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Research Article

Evaluation of Different States of Progressive Failure in Steel Structures with Special Ductility

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Abstract: Progressive failure is a catastrophic phenomenon in structures that can happen due to natural disasters or human factors. In the progressive failure mechanism, a single local failure may cause substantial deformation that leads to the collapse of a structure. The numerous life and financial losses that may occur in the structure due to the progressive failure mechanism make it essential to study the strength and capacity of the structures against this phenomenon. In the current study, diverse scenarios of column removal are analyzed on the progressive failure process of a 10-story steel frame. The frame in question has a distinct bending frame system that is designed and controlled regarding internal regulations. The progressive failure process is done by the alternative load path method with different column removal scenarios in OpenSees software, nonlinear static analysis (push down), and based on GSA instructions using the load path method. The results of this study reveal that in all the studied cases, by changing the column removal position from the ground floor to the upper floors, it is observed that the resistance force of the frame against progressive failure is reduced. With each change in the column removal position, the resistive force decreases by an average of 10.24% compared to its previous state. In all cases of changes in column removal position from the corner column to the side and middle, it can be seen that the behavior of the frame due to removing the side and middle columns is quite similar and the maximum force of the frame against progressive failure increases by 98.5% averagely.

Keywords: Progressive failure, Steel structure, Different scenarios, Column removal, OpenSees Software

1. Introduction

One of the things that have become the focus of engineers in recent decades is a progressive failure. Progressive failure investigation in buildings design has gained momentum for various reasons. Factors such as political and social changes also lead to an increase in accidents related to progressive failure. For example, terrorist attacks are probable all over the world. An example of events that drew the attention of structural engineers to the issue of progressive failure is the demolition of the Ronan Point building in London in 1968, after which institutions developed building codes to provide solutions to prevent and reduce the phenomenon of progressive failure. The events of September 11, 2001, and the demolition of the Twin Towers and adjacent buildings shocked researchers to investigate accurately the phenomenon of progressive failure, which led many researchers around the world to study how progressive failure occurs in the tower The World Trade Center. In the aftermath of 9/11, progressive failures of high-rise buildings were considered. The first regulation on progressive failure GSA[1] was published in 2003, which was an important step in helping researchers in this area. Following the GSA Regulation in 2003, the Department of Defense issued Regulation UFC4-023-03 [2]. A new wave of research in line with the progressive failure emerged after the publication of this regulation, which was widely used by researchers. With the endorsement of the NIST Code [3] in 2007 and the amendment of the UFC Code in 2009, significant measures were taken to avoid the progressive failure of structures. UFC 2009 regulation according to ASCE7-05 regulation [4] defines progressive failure as "the spread of an initial local failure from one element to another of a structure that ultimately leads to the collapse of the entire structure or a great part of it." The ASCE7-05 standard also states that the building must be designed in such a way that it remains stable in the face of local failure of the entire structural system and does not allow failure to

[1] General Services Administration

occur improperly from its location to other components. According to ASCE7-05, the two main approaches to prevent progressive failure are direct design and indirect design. The direct design offers obvious necessities for structural resistance to progressive failure, including alternative load path (AP) methods and specific local resistance (SLR) methods. In indirect design, resistance to progressive failure is achieved through minimum levels of strength, cohesion, and ductility. Regulation UFC4-023-03 introduces the tensile strength (TF) method in indirect design. The AP method reveals that the structure can redistribute the load after column or wall removal, according to which the deformation and internal forces created in the members do not exceed the permissible values. In the AP method, the structure resists failure due to membrane flexural response. The types of analysis methods in the AP method are linear static analysis, nonlinear static analysis, and nonlinear dynamic analysis. Generally, the results of AP analysis provide better results than other methods and the use of this method is valid for researchers and designers. The SLR-specific local resistance method provides a certain level of shear and flexural strength for the perimeter columns of the building. The flexural strength is equal to the maximum applied unit across the height of the column, which leads to its flexural failure, i.e., or three joints are formed in the joint or a similar failure occurs in it. In other words, by using a single load for the flexural strength of the base, the column and its connection should not be broken in the cut. When the shear capacity is formed before the flexural capacity, a sudden failure occurs in the member, which leads the structure to failure and collapse. The TF method of the building must be connected, that is, it must have continuity, ductility, and alternative load transfer paths. Tensile strength forces through which a structural system resists progressive failure can be supplied through existing structural elements using conventional methods [7].

Among the studies conducted in this field one can mention the study done by Lee et al. (2016), that they conducted a numerical and laboratory study of the progressive failure of a concrete frame with a masonry infill panel without opening. To this end, in the first step, the four-opening, two-story frame with a scale of one-third, which had a masonry infill panel only in the second story, was evaluated in a laboratory. In the next step, after validation, numerical modeling was done to investigate the significant and dominant factors in the behavior of the tested frame. The results of this study have shown that the masonry frame has a significant effect on the strength of the concrete frame against progressive failure and the behavior of the concrete frame. In 2016, Shan et al. examined the effect of infill walls with openings on the progressive collapse of reinforced concrete frames in a laboratory study. For this purpose, concrete frames without infill walls and concrete frames with infill walls with openings were evaluated and compared in the laboratory. The results of this experiment reveal that the presence of folding frames increases the stiffness, reduces the ductility, and increases the maximum strength of reinforced concrete frames against progressive failure [7]. In 2017, Brinesi and Parisi developed fragility curves based on progressive failure in reinforced concrete frames. In this research, a probabilistic framework has been investigated for analyzing structures and preparing fragility curves under progressive failure on low-rise frames [8]. Eren (2019) examined the effect of the presence of an infill wall on the behavior of reinforced concrete frames under progressive failure. The results of this study reveal that the presence of infill walls increases the stiffness and increases the maximum strength of reinforced concrete frames against progressive failure [9]. Gholampour (2018) investigated the effect of column removal on progressive failure on the seismic performance of dual steel structures. The results of this study state that the most critical case of column removal is the removal of the side column. In all three structures, the removal of the column at ground level creates the most critical situation for the structure compared to the higher levels. The removal of the corner column and the braces attached to it rejects the level of life safety performance and as the height of the structure increases, the robustness index increases [10]. Mehdizadeh and Karamuddin (2018) investigated the possibility of progressive failure in steel bending frames (normal, medium, and special) due to the removal of the column. The results reveal that the possibility of damage in special steel bending frames is more than medium and ordinary bending frames. The results also show that unlike seismic retrofits, which provide ductility as an important way to reduce damage to buildings, in the event of gravity failure, increased strength and stiffness of the members can limit the spread of the failure [11]. The examined frames are designed and controlled according to internal regulations. These are analyzed using OpenSees software with an alternative load path method to analyze different scenarios of column removal on the progressive failure process of a 10-story steel frame.

2. Frame design

The frames studied in this research, according to Figure 1, have 10 stories with a lateral bearing system of the bending frame. Some of the design specifications and sections are presented in Tables 1 and 2. The design of the frames is based on the internal regulations (Chapter 6 and Chapter 10 of the National Regulations) and the standard 2800, fourth edition [15, 14, and 13]. In this research, structures are first designed in ETABS software and then modeled to investigate the phenomenon of progressive failure in OpenSees software [16].

Table 1: Software model design parameters

Design parameters	Value
Dead load	5 (kN/m^2)
Live load	2 (kN/m^2)
Height of stories	3.2 m
Span length	6 m
Steel	240 (kN/m^2)

Table 2: Sections used in the software model

Classification of stories	Sections used	
First, second and third stories	Beam	IPE300
	Column	BOX400*400*15
Fourth, fifth and sixth stories	Beam	IPE270
	Column	BOX350*350*15
Seventh and eighth stories	Beam	IPE240
	column	BOX300*300*15
Ninth and tenth stories	Beam	200 IPE
	column	250*250*50 BOX

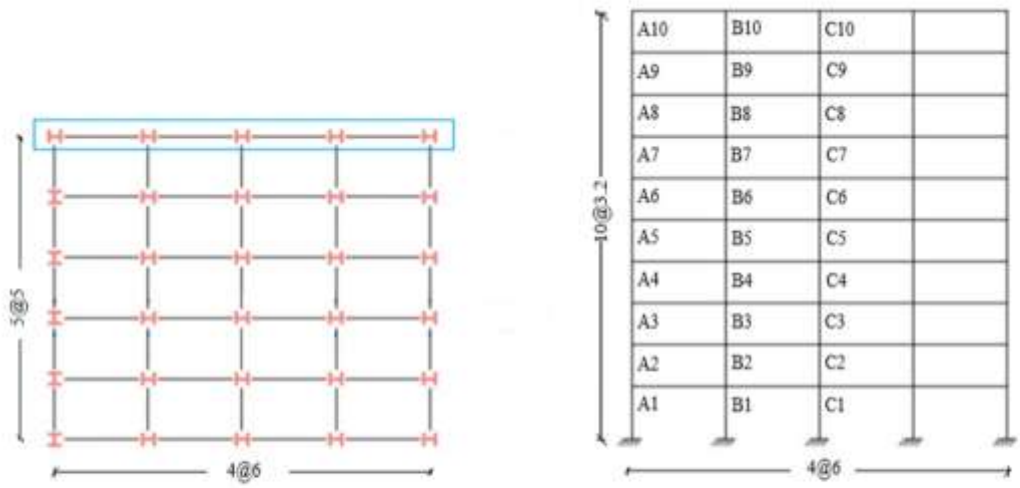

Figure 1: Plan image and view of the studied frame

2.1. Modeling details

OpenSees finite element software was used to investigate the progressive failure in the frame under study. OpenSees finite element software is a powerful open-source software that analyzes a variety of structures using the finite element method. Macro modeling is done in OpenSees software. For steel sections, Steel01 with yield strength and the final strength for steel rebars are 240 and 360 MPa, respectively. Steel01 is a two-line uniaxial with kinematic hardening and isotropic hardening. Non-linear column beam elements were used for frame beam and column elements; to evaluate the actual behavior of the element in the analysis. To estimate the geometric nonlinear behavior, a convergent transformation is used. In this type of transformation, nonlinear geometric transformations are calculated quite accurately from the local system to the general system.

3. Validation

It is very difficult to evaluate progressive failure using a real-scale laboratory model. The finite element method is a suitable option to investigate the phenomenon of progressive failure, which can be used to study a variety of models under the effect of progressive failure. In this study, to validate the software model, Shan et al. [7] laboratory model, whose geometry and details of the laboratory model are shown in Figure 2 and Table 2, has been used. The main goal of Shan and his colleagues was to evaluate and compare the performance of a two-story, four-span concrete frame at one-third scale, with and without infill wall. To this end, they and their colleagues simulated the progressive failure scenario in laboratory samples by applying a quasi-static load on the center column. The loading was applied according to the pushdown method, in the form of displacement control, and applied by two jacks. Likewise, to prevent off-plate drift, the laboratory specimens were correctly secured by rollers placed on either side of the frame. In making the laboratory sample for the first and second stories, concrete with compressive strength of 41.3 and 31.8 MPa, respectively, and rebars with yield strength and final strength of 415 and 588 MPa, respectively, have been used. Also, the compressive and shear strength of the masonry wall were 12.8 and 1.08 MPa, respectively. Table 2 shows the materials and elements used for modeling and validation in OpenSees software. Figure 4 shows the force-drift diagram of laboratory specimens. According to Figure 3, the laboratory sample modeling in OpenSees software has been done with acceptable and sufficient accuracy.

Table 3: Materials and elements used in the software model for validation

	Story height (mm)	**Opening length (mm)**	**Beam's bar**	**Column's bar**
Floor 1	1400	1700	4Φ 8	12Φ 8
Floor 2	1100	1700	4 Φ8	12Φ 8

Figure 2: Image of Shan et al. Laboratory sample [7]

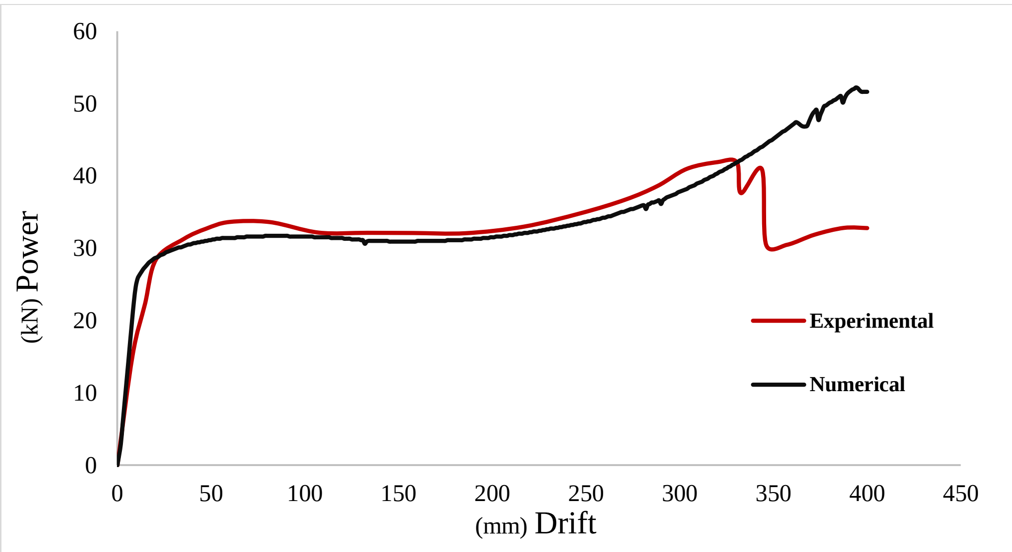

Figure 3: Comparison of the capacity curve of software models with laboratory models

4. Analysis results

In this study, nonlinear static analysis (Pushdown method) through alternative load path (AP) proposed by DoD and GSA regulations has been used for progressive failure analysis. Pushdown analysis can be done in two ways: load control and control drift. The aim of nonlinear static analysis in progressive failure analysis is to estimate the behavior of the structure by estimating the strength and deformation required by the members and comparing them. The frame understudy has 50 columns. In the software review, all columns are removed to analyze different scenarios of progressive failure; the results indicate the behavioral matching of symmetrical columns in the frame. Consequently, in this study, the total removal scenario of the column (corner, side, and middle) is 30 cases.

4.1. Evaluation of different scenarios of corner column removal (first case)

The first case of this study analyzes the effect of the abrupt removal of corner columns (1A to 10A) based on resistance-drift force diagrams and relative drift of stories. To better compare, the different scenarios in this section, Tables 3 and 4 have been used. In these tables, each of the different column removal modes is normal in line with the ground story column removal mode (1A) (comparing different modes based on ground story column removal), which specifies the effects of changing the column removal position in the frame.

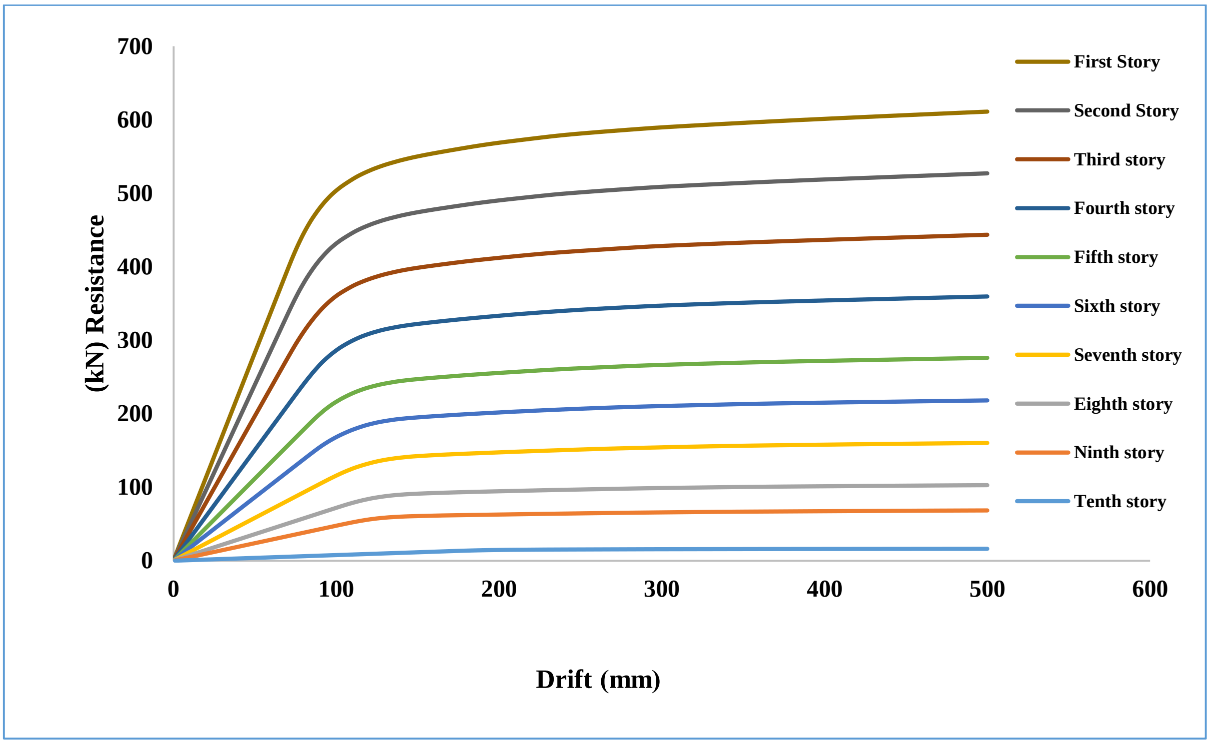

Figure 4: Resistance force-drift curve of different modes of corner column removal

Table 4: Comparison of different scenarios of corner column removal

Column Removal position	First Story	Second Story	Third Story	Fourth Story	Fifth Story	Sixth Story	Seventh Story	Eighth Story	Ninth Story	Tenth Story
Corner columns	1	0.859	0.719	0.577	0.44	0.346	0.25	0.159	0.106	0.022

Based on Figure 4 and Table 4, it can be seen that the maximum strength of the frame is in the condition that the ground story column (1A) has been removed. By changing the removal position of the column from the ground story to the upper columns (1A to 10 A), it is observed that the resistance force of the frame against progressive failure decreases. Consequently, it is inferred that the closer the removal position of the column to the last story, due to the reduction of the upper stories, the column is removed and the participation of the members of the structural force is reduced.

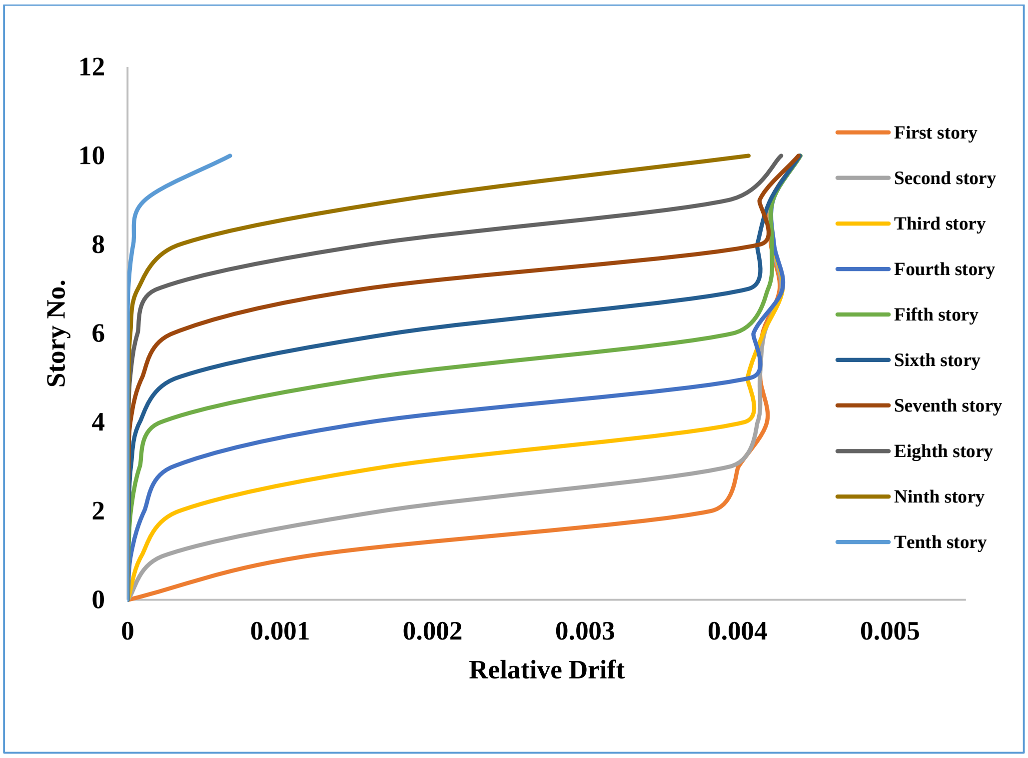

Figure 5: Evaluation of the relative drift curves of different corner column removal modes

Table 5: Comparison of the relative drift of different classes of corner column removal

Column removal position	First Story	Second Story	Third Story	Fourth Story	Fifth Story	Sixth Story	Seventh Story	Eighth Story	Ninth Story	Tenth Story
Corner First Story	1	1	1	1	1	1	1	1	1	1
Corner Story Second	0.2	0.435	0.986	0.986	0.99	1.002	1.002	1.002	1	1
Corner Third Story	0.076	0.088	0.423	0.963	0.98	1	1.004	1.004	1.002	1
Corner Fourth Story	0.017	0.028	0.074	0.38	0.98	0.985	1.004	1.005	1.003	1
Corner Fifth Story	0.0037	0.0053	0.02	0.051	0.38	0.952	0.98	1	1.002	1
Corner Sixth Story	0.0015	0.0018	0.0054	0.019	0.08	0.42	0.95	0.97	1	1
Story Seventh Corner	0.0006	0.0006	0.0016	0.0042	0.0225	0.07	0.362	0.98	0.98	1
Corner Eighth Story	0.0003	0.0003	0.001	0.001	0.0038	0.015	0.045	0.37	0.93	0.97
Corner Ninth Story	0.0002	0.0002	0.0003	0.0005	0.0013	0.004	0.016	0.08	0.422	0.92
Corner Tenth Story	0	0	0	0	0.0001	0.0004	0.0012	0.008	0.027	0.16

Regarding Figure 5 and Table 5, it can be seen that by removing the ground story column, drift has been applied to all stories. By changing the removal position of the column from the ground story to the upper columns (1A to 10 A), it is observed that the drift of the last story due to the removal of the column of that story has a lower value than other cases in the same story. This indicates the limited participation of members in this case of removal.

4.2. Evaluation of different scenarios of side column removal (second case)

The second case of this study analyzes the effect of the abrupt removal of corner columns (B1 to B10) based on the resistive force-drift diagrams and the relative drift of the stories. Tables 6, 7, and 8 have been used to better compare different scenarios in this section. In these tables, each of the different column removal modes is normalized to the ground story column removal mode (B1), which determines the effects of different side column removal scenarios on different stories.

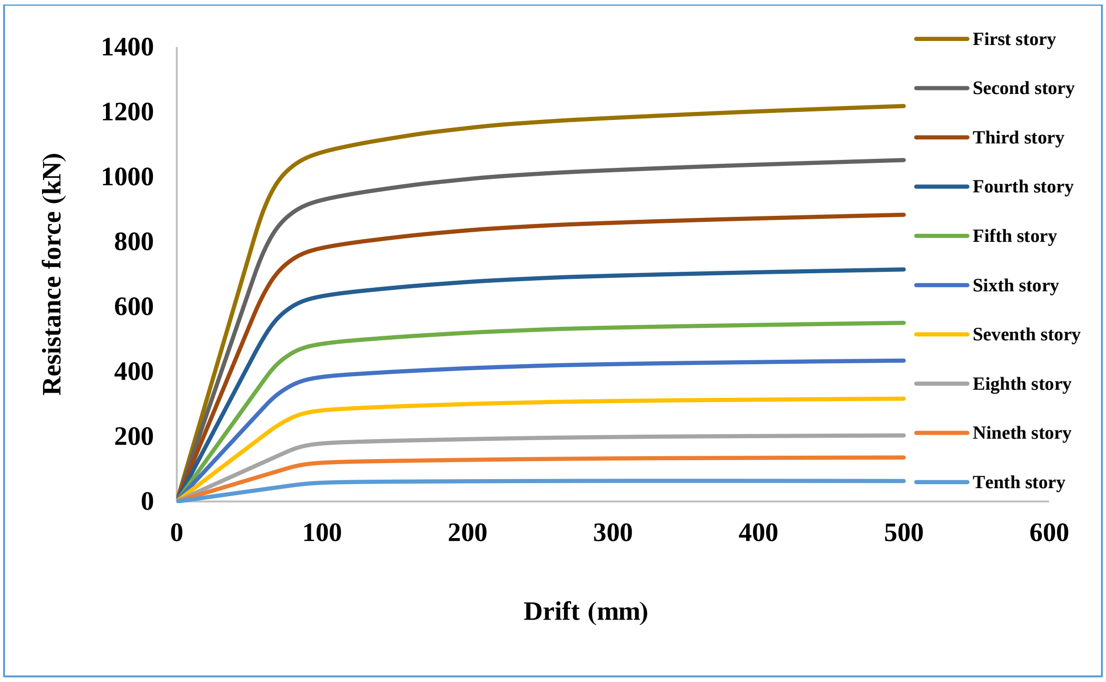

Figure 6: Force-drift curve of different modes of side column removal

Table 6: Comparison of different scenarios of side column removal

Column removal position	First Story	Second Story	Third Story	Fourth Story	Fifth Story	Sixth Story	Seventh Story	Eighth Story	Ninth Story	Tenth Story
Side columns	1	0.862	0.723	0.583	0.446	0.351	0.255	0.162	0.108	**0.0511**

Table 7: Comparison of the mean and maximum strength of side column removal in line with the side column

Column removal position	Corner	Side (Mean)	Side (Max.)
First Story	1	1.121	1.993
Second Story	1	1.129	1.994
Third Story	1	1.135	1.991
Fourth Story	1	1.152	1.988

Fifth Story	1	1.153	1.99
Sixth Story	1	1.158	1.986
Seventh Story	1	1.188	1.974
Eighth Story	1	1.176	1.978
Ninth Story	1	1.174	1.97
Tenth Story	1	4.082	3.875

According to Figure 6 and Table 6, it can be seen that the maximum strength of the frame is in the case that the ground story column (B1) has been removed. By changing the removal position of the column from the ground story to the upper columns (B1 to B 10), it is observed that the frame resistance force against progressive failure decreases. As the removal position of the column approaches the last story, due to the reduction of the upper floors of the eliminated column, and the reduction of the participation of the structural members of the resistive force, it is reduced. Table 7 compares the removal position of the side column compared to the corner column in two modes of average and maximum increase of resistance force. It can be seen that in all cases of removal except the removal of the last story column, the amount of resistant force of the frame has increased by 15.454% in the average case and by 98.5% in the maximum case. In the case of removing the last story column, the amount of resistant force of the frame has increased by 308.2% in the average condition and 287.5% in the maximum condition. This increase in force in the last story indicates the positive effect of the members on the removed member.

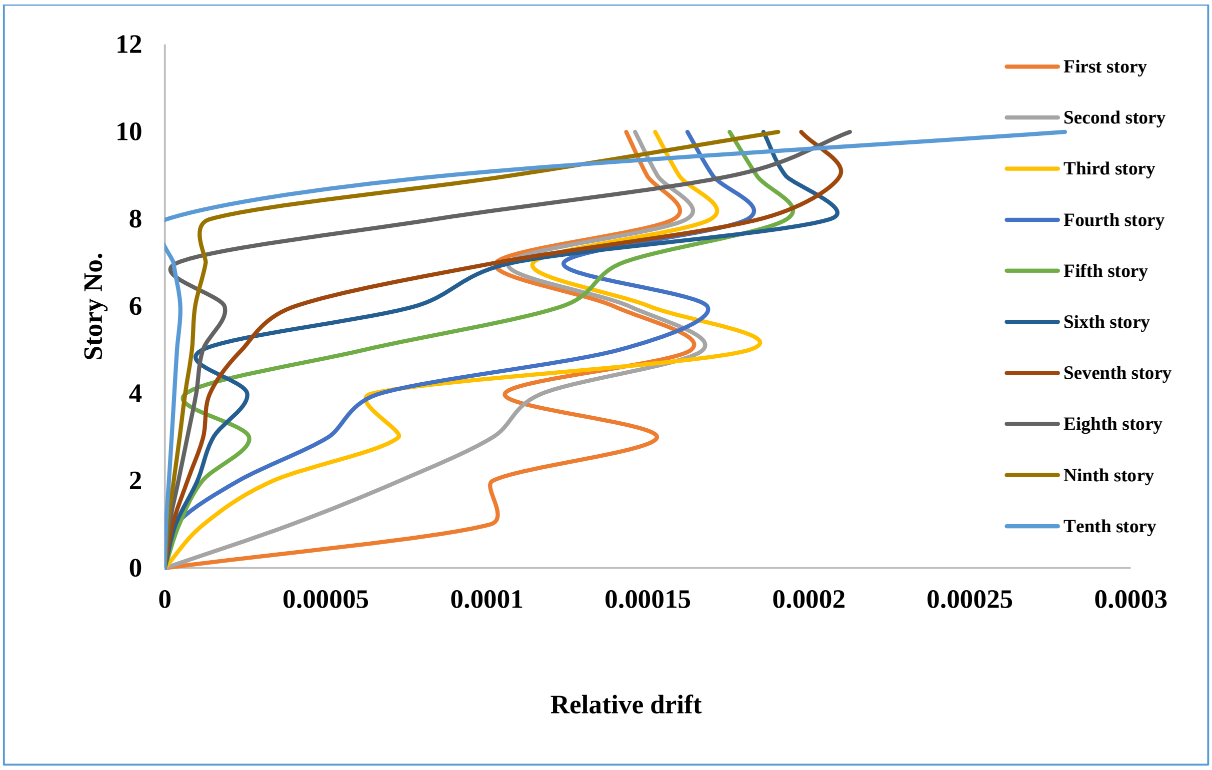

Figure 7: Evaluation of the relative drift curve of different modes of side column removal

Table 8: Comparison of relative drift of different classes of side column removal

Column removal position	Story First	Story Second	Story Third	Story Fourth	Story Fifth	Story Sixth	Story Seventh	Story Eighth	Story Ninth	Story Tenth
Side First Story	1	1	1	1	1	1	1	1	1	1
Side Second Story	0.39	0.716	0.67	1.109	1.023	1.034	1.038	1.026	1.0216	1.019
Side Third Story	0.12	0.33	0.475	0.61	1.11	1.078	1.112	1.073	1.066	1.062
Side Fourth Story	0.034	0.225	0.332	0.63	0.87	1.206	1.204	1.145	1.136	1.132
Side Fifth Story	0.045	0.115	0.171	0.062	0.38	0.89	1.382	1.23	1.227	1.224
Side Sixth Story	0.033	0.099	0.099	0.25	0.071	0.56	1.05	1.31	1.287	1.3
Side Seventh Story	0.024	0.07	0.08	0.132	0.146	0.29	1	1.17	1.4	1.38
Side Eighth Story	0.0142	0.042	0.047	0.093	0.0725	0.134	0.039	0.53	1.18	1.485
Side Ninth Story	0.0094	0.028	0.03	0.06	0.052	0.068	0.124	89	0.72	1.33
Side Tenth Story	0.0044	0.013	0.014	0.028	0.024	0.035	0.027	0.0043	0.58	1.95

Based on Figure 7 and Table 8, it can be seen that by removing the ground story column, drift has been applied to all stories. By changing the removal position of the column from the ground story to the upper columns (1B to 10B), it is observed that the lower stories drift of the removed column has a small value.

4-3- Evaluation of different scenarios of middle column removal (third case)

The third case of this study investigates the effect of abrupt removal of the middle columns (C1 to C10). In this section, to investigate the effect of abrupt removal of the middle columns (C1 to C10), the resistance-drift force diagram of the upper node of the removed column and the relative drift diagram are compared. To compare better the different scenarios of abrupt removal of the middle columns (C1 to C10) presented in Figures 8 and 9, Tables 9, 10, and 11 have been used. In these tables, each of the different scenarios studied is normalized regarding the ground story (C1) side column removal scenario, which identifies the effects of different middle column removal scenarios on different stories

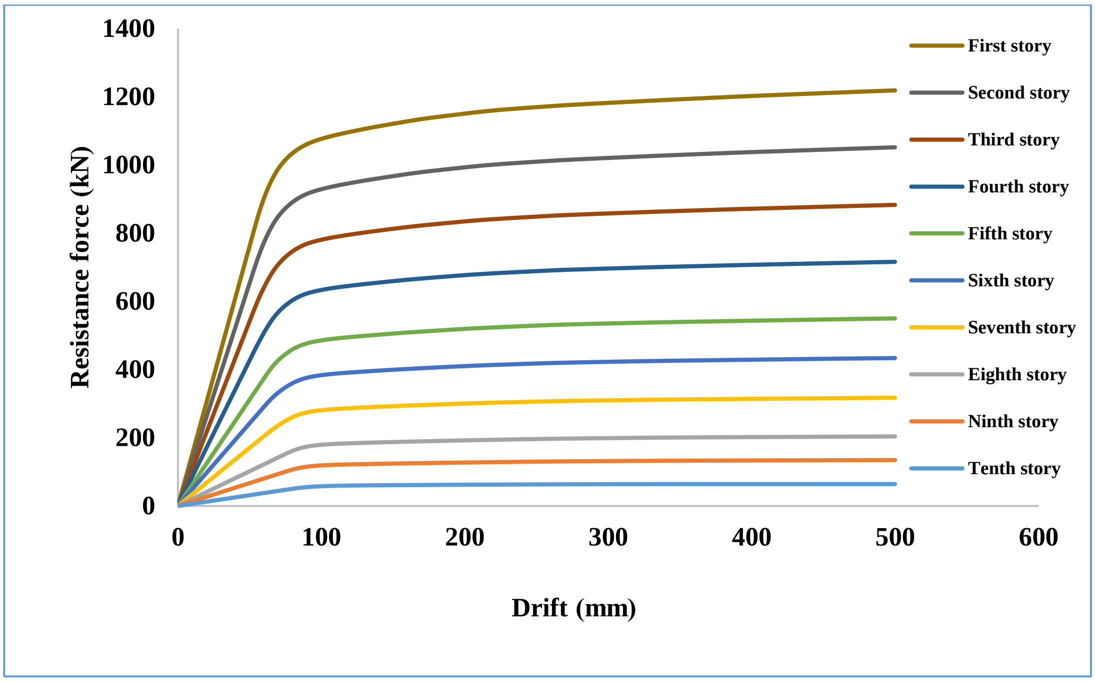

Figure 8: Force-drift curve of different modes of middle column removal

Table 9: Comparison of different scenarios of middle column removal

Column removal position	First story	Second story	Third story	Fourth story	Fifth story	Sixth story	Seventh story	Eighth story	Ninth story	Tenth story
Middle columns	1	0.862	0.723	0.584	0.445	0.351	0.255	0.162	0.108	0.0519

Table 10: Comparison of the mean and maximum strength of the removal of the middle column compared to the corner column

Column delete position	Corner	Medium (average)	Medium (maximum)
First story	1	1.123	1.994
Second story	1	1.131	1.995
Third story	1	1.137	1.993
Fourth Story	1	1.155	1.991
Fifth story	1	1.156	1.991
Sixth story	1	1.6	1.987
Seventh story	1	1.194	1.98
Eighth story	1	1.18	1.98
Ninth story	1	1.178	1.969
Tenth story	1	4.166	3.956

According to Figure 8 and Table 9, it can be seen that the maximum strength of the frame is in the case that the ground story column (C1) has been removed. By changing the column removal position from the ground story to the upper columns (C1 to C10), it is observed that the frame resistance force decreases against progressive failure. As the column removal position approaches the top story, due to the reduction of the upper stories of the eliminated column, and the reduction of the participation of the structural members of the resistive force, it is reduced. Table 10 compares the removal position of the middle column in line with the corner column in two modes of average and maximum increase of resistive force. It can be seen that in all removal modes except the last floor column, the amount of frame strength has increased by 15.732% on average and 98.7% at maximum. In the case of removing the last floor column, the amount of resistant force of the frame has increased by 316.6% in the average condition and 295.6% in the maximum condition.

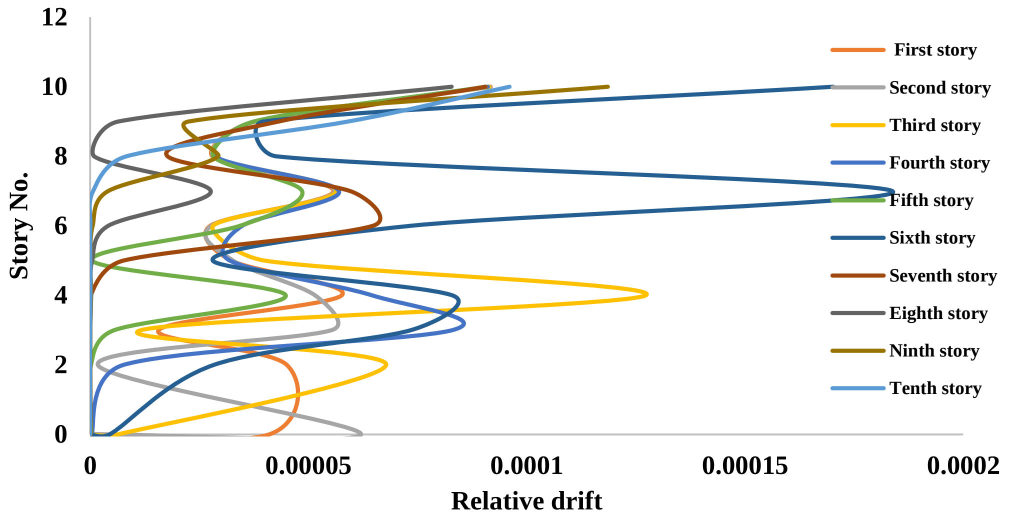

Figure 9: Evaluation of the relative drift curve of different modes of middle column removal

Table 11: Comparison of relative drift of different cases of middle column removal

Pillar removal position	1st story	2nd story	3rd story	4th story	5th story	6th story	7th story	8th story	9th story	10th story
Middle first story	1	1	1	1	1	1	1	1	1	1
Middle second story	0.39	0.72	0.67	1.11	1.023	1.034	1.04	1.025	1.02	1.02
Middle third story	0.12	0.33	0.48	0.61	1.11	1.08	1.112	1.073	1.07	1.063
Middle fourth story	0.035	0.23	0.33	0.63	0.87	1.2	1.2	1.145	1.136	1.324
Middle fifth story	0.045	0.115	0.18	0.62	0.38	0.88	1.38	1.22	1.23	1.23
Middle sixth story	0.033	0.1	0.099	0.25	0.071	0.55	1.05	1.31	1.29	1.3

Middle seventh story	0.024	0.07	0.078	0.13	0.146	0.29	1	1.17	1.4	1.38
Middle eighth story	0.0142	0.042	0.046	0.093	0.072	0.14	0.039	0.53	1.18	1.485
Middle ninth story	0.009	0.028	0.03	0.062	0.052	0.07	0.124	0.09	0.72	1.33
Middle tenth story	0.0044	0.013	0.014	0.028	0.023	0.04	0.027	0.004	0.584	1.95

According to Figure 9 and Table 11, it can be seen that by removing the ground story column, drift has been applied to all stories. By changing the column removal position from the ground story to the upper columns (C1 to 10 C), it is detected that the drift of the lower stories of the removed column is small.

5. Conclusion

Nowadays, regarding the spread of factors such as terrorist attacks, strikes, earthquakes, etc., the prominence of the progressive failure phenomenon is becoming clear. For this reason, progressive failure in the detection of structures stability is essential. In the current study, diverse states of progressive failure (removal of corner, side, and middle columns) on the progressive failure process of a 10-story steel frame with a special bending system have been carefully analyzed in OpenSees software using an alternative load path method. The main results of this study are as follows:

- In all the studied cases, by changing the position of the column removal, respectively from the ground story to the upper stories, it is observed that the resistance force of the frame against the progressive failure is reduced. With each column removal position changing, the resistive force decreases by an average of 10.243% compared to its previous state.
- By changing the location of the column removal from the corner to the side and middle column, it is observed that the frame resistance force against progressive failure increases. By changing the position (except the last story) of the column from the corner to the side and middle, it increases by an average of 15.45 and 15.73 percent, respectively, and in the last story, it increases by 308.2 and 316.6 percent, respectively.
- According to the diagrams and tables, the removal of the side and middle columns, all cases have the same behavior. Accordingly, it can be said that in the progressive failure, the behavior of the side and middle columns is quite similar.

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