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# Modeling the Effect of RC Column Failure over the Frames

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## Abstract

The locally or entirely collapse of a structure triggered by failure of one or a couple elements can be considered as progressive collapse. New load distribution and additional loads may be created for the remaining elements of the frame. To accurately understand the progressive collapse mechanism, it is needed to accurate estimation of load distribution after failure of an element. The removal of a column and pushdown analysis is a widely used approach to evaluate the progressive collapse mechanism. However, in this study, effect of removal of three different columns on the frame are studied under two conditions; a) removal of column and pushdown analysis, b) loss on the axial capacity of column under cyclic loading. To axial capacity loss of reinforced concrete column, author's previously developed axial capacity model is employed. A 2D three-story five-bay benchmark frame is analyzed under pushdown and quasi-static cyclic loading. Distribution of loads after failure of a column is investigated under six different scenarios.

**Key words:** Progressive collapse, Reinforced concrete frame, Reinforced concrete column, OpenSees.

## 1. Introduction

The locally or entirely collapse of a structure triggered by failure of one or a couple elements can be considered as progressive collapse [1]. The occurrence of progressive collapse could be rare; however, the results of the failure can be catastrophic in terms of economical and life. To show importance of the progressive collapse, Kiakojouri et al. [2] listed major progressive collapses for last sixty years. Thus, the progressive collapse mechanism has been experimentally and analytically being studied [3-6]. The studies may be considered into two categories as subassembly of structure and entire structures. Two-span beam-column subassembly can be considered as base for progressive collapse analysis. The beam-column subassembly is tested and analyzed in many studies [3,4]. Addition to subassembly, entire structures and frames are also considered to evaluate progressive collapse behavior. Sudden loss of columns and its influence over the frame and structure has been widely studied [13-15]

Developing an analytical model based on subassembly experiments and applying the model on the entire structure is a common way to create a progressive collapse analysis. However, on the entire structure analysis, a pushdown method is generally employed. The main propose of this study is developing an analytical method to simulate the effect of a column failure over the frame by including axial displacement of an RC column.

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This study focusses on the redistribution-type collapses which is commonly observed on frames structures [2]. Alternate load path (ALP) method is widely accepted and employed method to evaluate and simulate the progressive collapse mechanism of reinforced concrete (RC) structures. Furthermore, ALP can be easily applied to finite element analysis of structures. Briefly, removing a column from an RC frame and pushdown analysis is a way to apply ALP. In this study, alternative load path after shear-axial failure of a column is investigated. To simulate the behavior of frame and evaluate the progressive collapse mechanism, a 2D three-story and five-bay prototype RC frame is created in this study. Three pushdown analysis is conducted for three different column removal scenarios. Due to being symmetric, three scenarios cover all possible failure paths. However, sudden removal of a column can be occurred on direct cut of column or impact effect. Under earthquake, sudden loss of entire capacity is not expected to happen. Thus, addition to pushdown analysis, cyclic analysis is also employed in this study. By using 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. In this study, an open-source structure engineering software, OpenSees [7] is used for modeling the frame and analysis.

## 2. Details of Prototype RC Frame

A three-story and five-bay prototype 2D reinforced concrete frame is employed to simulate the effect of columns' capacity loss on the behavior of the frame (Figure 1). The length of the columns is 2.8 m and the length of the beams is 4.0 m.

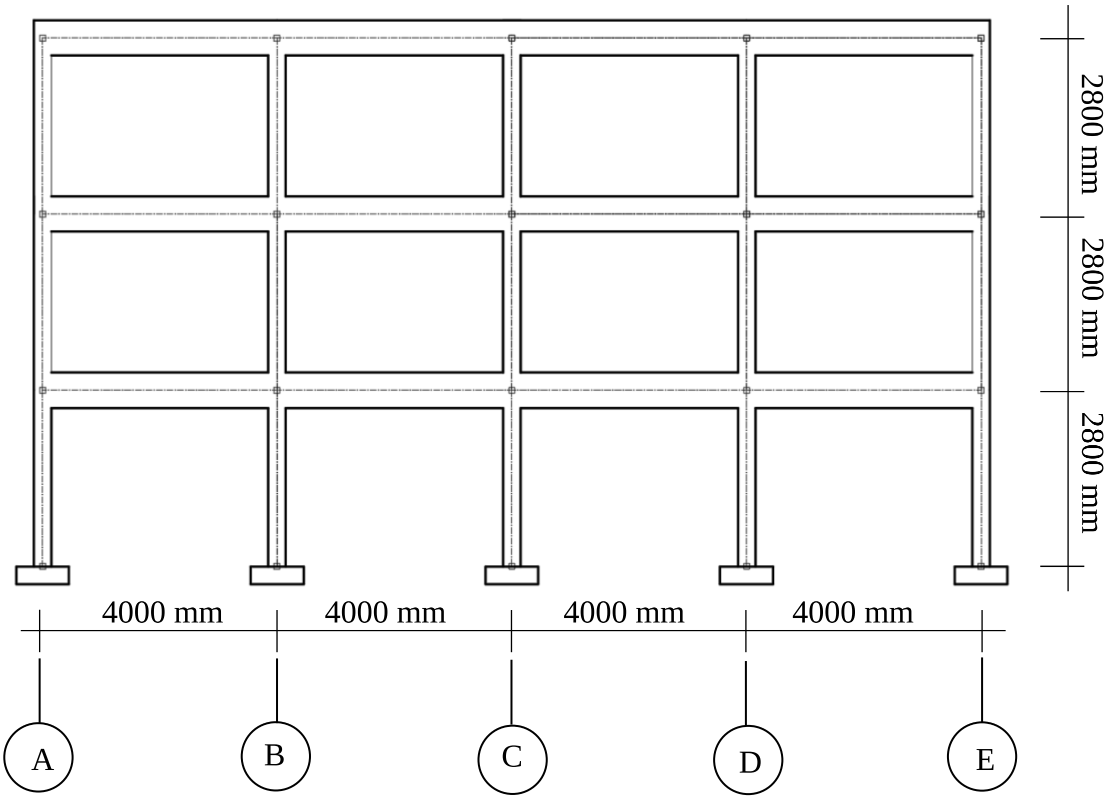


**Figure 1.** Details of representative 2D reinforced concrete frame.

Two different analyses are conducted on the created frame; i) pushdown and ii) cyclic analysis. The first one includes removal of a column and pushing downward the top of the removed column. Then, the behavior of other columns on the frame are monitored. Furthermore, in the second analysis, a cyclic displacement history is applied to the frame. The degradation of lateral and axial capacity effect on the frame is studied. Thus, the prototype 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 2). Transverse reinforcement spacing to column depth ratio, *s/d*, is 1.25 and 0.75 for ductile and non-ductile columns, respectively.

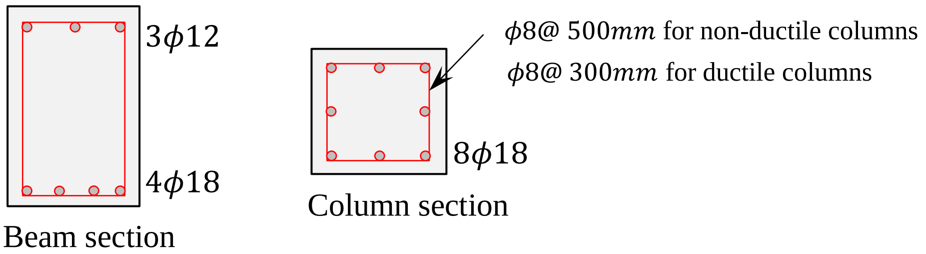


**Figure 2.** Details of column and beam section.

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.

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 (Figure 3). Furthermore, for the elements, forced-based-beam-column element with five integration points is used.

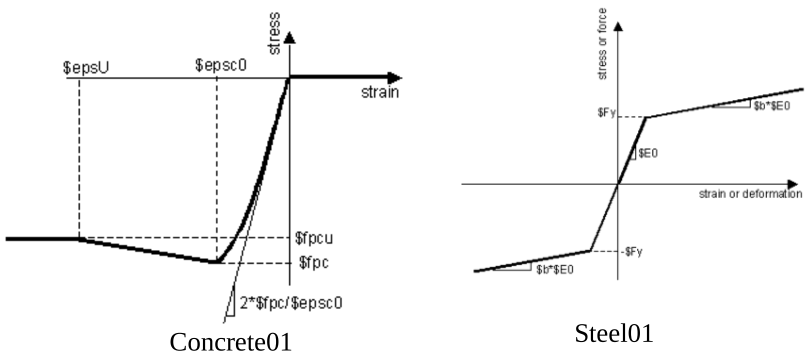


**Figure 3.** Stress-strain relationship for the materials used in the model from OpenSees Liabrary [12].

## 3. Modeling RC Elements

The lateral displacement of an RC column can be calculated by adding three different displacement components as; i) flexural, ii) slip, and iii) shear displacement [8]. In the analytical model, calculating three displacement components separately and combining the into together is widely accepted method [8,9]. The method includes zero-length springs adding at the ends of a flexural element as shown in Figure 4. The flexural element calculates flexural displacement component; while, the rotational and lateral springs calculate the slip and shear displacement components, respectively.

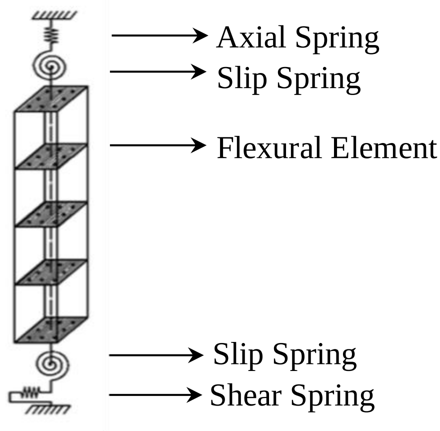


**Figure 4.** OpenSees model for non-ductile columns [11].

The novelty of this study is adding vertical spring at the top of the flexural element which calculates the axial displacement during the analysis. 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 developed method, the stiffness of axial spring changes based on the lateral shear displacement of the column obtained from the lateral spring at the end of the column. The lateral shear strength degradation leads softening of axial spring which caused additional axial displacement. The shear failure of the column is followed by the axial failure and shortening of the column. The method provides axial-shear interaction over the behavior of the column. The further details of modeling procedure of non-ductile columns and details of the models can be found on Bicici (2018) [10].

Addition to the columns, in this study, the beams of the frame are modeled with flexural elements. The force-based-beam-column element with five integration points is employed for both beams and columns. No additional modeling technique is used for the joints of the frame, because the RC joints during the progressive collapse is out of the scope of this study.

## 4. Analysis

Pushdown and cyclic analyses are conducted with the benchmark 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 three conditions; absence of Column A, Column B, and Column C. In this case, due to being symmetric, all possible failure scenarios are covered. In same way, the cyclic analysis of the frame is also conducted under three different conditions. The removed columns in pushdown analysis are designed as non-ductile column. The further details and results of six analyses are presented in the following sections.

### *4.1. Pushdown Analysis*

In pushdown analysis, a column in the frame is removed and the top of the removed column pushed down until it reached the capacity. During the analysis, the changes in the axial load on the remaining columns are recorded corresponds to the applied displacement. Schematic presentation of the pushdown analysis for three different column removal are shown in Figure 5.

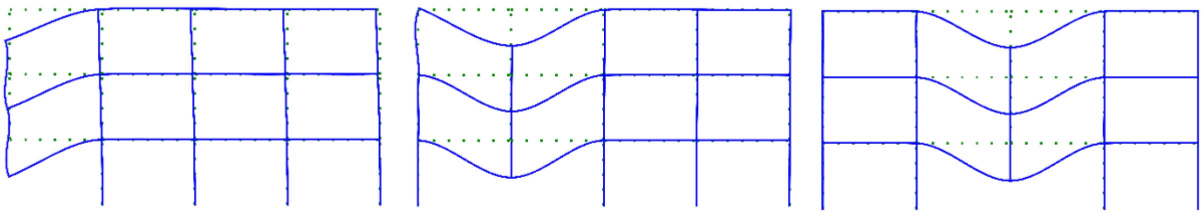

**Figure 5.** Schematic presentation of pushdown analysis for three different scenarios.

The calculated relationship between the displacement of the top of the removed columns and the axial load on the other columns are shown in Figure 6. The analysis results of removal of column A, B, and C, are shown in Figure 6a, 6b, and 6c, respectively. The top of the removed columns pushed down for 20 cm.

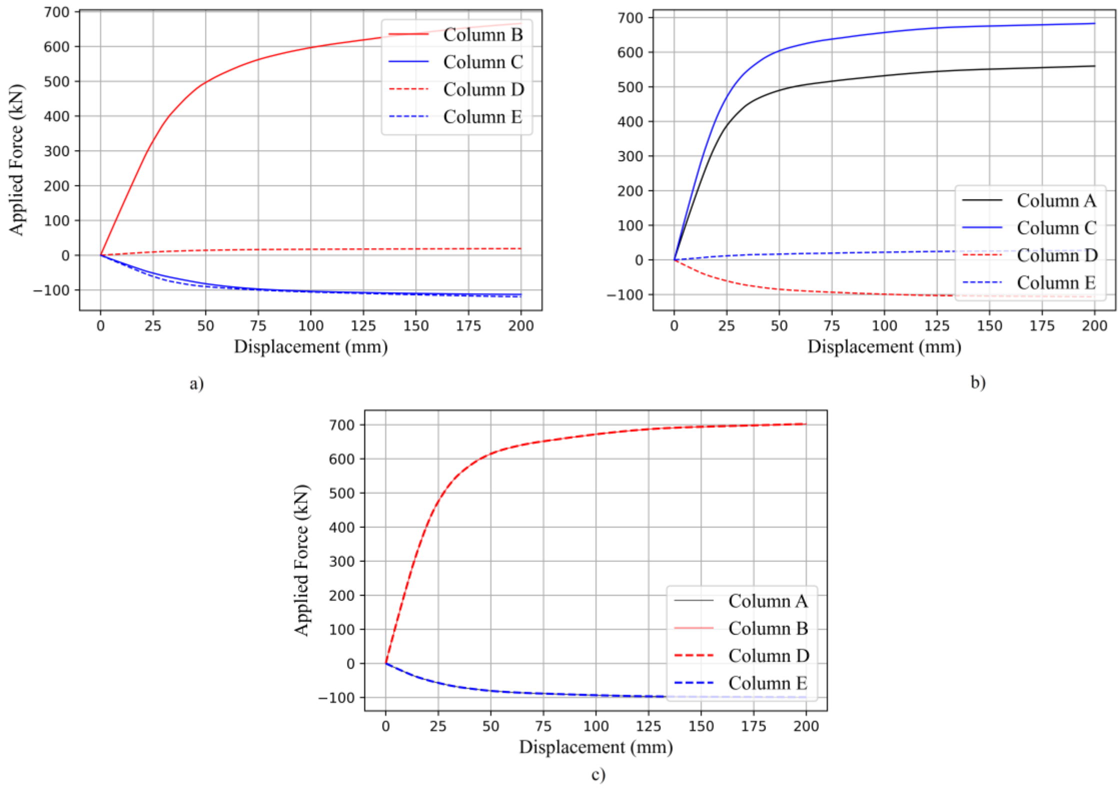


**Figure 6.** Calculated axial load-displacement relationship of pushdown analysis for removal of a) column A, b) column B, and c) column C.

### *4.2. Cyclic Analysis*

Quasi-static lateral cyclic analysis is conducted with the created prototype RC frame. The removed columns from the pushdown analysis are included into the analysis as designed as non-ductile column. Axial-shear failure in early stage of loading and lateral and axial strength loss is expected in these columns. The effect of failure in the frame is investigated and the results are compared with the results of pushdown analysis.

In the numerical analysis, a cyclic displacement history is applied at the top of the frame, then, lateral and axial reactions for each column is monitored. Besides, the axial displacement of the top of the non-ductile column is also calculated during the analysis. Lateral load-displacement, lateral-axial displacement, and axial load change at the columns are meticulously studied to clearly understand the potential progressive collapse behavior of the frame.

In the first cyclic analysis, column A is designed as non-ductile. Lateral strength degradation and loss of axial capacity is expected column. This degradation and loss of capacity will lead additional load for other members of the frame. Lateral load-displacement and axial-lateral displacement relationships of the first story columns are presented in Figure 7. The column A experienced early shear and axial strength degradation. The softening of axial strength on the column A led further downward axial displacement.

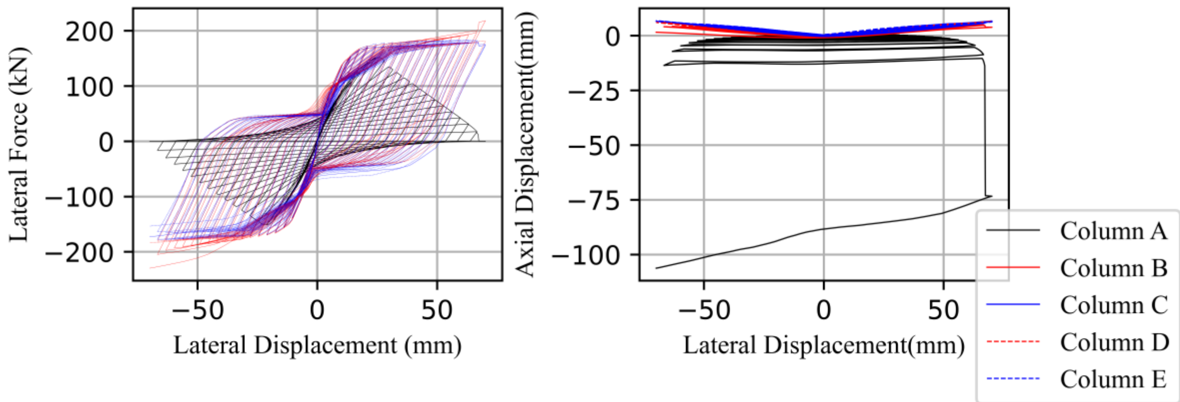


**Figure 7.** Calculated lateral load-displacement and axial-lateral displacement relationships of frame with failure of column A.

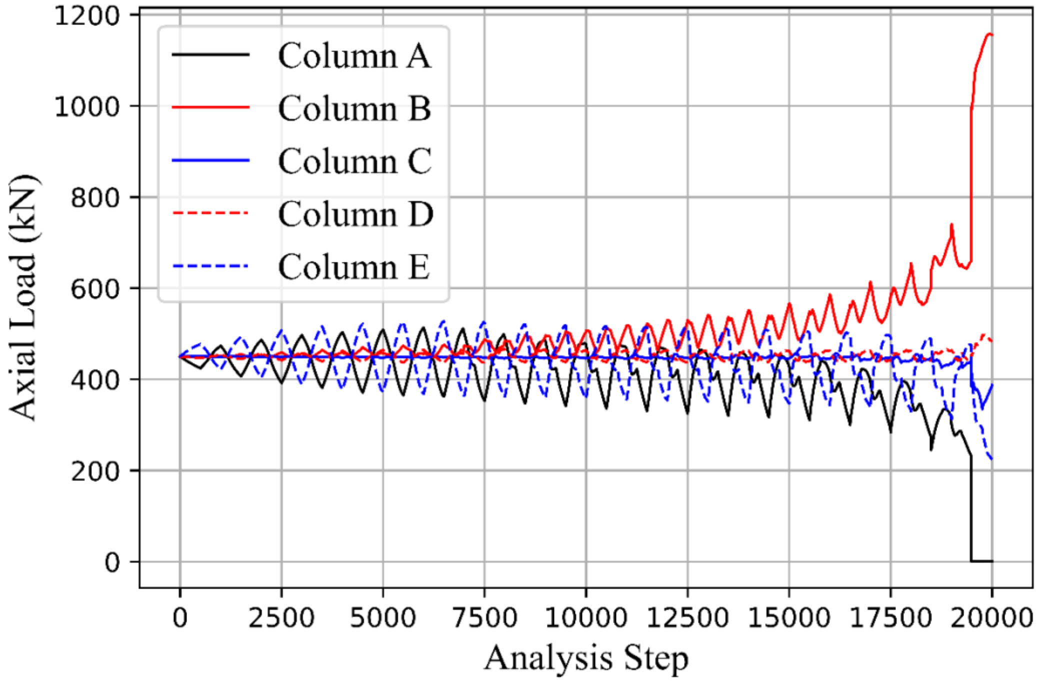


**Figure 8.** Change of axial force for the first-story columns during the analysis simulates failure of column A.

Additionally, Figure 8 shows variety of axial force for first story columns during the analysis and capacity loss of column A. As can be seen from the Figure 8, the decrease on the column A led increase of axial load on the columns B and D, while axial load decrease is observed for columns C and E.

In the second cyclic analysis, column B is designed as non-ductile column. The effect of shear strength degradation and axial capacity loss of a column in the frame is investigated during the analysis. The calculate lateral load-displacement and axial-lateral displacement relationships of the first story columns for the second analysis are shown in Figure 9. The degradation of lateral shear strength of the column B led softening of axial capacity of the column which caused increase in axial displacement of column B.

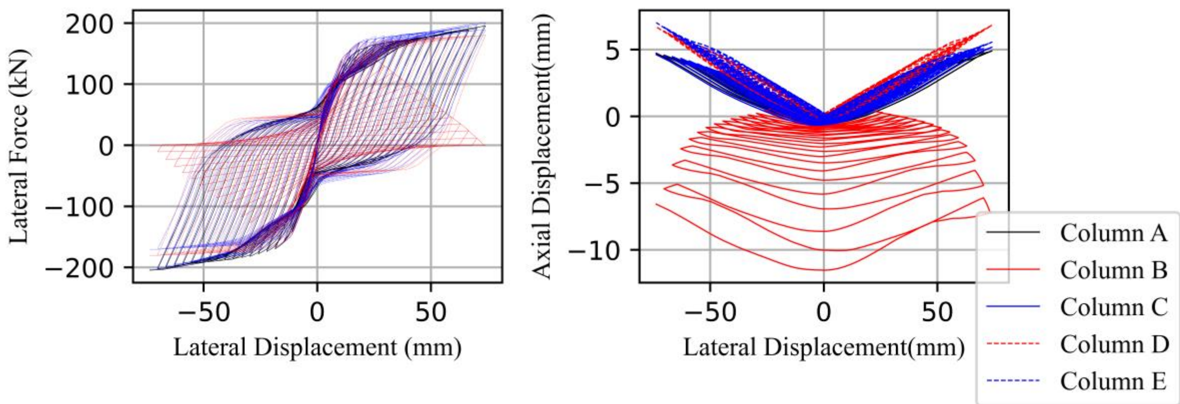


**Figure 9.** Calculated lateral load-displacement and axial-lateral displacement relationships of frame with failure of column B.

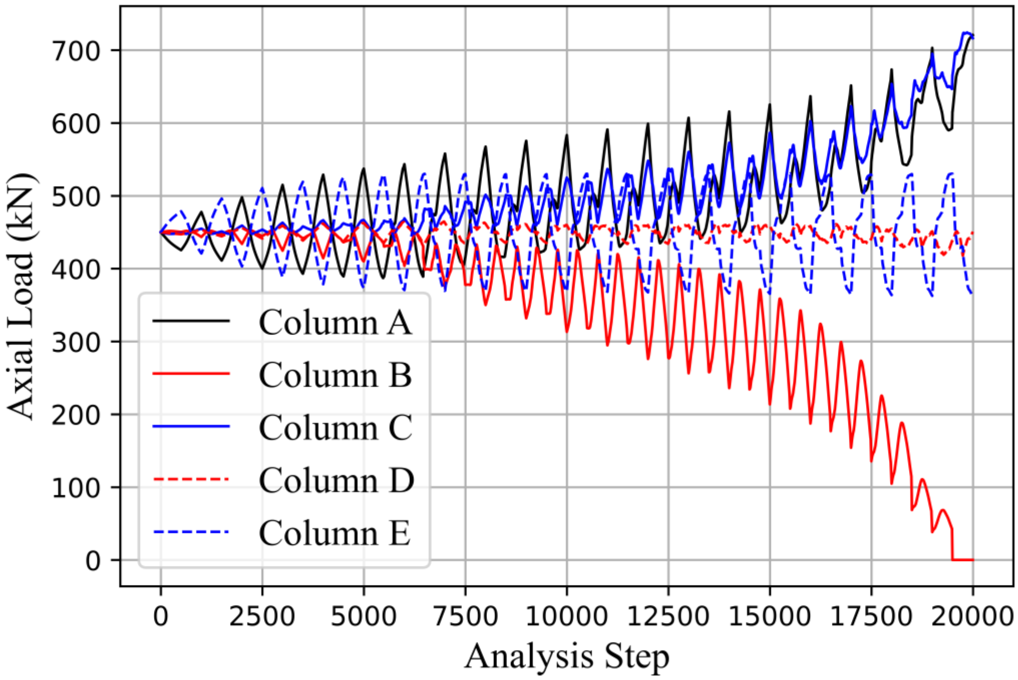


**Figure 10.** Change of axial force for the first-story columns during the analysis simulates failure of column B.

Additionally, Figure 10 shows change of the axial loads for the first story column during the analysis. From the figure, it is concluded that, the axial load decrease in the column B led dramatically increase of axial load for columns A and C.

In the third cyclic analysis, column C is designed as non-ductile column. The effect of shear strength degradation and axial capacity loss of column C in the frame is investigated during the analysis. The calculate lateral load-displacement and axial-lateral displacement relationships of the first story columns for the third analysis are shown in Figure 11. The degradation of lateral shear strength of the column C led softening of axial capacity of the column which caused increase in axial displacement of column C.

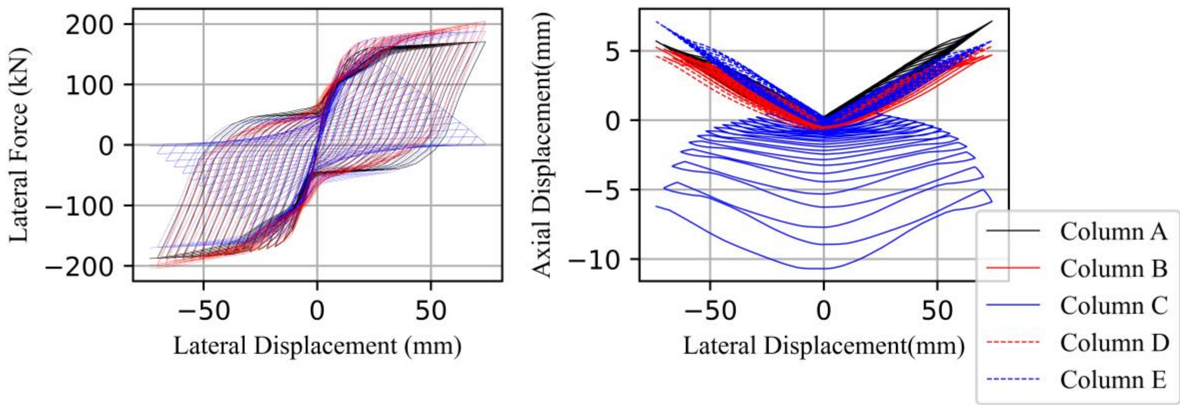


**Figure 11.** Calculated lateral load-displacement and axial-lateral displacement relationships of frame with failure of column C.

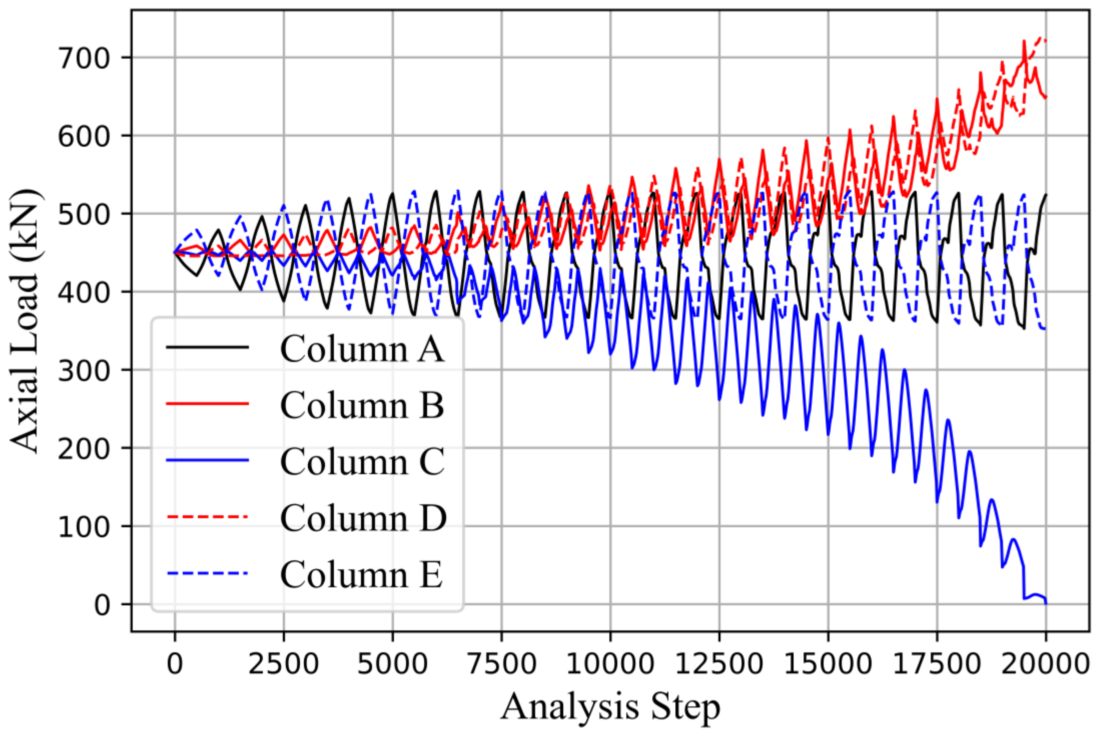


**Figure 12.** Change of axial force for the first-story columns during the analysis simulates failure of column C.

Additionally, Figure 12 shows change of the axial loads for the first story column during the analysis. From the figure, it is concluded that, the axial load decrease in the column C led dramatically increase of axial load for columns B and D.

### *4.3. Discussion of the Results*

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 the proposed method as can be seen Figures 7, 9 and 11 for the non-ductile columns A, B, and C, respectively. Furthermore, the axial load change due to failure of non-ductile column are presented in Figures 8, 10, and 12 for the failure of column A, B, and C, respectively.

For the failure of column A, Figure 6a and 8 can be compared. The pushdown analysis calculates the dramatic axial load increases for column B (Figure 6a). In column D, a slight increase is observed in cyclic analysis same in pushdown analysis. Besides, for the column C and E, the tension axial load is created in pushdown analysis. The same behavior is observed in the cyclic analysis (Figure 8). As a conclusion, the cyclic analysis predicts same results with pushdown analysis. However, the axial load increase is calculated higher for cyclic analysis due to oscillation of the frame.

For the failure of column B, Figure 6b and 10 can be compared. The pushdown analysis calculates the dramatic axial load increases for column A and C (Figure 6b). In cyclic analysis, different from the pushdown analysis, the 700 kN axial load increase is reach for both column A and C with the nearly axial displacement of 10 mm. The cyclic analysis calculates higher axial load change than pushdown analysis. The trend of axial load change for the pushdown analysis matches with the cyclic analysis.

For the failure of column C, Figure 6c and 12 can be compared. The pushdown analysis calculates the dramatic axial load increases for column B and D (Figure 6c). The axial load increase in cyclic analysis is higher than the pushdown analysis.

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.

## 5. Conclusions

Progressive collapse can be defined as partially or entirely failure of a structure after failure of an element. New load distribution and additional loads can be created after failure and capacity loss of an element on the frame. To simulate the failure and progressive collapse mechanism, Alternate load path (ALP) method is widely accepted and applied in the literature. 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 three-story, five-bay frame. three different column removal is considered to cover all possible failure scenarios. Furthermore, the cyclic analysis is also conducted with the frame. The removed column on the pushdown analysis are designed as non-ductile column expected to experience early shear-axial failure. To model axial displacement, 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. The effect oscillation over the frame axial load is simulated with the proposed method which may be more applicable for the cyclic loading such as earthquake. Furthermore, the failure of an RC column more influential for the neighboring columns. The axial load carried by the failed column is redistributed over the other columns of the frame. After careful investigation, it is observed that the more axial load increase is more severe for the failure of Column A. This may lead the conclusion that the effect of column failure over the frame is highly related to the number of neighboring columns.

## Acknowledgements

This study is extended and enhanced version of a study titled as "*Load Distribution after Failure of an RC Column on Moment-Resistant Frames*" and presented at ISHAD 2022 by the author.

## Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Author Contribution

E. Bicici designed the finite element model and the computational framework, and carried out the calculations considering the implementation and wrote the manuscript.

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