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Effect of span length on progressive collapse behaviour of steel moment resisting frames

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ABSTRACT

This paper presents results of an investigation into the effect of span length on progressive collapse behaviour of seismically designed steel moment resisting frames which face losing one of their columns in the first story. Towards this aim, several nonlinear static and dynamic analyses were performed for three frames designed for a high seismic zone considering various span lengths. The analysis results revealed that beams and columns of the studied frames had adequate strength to survive one column loss in the first story. However, in order to determine the residual strength of the frame, a series of nonlinear static analyses called pushdown analyses were performed. It was shown that by decreasing the span length to half, the strength of the studied frames increases 1.91 times based on the performance-based analysis perspective. Besides, results of nonlinear static analyses revealed that by increasing the applied loads, the investigated structures are more susceptible to progressive collapse when they lose an internal column.

1. Introduction

Progressive collapse is a disastrous phenomenon in which failure of one key structural member leads to failure of other members, and this in return, leads to partial or even entire collapse of the structure [1]. Plane impact, car collision and gas explosions are a few examples of the hazards which can produce such an event [2]. As structures are not generally designed for such unusual events that may result in structural element removal, they might fail catastrophically. Most building codes recommend only general strategies for mitigating the effect of progressive collapse in structures which might be overloaded beyond their design loads, while the American code, ASCE 7-05 [1], deals with progressive collapse in detail. Besides this, a few other design guidelines for structures to resist progressive collapse are presented elsewhere such as in the General Service Administration (GSA) [3] and Unified Facility Criteria (UFC) [4]. GSA describes cases in which one of a building's columns is removed and the damaged structure is examined to check the system responses in order to reduce the catastrophic effects of progressive collapse in structures according to the Alternate Path Method (APM). The UFC methodology, on the other hand, is a performance-based design strategy, and is partially in line with the GSA procedures.

Since the Oklahoma City bombing, progressive collapse analysis of structures has been looked at in several studies. Liu [5] demonstrated that catenary action can reduce the bending moment considerably through axially restraining the beam. Park and Kim [6] investigated the progressive collapse potential of steel structures with various seismic connections. The analysis results revealed that Reduced Beam Section (RBS) connections provide the highest load resisting capacity against collapse owing to their highly ductile behaviour. They also concluded that loss of an outer column makes the structure more vulnerable to progressive collapse than loss of an interior column. Kim and Kim [7] showed that progressive collapse potential diminishes as the number of stories increase. Khandelwal et al. [8] found that an eccentrically braced frame is much less prone to progressive collapse compared to a special concentrically braced frame. Kim et al. [9] showed that the dynamic amplification factor may be larger than 2, which is suggested by both GSA and UFC. Fu [10] stated that under the identical normal circumstances, column elimination at a higher level will certainly generate greater vertical displacement compared to column elimination at the ground level. Kim et al. [11] deduced that among a variety of braced frame structures, the inverted V-type braced frame demonstrates a remarkably ductile behaviour for progressive collapse. Asgarian and Hashemi Rezvani [12] showed that the number of braced spans affects robustness of a concentrically braced frame. Chen et al. [13] investigated progressive collapse resistance of a two-story steel moment resisting frame after sudden removal of a perimeter column in the ground floor with and without concrete slabs through an experimental study. The results indicated that concrete slabs play a significant role during the process of load redistribution and cause a reduction of progressive collapse potential. Chen et al. [14] investigated contribution of horizontal bracing to the resistance of a steel moment resisting frame against progressive collapse and concluded that compared to the model without horizontal braces, the displacements and rotation angles in the model with horizontal braces were much smaller. Gerasidimis [15] assessed the progressive collapse vulnerability of steel frames to corner column loss and proposed an analytical method to indicate the collapse mechanism

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of a steel frame for the case of a corner column loss through the development of critical ductility curves. Tavakoli and Rashidi Alashti [16] studied the potential of multi-story moment resisting steel frame buildings with damaged columns in different locations under seismic loading. Their analysis results showed that in the case of internal column removal, the structure is more robust than in the case of a corner column removal. They also stated that as the number of stories and bays increases, the capacity of the structure to resist progressive collapse under lateral loading increases. This is mainly due to the participation of a larger number of structural elements in the redistribution of excess loads. Hosseini et al. [17] and Yousefi et al. [18] investigated the vulnerability of a 10-story office steel moment resisting frame, and concluded that removing a corner column in the ground floor leads to failure of the adjacent bay.

Reviewing literature related to the topic, it is evident that the effect of span length on the progressive collapse behaviour of steel moment resisting frames has not received adequate attention in the past among scholars. This study, therefore, aims to investigate the effect of span length on the progressive collapse behaviour of seismically designed steel moment resisting frames. For this purpose, three steel moment resisting frame buildings were designed with various span lengths for a certain frame length. The exterior frames were then studied against column loss scenarios in the first story as per the UFC. Besides, Dynamic Amplification Factor (DAF) and Demand over Capacity Ratio (DCR) were calculated to have a better understanding of the structural behaviour with the loss of one column in the first story. Furthermore, by performing Pushdown Analysis (PDA) which is a nonlinear static analysis, structural strength can be determined for any performance level as per ASCE 41-06 [19]. This, on the other hand, leads to detecting probable failure modes and determining the effect of span length on the overload carrying capacity of the investigated steel moment resisting frames.

2. Investigated structures

In this study, three 6-story steel moment resisting frame buildings were designed for a high seismic zone. As shown in Figs. 1 to 3, the buildings are square in plan and have three different span lengths of 4 m, 6 m and 8 m, respectively for a frame length of 24 m in each direction. The height of all stories is 3.2 m.

For the design, dead and live loads of 5.4 kN/m^2 and 2.45 kN/m^2, respectively were applied to all stories except the roof for which the dead and live loads were considered as 4.41 kN/m^2 and 1.47 kN/m^2, respectively. Furthermore, the perimeter wall weights of 3.04 kN/m and 5.88 kN/m were applied to the roof and the other stories, respectively. Tables 1 to 3 show the selected steel cross-sections for the investigated frames. In these tables, Frame 1, Frame 2 and Frame 3 represent external frames of buildings with span lengths of 4 m, 6 m and 8 m, respectively.

In the current study, in order to investigate the effect of span length on the response of moment resisting frames subject to sudden column loss, a generic building with a length of 24 m in both directions (X and Y) and 6 stories tall was studied. Towards this aim and for the generic building, three different configurations were selected. Firstly, moment resisting frames with 6 spans of 4 m (Frame 1), secondly, moment resisting frames with 4 spans of 6 m (Frame 2) and finally, moment resisting frames with 3 spans of 8 m (Frame 3). Since the story areas and the applied gravity loads were similar, the design lateral force is calculated to be similar. As is seen in Tables 1 to 3, the longer the span, the larger the column; the combined effects bring a similar stiffness for the different frames. This can also be deduced by looking at the natural frequencies of these frames being of similar values which are obtained by performing modal analyses. The first fundamental periods of Frame 1, Frame 2 and Frame 3 are 1.1352 s, 1.1086 s and 1.0565 s, respectively. The second fundamental periods of these frames are 0.9617 s, 1.0591 s and 0.8992 s, respectively while the third ones are 0.9451 s, 0.9842 s and 0.8646 s, respectively.

3. Progressive collapse analysis methodology

As per UFC, there are three procedures for analyzing structures subjected to progressive collapse: 1) Linear Static Procedure (LSP) which is the simplest one and is a common practice utilized in the structural analysis and design. In this analysis, material is assumed to be linearly elastic; no geometric nonlinearity is considered; and structure is supposed to experience small deformations; 2) Nonlinear Static Procedure (NSP), in which both geometric and material nonlinearities are considered; 3) Nonlinear Dynamic Procedure (NDP) which involves inertia and damping effects and is the most accurate and the most complex of all. The NDP method was utilized in the current study.

3.1. Column removal scenarios

For investigating the effect of column loss on the structural behaviour of steel moment resisting frames with various span lengths, two

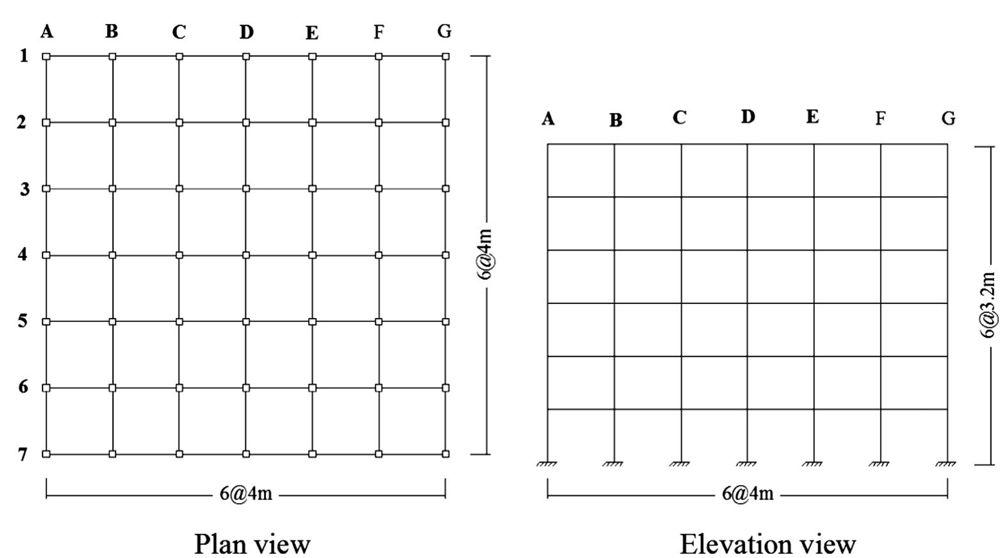

Fig. 1. Elevation and plan views of building with the span length of 4 m.

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