Engineering Structures 123 (2016) 141–154

Contents lists available at ScienceDirect

Engineering Structures

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

A method for preliminary seismic design and assessment of low-rise structures protected with buckling-restrained braces

Hector Guerrero [a,*], Tianjian Ji [a], Amador Teran-Gilmore [b], J. Alberto Escobar [c]

[a] The University of Manchester, UK
[b] Universidad Autonoma Metropolitana, Mexico
[c] Institute of Engineering, Universidad Nacional Autonoma de Mexico, Mexico

ARTICLE INFO

Article history:
Received 3 October 2015
Revised 10 May 2016
Accepted 11 May 2016
Available online 11 June 2016

Keywords:
Buckling-restrained braces
Performance-based seismic design
Performance assessment
Seismic design method
Dual systems
Structural fuse

ABSTRACT

This paper proposes a method for preliminary Performance-Based Seismic Design (PBSD) of low-rise structures protected with Buckling-Restrained Braces (BRBs). It is assumed that a frame structure protected with BRBs, termed as a dual structure, is rationally represented by a dual single-degree-of-freedom (SDOF) oscillator whose parts yield at different displacement levels. The formulation of the method is presented for SDOF structures. This simplification is validated using a case study example. A comparison of the responses between conventional and dual structures shows that, when designing dual structures, the common practice of using conventional design spectra may lead to biased designs. One of the main advantages of the method is that, during its application, information useful for preliminary and quick assessment of structures is generated, facilitating the application of the PBSD philosophy. A case study example is conducted to show its applicability and its potential for preliminary assessment of structures. Regarding its limitations, the method is valid for low-rise regular buildings with rigid in-plane diaphragms, and whose dynamic response is dominated by their fundamental mode of vibration.

1. Introduction

There is great concern about the levels of economical damage observed after recent earthquakes in structures designed with code procedures because losses have surpassed expectations by a large amount [1]. As a result, some strategies have been proposed (a) to estimate expected damage in a more reasonable way and (b) to reduce it.

To estimate damage in a realistic and reliable way, Performance-Based Seismic Design (PBSD) has been proposed to predict and evaluate the performance of buildings (or facilities) with clear understanding of risk [1,2]. PBSD is superior to code provisions because it is able to predict different types of losses for different shaking intensities in a probabilistic manner, while codes mainly intend to provide resistance to avoid collapse without a clear understanding of risk of collapse or extension of damage and repair cost [2]. However, implementation of PBSD is often reserved for critical facilities only, due to the required increase of engineering design involvement. Procedures that facilitate its implementation are still needed.

To reduce damage, protection technologies such as Buckling-Restrained Braces (BRBs) have been developed and implemented in structures because they are very effective to dissipate energy [3,4] and help to control lateral displacements and inter-storey drifts [5]. Moreover, they can be used as structural fuses; i.e. devices that concentrate damage and are easy to replace while the main structure remains undamaged [6]. An attractive solution is achieved when they are combined with moment-resisting frames because they allow the reduction of inter-storey drifts [5] and permanent (or residual) deformations [7,8].

In order to design structures protected with BRBs, methods based in the control of the response have been proposed recently. Most of these methods were proposed only for BRB frames, defined as systems whose lateral resistance is only provided by BRBs while the contribution of the frame is neglected [9–11]. However, the contribution of the main structure may represent a significant amount of capacity and should be taken into account when designing and assessing structures equipped with BRBs. In this regard, Maley et al. [5], Lin et al. [12] and Sutcu et al. [13] have proposed methods based in the Direct Displacement-Based Design methodology [14]. In this approach, the hysteretic damping provided by inelastic deformation of the BRBs is replaced by an equivalent viscous damping to convert the nonlinear system into an equivalent linear system. Vargas and Bruneau [6] proposed a method based

* Corresponding author.

http://dx.doi.org/10.1016/j.engstruct.2016.05.015
0141-0296/

on a parametric formulation that considered the contribution of the BRBs and the main structure. Unfortunately, some key parameters such as maximum displacement ductility, stiffness ratio and strength ratio were selected arbitrarily; which led to limited control of the design process. Teran-Gilmore and Virto-Cambray [15] proposed a displacement-based method; which considered the contribution of the BRBs and the main structure to the capacity. This method, applicable for structures not significantly affected by higher modes and flexural behaviour, provides a basis for the development of the method proposed here. On the other hand, current methods in the literature use spectra as design input; which normally are generated based on elastic-perfectly plastic oscillators, referred hereafter as conventional oscillators. Since they behave differently to dual oscillators, this may lead to biased designs (as will be seen in the next section).

In this paper, a method for seismic design of buildings equipped with BRBs is proposed. To control the lateral displacement demands, it takes into account explicitly the parameters affecting the behaviour of structures equipped with BRBs such as the relative contribution of the BRBs and the main structure to the lateral capacity of the dual system. Instead of using design spectra generated from conventional oscillators, it uses seismic records to solve the dynamic equation of motion for dual oscillators; which leads to better estimation of the response. Key parameters such as ductility are not arbitrarily selected but estimated at the beginning of the design process as a function of the geometric and mechanical properties of the structural members. The method facilitates the implementation of PBSD because it generates statistics of the response that allows a rapid assessment of the performance. This benefits designers and stakeholders in making more intelligent decisions based not only on initial construction costs but also in life-cycle considerations at the beginning of the design process [1].

The structure of this paper is as follows. Section 2 presents the idea of designing single-degree-of-freedom (SDOF) structures with BRBs and compares the response of conventional and dual SDOF oscillators. Section 3 presents a definition of multi-degree-of-freedom (MDOF) structures equipped with BRBs and presents a method for their design. Design and assessment of an example building are conducted in Sections 4 and 5. Discussion and conclusions are presented, respectively, in Sections 6 and 7.

2. BRBs and SDOF structures

2.1. Buckling-restrained braces

The properties of BRBs have been well documented elsewhere (e.g. [4]). In this paper only a brief summary is offered. Two types of BRBs are commonly available: all-steel BRBs (e.g. [16]) and unbonded BRBs (e.g. [17]). For illustration, a typical unbonded BRB is shown in Fig. 1a, which consists of two parts: a core and a case. The core is commonly made of a steel plate which is weaker in the central zone in order to concentrate the plastic deformation there. The case is normally made of a steel tube filled with mortar to restrain the core and avoid buckling due to compressive loads. An unbonding material is located between the core and the mortar to avoid direct interaction. As observed in Fig. 1b, when a BRB is subjected to cyclic axial loads, a stable hysteretic behaviour is appreciated with slightly higher capacity in compression than in tension. For simplicity and for illustration purposes, an equivalent bilinear hysteretic model (Fig. 1c) is used for the BRB to develop the parameters of the proposed method. However, diverse hysteretic characteristics can be used during the design process.

The load capacity of a BRB can be estimated as $P_{ye} = f_{ye}A$; being f_{ye} and A the expected yielding stress of the composing material of the core and the corresponding cross-sectional area of the weaker part. It shall be noted that expected rather than nominal properties are considered. The yielding displacement can be estimated from:

$$d_{ye} = \frac{1}{f_k}\frac{L}{AE}P_{ye} = \frac{1}{f_k}\frac{f_{ye}}{E}L \tag{1}$$

where E is the modulus of elasticity; L is the total length of the BRB; and f_k is a factor that takes into account the geometry of the core, that can be established from catalogues of the manufacturers, and that can take values between 1.2 and 2 or even higher. For the sample BRB of Fig. 1a, f_k can be estimated as [17]: $f_k = 1/[\eta(1-\gamma)+\gamma]$; being $\eta = A/A_{end}$ and $\gamma = L_y/L$.

2.2. The idea of designing frames with BRBs

First, the differences between frames and frames with BRBs need to be distinguished. When the beams of a frame yield, a bi-linear behaviour is usually exhibited. If the columns of that same frame yield at a later time, it may develop a tri-linear behaviour. In this situation, the beam and column are structural members of the frame, and the frame can be treated as a SDOF oscillator with bi-linear behaviour (in exceptional cases, tri-linear behaviour may be observed). For a frame with a BRB, the BRB is not necessarily part of the frame. Thus the BRB can be designed in parallel with the frame because it does not add a new degree of freedom, and the frame and the BRB form two sets of bi-linear curves – which together are called *dual system*.

For convenience, moment resisting frames (MRFs) are referred hereafter as conventional structures (Fig. 2a) while MRFs equipped with BRBs are referred as dual structures or dual systems (Fig. 2b).

When a conventional structure is subjected to a major earthquake, the structure may be damaged due to large deformation demands, as shown in Fig. 2a. If a BRB is installed into the structure (to form a dual structure), it is expected that the BRB would absorb a good amount of energy and be damaged while the structure remains in its elastic range of deformation (Fig. 2b). This requires a rational design of the BRB or of the frame and the BRB. This subsection provides the basic idea for such a design.

While the response of a conventional structure can be usually modelled using a bi-linear single degree-of-freedom (SDOF) oscillator with mass m, damping coefficient c_1 and stiffness k_1, that of a dual structure can be modelled using a dual SDOF oscillator consisting of the SDOF oscillator and a secondary part (representing the device) with damping coefficient c_2 and stiffness k_2, as shown in Fig. 3a. Fig. 3b illustrates the load and deformation capacities of the dual oscillator in which the primary part starts to yield at d_{y1} when subjected to a force V_{y1} and the secondary part yields at d_{y2} when it experiences a force of V_{y2}. The combined capacity of the dual oscillator is illustrated in a dashed line in Fig. 3b. Then, the question is how to select properly the properties of the main structure (d_{y1} and k_1, and hence V_{y1}) and those of the BRB (d_{y2} and k_2, and hence V_{y2}) that allow controlling satisfactorily the displacement demands induced by earthquake actions while ensuring that the BRB yields first.

In this paper, it is proposed that the moment resisting frame is initially designed under the condition of gravity loads. This provides the initial values of the primary part (i.e. d_{y1} and the lower limit of k_1). Then, one of the next approaches may be followed to control the displacement demands: (1) by fixing the initial values of d_{y1} and k_1, find the values of d_{y2} and k_2; or (2) for a desired proportion of the BRB to the load capacity, find the properties of both the primary and secondary parts. Both approaches are addressed in the following subsections.