Engineering Structures 81 (2014) 302–308

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Probabilistic assessment of strain hardening ratio effect on residual deformation demands of Buckling-Restrained Braced Frames

M.A. Mahdavipour *, A. Deylami

Department of Civil and Environmental Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran

ARTICLE INFO

Article history:
Received 15 August 2013
Revised 30 September 2014
Accepted 2 October 2014

Keywords:
BRBFs
Strain hardening ratio
PSDA
Residual drift
Seismic demand

ABSTRACT

In this study the effect of steel core strain hardening ratio of Buckling-Restrained Braces (BRBs) on residual drift demands of Buckling-Restrained Braced Frames (BRBFs) was assessed by using Probabilistic Seismic Demand Analysis (PSDA) methodology. Results show that by mere 1% change in strain hardening ratio, the residual drift demands of low and medium-rise studied frames experienced significant increment and restoring ability of BRBFs reduced meaningfully. On the other hand, maximum drift demands were approximately independent from strain hardening ratio. Given that, the large permanent drifts can make serious serviceability issues after earthquakes, accurate material tests play an important role in structural safety.

1. Introduction

Since Buckling-Restrained Braced Frames (BRBFs) were created, they are used in practical construction projects especially in the United States and Japan [1,2]. Stable and symmetric nonlinear behavior of Buckling-Restrained Braces (BRBs), make these structural elements to behave as the energy absorbing devices during the earthquakes, and cause the principal structural elements (Beams and Columns) used in BRBFs remain in elastic range [1,3]. This behavior concentrates damages in BRBs which could easily be replaced after earthquakes.

In general, a typical BRB consists of two main parts: 1 – The steel core designed to yield in tension and compression axial loads and dissipate energy. 2 – Casing or restraining mechanism which controls the steel core in the compression against buckling. This part is usually made of an outer steel tube filled with concrete mortar [1]. In order to take away the axial loads transferring from core to mortar, a gap or separating material is used between them. This gap also makes the core expansion possible under compression loads [1]. Fig. 1 shows the main components of a BRB and Fig. 2 presents the symmetrically stable cyclic behavior of a typical BRB.

As shown in Fig. 2, post-yield stiffness of BRBs is low due to BRBs yielding mechanism [3,6]. In contrast to flexural yielding, when the core of a buckling restrained brace is yielded under axial loads, all its fibers turn to plastic range and its section is yielded completely. Therefore, there is no elastic fiber to apply restoring forces after unloading. This negative feature leads to concentrating large residual deformation in a story containing BRBs and raises doubts about using BRBs in new constructions [3,6]. Analytical studies have shown that the magnitude of interstory residual drifts could reach to 0.5% for earthquakes with 10% probability of exceedance in 50 years. Furthermore they have shown that residual interstory drifts could exceed 1% for a seismic hazard level with 2% probability of exceedance in 50 years [3]. In addition, large-scale experimental studies have reported large residual deformations in BRBFs. According to these studies the residual interstory drift could be 1.3% and 2.7% for earthquakes with 10% and 2% probability of exceedance in 50 years respectively [3]. These amounts of residual drifts could make serious problems in serviceability of BRBFs after earthquake and raise the repairing cost. Moreover, the residual drifts can change the structure condition for aftershocks or future events. Therefore, the evaluation of the residual drift is so essential to Performance-Based Design of structures that some seismic provisions have recommended some limit states for residual drifts (e.g. FEMA-356) [7,8].

On the other hand, the strain hardening ratio which is known as a main nonlinear parameter can affect the post-yield stiffness of

---

* Corresponding author at: No. 25, Maskan-Va-Shahrsazi Ave., P.O. Box 8915674751, Yazd, Iran. Tel.: +98 351 6290210.

E-mail addresses: a.mahdavipour@aut.ac.ir (M.A. Mahdavipour), deylamia@aut.ac.ir (A. Deylami).

http://dx.doi.org/10.1016/j.engstruct.2014.10.004
0141-0296/© 2014 Elsevier Ltd. All rights reserved.

BRBs; therefore, it plays key role in making restoring forces and changing the residual drift demands of BRBFs [9].

2. Objective and scope

In this investigation the effect of strain hardening ratio on BRBFs deformation demands was assessed by using Probabilistic Seismic Demand Analysis (PSDA) methodology. Four low and medium-rise BRBFs were studied with different ratios of strain hardening (0.0–4.0%) in order to find out the level of dependence between residual drift demands and strain hardening ratio. PSDA methodology considers different sources of uncertainty to obtain structural responses. In consequence, using demand hazard curves for studying the strain hardening ratio effect gives more reliable results and leads to a better judgment.

3. Probabilistic Seismic Demand Analysis

Earthquakes and their consequences are inherently probabilistic and it is necessary that earthquake engineers use a probabilistic procedure to assess the structural responses due to future ground motions [8,10,11]. On the other hand, the Probabilistic Seismic Demand Analysis (PSDA) methodology as a sub-division of Performance-Based Earthquake Engineering approach (PBEE) [12], is able to consider different sources of uncertainty (record to record and intensity to intensity) which could affect the structural responses [8,10]. In fact, the PSDA methodology is an application of total probability theorem which is shown mathematically as follows [8,10–13]:

$$\lambda_{\mathrm{EDP}}(\mathrm{edp}) = \int_0^\infty P(\mathrm{EDP} > \mathrm{edp}|\mathrm{IM} = \mathrm{im}) \cdot \left|\frac{\mathrm{d}\lambda_{\mathrm{IM}}(\mathrm{im})}{\mathrm{d(im)}}\right| \mathrm{d(im)} \tag{1}$$

According to Eq. (1), $\lambda_{\mathrm{EDP}}(\mathrm{edp})$; the Mean Annual Frequency (MAF) of exceedance of a specified engineering demand parameter (edp) could be computed by integration the probability of structure responses in all possible ground motion intensity levels [8,11,13]. In this equation EDP is defined as Engineering Demand Parameter (e.g. interstory drift ratio, residual interstory drift ratio, etc.) and IM identifies the ground motion intensity measure (e.g. spectral elastic acceleration at the first mode period of vibration $S_a(T_1)$) [8,10]. The conditional probability $P(\mathrm{EDP} > \mathrm{edp}|\mathrm{IM} = \mathrm{im})$ for a specified structure can be obtained by using nonlinear dynamic analyses for a given set of ground motions scaled into an intensity measure which is equal to im (IM = im) [8,10–12]. In order to use this term in closed form, a Cumulative Distribution Function (CDF) must be fitted on outcome responses of the structure from nonlinear dynamic analyses at a specific intensity measure (im) [8,10]. Some research have been done to identify an appropriate and accurate CDF to compute $P(\mathrm{EDP} > \mathrm{edp}|\mathrm{IM} = \mathrm{im})$ [8]. As a well-known CDF, lognormal Cumulative Distribution Function can fit the structure responses and evaluates $P(\mathrm{EDP} > \mathrm{edp}|\mathrm{IM} = \mathrm{im})$ accurately. This function uses only statistical parameters to describe the cumulative distribution of EDPs as follows [8,14,15]:

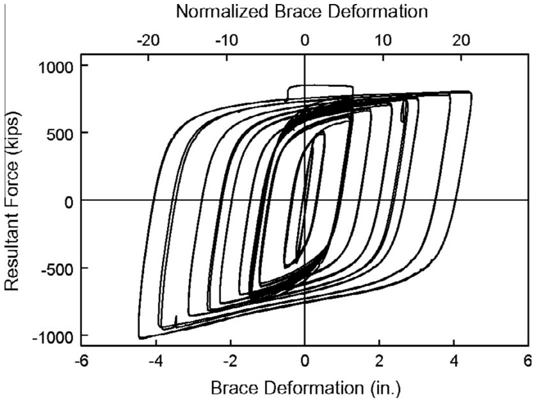

Fig. 2. Symmetrically stable cyclic behavior of a typical BRB [5].

$$P(\mathrm{EDP} > \mathrm{edp}|\mathrm{IM} = \mathrm{im}) = 1 - \Phi\left[\frac{\mathrm{Ln(edp)} - \mu_{\mathrm{Ln(EDP)}}}{\sigma_{\mathrm{Ln(EDP)}}}\right] \tag{2}$$

where $\Phi[.]$ is known as standard normal Cumulative Distribution Function and $\mu_{\mathrm{Ln(EDP)}}$ and $\sigma_{\mathrm{Ln(EDP)}}$ represent the mean and standard deviation of the natural logarithm of the EDPs respectively, at intensity level im [14,15].

The second term in the integral (Eq. (1)) is $\left|\frac{\mathrm{d}\lambda_{\mathrm{IM}}(\mathrm{im})}{\mathrm{d(im)}}\right|$ that $\lambda_{\mathrm{IM}}(\mathrm{im})$ refers to the mean annual frequency of a ground motion intensity measure (IM), exceeding a specific level of intensity (im) and denotes the seismic hazard at a specific site [8,11,13]. The information about this term is usually provided by seismologists (e.g. the USGS database) and is presented as site hazard curves for different period of vibrations and a given ratio of damping (5% typically) [13]. In this study, all investigated frames are located on a site at Los Angeles which its hazard curves have been provided by USGS database [16]. These hazard curves are shown in Fig. 3 for different period of vibrations and 5% of damping ratio.

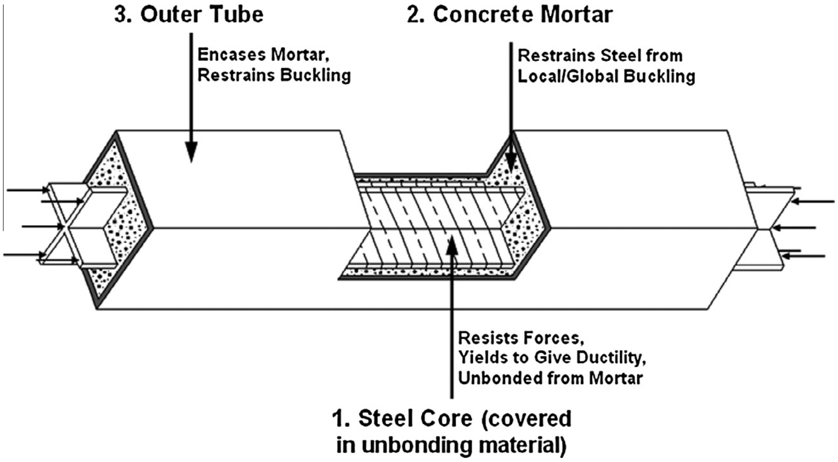

Fig. 1. The main components of a BRB [4].