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Fragility Analysis of Steel Moment Frames with Various Seismic Connections Subjected to Sudden Loss of a Column

Junhee Park [a*], Jinkoo Kim [b], Minkyu Kim [a]
[a] *Korea Atomic Energy Research institute, 1045 Daedeok-daero, Youseong, Daejeon, 305-353,*
[b] *Sungkyunkwan University, Department of Architectural Engineering*

[*] *Corresponding author:jhpark78@kaeri.re.kr*

1. Introduction

The progressive collapse refers to the phenomenon that local damage of structural elements caused by abnormal loads results in global collapse of the structure. An abnormal load includes any loading condition that is not considered in normal design process but may cause significant damage to structures. The potential abnormal loads that can trigger progressive collapse are categorized as: aircraft impact, design/construction error, fire, gas explosions, accidental overload, hazardous materials, vehicular collision, bomb explosions, etc. [1]. For realistic simulation of progressive collapse, the analysis process needs to include uncertain characteristics of material properties. Nevertheless, most of recent researches have been conducted based on deterministic approaches where the nominal or average values of the design parameters were used [2]. The progressive collapse mechanism and the capacity of structures can be affected by probabilistic properties of the design parameters and load combinations.

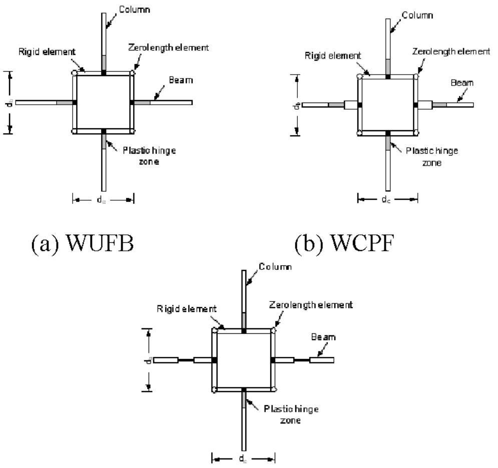
The objective of this study is to investigate the progressive collapse potential of steel structures with 'welded unreinforced flange-bolted web' (WUFB), 'reduced beam section' (RBS), and 'welded cover plated flange' (WCPF) connections. To take the uncertainty in material properties into account, fragility analysis were carried out considering variation of design variables such as yield strength, live load, and elastic modulus. The beam-end rotation was used as a criterion for initiation of progressive collapse.

2. Analysis model and Results

2.1 Modeling of connections

In the model structure three types of seismic connections were applied: WUFB (welded unreinforced flange-bolted web connections), WCPF (welded cover-plated flanges), and RBS (reduced beam section). Fig. 1 shows the analysis modeling of each connection type. For modeling of the WUFB connections uniform beam cross-sectional dimension was used, whereas in RBS connections, which were developed after Northridge Earthquake, the equivalent cross-sectional dimension proposed by Lee [3] was used to accommodate the effect of the reduced cross-sectional area at beam ends. The cross-sectional areas at beam ends were increased to model the WCPF connections as shown in Fig. 1(b).

In this paper the limit states of seismic connections given in the FEMA-356 were mainly used to define failure of connections because it provides more detailed limit states for steel beam sections considering variation of beam depth.



(a) WUFB (b) WCPF

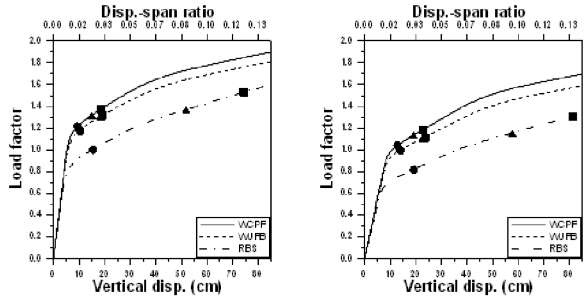
(c) RBS

Fig. 1. Modeling of beam-column joints

2.2 Nonlinear static analysis results

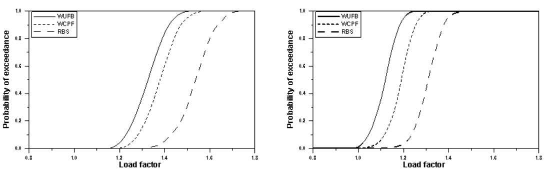
Figure 2 shows the nonlinear static pushdown analysis results of the model structure with various connection types. Mean values for design variables were used to model the structure. Displacement-controlled pushdown analysis was carried out with a first-story column removed. The horizontal and the vertical axes represent the vertical displacement of the beam-removed column joint and the load factor, respectively. The load factor of 2.0 corresponds to the state that the applied vertical load reached the load specified in the GSA guideline, 2(dead load+0.25×live load). The maximum load factor less than 2.0 implies that the structure may collapse as a result of removing one of the columns. The filled circles, triangles, and squares marked on the pushdown curves represent the vertical displacements corresponding to the IO (Immediate Occupancy), LS (Life Safety), and CP

(Collapse Prevention) limit states, respectively. It can be noticed in Fig. 2 that the model structure with WCPF connections shows highest strength, whereas the structure with RBS connections shows the lowest strength when a first story column is removed. However the structure with RBS connections turned out to have the largest ductility against failure. It also can be observed that the maximum strengths are higher when an internal column is removed than when an external column is removed. This implies that the progressive collapse potential of the model structure is higher when an exterior column is removed than when an interior column is removed.



(a) Removal of an interior column
(b) Removal of an exterior column

Fig. 2. Pushdown curves of the model structure with various connection types



(a) Removal of an interior column
(b) Removal of an exterior column

Fig. 3. Comparison of fragility curves at CP stage

3. Fragility analysis

Through fragility analysis the probability of failure at various loading states can be obtained. Further, structures can be designed to have a desired probability of failure using the load factor determined from the fragility analysis. For fragility analysis of a structure subjected to progressive collapse under gravity load, the probability for vertical displacement to exceed a given limit state is computed. In the analysis the First-Order Second Moment (FOSM) method was applied assuming that the mean and the standard deviations had log-normal distribution. Figure 3 plots the fragility curves of the structure with each connection type at the CP limit state. When an interior column was removed, the structures with WUFB, WCPF, and RBS connections reached 100 % probability of exceeding the CP limit states at the load factor of 1.5, 1.6, and 1.7, respectively. When an exterior column was removed, the load factors reduced to approximately 1.2, 1.3, and 1.4, respectively. This implies that the RBS connections have highest progressive collapse-resisting capacity and that the loss of an exterior column is more vulnerable for progressive collapse than the loss of an exterior column.

4. Conclusion

The analysis results showed that the probability of exceeding the IO limit state is smallest in the structure with WCPF connections. However the structure with RBS connections turned out to have the smallest probability of exceedance of the CP limit state due to large ductility capacity. This implies that the structure with RBS connections has the largest progressive collapse resisting capacity when a column is suddenly removed. It was also observed that at 90% probability of exceeding the CP limit state the load factors ranged 1.42～1.64 when an interior column was removed and 1.19～1.39 when an exterior column was removed. Therefore when the GSA recommended gravity load of 2(dead load +0.25 live load) is applied as a static load, the model structure with any of the connection type considered in this study may collapse by the sudden removal of a column. It was also observed that the probability of failure of seismic connections depends largely on the limit states provided, and therefore precise limit states need to be provided for realistic prediction of progressive collapse.

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