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On the Performance of Steel Buildings with Skewed Beams against the Progressive Collapse †

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Abstract: This research studies the performance of 2- and 4-story steel building models against the progressive collapse in two cases: (1) skewed beam-column connections, (2) straight cleated beam-beam connections. Nonlinear static and dynamic analyses were performed and then the time history analysis was performed under the simultaneous effect of the two horizontal components of 3 earthquake records and two column removal scenarios. The results showed that the 60 degrees skewed connection had a weaker performance than the straight connection and according to plastic hinge distribution, it was observed that the mentioned connection did not provide the life safety performance level.

Keywords: progressive collapse; skewed beam-column connection; straight cleated beam-beam connection; push-down analysis; nonlinear dynamic analysis

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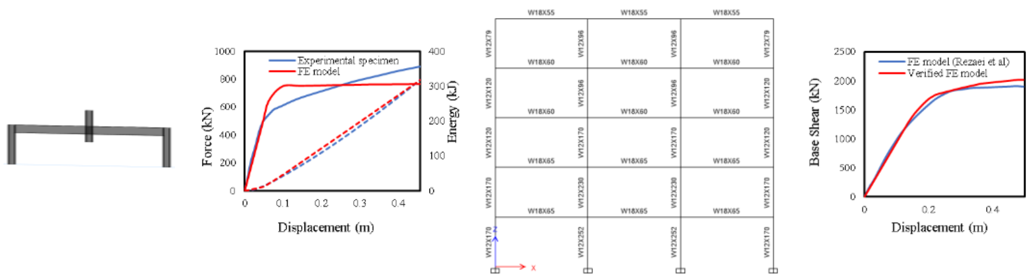
1. Introduction

The progressive collapse of structures is generally caused by a local failure caused by accidental actions such as fire, gas explosion, car collision, design and construction errors, or environmental corrosion, and leads to the failure of a wide range of the building until its total failure. Khandelwal et al. [1] evaluated the progressive collapse of special and intermediate moment frames and observed that the configuration and strength of the system are more effective than the construction details for ductility in the resistance of the structure against the critical member removal scenario. Kim and Kim [2] investigated the seismic performance and progressive collapse of steel moment frames with three types of seismic connections and concluded that the progressive collapse potential of structures designed for moderate earthquake risk is significantly different according to the type of connection and structures designed for high earthquake levels are safer against progressive collapse caused by sudden removal of a column. Sometimes due to architectural issues, consideration of skewed beams in building plans are inevitable [3,4]; on the other hand, using skewed beams cause that the adjacent connections are subjected to extra forces and moments, and this situation may have adverse effect on the performance of steel buildings against the progressive collapse. In this regard, the present study investigates the resistance of two and four-story building models against the progressive collapse in which one group of models have skewed beam-column connections with the inclination angles of 15, 30, 45, and 60 degrees, and the second group of models have straight cleated beam-beam connections corresponding to any considered angle. The performance of considered steel building models were studied using non-linear static (i.e., Push-Down) and non-linear dynamic analyzes according to the UFC regulations [5]. It should be noted that the modeling methods used in this study are validated in two steps. The best and weakest modes are determined based on the results and finally, in order to evaluate the performance of a building that loses one of its members during an earthquake, the two-story model was subjected to simultaneous analysis of the time history and column removal scenario.

2. Materials and Methods

To ensure the accuracy of the modeling procedure used in this study, the results of numerical modeling by ETABS were compared with the results of experimental and analytical studies performed by Sadek et al. [6] and Rezaei et al. [7]. Figure 1 shows the comparison of the results obtained from ETABS and existing studies [6,7]. According to Figure 1a, it is seen that the experimental and numerical results are different in the range of inelastic behavior and hence, the amount of the dissipated energy for both two diagrams was compared and it was concluded that the amount of this parameter is almost the same for both numerical and experimental diagrams which approves the accuracy of the considered finite element modeling procedure for the pushdown analysis. It seems that one of the reasons for the difference of both diagrams in the range of inelastic behavior is that the assigned plastic hinges in ETABS are considered as concentrated hinges, while in reality, the yielded region of the members are expanded in a certain length. Also, in order to validate the considered modeling method for consideration of the nonlinear behavior of building models, the results obtained by ETABS were compared to the results obtained by Rezaei et al. [7] as depicted in Figure 1b, which are in a good agreement.



(**a**) (**b**)

Figure 1. (**a**) The model of experimental specimen tested by Sadek et al. and comparison of the vertical force-displacement and energy diagrams of the span mid-point under push-down analysis, (**b**) The 5-story building model with a moment-resisting frame and comparison of the capacity curves obtained by pushover analysis.

In order to investigate the progressive collapse behavior of the steel structures with skewed beam-column connection, 2 and 4-story building models were considered in two cases: (1) skewed beam-column connections at angles of 15, 30, 45, and 60 degrees, (2) straight cleated beam-beam connections corresponding to any considered angle. To this aim, nonlinear static (push-down) and nonlinear dynamic analyzes were performed based on UFC standard. According to the UFC regulations, for the push-down analysis, the gravity load is multiplied in the spans around the removed column by a coefficient called the dynamic increase factor and then, the top node of the removed column structure is pushed down in the form of displacement-control procedure. In this method, which is suitable for obtaining the capacity of the structure, the structure is pushed up to its final capacity and finally the force-displacement curve is obtained. In order to evaluate the performance of the structure against progressive collapse, according to Equation (1), a factor called load proportion factor (LPF) is defined. Obtaining values greater than or equal to one for this coefficient indicates that the structure has the ability to withstand gravity load due to the removal of the column and progressive collapse does not occur, and if this coefficient is smaller than one, there is a possibility of progressive collapse.

$$\text{Load proportion factor} = (\text{Balance load corresponding to the failure displacement})/(\text{Total gravity load}) \quad (1)$$

In the nonlinear dynamic analysis method, the structure is analyzed under the effect of the gravity load combination introduced in the UFC regulation, and then the column forces are determined according to the desired column removal scenario; the calculated values of internal forces and moments are applied in a concentrated form at the top node of the removed column, and during a time history analysis, the equivalent forces of the desired column are dynamically removed. The considered building plans with skewed beam-column connections and corresponding straight cleated beam-beam connections were as shown in Figure 2a,b. Based on the specifications of UFC guideline, the considered scenarios for removing columns were also selected as presented in Table 1.

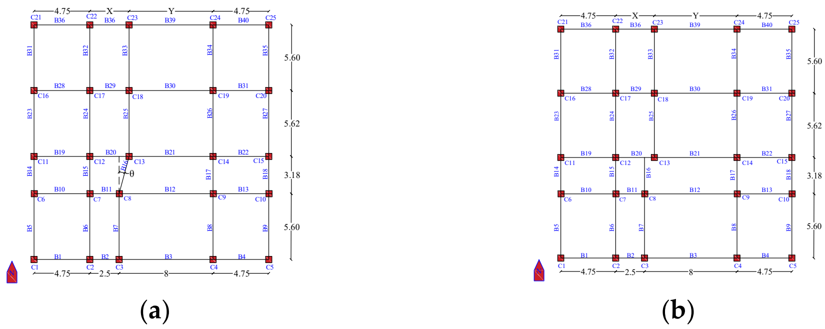


Figure 2. Plans of models to study the effect of skewed connection in the progressive collapse: (**a**) skewed beam-column connection, (**b**) straight cleated beam-beam connection (All dimensions are in meters.).

Table 1. The considered column removal scenarios.

Scenario Number	1	2	3	4	5	6	7	8	9	10	11	12
Label of the removed column	C1	C3	C5	C7	C8	C11	C12	C13	C15	C21	C23	C25

Finally, the time history analysis was performed considering the simultaneous effect of the horizontal components of 3 earthquake records and two column removal scenarios to evaluate the behavior of the 2-story building model. The characteristics of the selected records are shown in Table 2.

Table 2. Specification of pulse near-field records based on FEMA P695.

Record Seq. No.	PGV(cm/s)	PGA(g)	Recording Station	Name	Year
181	111.9	0.44	El Centro Array #6	Imperial Valley-06	1979
292	45.5	0.31	Sturno	Irpinia, Italy-01	1980
802	55.6	0.38	Saratoga-Aloha	Loma Prieta	1989

In this research, different parameters such as the load proportion factor (LPF), the vertical displacement time history of the joint above the removed column, distribution of plastic hinges, column axial forces and rotation of plastic hinges were compared with each other to investigate the performance of the considered building models against the progressive collapse.

3. Results and Discussion

As the value of load proportion factor (LPF) is increased compared to 1, the performance of the building against the progressive collapse improves and the building can tolerate the gravity load. According to the diagrams shown in Figure 3a–d, in the models with both skewed beam-column connections (A) or straight cleated beam-beam connections (B), the column removal scenario of 4 has a better performance compared to other scenarios. In general, the corner column removal scenarios have the weakest performance against the progressive collapse; however, the LPF ratio is greater than 1 in all column removal scenarios for the considered 2-story building models. As shown in Figure 3e,f, after the removal of the column, despite the increase in the value of the axial force of all the columns, major changes and redistribution of the axial forces occur in the columns around the removed column, which reveals the importance of paying attention to these columns.

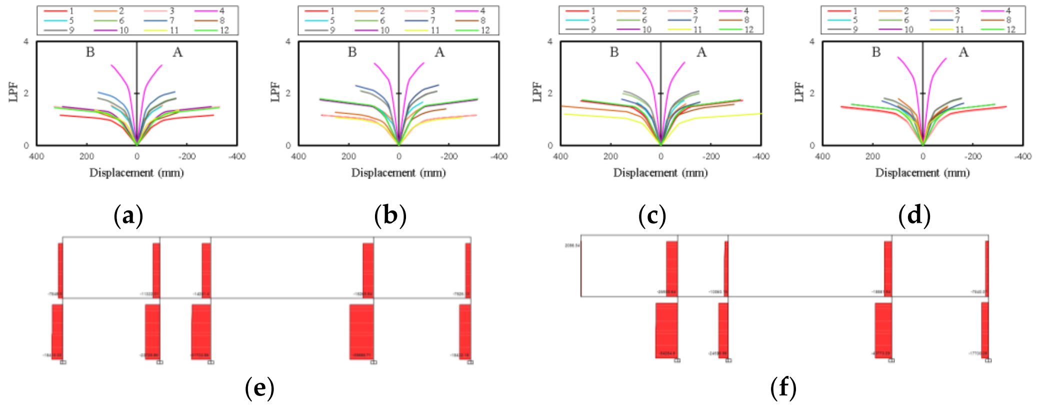


Figure 3. LPF-displacement diagrams of two-story buildings with skewed beam-column connection (A) and corresponding straight cleated beam-beam connection (B) at angles of: (**a**) 15, (**b**) 30, (**c**) 45, (**d**) 60 degrees and values of axial forces for the scenario number of 1 in the two-story model with a 30° skewed beam-column connection: (**e**) before removing the column, (**f**) after removing the column (The unit of forces is in kg).

According to Figure 4, it can be seen that in four-story buildings, the scenarios of removing internal columns have the best performance from the point of view of the LPF, while the scenarios of removing corner and side columns have a poor performance. So that the scenario number of 4 shows the best performance against progressive collapse.

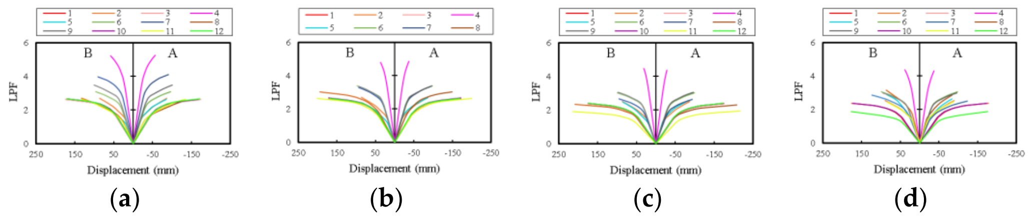


Figure 4. LPF-displacement diagrams of four-story buildings with skewed beam-column connection (A) and corresponding straight cleated beam-beam connection (B) at angles of: (**a**) 15, (**b**) 30, (**c**) 45 and (**d**) 60 degrees.

The diagrams depicted in Figures 5 and 6 show the changes in the vertical displacement value at the joint above the removed column for the 2-story and 4-story buildings under the nonlinear dynamic analysis.

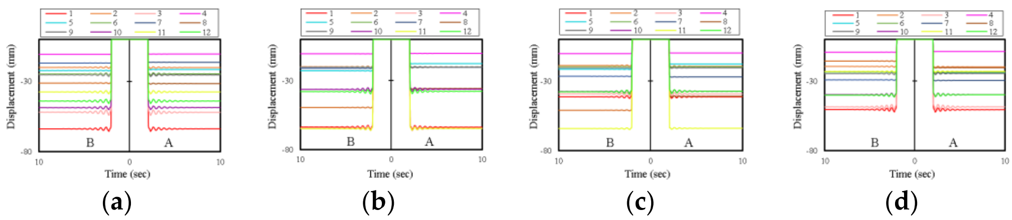
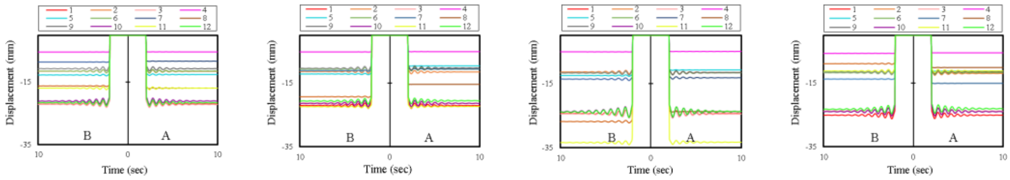


Figure 5. Vertical displacement-time diagrams of two-story buildings with skewed beam-column connection (A) and corresponding straight cleated beam-beam connection (B) at angles of: (**a**) 15, (**b**) 30, (**c**) 45 and (**d**) 60 degrees.



(**a**) (**b**) (**c**) (**d**)

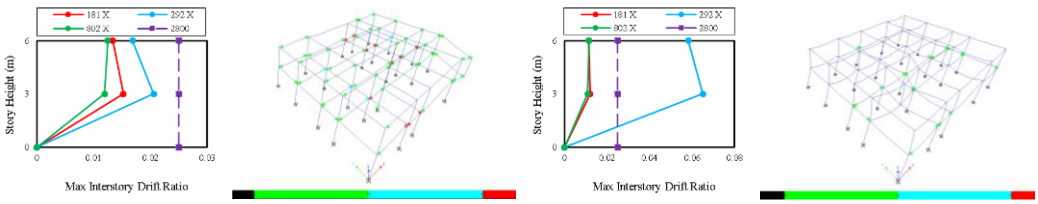
Figure 6. Vertical displacement-time diagrams of four-story buildings with skewed beam-column connection (A) and corresponding straight cleated beam-beam connection (B) at angles of: (**a**) 15, (**b**) 30, (**c**) 45 and (**d**) 60 degrees.

Figure 7 shows the vertical displacement time-history of the joint above the removed column for the 2-story building models with skewed beam-column connections with angles of 30 and 60 degrees under the simultaneous effect of two horizontal components of an earthquake record number 181. According to Figure 7, it is seen that due to the column removal during the earthquake, there was a sudden increase in the vertical displacement of the joint, which can have adverse effects on the seismic performance of the structure. These results highlight the necessity of considering the resistance of each building against the progressive collapse.

(**a**) (**b**)

Figure 7. Vertical displacement-time diagrams of the 2-story building models with a: (**a**) 30 degrees skewed connection and the scenario number 4, (**b**) 60 degrees skewed connection and the scenario number 3.

As shown in Figure 8, it can be seen that in the model with a 30-degree connection in column removal scenario number 4, the value of the interstory drift ratio in X direction is lower than the limit imposed by the Standard 2800 [8], which is equal to 0.025. While in the X direction of the two-story building with a skewed connection of 60-degrees with the corner column removal scenario number 3, the maximum value of the interstory drift ratio has far exceeded the 0.025. Moreover, according to the distribution of plastic hinges (Figure 8), it is seen that in the model with 30 degrees skewed connection, the life safety performance level was provided, but the performance level of the model with 60 degrees skewed connection exceeded the collapse prevention performance level. Therefore, it is concluded that the buildings with skewed connections are more sensitive to the progressive collapse especially when the corner columns are removed. Considering the importance of the investigation of buildings' performance against the progressive collapse, it is suggested that this issue to be studied in future research for the novel beam-column connections [9,10].



(**a**) (**b**)

Figure 8. Maximum interstory drift ratio diagram and distribution of plastic hinges of the two-story models with a: (**a**) 30-degree skewed connection and the column removal scenario number 4 and (**b**) 60-degree skewed connection and the column removal scenario number 3.

4. Conclusions

Based on the obtained results, it was concluded that with the increase in the number of floors of the building, due to the increase in the degree of indeterminacy and the more redistribution of forces and moments, better performance against progressive collapse is observed. Moreover, the corner column removal scenarios have a weaker performance compared to the internal column against the progressive collapse and are more likely to fail in providing the life safety performance level. Therefore, even though the buildings have a good performance against progressive collapse if they meet the design codes' specifications, it is recommended that after designing the building, in order to ensure its resistance against progressive collapse, at least one scenario of removing the corner column should be investigated. Moreover, in the case of a skewed connection or a straight cleated beam-beam connection, due to the possibility of weaker performance, a column removal scenario in columns around that area based on UFC regulation should be checked. Based on a considered weighting system in this research, it is recommended that if there are skewed beam-column connections with an angle of 60-degrees or more, straight cleated beam-beam connections should be replaced.

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