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Probabilistic seismic demand assessment of residual drift for Buckling-Restrained Braced Frames as a dual system

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ABSTRACT

The main drawback of Buckling-Restrained Braced Frames (BRBFs) is low post-yield stiffness of steel cores that leads to concentrate large residual drift in a story after earthquakes. Residual drifts not only cause serviceability issues but also increase the potential damage during aftershocks or future events. In this study seismic demands of low and mid-rise BRBFs and Dual-BRBFs were studied using the Probabilistic Seismic Demand Analysis (PSDA). By comparing demand hazard curves of frames it was concluded that using of BRBFs as a dual system could reduce the residual drift demand significantly. It can improve the revival capacity of such structures after earthquakes with low repairing cost. In the other part of this study, two different nonlinear models including a deteriorating model and a non-deteriorating model were used to explore the effect of degradation on Dual-BRBFs seismic demands. It was observed that the residual deformations are more sensitive to degradation than maximum deformations. Although the deterioration is not serious because of large BRBs stiffness which keeps MRFs in low range of nonlinearity.

1. Introduction

Nowadays, Buckling-Restrained Braced Frames (BRBFs) are used more and more as a good lateral force-resisting system [1]. A typical Buckling-Restrained Brace (BRB) usually is composed of the following two components: (1) the core of brace designed to yield under axial cyclic loading to dissipate energy. (2) Casing that restraints the steel core against buckling [2]. In order to eliminate axial forces in casing, a debonding material is used to provide enough split-up between core and casing [2]. Comprehensive experimental studies on the assemblage of these components have shown stable and symmetric hysteretic behavior under cyclic loading. The nonlinear behavior of this system leads to large amount of energy dissipation [1–3]. Fig. 1 shows components of a typical BRB system and its cyclic behavior.

In spite of their proper function, a main drawback of BRBFs is low post-yield stiffness of their steel cores that provides minimal returning forces and leads to concentrate large residual drifts in a story of structure after earthquakes [3,5]. In addition, some research have identified the post-yield stiffness as a main parameter to influence the residual deformations of nonlinear systems [6,7].

Analytical studies of BRBFs have reported the residual drifts with a mean value greater than 0.5% for Design Basis Earthquakes (DBE) (10% in 50 years), and greater than 1% for the Maximum Considered Earthquakes (MCE) (2% in 50 years) [3]. Moreover, the outcome of a large-scale hybrid pseudo dynamic test on BRBFs has shown 1.3% and 2.7% of residual interstory drifts for the DBE and MCE earthquakes respectively [8]. Therefore, some studies have been done to improve low post-yield stiffness of BRBFs by using them as a dual system [3,5]. The purpose of using two different systems as a dual frame is to complete each other and compensate for disadvantages [3]. Kiggins and Uang (2006) have shown that in BRBF–SMRF dual systems, residual interstory drifts will be decreased about 50%, while maximum interstory drift will be reduced 10% compared to the simple BRBF systems [3,5]. Mahdavipor and Deylami have also investigated the effect of hardening ratio on BRBFs seismic demands. Results of this research have shown that by 1% change in strain hardening ratio, the residual drift demand of BRBFs will experience significant increase and restoring ability of them will reduce notably [7].

On the other hand, the estimation of residual deformation demands can be important in structures performance-based design [9]. Therefore, some of well-known seismic provisions specify limiting values on residual deformations (e.g., FEMA 356). Although they do not identify a specific procedure to estimate residual deformation demand [9,10]. The magnitude of residual deformations

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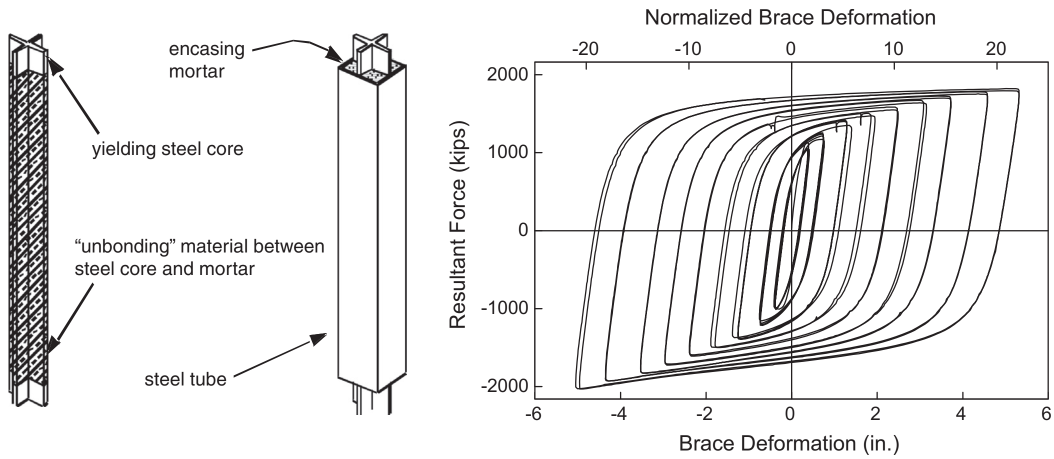

(a) Components of a BRB system [2]. (b) Typical cyclic behavior of BRBs [4].

Fig. 1. (a) Components of a Buckling-Restrained Brace and (b) typical cyclic behavior of BRBs [4].

not only is important to determine the revival capacity of a structure, but also is particularly effective on seismic behavior of structures in aftershocks or future events [9,11]. Hence, a reliable evaluation of residual deformation demand should be utilized in seismic performance-based assessment of existing structures or the new ones [9,11,12].

2. Objective and scope

However BRBF as dual system has been investigated in prior studies. They have used simple nonlinear time history analysis without a probabilistic framework that could consider different sources of uncertainty. In addition, these studies used a non-deteriorating model for MRFs in Dual-BRBFs. This paper will focus on seismic demand assessment of BRBFs and Dual-BRBFs using Probabilistic Seismic Demand Analysis (PSDA) methodology. A probabilistic framework gives more reliable results and leads to a better judgment. The effect of using BRBFs as a dual system can be investigated by comparing demand hazard curves for different responses (e.g. Maximum residual interstory drift ratio, residual roof drift ratio, etc.). On the other hand, all studied models of Simple-BRBFs and Dual-BRBFs in this investigation have been designed according to the well-known codes. As a result, the expected level of residual deformation demands in such structures can be found. Moreover, in this research a deteriorating lumped plastic hinge model (Modified Ibarra–Krawinkler plastic hinge) and a non-deteriorating distributed plasticity model (fiber model) will be compared to find out the effect of deterioration and analytical model on Dual-BRBFs seismic demands. Finally the ability of Simple-BRBFs and Dual-BRBFs to continue serviceability after a Design Basis Earthquake (10% probability of exceedance in 50 years) will be discussed. In this paper the term "revival capacity of frame" will be used to refer this ability.

3. Probabilistic Seismic Demand Analysis methodology

Earthquakes and their effects on structures are probabilistic inherently. Therefore, it is appropriate to use a probabilistic approach to estimate expected responses of structures under future earthquakes [13]. Performance-Based Earthquake Engineering (PBEE) is known as a reliable approach to consider probabilistic parameters in seismic assessment of existing structures, or designing new buildings [13,14]. For this purpose PBEE uses the Probabilistic Seismic Demand Analysis (PSDA) to obtain Mean Annual Frequency (MAF) of exceedance of a response parameter in a structure which has built on a specific seismic site condition. This analysis can consider different sources of uncertainty (e.g. Record to record uncertainty, etc.) [9,11,12]. In general, PSDA approach is an application of the total probability theorem. According to PSDA the mean annual frequency of exceedance of a predefined engineering demand parameter (edp) is computed by integration the probability of structure responses over all possible levels of ground motion intensity. It can be shown mathematically as follows [9,13,14]:

$$\lambda_{\mathrm{EDP}}(\mathrm{edp}) = \int_0^\infty \mathrm{P}(\mathrm{EDP} > \mathrm{edp} | \mathrm{IM} = \mathrm{im}) \cdot \left| \frac{\mathrm{d}\lambda_{\mathrm{IM}}(\mathrm{im})}{\mathrm{d}(\mathrm{im})} \right| \mathrm{d}(\mathrm{im}) \tag{1.3}$$

where, the EDP is an Engineering Demand Parameter (e.g. Roof drift, Residual interstory drift, etc.) and IM is a ground motion Intensity Measure (e.g. Spectral elastic acceleration at the first mode period of vibration $S_a(T_1)$, PGA, etc.) [9]. The outcome of this equation is $\lambda_{\mathrm{EDP}}(\mathrm{edp})$ that expresses the mean annual frequency of exceedance of a predefined engineering demand parameter edp. On the other hand, $\lambda_{\mathrm{IM}}(\mathrm{im})$ refers to mean annual frequency of ground motion intensity parameter (IM) that is exceeding a specified level of intensity measure (im) [9,14]. In addition the term $\mathrm{P}(\mathrm{EDP} > \mathrm{edp}|\mathrm{IM} = \mathrm{im})$ represents the conditional probability of exceedance of a specified edp, which can be calculate from nonlinear dynamic analysis with a set of ground motions scaled into predefined level of intensity measure (im) [9,11,12]. Fig. 2 shows the main concept of PSDA methodology.

The main purpose of the current study was to investigate residual and maximum drift demand of BRBFs and Dual-BRBFs. Therefore, maximum Interstory Drift Ratio ($\mathrm{IDR}_{\max}$), maximum Residual Interstory Drift Ratio ($\mathrm{RIDR}_{\max}$), Roof Drift Ratio (RDR) and Residual Roof Drift Ratio (RRDR) are selected as EDPs. Also, elastic spectral acceleration at the fundamental structural period ($S_a(T_1)$) is selected as IM parameter. It is the most used in other research studies and leads to less dispersion in structural responses in comparison with Peak Ground Acceleration (PGA) [6,13–15]. For example, by using $\mathrm{RIDR}_{\max}$ as EDP and $S_a(T_1)$ as IM Eq. (1.3) can be written as follows:

$$\lambda_{\mathrm{RIDR}_{\max}}(\mathrm{ridr}_{\max}) = \int_0^\infty \mathrm{P}(\mathrm{RIDR}_{\max} > \mathrm{ridr}_{\max} | S_a(T_1) = s_a(T_1)) \cdot \left| \frac{\mathrm{d}\lambda_{S_a}(s_a)}{\mathrm{d}(s_a)} \right| \mathrm{d}(s_a) \tag{2.3}$$