400	1,884	1,884
	Exterior	400x400	1,884	4,824

The maximum negative and positive moments on beams and the axial forces on columns at different locations are investigated. Based on the analysis results, the highly affected members are the interior and edge columns due to the loss of an edge column. Additionally, it can be concluded that due to the addition of braces in model 3, the maximum reduction was in the moments on exterior beams and the axial forces on interior columns. The negative moments were reduced by approximately 100 %, and the reduction in the positive moment was approximately 150 % in the exterior beams. The axial forces in interior columns showed an average reduction of approximately 15 %. Table 3 shows the list of failed columns in models (2) and (3). It can be concluded that adding braces reduces the DCR for interior columns and decreases the number of failed columns. However, this was not the case in the edge columns, where the DCR stays approximately the same.

To capture the effect of braces on interior columns, the m-factor and DCR are compared in Models (2) and (3), as shown in Figures 5 and 6, where the value in brackets represents the DCR, and the other value represents the m-factor. It is clear that the reduction in DCR was the lowest on lower floors and increased on higher floors. The maximum reduction was 65 % on higher floors, and the minimum was approximately 5 % on lower floors.

Table 3: Failed columns

Model No.	**Failed columns**	**Story**
Model (2)	D-2	1st,2nd
	C-1	All
	E-1	All
Model (3)	D-2	1st
	C-1	All
	E-1	All

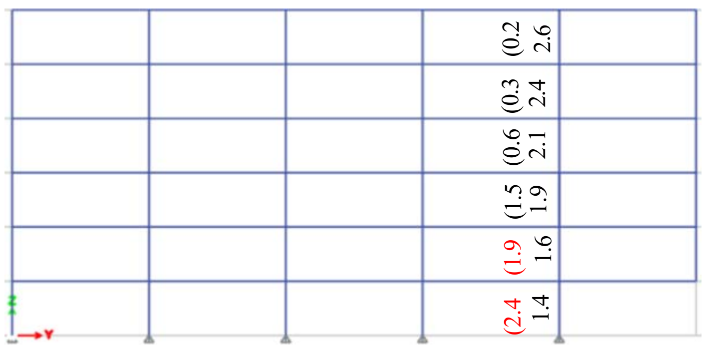

Figure 5: m-factor and DCR for the D-2 interior column (Model 2)

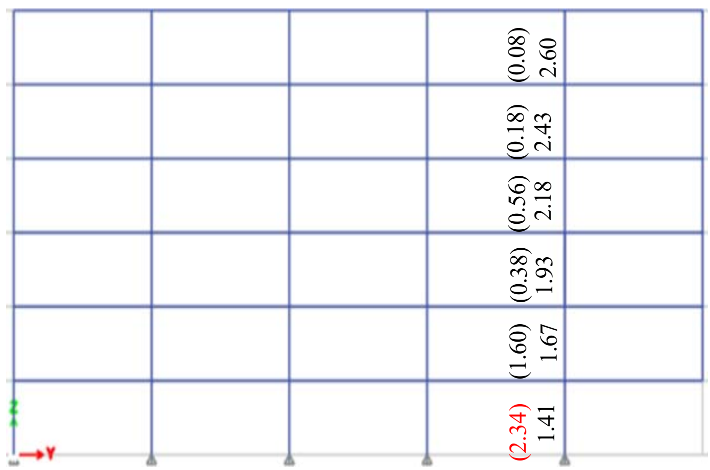

Figure 6: m-factor and DCR for the D-2 interior column (Model 3)

4 Conclusions and Contributions

An assessment of an edge column removal has been discussed in this paper, and the following are concluded:

1. For a linear static analysis, and in the case of edge column removal, the exterior beams, edge columns, and interior columns, which were the nearest to the position of the collapse, were found to be the most susceptible elements to higher moments and shear values.
2. Braces efficiently reduce structural members' moments and axial forces, especially in the exterior beams and interior columns. Hence, this will lead to an effective and more economical design.
3. The results of the design show that the addition of braces reduces the DCR in interior columns, especially in columns on higher floors. However, braces do not affect the DCR in edge columns near the location of the collapsed column.
4. The reduction in DCR due to the addition of braces reached approximately 65 % in some floors and the reduction in moments reached more than 100 %. Hence, the addition of braces is effective in reducing the forces on most of the structural members by the redistribution of the forces.

Finally, this research paper can be further extended to study the behavior of the building under a progressive collapse of an edge column of buildings of multiple floors/heights and account for dynamic analysis to cover more areas in the topic of progressive collapse.

Acknowledgments

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