©2022 Published in 6th International Symposium on Natural Hazards and Disaster Management
21-23 October 2022 (ISHAD2022 Bursa - Turkey)
https://doi.org/10.33793/acperpro.XXXX

Load Distribution after Failure of an RC Column on Moment-Resistant Frames

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Abstract:

Progressive collapse can be defined as partially or entirely failure of a structure after failure of an element. Capacity loss of an element creates new load distribution and additional loads for other parts of the structure. To accurately evaluate the progressive collapse of the structure, it is needed to accurate estimation of load distribution after failure. Sudden removal of a column is a widely used approach to evaluate the progressive collapse estimation of the structures. However, in this study, effect of removal of two different columns on the frame are studied under two conditions; a) sudden removal of column, b) progressive loss on the axial capacity of column. To model progressive axial capacity loss, author's previously developed axial capacity of reinforced concrete column model is used. A 2D two-story two-bay benchmark frame is analyzed under pushdown and quasi-static cyclic loading. Distribution of loads after failure of a column is investigated under four different scenarios.

Key words: progressive collapse, reinforced concrete frame, reinforced concrete column.

1. Introduction

Progressive collapse can be defined as the process of the locally or entirely collapse of a structure triggered by failure of one or a couple elements [1]. Probability of progressive collapse can be considered as rare; however, the results of the failure can be catastrophic. To show importance of the progressive collapse, Kiakojouri et al. [2] listed major progressive collapses for last sixty years. In same study, researches about progressive collapse are also listed. The topic has become more popular after 9/11. After 2000, several guidance and codes to prevent progressive collapse are developed and publish. Furthermore, progressive collapse of RC frames is also widely studied topic [3-6].

The most common method to evaluate progressive collapse process and probability is alternate load path (ALP) method. ALP is also easily applicable to finite element analysis. Removal of critical column is widely applied method in ALP. Thus, in this study, removal of two columns are analyzed to determine progressive collapse of 2D two-story and two-bay RC frame. Pushdown analysis is conducted on two different scenarios; i) removal of first-story middle column, and ii) removal of first-story left column. Sudden removal of a column can be occurred on direct cut of column or impact effect. However, under earthquake, sudden loss of entire capacity is not expected to happen. Thus, addition to pushdown analysis, cyclic analysis is also conducted.

This study focus on the redistribution-type collapses which is commonly observed on frames structures [2]. In this study, a representative 2D two-story and two-bay RC structure is analyzed to determine load distribution after failure of a column. New load path after failure is determined. A pushdown analysis is conducted with absence of failed column to evaluate the envelope and limit

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of the capacity. Then, with a quasi-static cyclic analysis, the progress of axial failure due to loss of shear strength capacity on non-ductile column is simulated. The effect of axial failure of non-ductile column over the frame is studied and compared with the results of pushdown analysis.

2. Description of the Analyzed Structure and Methods

A representative benchmark 2D two-story and two-bay RC frame is created in this study. Middle and left columns of first-story are designed as non-ductile column for different analysis to investigate the relationship between the location of the column and collapse behavior. The details of the RC frame are described in the following section.

2.1. Details of the Elements of the Structure

A two-story and two-bay virtual 2D structure is used to simulate the effect of column loss over the frame. The presentative frame designed by following strong-beam-weak-column principle contradictory to earthquake resistant design philosophy to simulate column failure under cyclic loading. The shear dominant behavior is expected from the non-ductile columns which lead early decrease on both lateral and axial capacity of the column. The beams of the frame are designed as 450 mm wide and 600 mm height. The beam has four No.18 bars and three No.12 bars as bottom and top reinforcement, respectively. The columns are modeled as 450 mm square. The columns have eight No.18 bars as longitudinal direction. Additionally, No.8 bar with 500 mm are used as transverse reinforcement for non-ductile columns. For ductile columns, the spacing of the transverse reinforcement is 300 mm. Figure 1 shows further details of the frame and elements. The concrete compressive strength is assumed as 20 MPa and yield strength of reinforcing steel is assumed as 420 MPa. Furthermore, axial load applied to the columns which equals to the 15% of capacity of the columns. The length of the columns is 2.8 m and the length of the beams is 4.0 m.

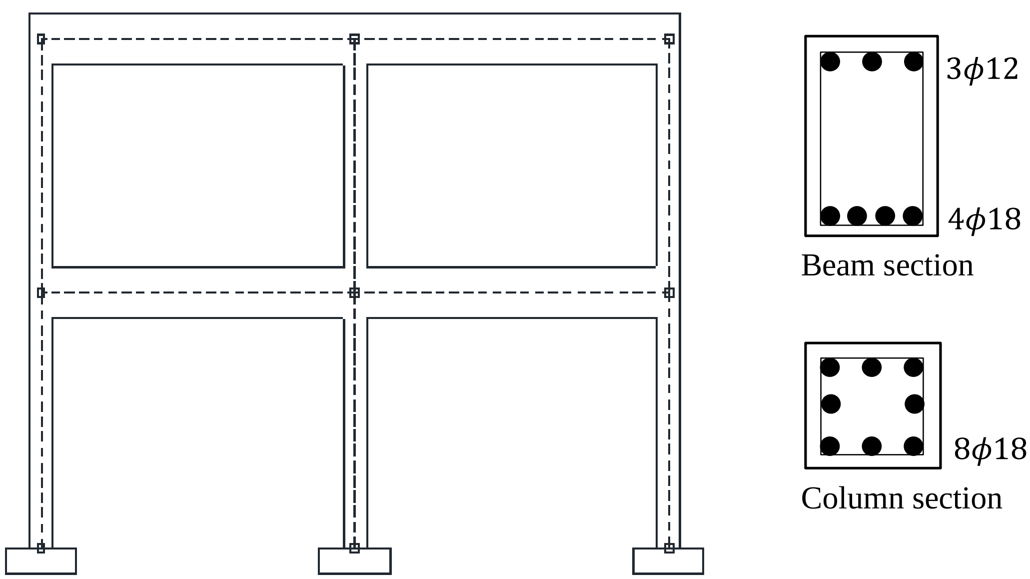

Figure 1. Details of representative 2D reinforced concrete frame

An open-source structure engineering software, OpenSees [7] is used for modeling the frame and analysis. Distributed plasticity with fiber section approach is utilized for modeling RC elements. In OpenSees library, there are several options for material modeling. In this study, *concrete01* and *steel01* is used for concrete and reinforcing steel, respectively. Furthermore, for the elements, *forced-based-beam-column* element with five integration points is used.

2.2. Modeling of Non-Ductile Column

Lateral displacement of an RC column is sum of three lateral displacement components; i) flexural, ii) slip, and iii) shear displacement [8] (Figure 2). Modeling three displacement components separately and combining the into together is widely accepted method [8,9]. Adding rotational springs for slip behavior and lateral spring for shear behavior at the ends of a flexural element is an effective method to combine displacement components together. Additionally, in this study, an axial spring is included to simulate axial displacement of the column. In this study, previously proposed method by the author is used to calculate axial displacement of an RC column. The method is developed based on lateral shear displacement component of total lateral displacement. In the method, during analysis, the axial spring monitors lateral spring at the end of the column and with decreasing lateral shear strength of the column, the stiffness of axial spring reduced to simulate axial capacity loss. In this way, axial-shear interaction is provided for the model. Further details of modeling procedure of non-ductile columns and details of the models can be found on Bicici (2018) [10].

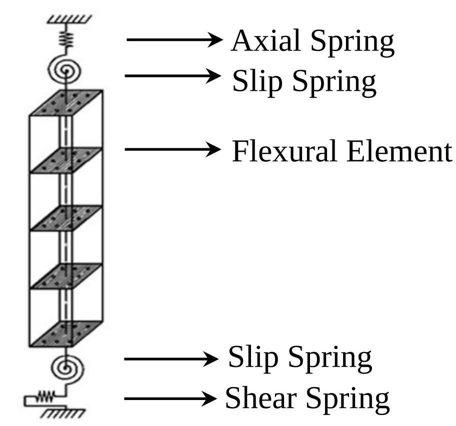

Figure 2. Modeling of Non-ductile column

The yield and flexural strength of the RC columns is calculated as 141 and 170 kN, respectively, from moment-curvature analysis of the column's section. The shear strength of the column is calculated as 181 kN with Equation 1 obtained from Sezen (2008) [11].

$$V_n = k\left[\left(\frac{0.5\sqrt{f_c'}}{a/d}\sqrt{1+\frac{P}{0.5\sqrt{f_c'}\cdot A_g}}\right)0.8\,A_g + \frac{A_v\cdot f_{yv}\cdot d}{s}\right] \qquad (1)$$

where f_c' is compressive strength of concrete, A_g is area of cross-section, P is axial load of the column and d is the effective depth of the column section. A_v is area of transverse reinforcement, f_{yv} is yield strength of transverse reinforcement, s is the spacing of transverse steel, and k is a parameter to account for reduction in shear strength. k is 1.0 and 0.7 for displacement ductility of less than 2 and higher than 6, respectively and linearly varies for intermediate ductilities. a is the shear span length of the column, which is $L/2$ for double curvature columns and L (length of the column) for cantilever columns. The comparison of the yield, flexural, and shear strength of the column leads the conclusion that the column belongs to the Category III which means early shear strength degradation is expected during the analysis.

3. Analysis

Pushdown and cyclic analyses are conducted with the created 2D RC frames. By pushdown analysis, the capacity and the behavior of the frame with absence of column is studied. Then, with cyclic analysis, the effect of axial capacity loss of column is observed. Finally, the results of both analyses are compared. Pushdown analysis is conducted under two condition; absence of middle and left column. In same way, the cyclic analysis is also studied by assuming middle column as non-ductile column and left column as non-ductile column. Details of these four analysis is presented in following sections.

3.1. Pushdown Analysis

In pushdown analysis, to estimate the capacity of frame without failed column, the top of the removed column is pulled down and the axial reaction at the other columns are recorded. Schematic presentation of the pushdown analysis for both middle column removal and left column removal is shown in Figure 3.

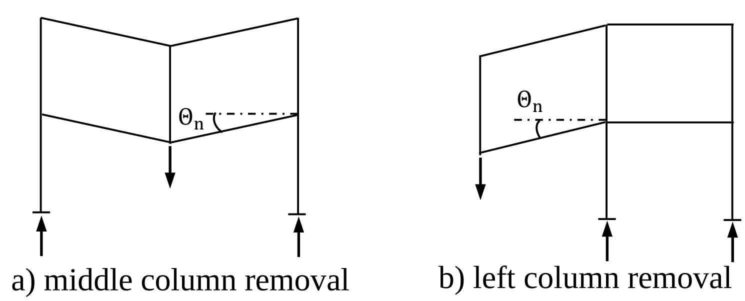

Figure 3. Schematic presentation of pushdown analysis for both cases

The calculated relationship between the rotation of the beam and the axial load created on the non-failed columns are shown in Figure 4a for middle column and Figure 4b for left column removal. The figures the total axial load change after failure is also shown.

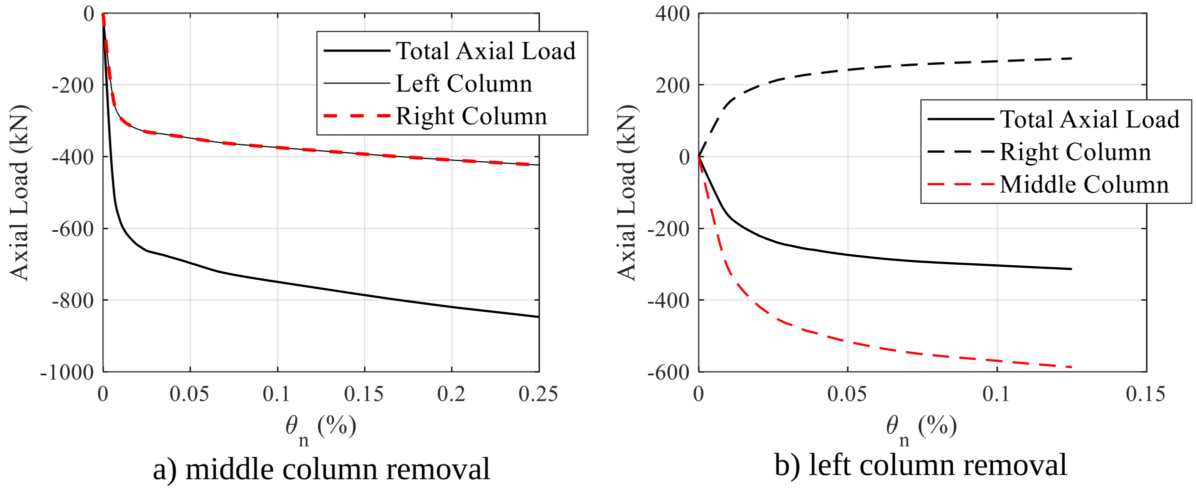

Figure 4. Calculated axial load-beam rotation relationship of pushdown analysis for both cases

3.2. Cyclic Analysis

Addition to the axial pushdown analysis, quasi-static lateral cyclic analysis is conducted to simulate frame behavior. During analysis, cyclic displacement history is applied at the top of the frame, then, base reactions for each column is recorded. Lateral load-displacement, lateral-axial displacement, and axial load change at the columns are investigated to accurately understand the progressive collapse behavior of the frame.

In the first cyclic analysis, middle column is designed as non-ductile. Lateral strength degradation and loss of axial capacity is expected for the middle column. This degradation and loss of capacity will lead additional load for other members of the frame. Figure 5 shows both calculated lateral load-displacement and axial-lateral displacement relationships of frame. As expected, the middle column showed early shear strength degradation. According to the axial displacement model used in this study, this degradation leads the softening the axial capacity of the column which caused additional axial displacement.

Additionally, Figure 6 shows variety of axial force for three first story columns during the analysis. As can be seen from the Figure 6, the decrease on the middle column leads increase of axial load on the other columns.

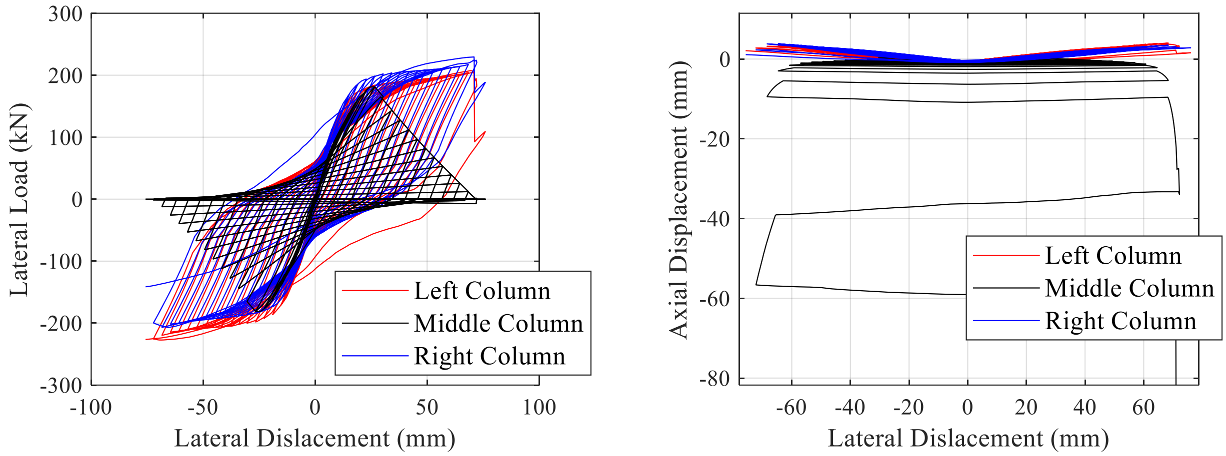

Figure 5. Calculated lateral load-displacement and axial-lateral displacement relationships of frame with failure of middle column

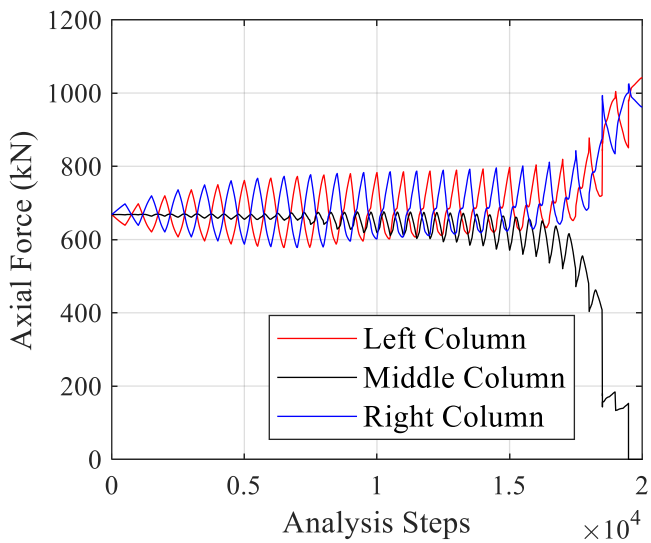

Figure 6. Change of axial force for three first-story columns during the analysis

In the second cyclic analysis, left column is designed as non-ductile column. The effect of shear strength degradation and axial capacity loss of a side column is investigated during the analysis. Figure 7 shows both calculated lateral load-displacement and axial-lateral displacement relationships of frame. The degradation of lateral shear strength of the left column led softening of axial capacity of the column which caused increase in axial displacement of left column.

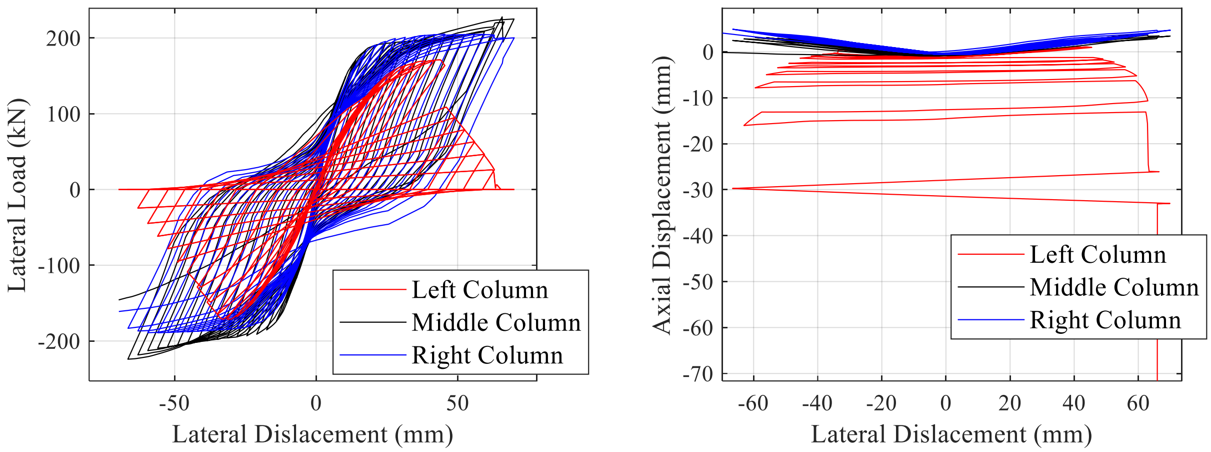

Figure 7. Calculated lateral load-displacement and axial-lateral displacement relationships of frame with failure of left column

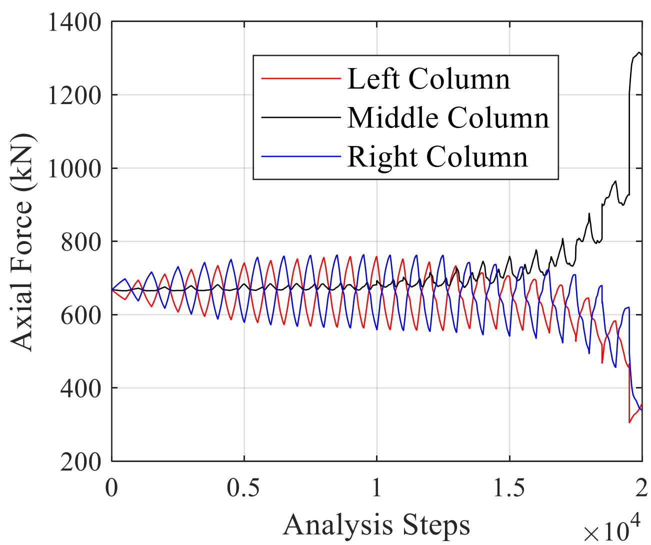

Figure 8. Change of axial force for three first-story columns during the analysis

Additionally, Figure 8 shows change of the axial loads for each three first story column during the analysis. From the figure, it is concluded that, the axial load decrease in the left column led additional axial load for the middle column. However, the right column is also experienced decline of axial load which is compatible with the results of pushdown analysis. The results and comparison of these four analysis is discussed in following section.

4. Discussion

The expected progressive collapse behavior is calculated by pushdown analysis. Then, the cyclic analysis with non-ductile column is conducted to simulate collapse under cyclic loading such as earthquake.

Shear strength degradation and axial capacity loss are accurately simulated with model as can be seen Figures 5 and 7. The axial capacity loss of middle column led additional axial load to the other columns (Figure 6). However, when the left column lost its axial load capacity, the middle column experienced additional load, and the axial load in right column is decreased (Figure 8). The same results obtained from pushdown analysis as can be seen in Figure 4.

Pushdown analysis provides possible load distribution after the failure. When comparison of pushdown and cyclic analysis is made the conclusion can be seen as pushdown analysis may give an idea for expected behavior for progressive collapse, however, modeling decrease on axial capacity of column gives more realistic results.

Conclusions

Progressive collapse can be defined as partially or entirely failure of a structure after failure of an element. Capacity loss of an element on frame structures creates new load distribution and additional loads for other parts of the structure. Alternate load path (ALP) method is widely accepted method to evaluate the progressive collapse of a frame structure. To accurately evaluate the progressive collapse of a structure, it is needed to accurate estimation of load distribution after failure.

In this study, pushdown analysis is conducted the simulate the scenario of sudden column removal from a 2D two-story, two-bay frame. Two different column removal is considered as; middle and left column removal. Furthermore, loss of axial strength capacity under cyclic loading is also studied. To model axial loss, author's previously proposed model is used. In this model, the axial stiffness of the column is decreased with respect to the lateral shear strength degradation of the column.

Pushdown analysis provides possible load distribution after the failure. The additional axial load for non-failed columns can be easily estimated with pushdown analysis. However, to get realistic behavior of the frame after failure, cyclic analysis is more suitable.

This study is limited with a 2D two-story two-bay RC frame. Additionally, the main focus of this study is the axial load distribution of the frame. To better understand the progressive collapse, further study is needed such as; 3D and more complicated structures.

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