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Analyzing and Enhancing the Resilience of Steel Moment Frame Structures Against Progressive Collapse

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Abstract: The present study scrutinizes the decision-making strategies and enhancement techniques aimed at minimizing progressive collapse in steel moment frame structures. Comparative analyses of both three-story and five-story frames were carried out, focusing on the reinforcement of external frames through the introduction of bracing. Employing ABAQUS, a sophisticated finite element software, simulations of these frames resulted in the exploration of 16 unique steel frame configurations. In an assessment of column loss impact, the middle column of the lowest story in the supporting frame was deliberately removed. Findings reveal that the axial force of the beams adjacent to the removal site in the three-story frame escalates approximately 2.15 times in relation to the values connected with corner beam extraction. Conversely, the increase in axial force of the beams adjacent to the column removal in the five-story frame varied between 5% and 49% of the respective values for beam removal conditions. Furthermore, a reduction in maximum displacement was found to correlate with an increase in the number of stories. Maximum displacements in five-story frames were observed to be roughly 7% to 22% of the corresponding values in three-story frames, with variability depending on the location of the removed column. These results indicate that the effectiveness of bracing-based reinforcement to prevent progressive collapse in steel moment frame structures intensifies with the increase in the number of stories. This performance enhancement against progressive collapse becomes particularly significant for structures comprising a higher number of stories.

Keywords: Progressive collapse; Seismic improvement; Steel moment frame

1 Introduction

In recent times, seismic enhancement of structures has been underscored due to a myriad of reasons, including regulatory changes and shifts in building usage. This investigation evaluates the performance of such edifices post-seismic improvement, particularly in connection with progressive collapse, and scrutinizes the efficacy of such advancements in mitigating the risks of large-scale progressive collapse [1]. Progressive collapse analysis typically employs finite element software to model the abrupt removal of one or more structural components, causing a redistribution of load to the remaining elements [2]. Structural failure could ensue if sudden load application is disregarded during the design phase, leading to the potential collapse of a significant part or the entire structure.

Studies have been conducted to understand this phenomenon better. For instance, Khandelwal et al. [3] explored progressive collapse in steel brace frames designed according to seismic criteria. In their investigation, two-dimensional models of two prevalent braced frame categories, specifically SCBF and EBF frames, were analyzed using the APM method to ascertain their resistance to progressive collapse. Their simulations suggested that EBF brace frames, designed with high seismic risk in mind, sustained less damage than the SCBF system when faced with progressive collapse under gravity load.

Tavakoli and Kiakojori [4] turned their attention to the methods of column removal and proposed a new approach for dynamic deletion of beams. In their study, the reaction of a five-story steel moment frame structure was examined under varying scenarios. They discovered that abrupt beam removal resulted in a larger response than the gradual elimination of a column.

Tavakoli and Alashti [5] conducted research on progressive collapse in steel moment frame systems, particularly focusing on corner effects. Their non-linear static analysis of both 2D and 3D frames, comprising 5- and 15-story buildings with 4 and 6 openings, utilized the UFC code for replacement analysis. Their findings indicated a higher structural resilience when the middle column, as opposed to the corner column, was removed.

Liu and Pirmoz [6] put forth a novel method to predict the maximum structural response of a building frame using non-linear static analysis. This study employed a pulldown energy-based analysis and found that it was less computationally complex and costly compared to the non-linear time analysis results used as a baseline. The study revealed a simpler process for assessing the potential of progressive collapse in a building with a suddenly removed beam when compared to the common pushdown method.

Faghihmaleki et al. [7] explored the fortification of reinforced concrete frames against progressive collapse and earthquakes using steel braces. They employed non-linear dynamic analysis to assess performance during progressive destruction, where retrofitting was achieved through steel braces. Their results suggested a predisposition towards progressive collapse in reinforced concrete frames when beams are removed. However, when retrofitting with steel braces was undertaken in full layout mode, V-braced and inverted-V-braced frames demonstrated enhanced structural strength against progressive collapse, with the V-braced frame displaying superior performance over the inverted-V-braced frame.

A robustness index based on risk analysis was introduced by Faghihmaleki and Abdollahzadeh [8], taking into account both the percentage and extent of progressive collapse. This index was applied to evaluate the performance of a 4-story steel moment frame building improved using two distinct methods: the concentrically braced frame and the buckling-restrained brace. They offered a method to acquire all effective parameters in the desired robustness index. Comparisons were made between the behavior of the primary and improved structures, and the results were subsequently documented.

Mashadi et al. [9] proposed an amendment to understand the relationship between the likelihood of progressive collapse and the analyzed structures. To assess the impact of parameters on the DIF parameters, flexural frames of varying lengths and stories were designed. Non-linear dynamic analysis and step-by-step non-linear analysis were carried out. Their results indicated that gravitational loads and member characteristics, such as the ratio of secondary stiffness, influenced DIF calculations for the removed beam members. The empirical relationships proposed in this study for gravitational loads and the demand flexibility ratio of secondary elastic stiffness are suggested for use in non-linear static analysis.

The fusion of seismic improvement techniques with progressive collapse resistance is anticipated to yield effective strategies for fortifying structures against progressive collapse. This study delves into the impact of such improvements against progressive collapse. Moreover, the demands of modern urbanization necessitate a harmonious relationship between existing structures or those under construction, as the destruction of a single structure could inflict damage on neighboring buildings, disrupt city operations, and lead to societal repercussions.

2 Methodology

The present study utilized a methodological approach predicated on an exhaustive assessment of enhancement strategies for structural flexural frames in buildings, aiming to optimize resistance against progressive collapse. Initially, comprehensive analyses were undertaken on two unique steel structures, both integrated with a corner flexural system. These structures, designed adhering to the AISC341-16 regulation [10], differed in their number of stories: one was three-story, and the other five-story.

After preliminary analyses, boundary frames of these edifices were bolstered by incorporating bracing, a proven mitigation technique against progressive collapse. This simulation was conducted employing the ABAQUS finite element software.

The study design contemplated several variables. The number of building stories was one such variable, with the choice between 3 and 5 stories. The position of beam deletion in the plan was another, with possibilities encompassing no removal, corner frame removal, and median frame beam removal. Lastly, the position of beam deletion across the stories was also considered, where the beam could be deleted in the 1st, 2nd, or 3rd story.

In total, 16 steel frames were simulated, as detailed in Table 1. Various output parameters such as stress, strain, and axial force strength were used to compare and contrast each of these frames. This approach facilitated a comprehensive understanding of the most efficacious strategies for reinforcing structural flexural frames against progressive collapse. It is anticipated that the findings will offer valuable insights for future design and construction practices within the realm of structural engineering. The theoretical and practical implications of these findings can be further explored, setting the foundation for subsequent research to fine-tune these enhancement strategies and to expand their applicability to a broader range of structures.

Table 1. Introducing studying modes in present research

Status	Column deletion story	Location of column deletion	Building	Mode
Unreinforced	Without deletion	Without deletion	0	1
	Without deletion	Without deletion		2
	1			3
Reinforcement	2	Corner column		4
with increased	3		3	5
bracing	1			6
	2	Middle column		7
	3			8
Unreinforced	Without deletion	Without deletion		9
	Without deletion	Without deletion		10
	1			11
Reinforcement	3	Corner column		12
with increased	5		5	13
bracing	1			14
	3	Middle column		15
	5			16

3 Geometrical Specifications of the Studied Models

In the study under review, two buildings were evaluated, one consisting of three stories and the other five stories. Both buildings were constructed using St 37 construction steel, characterized by a final stress of 3,700 $\mathrm{kg/m^2}$ and a yield stress of 2,400 $\mathrm{kg/m^2}$. The buildings were identical in plan across all stories, featuring a uniform story height of 3.20 meters. The structural system comprised a medium moment frame in both directions, with beams rigidly connected and affixed to the base of the beam.

The story of the structure was designed as a block and joist type. Dead and live loads for the stories were set at 335 and 200 $\mathrm{kg/m^2}$, respectively, while for the roof, these values were 200 and 150 $\mathrm{kg/m^2}$, respectively. Seismic loading assumed that the structure is located in one of the four seismic zones of Iran. The design of the structures adhered to the AISC341 code, considering the effects of dead, live, and earthquake loads.

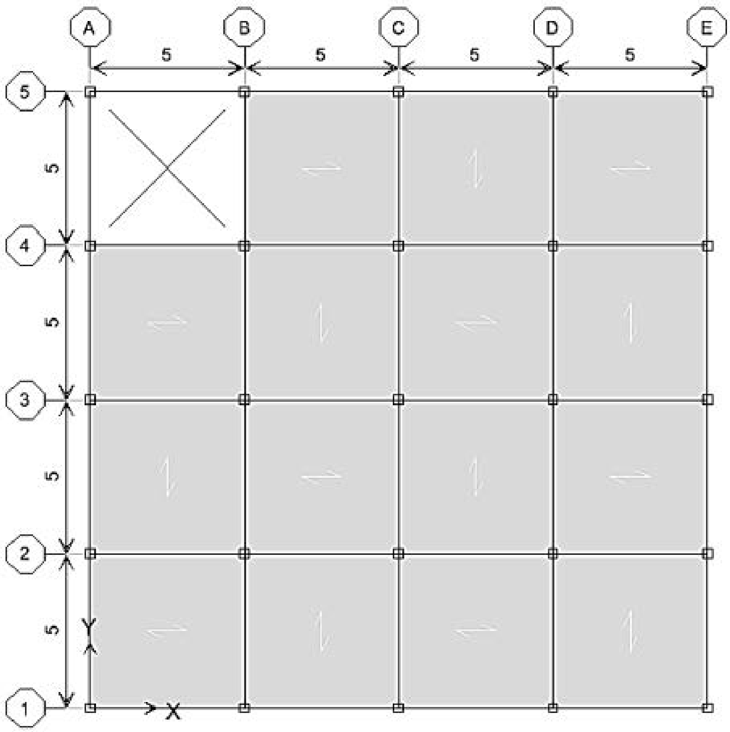


Figure 1. Typical plan of studying buildings

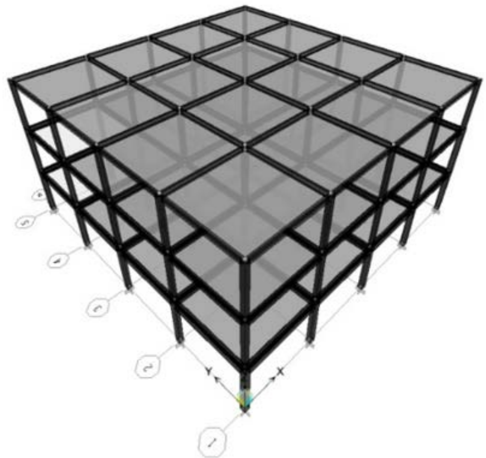


Figure 2. Studying three-story building

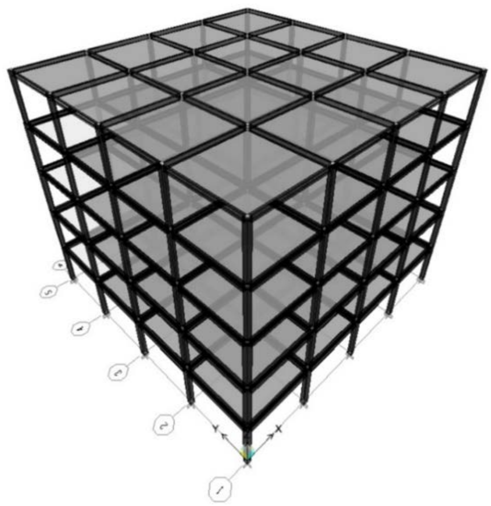


Figure 3. Studying five-story building

Table 2. The results of designing three-story steel building members

Bracing	Beam	Column	Stories
Box 20 × 2.0	IPE 320	Box 25 × 25 × 2.0	1
Box 20 × 2.0	IPE 320	Box 25 × 25 × 2.0	2
Box 20 × 1.6	IPE 300	Box 20 × 20 × 2.0	3

Table 3. The results of designing five-story steel building members

Bracing	Beam	Column	Stories
Box 25 × 1.6	IPE 340	Box 40 × 40 × 2.4	1
Box 25 × 1.6	IPE 340	Box 40 × 40 × 2.4	2
Box 25 × 1.6	IPE 340	Box 35 × 35 × 2.0	3
Box 20 × 1.6	IPE 320	Box 35 × 35 × 2.0	4
Box 20 × 1.6	IPE 320	Box 35 × 35 × 2.0	5

The design process entailed several steps, aiming to select sections that were closest to the optimal mode in terms of stress and lateral movement of the structure. At the same time, the components were designed for simplicity and uniformity. The results of the structural design are presented in Table 2 and Table 3. Figure 1 depicts the plan of the types of buildings investigated, while Figure 2 and Figure 3 illustrate the 3D structure of the 3-story and 5-story buildings, respectively. The vibratory natural periods for the first and second modes of the structure were determined to be 1.1 and 0.35 s, respectively.

3.1 Characteristics of the Accelerometers Used

To accurately capture the effects of ground motion, accelerometers should reflect the actual movement of the ground at the construction site during an earthquake. A minimum of three accelerometer pairs, corresponding to the horizontal components of three earthquakes with similar site characteristics, should be selected. In this study, 10 real earthquake records from the Pacific Earthquake Engineering Research Center (PEER) database (Table 4) were employed to fulfill this requirement. The ASCE US 7-10 Code methodology was utilized to scale the selected earthquakes relative to the 5% damping and Type D soil spectrum. The results, expressed as scale factors (SF) in two directions, are presented in Table 4. In Table 4, M_W, Dist, t_{tot}, and Vs denote the moment magnitudes, the distance from the fault zone, the duration of the earthquake, and the average shear wave velocity of the soil in the area to a depth of 30 meters, respectively.

Table 4. Characteristic of accelerated applied

Record ID	PEER ID	Event	Station	Comp.	M_W	Dist (km)	t_{tot} (s)	Vs (m/s)	SF	
									X	Y
1	1233	Chi-Chi, Taiwan	CHY082	E	7.62	36	90	194	2.47	3.66
2	1153	Kocaeli	KOERI Botas	090	7.51	127	102	275	3.25	3.8
3	851	Landers	CDMG 14368 Downey - Co	000	7.28	157	70	272	3.75	1.42
4	1810	Hector	Mecca - CVWD Yard	090	7.13	92	60	345	4.11	3.9
5	1629	St Elias, Alaska	USGS 2728 Yakutat	279	7.54	80	83	275	1.5	
6	777	Loma Prieta	USGS 1028 Hollister City Hall	090	6.93	28	39	199	1.44	2.5
7	1043	Northridge-01	Neenach - Sacatara Ck	090	6.69	52	48	309	4.44	4.55
8	428	Superstition Hills-02	Westmorland Fire Sta	180	6.54	13	40	194	3.98	4.20
9	172	Imperial Valley-06	El Centro Array #1	140	6.53	22	39	237	1.50	2.10
10	2615	Chi-Chi, Taiwan- 03	TCU061	N	6.20	40	107	273	2.50	3.8

4 Finite Element Method Used in the Simulation of Frames

The methodology section of this study outlines the finite element analysis employed, with the aid of ABAQUS software, to simulate the behavior of frames. Model geometry was formulated initially, ensuring the thoughtful integration of specified load compositions to model the physical forces acting on the system. A notable aspect of the model design was the exclusion of the incremental gravity load for columns located on upper stories. Rather than factoring in these forces directly, they were imposed as gravity loads at the terminations of the elements missing from the upper story components in subgraph (a) of Figure 4 [11].

In the subsequent analysis, the aggravated load of gravity (G_{LD}) pertinent for controlled efforts in a linear static method, was computed by altering the load form. The equation to illustrate this alteration is expressed as:

$$G_{LD} = \Omega_{LD}[(0.9 \text{ or } 1.2)\text{D} + (0.5 \text{ L or } 0.2 \text{ S})] \quad (1)$$

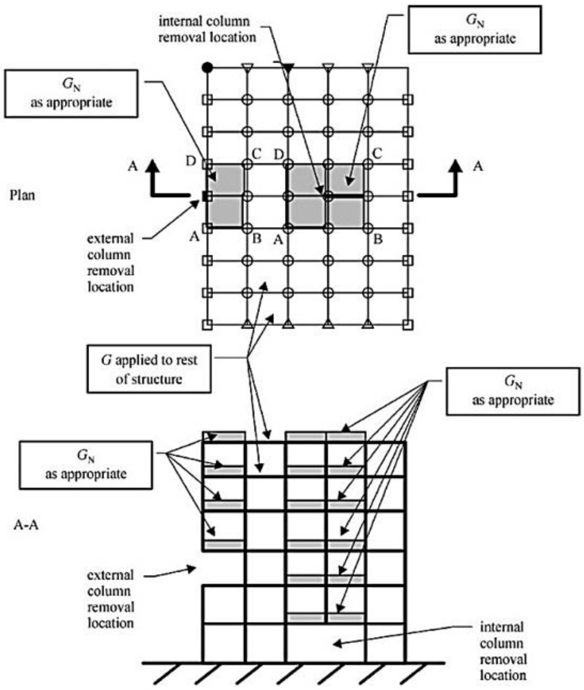
where, D stands for the load related to the perspectives of the werewolves, L symbolizes the live load (considering the ASCE load-reduction factor), and S is indicative of the snow load. Ω represents the load-increasing coefficient utilized in the computation of control efforts with deformation.

Mirroring the methodology employed in the initial stages of the model design, the aforementioned gravity load increase for the upper-story columns was omitted and factored into the load combination (10) as:

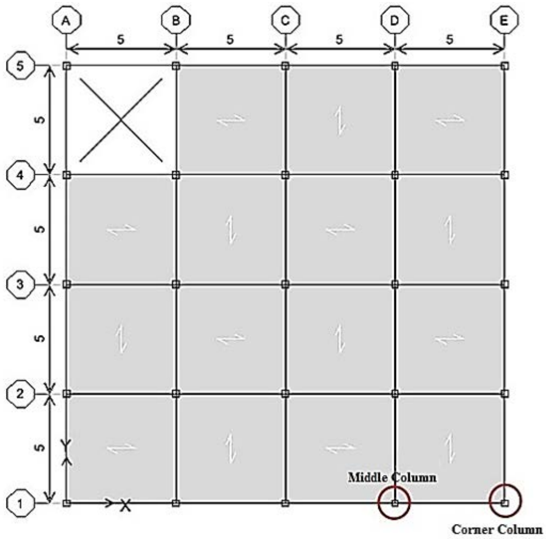
$$\text{G} = [(0.9 \text{ or } 1.2)\text{D} + (0.5 \text{ L or } 0.2 \text{ S})] \quad (2)$$

Here, G is the gravity load.

This research also incorporates parameters such as the removal of the beam in the structural plans and layouts, with subgraph (b) of Figure 4 marking the locations where the columns were removed, as shown in the plan.



(a) Burden and their effect location for deleting columns [11]



(b) The location of deleted columns in present study

Figure 4. The location of deleted columns

5 Assess the Results of the Analysis

In the pursuit of evaluating the potential for progressive collapse, the methodology involves the creation of geometry and modelling with the aid of the finite element software, ABAQUS [12]. Three-dimensional finite element models are constructed, comprising of structural components like beams and columns. These constituents are identified as deformable. The defined materials are assigned to the components via the Property module. Further, the Interaction module is deployed for the establishment of contacts and interplays between different levels. Lastly, the loading and the application of boundary conditions are executed through the Load module [13].

5.1 Mode 1: Non-resistant Three-story Building without Elimination

The stress distribution for an average three-story bending frame without column removal or reinforcement is illustrated in Figure 5. In this configuration, the maximum strain is found to be 0.00251, with a maximum axial force of 57.19 kN and a maximum stress of 65.75 MPa.

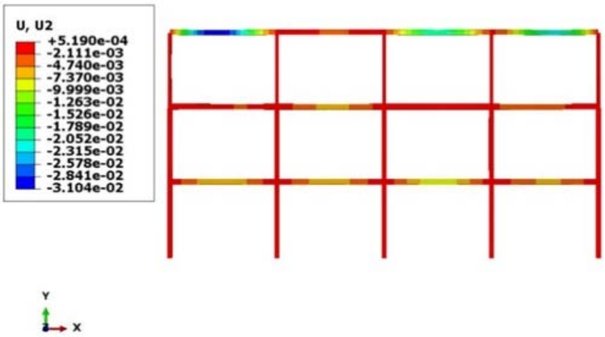


Figure 5. Stress distribution arising analysis in Mode 1

5.2 Mode 2: Reinforced Three-story Building with Bracing without Elimination

The analysis results for a reinforced three-story steel frame with added bracing, but without column removal, are presented in Figure 6. In this scenario, the maximum strain is 0.00214, the maximum axial force is 108.3 kN, and the maximum stress is 56.26 MPa.

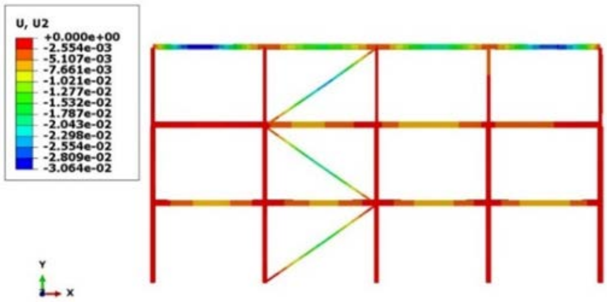


Figure 6. Stress distribution arising analysis in Mode 2

5.3 Mode 3: Reinforced Three-story Building with First-story Corner Column Deletion

Figure 7 displays the results of the analysis for a reinforced three-story frame with the first-story corner column removed. In this mode, the maximum strain is 0.00976, the maximum axial force is 278.7 kN, the maximum stress is 197.10 MPa, and the maximum displacement at the column deletion location is 570 mm.

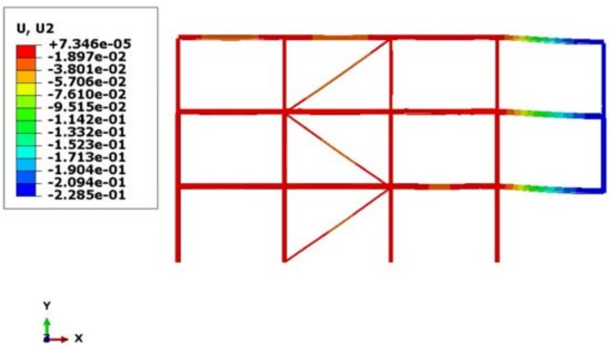


Figure 7. Stress distribution arising analysis in Mode 3

5.4 Mode 4: Reinforced Three-story Building with Second-story Corner Column Deletion

The analysis results for a reinforced three-story frame with the second-story corner column removed are shown in Figure 8. In this mode, the maximum strain is 0.01164, the maximum axial force is 244.9 kN, the maximum stress is 56 MPa, and the maximum displacement at the column deletion location is 370.40 mm.

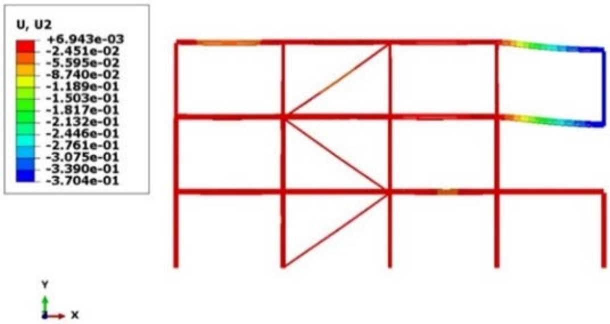


Figure 8. Stress distribution arising analysis in Mode 4

5.5 Mode 5: Reinforced Three-story Building with Third-story Corner Column Deletion

In Figure 9, the results of the analysis for a reinforced three-story frame with the third-story corner column removed are displayed. In this mode, the maximum strain is found to be 0.01810, the maximum axial force is 281.20 kN, the maximum stress is 106.60 MPa, and the maximum displacement at the column deletion location is 440.70 mm.

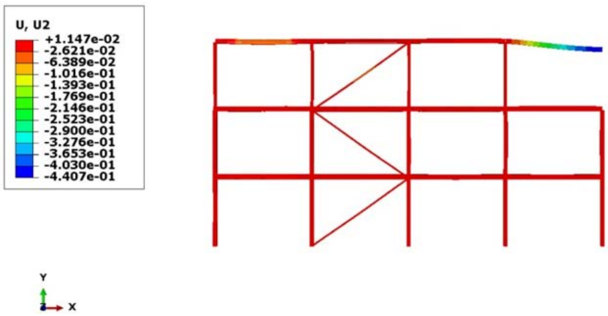


Figure 9. Stress distribution arising analysis in Mode 5

5.6 Mode 6: Reinforced Three-story Building with First-story Corner Column Deletion

The analysis results for a reinforced three-story frame with the first-story corner column removed are shown in Figure 10. In this mode, the maximum strain is 0.02207, the maximum axial force is 558.3 kN, the maximum stress is 275.8 MPa, and the maximum displacement at the column deletion location is 575 mm.

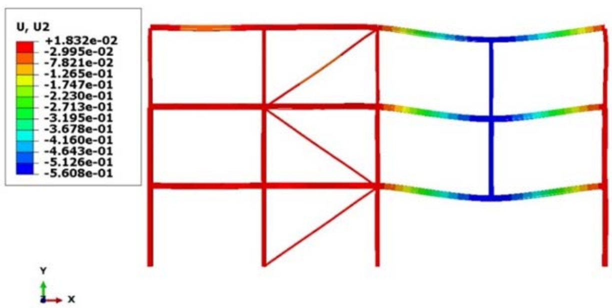


Figure 10. Stress distribution arising analysis in Mode 6

5.7 Mode 7: Reinforced Three-story Building with Second-story Corner Column Deletion

Figure 11 presents the results of the analysis for a reinforced three-story frame with the second-story corner column removed. In this mode, the maximum strain is 0.01861, the maximum axial force is 344 kN, the maximum stress is 197.8 MPa, and the maximum displacement at the column deletion location is 610 mm.

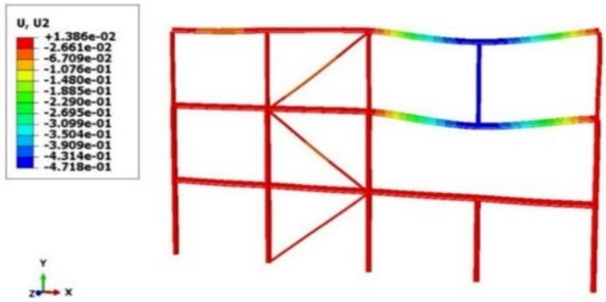


Figure 11. Stress distribution arising analysis in Mode 7

5.8 Mode 8: Reinforced Three-story Building with Third-story Corner Column Deletion

The analysis results for a reinforced three-story frame with the third-story corner column removed are displayed in Figure 12. In this mode, the maximum strain is 0.01055, the maximum axial force is 224.5 kN, the maximum stress is 144.6 MPa, and the maximum displacement at the column deletion location is 659 mm.

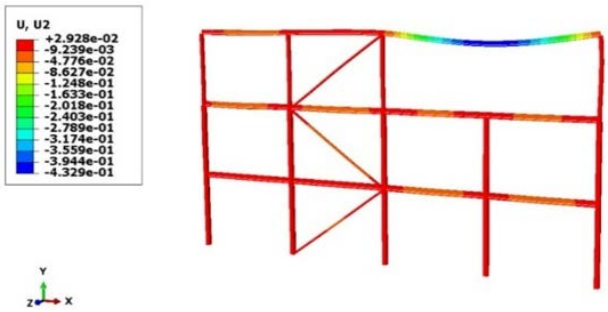


Figure 12. Stress distribution arising analysis in Mode 8

5.9 Mode 9: Non-resistant Five-story Building without Elimination

In Figure 13, the stress distribution, axial force of columns, and stress distribution for an average five-story bending frame without column removal or reinforcement are shown. In this mode, the maximum strain is 0.00167, the maximum axial force is 485.7 kN, and the maximum stress is 56.12 MPa.

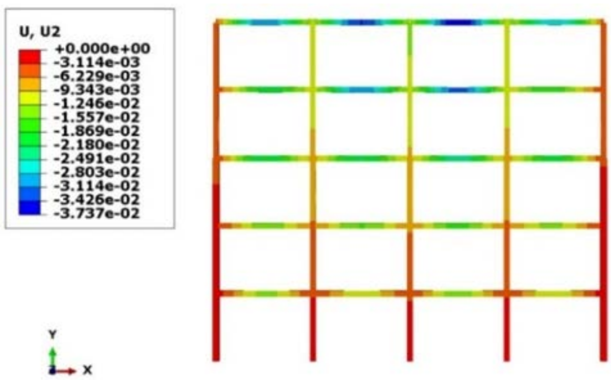


Figure 13. Stress distribution arising analysis in Mode 9

5.10 Mode 10: Five-story Building with Bracing, Unreinforced, without Column Deletion

Figure 14 presents the results of the analysis for a five-story steel frame reinforced with added bracing but without column removal. In this mode, the maximum strain is 0.00167, the maximum axial force is 412.8 kN, and the maximum stress is 60.36 MPa.

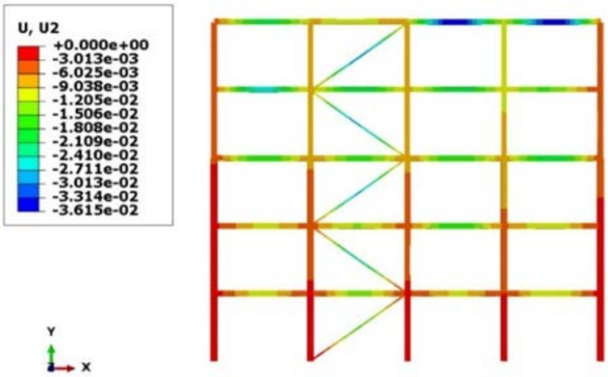


Figure 14. Stress distribution arising analysis in Mode 10

5.11 Mode 11: Reinforced Five-story Building with First-story Corner Column Deletion

Figure 15 displays the results of the analysis for a reinforced five-story frame with the first-story corner column removed. In this mode, the maximum strain is 0.00958, the maximum axial force is 489.9 kN, the maximum stress is 209.2 MPa, and the maximum displacement at the column deletion location is 468 mm.

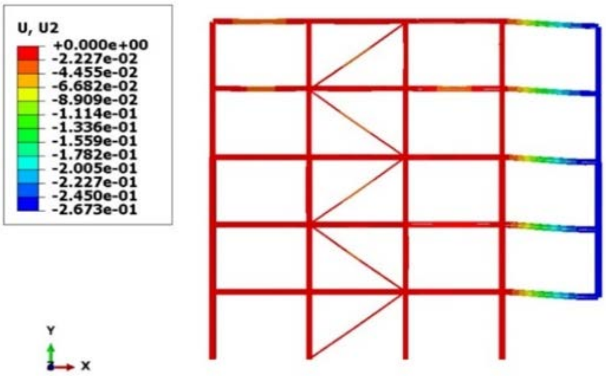


Figure 15. Stress distribution arising analysis in Mode 11

5.12 Mode 12: Reinforced Five-story Building with Second-story Corner Column Deletion

The analysis results for a reinforced five-story frame with the second-story corner column removed are shown in Figure 16. In this mode, the maximum strain is 0.00862, the maximum axial force is 451.20 kN, the maximum stress is 138.3 MPa, and the maximum displacement at the column deletion location is 500 mm.

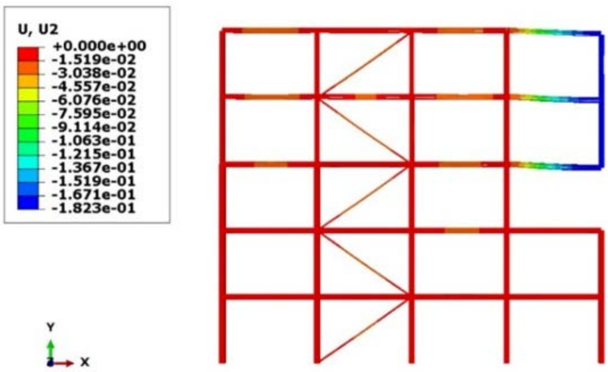


Figure 16. Stress distribution arising analysis in Mode 12

5.13 Mode 13: Reinforced Five-story Building with Third-story Corner Column Deletion

Figure 17 presents the results of the analysis for a reinforced five-story frame with the third-story corner column removed. In this mode, the maximum strain is 0.00464, the maximum axial force is 423.6 kN, the maximum stress is 121.1 MPa, and the maximum displacement at the column deletion location is 559 mm.

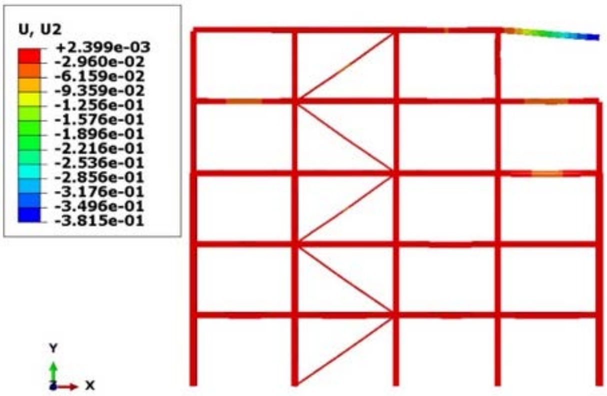


Figure 17. Stress distribution arising analysis in Mode 13

5.14 Mode 14: Reinforced Five-story Building with First-story Corner Column Deletion

The analysis results for a reinforced five-story frame with the first-story corner column removed are displayed in Figure 18. In this mode, the maximum strain is 0.001689, the maximum axial force is 728.8 kN, the maximum stress is 249.4 MPa, and the maximum displacement at the column deletion location is 450 mm.

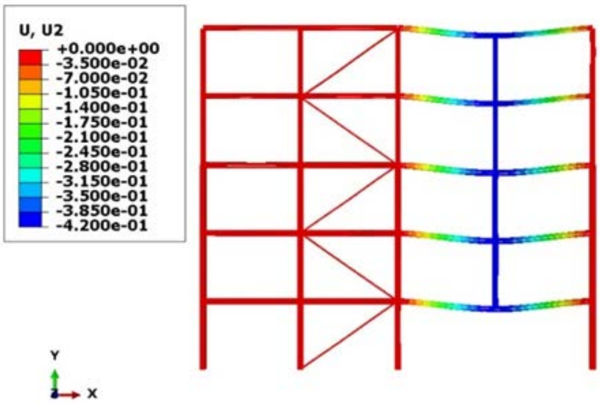


Figure 18. Stress distribution arising analysis in Mode 14

5.15 Mode 15: Reinforced Five-story Building with Second-story Corner Column Deletion

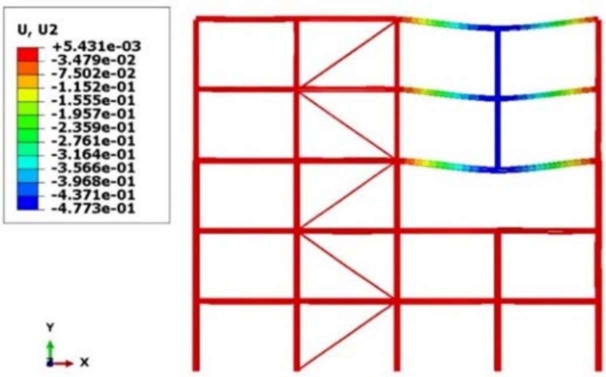


Figure 19. Stress distribution arising analysis in Mode 15

Figure 19 shows the results of the analysis for a reinforced five-story frame with the second-story corner column removed. In this mode, the maximum strain is 0.01732, the maximum axial force is 543.4 kN, the maximum stress is 267.8 MPa, and the maximum displacement at the column deletion location is 477.3 mm.

5.16 Mode 16: Reinforced Five-story Building with Third-story Corner Column Deletion

The analysis results for a reinforced five-story frame with the third-story corner column removed are presented in Figure 20. In this mode, the maximum strain is 0.00910, the maximum axial force is 443.10 kN, the maximum stress is 123.4 MPa, and the maximum displacement at the column deletion location is 545 mm.

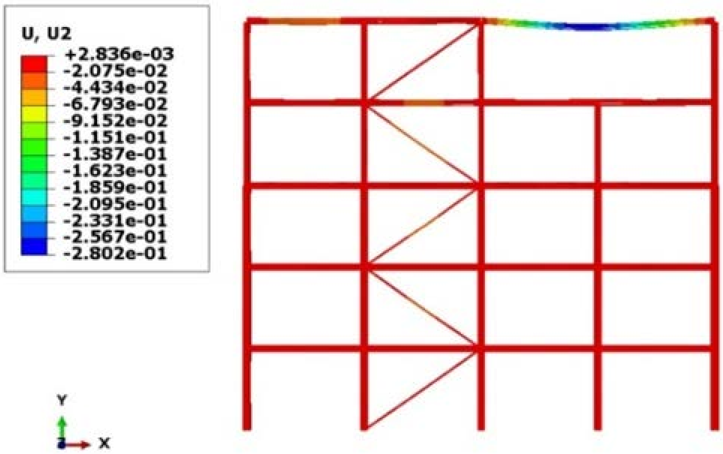


Figure 20. Stress distribution arising analysis in Mode 16

6 Interpretation of Results

The results obtained from the analysis of steel frames, evaluated across 16 different cases, are presented and interpreted in this section. The focus of this study was on the progressive collapse of steel moment frames and the efficacy of reinforcements via the introduction of bracings. As delineated in Table 5, comparisons were made among the maximum stress values, the maximum beam strength, and the maximum strain employed in frames across four scenarios wherein the beam remained intact.

Table 5. Comparing the results of reinforced frames with unreinforced frames

Axial force of column (kN)	Strain	Stress (MPa)	Type of frame	Mode
57.19	0.00251	65.75	Bending three story frame without deletion of column	1
108.30	0.00214	56.26	Bending three story reinforced with the addition of bracing in the mode without deletion of column	2
485.70	0.00167	56.12	Bending five story frame without deletion of column	9
412.80	0.00167	60.36	Bending five story reinforced with the addition of bracing in the mode without deletion of column	10

Table 5 illustrates the distinction between reinforced and unreinforced frames. A notable observation from Table 4 is the 14% reduction in both strain and stress following the incorporation of braces into three-story flexural frames designed to withstand gravity charges. However, a consequent increase was registered in the maximum force of the axial force, thereby affecting the footing. The trend varies with an increase in height. The five-story frame, when subjected to additional wind force, demonstrated a significant variation in both stress and strain, coupled with an approximately 15% reduction in the axial force of the columns. The maximum magnitude of the axial force in the columns of the omitted area is further compared in Figure 21.

A critical factor explored in progressive collapse-related studies is the distribution of central forces in the beams [12]. The axial force variation of columns in the vicinity of the deletion site, relative to the state prior to deletion, serves as a measure of structural resistance against progressive collapse [13]. In this study, the peak strength of beams adjacent to the deletion position was computed for 12 different cases, wherein the beam was removed at various positions. Figure 21 displays a comparison of these values. It is inferred that, in terms of axial force of the surrounding beams to the deletion site, the most critical scenarios are ones where the central frame is removed at the lowest level. The axial force of beams around the deletion site in the middle of the three-story frame was found to be approximately 2.15 times higher than the values associated with the removal of beams in the corner (as per in subgraph (a) of Figure 4, more beams are positioned around the middle columns, and therefore, their removal leads to a greater destructive effect compared to the removal of corner columns). The ratio of increase in the axial force of the beams around the omission varied between 5% and 49% of the corresponding values for the modes of beam deletion. Consequently, during the reinforcement of steel flexural frames, the increased criticality of the deletion of median beams necessitated a higher emphasis on these beams and the changes in axial force, as compared to the deletion of corner beams. The resultant changes are further demonstrated in Figure 22 and Figure 23.

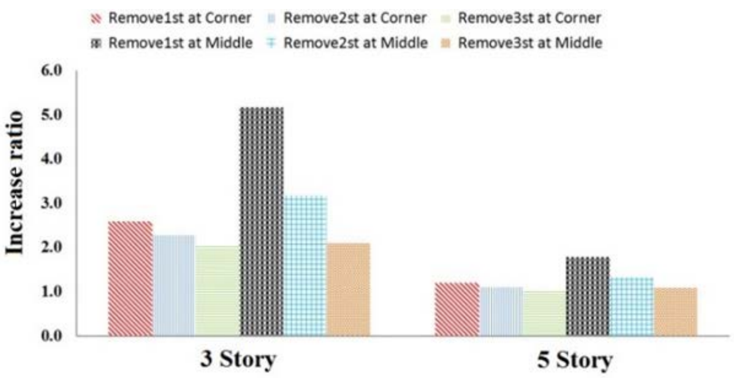


Figure 21. Comparing the ratio of maximum increase of axial force of columns around deletion surrounding

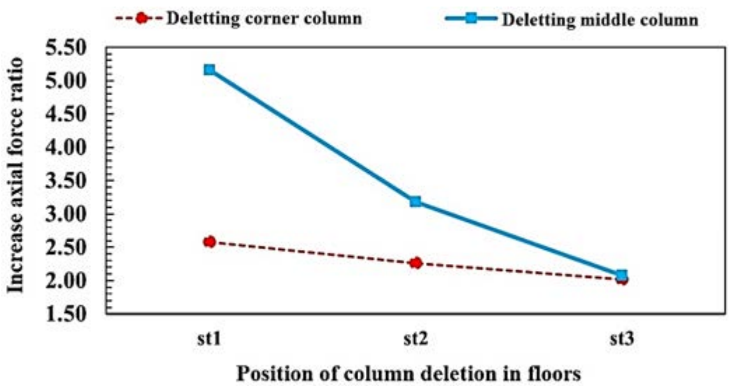


Figure 22. The ratio of increasing axial force of the columns around deletion place with the purpose of surveying the position of column deletion in plan and stories (three-story frame)

The section discussed revolves around Figures 22 to 25 and the changes in structural behavior upon column or beam removal, with the analyses carried out in a multistory steel frame. A focus is placed on the axial force of columns and beams, the generated stress within the steel frames, and the displacement of beams in response to different deletion scenarios. To adhere to the editorial guidelines of prominent academic journals such as Science and Nature, the provided text has been restructured, edited for clarity, and reformatted to align with accepted academic English conventions.

An increase in axial forces was observed in the columns adjacent to the deletion position in the lowest three-story frame, as presented in Figure 22. This increase varied from 1.27 to 2.4 times the corresponding values pertaining to column deletion modes, with higher values in the top levels due to the cumulative load from the lower floors.

In contrast, Figure 23 presents the changes in axial forces in beams adjacent to the deletion position in the lowest story of a five-story frame. Here, increases ranged between 15% and 64% of the values corresponding to beam deletion modes, with higher values in the top levels. This is indicative of the fact that upon removal of a beam on the first story, the axial force changes surpass those in the second and third stories. This can be attributed to the higher gravitational load on lower stories, making the structure more sensitive to column removal and therefore more prone to changes in structural behavior. It has been documented that beam removal at the lowest level can create a more critical situation for the building [14].

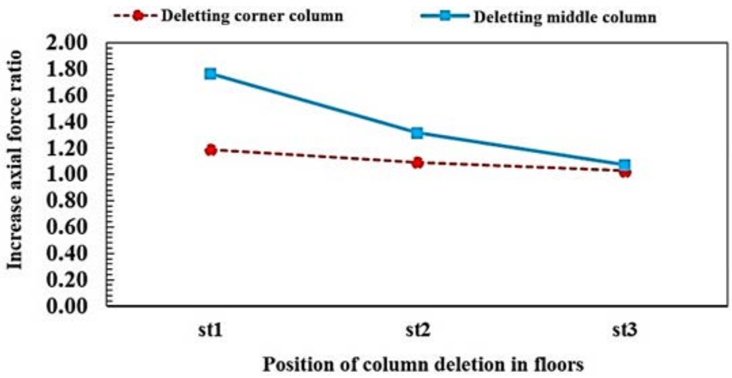


Figure 23. The ratio of increasing axial force of the columns around deletion place with the purpose of surveying the position of column deletion in plan and stories (five-story frame)

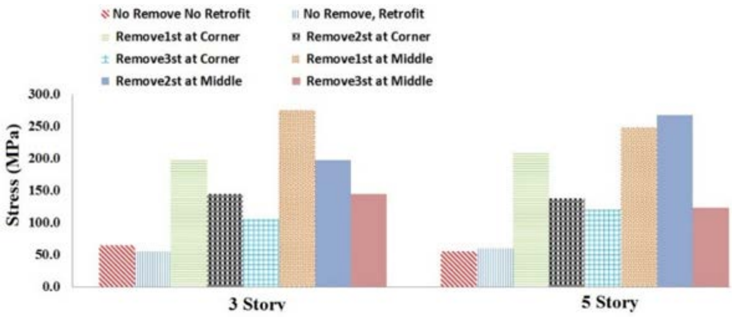


Figure 24. Comparing the maximum made stresses in studying steel frames

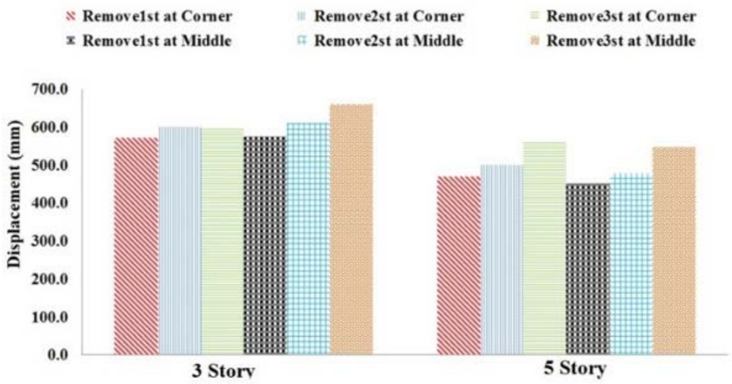


Figure 25. The maximum displacement of column deletion place in reinforced steel bending frames

Figure 24 delves into the investigation of maximum stress generation within steel frames. It was observed that when beams are removed from the middle pane of both three-story and five-story frames, the induced stress in the reinforced steel frames significantly exceeds that when a beam is removed from the frame corner. Specifically, maximum stress generated in three-story frames with a removed intermediate beam is 35% to 39% higher than the corresponding values for column deletion. For five-story frames with removed middle beams, the maximum stress is 2% to 93% higher than the corresponding values. Nevertheless, the deletion of a beam in lower stories generally results in lower stress responses.

Lastly, Figure 25 compares the maximum displacement position of beams in the reinforced steel flexural frames. An increase in the number of stories leads to a decrease in the maximum displacement position of beams, which falls within 7% to 22% of the corresponding values in three-story frames. This outcome suggests that in flexural frames of steel, where bracing is applied as a strengthening method against progressive collapse, an increased number of stories enhances the influence of this method to improve the structure's resistance against progressive collapse.

7 Conclusion

This investigation scrutinized the performance of reinforced steel frames under progressive collapse by introducing various steel braces. Consideration was given to parameters such as the number of stories, beam deletions in plan, and column deletion positions within stories. Abaqus software was employed for frame simulation, and the study arrived at several conclusions:

(1) The incorporation of steel braces into three-story moment frames displayed a 14% decrease in both strain and stress against gravity loads. However, an increase was observed in the peak axial force across beams. As the beam height increased, divergent results were noted with significant fluctuation in stresses and strains, and a reduction of about 15% in the axial force of the beam within a five-story frame.

(2) Notably, the axial force increase in beams surrounding the deletion site in the middle of the three-story frame was approximately 2.15 times greater than the corresponding values tied to beam deletions at the corner. Similarly, the axial force increase in beams around the omission varied from 5% to 49% of the values corresponding to the deletion modes of the beams.

(3) Emphasis on the middle beams and axial force changes proved necessary when compared to corner beam deletion.

(4) The axial force increase in the beam adjacent to the deletion position at the lowest level of the three-story frame ranged between 1.27 - 2.4 times the values corresponding to beam deletion modes at the highest level.

(5) Axial force increase in the beam adjacent to the deletion position at the lowest story of the five-story frame was approximately between 15% and 64% of the corresponding values related to beam deletion modes at the highest level. This suggests that beam removal at the first story yielded greater axial force changes than those in the second and third stories. This is likely due to the fact that beam removal in the lower stories, in the face of gravity load, renders the structure more vulnerable to additional beam deletions.

(6) The ratio of axial force variation for beams in a reinforced three-story steel frame ranged between 2.01 and 5.16 in maximum and minimum, respectively. For a five-story frame, this ratio was equal to 1.32 and 1.03 at the maximum and minimum, respectively. These results underscore that an increase in the number of stories reduces axial force ratios. This pattern was observed in both upper and middle beam deletion cases, suggesting that taller buildings might lessen the likelihood of progressive collapse in steel frames reinforced with steel braces. This reduction may be attributed to the fact that as the number of stories increases, more structural members assist in bearing loads, thereby contributing to the structural behaviour in the event of porter organ absence.

(7) Beam removal in the middle plan generated substantially higher stress within the reinforced steel frames than when the beam was removed at the frame corner in both three- and five-story frames. Consequently, the maximum stress produced in three-story frames, with the middle beam removed, was 35-39% higher than the corresponding values. Furthermore, the maximum stress created in five-story frames, with the middle beam removed, was about 2-93% higher than the values associated with the table deletion.

(8) An interesting observation was the decrease in maximum beam displacement position with an increase in the number of stories, which depended on the location of the deletion position. The maximum value of the corresponding displacements with the beam deletion mode in 5-story frames was approximately 7-22% of the values corresponding to the 3-story frames, depending on the deletion location. This suggests that the addition of steel braces in steel moment frames potentially improves the structure's resilience against progressive collapse.

This investigation has thereby provided valuable insights into the impact of various parameters and modifications on the performance of reinforced steel frames under progressive collapse. Further research could delve deeper into these relationships and explore additional parameters or modifications for even greater structural resilience.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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