Evaluation of the effect of buckling-restrained braces on structural and non-structural seismic fragility curves of steel building frames

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ABSTRACT

Seismic fragility curves serve as tools that relate earthquake damage to its intensity. These curves specify the probability of exceeding certain limit states associated with the considered damage measures as a function of the seismic intensity measure parameter. Among the engineering demand parameters that can be a measure of the damage of structural and nonstructural components as well as the comfort of the occupants, are the interstory drifts and the absolute floor accelerations. The aim of this paper is to derive and evaluate structural and non-structural fragility curves of steel building frames equipped with buckling-restrained braces (BRBs) at different damage states based on the above two engineering demand parameters. For this purpose, incremental dynamic analysis (IDA) of the finite element model of a ten-story building frame under 44 FEMA-P695 far-field earthquake records has been used in OpenSees software with Python interpreter (OpenSeesPy). Comparing the fragility curves of the frame model without BRBs and with BRBs showed that the addition of buckling-restrained braces to steel building frames significantly reduces the probability of damage to structural and drift-sensitive non-structural components in all four damage states (slight, moderate, extensive, and complete); but it does not have a positive effect on the seismic fragility of acceleration-sensitive non-structural components. Based on the results of this study, it is possible to quantitatively evaluate the effect of buckling-restrained braces on the probability of damage of structural and non-structural components of steel buildings at different damage states.

Keywords: Fragility curve, Buckling-restrained brace (BRB), Earthquake, Structural components, Non-structural components.

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1. Introduction

Buckling-restrained braces (BRBs) have been widely studied and used, especially in Japan, the United States, and Taiwan. Wakabayashi et al. [1] initiated work on a type of BRB consisting of flat steel plates placed between precast concrete wall panels. In Taiwan, experimental studies were conducted on BRBs, including tests on braces with a steel core made from low-yield-strength steel [2]. These braces were subjected to cyclic loading. Additionally, several large-scale tests were carried out by various researchers [3-4]. The seismic responses of building frames with different bracing systems, including BRBs and conventional braces, have also been evaluated and compared in several studies [5-6].

To probabilistically estimate the structural damage in BRB-equipped frames, fragility curves have been developed and evaluated in some cases. For instance, Ghowsi and Sahoo assessed the seismic fragility of buckling-restrained braced frames under near-field earthquakes [7]. Hu and Wang reported a comparative seismic fragility assessment of mid-rise steel buildings with buckling-restrained braced frames and self-centering energy-absorbing dual rocking core system [8]. Ouyang et al. analyzed the seismic fragility of an 8-story reinforced concrete frame with BRBs using a performance-based plastic design method [9]. They used a set of far-field ground motion records and evaluated the application of 16 different earthquake intensity measures (IMs) in seismic fragility analysis.

BRBs have emerged as a suitable choice for seismic force-resisting systems; however, structural performance is not the sole consideration in evaluating the effectiveness of a seismic-resistant system. The seismic performance of non-structural components is also important. Several studies have been conducted on the seismic fragility of non-structural components in some building systems [10–12]. However, most seismic fragility studies on steel building frames with BRB have focused on structural components. Therefore, the present study addresses seismic fragility analysis of both structural and non-structural components of a steel building frame equipped with BRB at various damage states. Comparison of the results with the building frame without BRB is also done.

2. Methodology

Fragility functions are useful tools for assessing the seismic vulnerability of structures. They are defined as the probability of exceeding a certain limit state (LS) for a given level of considered seismic intensity measure (IM) parameter.

$$\text{Fargility} = P\,[\text{DM} \geq \text{Ls} \mid \text{IM}] \tag{1}$$

Typically, a lognormal cumulative distribution function is fitted to the obtained fragility data in order to derive a continuous fragility curve [13]:

$$P\,[\text{DM} \geq \text{LS} \mid \text{IM} = x] = \Phi\left(\frac{\ln(x/\theta)}{\beta}\right) \tag{2}$$

where $\Phi()$ is the standard normal cumulative distribution function, θ is the median of the fragility function, and β is the standard deviation of $\ln(\text{IM} = x)$.

There are several procedures for performing nonlinear dynamic analyses to collect the data for estimating a fragility function. A common approach is incremental dynamic analysis (IDA), where an ensemble of earthquake ground motions is repeatedly scaled to different IM levels [14]. This analysis procedure is used in this study to evaluate the structural and nonstructural seismic fragilities of the building model for various performance objectives (damage states). Four damage states defined by HAZUS [15] are adopted here for structural and non-structural components, namely Slight, Moderate, Extensive and Complete damages.

44 horizontal components of 22 earthquake ground motions from the FEMA-P695 [16] far-field database are used in this study to perform the nonlinear dynamic analyses. The building models considered for analyses are 10-story building frames with and without BRBs.

3. Results and Discussion

The results are presented in the form of seismic fragility curves by varying the following parameters: the type of the building model (with or without BRB), the damage type (damage to structural components: S, damage to displacement-sensitive non-structural components: NSD, and damage to acceleration-sensitive non-structural components: NSA), and the damage state (Slight, Moderate, Extensive, and Complete). For example, Fig. 1 shows and compares structural and non-structural fragility curves for the building frame with and without BRB at the Extensive damage state.

The obtained results show that for all four damage states, the addition of BRBs to steel building frames significantly reduces the probability of damage to structural and drift-sensitive non-structural components; but it does not have a positive effect on the seismic fragility of acceleration-sensitive non-structural components. For instance, Fig. 1 shows that for the Extensive damage, the IM (= PGA) level with a 50% probability of damage (i.e., the median of the fragility function) increases with the addition of BRB by 82% and 63% in structural and drift-sensitive non-structural components, respectively; while it decreases by 7% in acceleration-sensitive non-structural components.

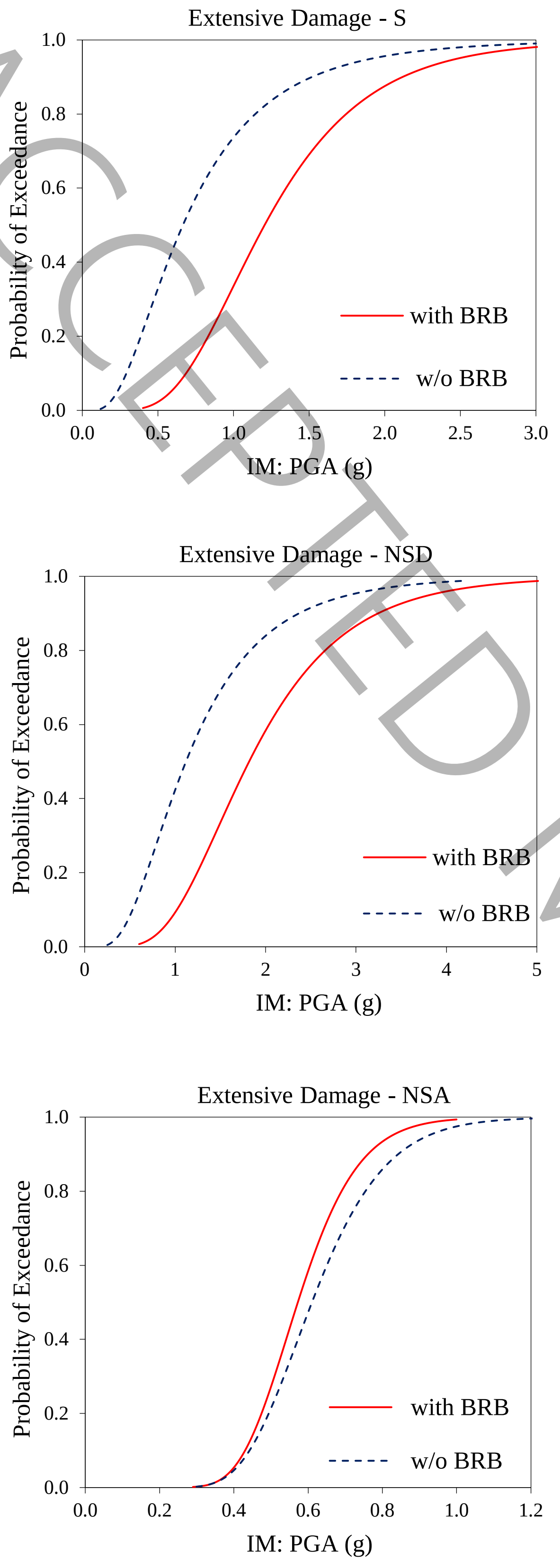

Fig. 1. Seismic fragility curves for structural and non-structural components of the building frame with and without BRB at the Extensive damage state

4. Conclusion

Seismic fragility curves derived for a 10-story steel building frame with and without BRBs shows that at all four damage states (i.e., Slight, Moderate, Extensive, and Complete), the addition of BRBs significantly reduces the probability of damage to structural and displacement-sensitive non-structural components. However, for acceleration-sensitive non-structural components, the addition of BRBs does not have a positive effect on the damage probability. The comparison of the heightwise distribution of peak seismic response quantities, obtained from the average of the 44 earthquake records, also confirms these findings. For all different damage states in the considered building model, the changes in the median of the fragility curves due to the addition of BRBs range from +54% to +82% for structural components, from +48% to +100% for displacement-sensitive non-structural components, and from -3% to -19% for acceleration-sensitive non-structural components.

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