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Effect of Lateral Load-Resisting Systems on Seismic Progressive Collapse of Steel Moment-Frames Cconsidering Column-Removal Scenarios

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ABSTRACT: Seismic progressive collapse conceptually means that during an earthquake event, some of the key elements of the structure reach the threshold of premature failure, for example, due to explosion caused by earthquake or design/operation problems. This process results in removing the damaged elements, redistributing unbalanced internal forces/moments, and increasing the stress in the adjacent elements, which is followed by local and/or global collapse of the structure. In this study, the seismic progressive collapse potential of steel moment frames with different structural systems was evaluated. 3-storey steel frame structures were simulated by the nonlinear beam-column element model with distributed plastic hinges that were available in the OpenSees Software. Nonlinear dynamic analyses were done on the models subjected to the earthquake records. The progressive collapse was then assessed using the statistical analysis and graphical results' interpretation/presentation in Excel Software and MATLAB Program. The structural systems included bending moment-frame systems, concentrically- and eccentrically-braced systems, as well as knee-braced system. The removal of the side-column resulted in higher value of the seismic response; the reason was that the side-column was linked to the frame only due to the beam connected to its upper node.

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1- Introduction

During the operational lifetime, building structures may be imposed to natural hazards such as earthquakes, severe storms, floods, and fire; and man-made hazards such as explosion and collision. Thus, the buildings are mostly designed for possible events that can occur during their lifetime. But extreme events, for which the buildings is not well-designed, may cause catastrophic damages and significantly reduce the reliability of the buildings. This has always an important principle for engineers who are responsible for the design of civil projects. Thus, one of the subjects that has been received increasing attention in recent decades is progressive collapse, which is useful and valuable to study and provide knowledge about the collapse limit state.

Seismic progressive collapse is a special type of the progressive collapse in which some of the key elements of the structure reach the threshold of premature failure, for example, due to explosion caused by earthquake, or design/operation problems. This results in removing the damaged elements, redistributing of internal forces, increasing the stress in the adjacent elements; followed by local and/or global collapse of the structure. One of the advantages of seismic design against the progressive collapse is that the structure designed by this method will have the sufficient strength to deal with earthquake loads and maintain with satisfactory safety margins for the occupants, after the failure of one element in gravity load-resisting system [1]. This subject has been recently addressed in several references [2]-[4].

Frequent use of steel moment frames in the construction industry of our country and the implementation of this structural system in vital structures such as power plants and hospitals, in addition to the possibility of explosion during an earthquake (inside the structure or in adjacent structures) demonstrate the importance of studying the seismic behavior of steel moment frames by progressive collapse analysis. Regarding that different lateral load-resisting systems have their unique characteristics, it is a central challenge to examine the impacts of these characteristics on the damage potential of steel moment frames. So in this research, the seismic collapse potential of steel buildings with different structural systems has been addressed.

Doing so, a 3-storey moment frame was modeled by means of a nonlinear beam-column element method with distributed inelasticity over the element length in OpenSees software [5]. The moment frame, equipped with concentric-, eccentric-, and knee-bracing systems, was imposed to the earthquake records. The results of the nonlinear dynamic collapse analysis were analyzed and compared in Excel and MATLAB software in the scheme of graphs and statistics.

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Table 1. Cross-section dimensions of steel elements

Struct. System	Column	Beam	Brace
Moment frame	BOX45x45	IPE240	---
X-brace	BOX45x45	IPE240	2UPN80x8
Eccentric-brace	BOX45x45	IPE240	2UPN80x8
Knee-brace	BOX45x45	IPE240	IPE200

2- Methodology

The structural systems included here are moment frame system, concentric X-brace system, and eccentric-brace system as well as knee-brace system. To introduce these models, the dimensions of the frame are assumed to be 2-m and the number of degrees of freedom in each node (DOFs) are assumed to be equal to 6, in which 3 DOFs are translational and the others are rotational. Moreover, it is assumed that x- and y-axes refer to the horizontal and vertical axes, respectively. Since the basic model is a steel moment frame, the key material in the modeling is steel that has been simulated by the Steel-02 material, as described in OpenSees achieve. Three accelerograms from the El Centro, San Fernando and Kobe earthquake were used in the nonlinear dynamic analysis, which are among the well-accepted accelerograms, mostly used in the earthquake engineering research studies. The cross-section dimensions of the steel elements has been given Table 1.

Modeling assumptions like inelasticity distribution over the element length, P-Delta effects in the columns, and rigid connection in beam-column joint, in addition to the removal of the desired column were included in the nonlinear dynamic analysis. However, deformations at connections and soil-structure interaction issues were not considered here. Besides, the floor diaphragms were simulated by means of an elastic shell element.

To validate the modeling approach and simulate the progressive collapse, a two-dimensional steel frame laboratory test was employed [6]. In this reference, a steel chimney frame was used. The middle column was then loaded downwards during the test and the load-displacement diagram was reported. After developing the verification model, its accuracy was confirmed by extracting the mode shapes by a free-vibration analysis. It is worth noting that the seismic progressive collapse was examined by including two scenarios: the former was based on the removal of a side column while the latter was based on the removal of a middle column. The procedure used in this paper includes the following steps: a) designing steel buildings with different lateral load-resisting systems; b) developing nonlinear models; c) performing a static analysis on each nonlinear model under distributed gravity loads; d) importing analyzed model into a new file in which a seismic analysis loop was applied in the desired step that was the time of PGA occurrence; e) removing a column element according to a predefined scenario; and, f) evaluating the impacts of the column removal.

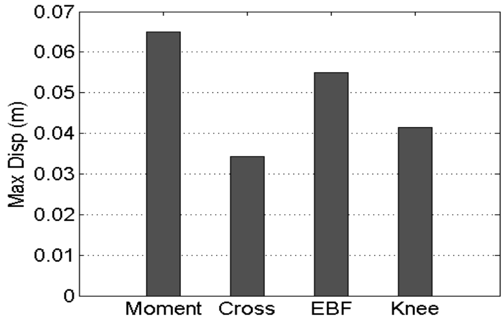

Fig. 1. Maximum nodal displacement at the top of the side-column eliminated in the building model under El-Centro earthquake record

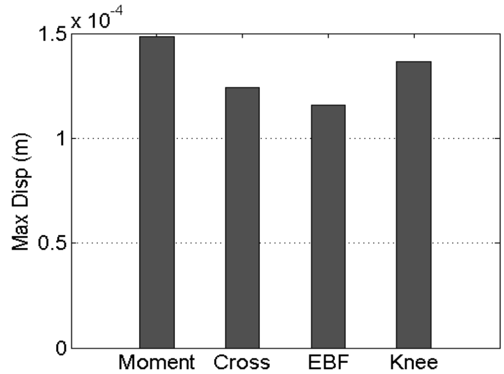

Fig. 2. Maximum nodal displacement at the top of the middle-column eliminated in the building model under San Fernando earthquake record

3- Discussion and Results

In this study, the results of displacement, velocity, and acceleration in a 3-storey frame structure, equipped with moment frame, X-brace, eccentric brace, and knee-brace systems were evaluated. The results were extracted for each earthquake excitation and for both of the scenarios (removal of a side-column or a middle-column), as it was mentioned before. A sample of the results has been shown in Figure 1.

It was evidenced that the least values of the maximum displacement, velocity, and acceleration were mostly reported by the moment frame with X-brace system. On the other hand, the maximum displacement was given for the moment frame system (see Figure 2). Regarding the displacement history, the statistics proved that the moment frame with X-brace system had the minimum permanent drift, under the San Fernando earthquake.

The seismic progressive collapse assessment could be more indicative if the response history of desired parameters was done. The outcome indicated that all the frames had permanent responses, especially in terms of displacement. Among the different lateral-load resisting systems, the moment frame with X-bracing had the least permanent displacement.

4- Conclusions

Seismic progressive collapse analysis of structures with different lateral load-resisting systems was performed by including moment frame, X-brace, eccentric brace, and knee-brace systems. Removal of a middle column or side column was included as two scenarios whereas 3 accelerograms formerly used in well-accepted studies were implemented in nonlinear dynamic analysis. In general, the outcomes proved that the seismic responses such as displacement, velocity, and acceleration were decreased by bracing the moment frame model. The trend was also observed in the case of permanent displacements. By X-bracing of the frame model, maximum reduction of the seismic responses was reported.

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