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Probabilistic progressive collapse analysis of steel-concrete composite floor systems

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ABSTRACT

The paper presents a probabilistic analysis of steel-concrete composite floor against progressive collapse considering uncertainties in strength and ductility of steel connections. Using component-based connection model, an analytical framework for developing probabilistic connection models is proposed. The connection models developed are further introduced in probabilistic structure analysis against progressive collapse. Tornado diagram-based sensitivity analysis is performed to determine the influential random variables for structural resistance capacity. Using Latin Hypercube sampling of both random structure variables and external loads, random realizations of structures are generated and progressive collapse analysis is carried out using pseudo-static pushdown method. The proposed framework is applied to study the vulnerability of composite floor. Fragility curves corresponding to three limit states are developed. Discussions on the influences of steel connection and slab continuity on collapse vulnerability are given. Finally, results from the present probabilistic method are compared with those from deterministic approach.

1. Introduction

Civil structures might be subjected to incidental accidents during their service time, such as explosion and impact. These incidents may cause damage to structure members and may even trigger the collapse of the building [1]. Although the failure probability of building structures is low, the consequence is catastrophic [2]. Therefore, progressive collapse resistant design of structural buildings is critical to the safety of structures.

Steel frame building is a common prototype building for moderate and high seismic regions. Because steel connections provide integrity for structure under column loss scenario, they are recognized as the most vulnerable part of typical steel buildings [3]. Therefore, extensive experimental studies [3–5] have been carried out to assess the rotation capacity resulting from catenary effect. Different failure modes were observed including bolt shear failure, plate bearing failure etc. [6]. With the advancement of computer resources, numerical simulations are typically utilized to evaluate the rotation capacity of steel connections in design practice. Compared with detailed micromodels, component-based model is a practical and simplified way to characterize the connection behavior [7]. It has been widely used by a number of researchers [8–10] and is proofed to be an effective methodology for capturing the axial force-moment interaction of connections resulting from catenary action effect.

Compared with researches on steel connections, studies on the robustness of steel-concrete composite floor systems are scarce. Research from Alashker [11] highlighted the 3D modeling technique and membrane effect from floor system. Although concrete slab contribute significantly to collapse resistance, computational studies from Alashker et al. [12] and Sadek et al. [13] indicated that composite floor systems with shear tab connection were susceptible to collapse under column removal scenario. Main [14] developed a simplified numerical model for steel composite floor system and proposed a new tie force demand formulation. Johnson et al. [15] conducted a 1:2 scale experimental test of a 3 × 3 bay composite floor system subjected to four difference column removal scenarios.

As described above, the previous discussed progressive collapse analyses were carried out with deterministic parameters. The progressive collapse assessment procedures in current design guidelines, such as UFC 4-023-03 [16], GSA [17] and EC1-1-7 [18], are also deterministic in nature. Large load combinations are used to compensate for structural safety and unknown factors. While such method may seem to provide a simple and seemingly conservative means of treating uncertainty, it cannot provide the probabilities that structures meet the performance objectives. In reality, random variability of material strength and geometry section sizes inevitably introduce fluctuations to the collapse resistance capacity. So far, only limited studies have focused on quantifying failure probability of building structures under column removal. Park and Kim [19] conducted fragile analysis of steel moment frames. The probabilities of failure against steel frame with various moment connections were obtained using FOSM method. Xu and Ellingwood [20]

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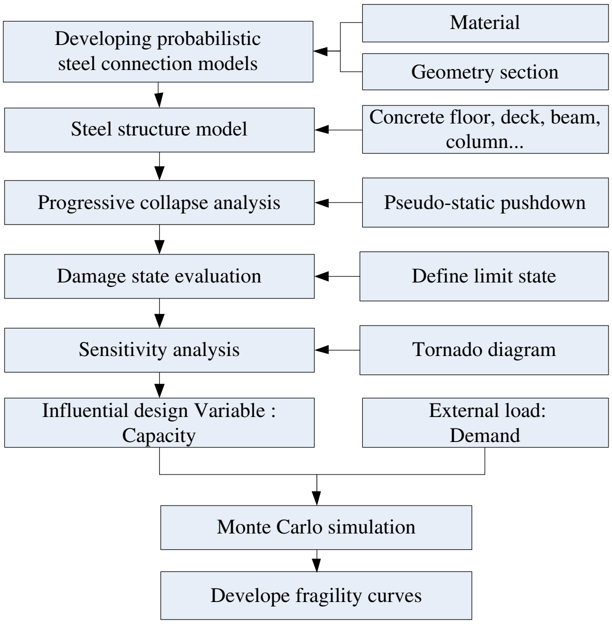

Fig. 1. Framework of probabilistic analysis considering uncertainties from steel connections.

developed a J-integral formulation of fracture demand model for pre-Northridge steel moment connections. Le and Xue [21] proposed a multi-scale numerical model and conducted a probabilistic analysis of RC frames under column loss.

Due to the uncertainties in material properties, geometry section and workmanship, ultimate strength and rotation capacity of steel connections under catenary actions inevitably fluctuate, as indicated from experimental test [22]. However, studies on quantifying variations in steel connections and probabilistic analysis of steel-concrete composite floor systems considering uncertainties of steel connections have not been found in the previous literatures. Motivated by these limitations, this paper presents a probabilistic analysis of steel-concrete composite floor system against progressive collapse considering uncertainties in the ultimate strength and ductility of steel connections. Within the framework of component-based connection, an analytical procedure for developing probabilistic steel connection models is presented. The connection models above are further introduced in probabilistic analysis of steel-concrete composite floor subjected to column loss. Fragility curves with respect to three limit states are obtained. Discussions on the influences of steel connections and slab continuity on structure collapse vulnerability are provided. Finally, results from probabilistic analysis are compared with those from deterministic approach.

2. Probabilistic assessment methodology

Fig. 1 presents the probabilistic assessment framework. As shown in Fig. 1, the framework contains two levels of uncertainty propagation. Firstly, an analytical framework for developing probabilistic steel connection models is proposed and detailed in Section 2.1. After that, the probabilistic connection model is introduced in stochastic analysis of structure systems. The flowchart of probabilistic structure analysis is presented in Section 2.2.

2.1. Development of probabilistic steel connection models

Because experimental tests on steel connections under monotonic axial loading have only begun to be carried out, experimental data are scarce. Therefore, in this paper, probabilistic connection models are developed analytically. Within the framework of component-based connection model, the Monte Carlo simulation method is adopted to propagate the uncertainties from material parameters and geometry sizes to the strength and ductility of steel connection. The procedure is presented in Fig. 2 as the following steps.

(1) Set up the component-based connection model according to the type of beam-column joint analyzed [23].
(2) Generate random variables such as material strength and geometry section sizes. Because the Monte Carlo simulation method does not provide a prior estimate of the sample size at a certain confidence level, convergence tests are conducted to determine the minimum sample size required in Monte Carlo simulations [24].
(3) Calculate the axial force-displacement curve of each component according to the material properties and connection configurations generated in step (2).
(4) Individual component springs at the same bolt level are assembled in series to create a single "effective spring" to capture all of the related deformations [7].

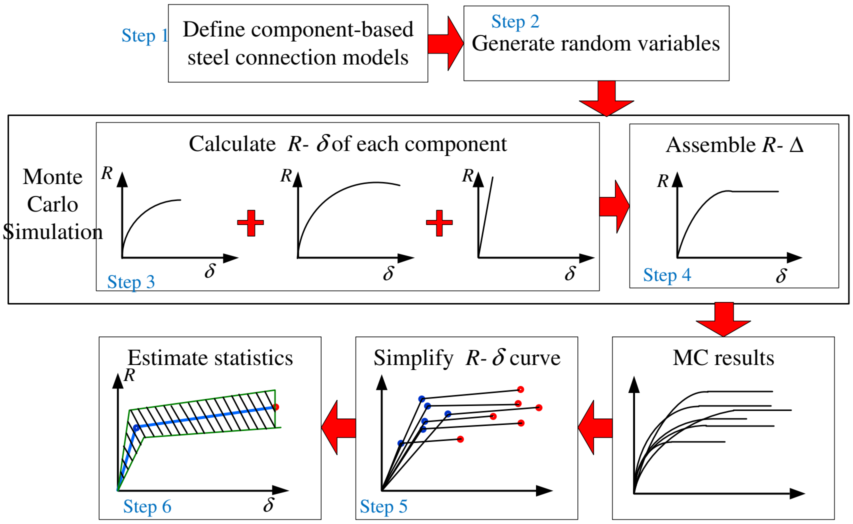

Fig. 2. Flowchart for developing probabilistic connection models.