A numerical model of the structural behavior of buckling-restrained braces

F. López-Almansa [a,*], J.C. Castro-Medina [b], S. Oller [c]

[a] Technical University of Catalonia, Architecture Structures Department, Avda. Diagonal 649, 08028 Barcelona, Spain
[b] Technical University of Catalonia, Department of Geotechnical Engineering and Geosciences, Campus Nord UPC, 08034 Barcelona, Spain
[c] Technical University of Catalonia, Strength of Materials and Engineering Structures Department, Campus Nord UPC, 08034 Barcelona, Spain

ARTICLE INFO

ABSTRACT

This work presents a numerical model of the cyclic structural behavior of dissipative buckling-restrained braces, commonly used as an alternative to classical concentric braces for seismic protection of building frames and other structures. Such devices are usually composed of a slender steel core embedded in a stockiest casing that is intended to prevent its buckling when it is under compression. The casing is made either of mortar or steel, and a sliding interface is interposed between the core and the casing to prevent excessive shear stress transfer. The behavior of the steel core is described by a damage and plasticity model; the behavior of the mortar casing is described by an isotropic damage model and the sliding behavior of the interface is described by a contact penalty model. These three models are implemented in the Abaqus software package following an explicit formulation. The ability of this algorithm to reproduce the cyclic behavior of buckling-restrained braces is verified in a number of representative yet simple situations. The accuracy of the proposed model is checked by comparison with experimental results; a satisfactory agreement is obtained. Preliminary conclusions are issued and further research needs are identified.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Energy dissipators are a convenient option for earthquake-resistant design of buildings and other civil engineering constructions since these devices absorb most of the input energy thus protecting the main structure from damage even under strong seismic motions [17,37]; many applications have been reported [24]. Several types of devices have been proposed; those based on plastification of metals (commonly termed as hysteretic) are simple, economical and reliable while have shown repeatedly their usefulness. Among them, the buckling-restrained braces are one of the dissipators that have been mostly used, mainly for seismic protection of building frames [43,11]. They consist of slender steel bars connected usually to the frame to be protected either like concentric diagonal braces or like concentric chevron braces (as shown by Fig. 1a). Under horizontal seismic excitations, the inter-story drift motion generates axial strains in such steel bars beyond their yielding points. The buckling of these core bars is prevented by embedding them in a stockiest encasing; such casing is usually composed either of steel elements [18,41] or of mortar coated with steel (see Fig. 1b). Some sliding interface between the steel core and the surrounding material is required to prevent excessive

shear stress transfer, since it would reduce the longitudinal stress in the core thus impairing the energy dissipation capacity. As well, that interface involves some clearance between the core and the mortar; such gap is required to allow the Poisson expansion of the core during compression.

The buckling-restrained braces possess several relevant advantages compared to other hysteretic devices:

- These dissipators constitute themselves a bracing system and no additional braces are required to connect each device to the main frame.
- Since the dissipative part of the device can encompass near the whole length of the brace, the required strain is rather low. Therefore, the plastic excursions are moderate; as the degree of plastification is uniform along the whole body of the core, expectedly the fatigue resistance will be high.
- A relevant experience is available since a number of individual and sub-assemblage tests have been carried out [41,7,22,38, 42,21,12,25] and many realizations have been reported, mostly in Japan [18], Taiwan [41], Canada [39] and the United States [7]. Preliminary versions of design codes have been proposed [19,20,31] and many references about design procedures are available [38,42,15,6,34,9].
- The ratio between the dissipated energy and the added material is the highest in the comparative devices [28]; such added material comprises the dissipators, the rest of the bracing system and the connections.

* Corresponding author. Tel.: +34 93 4016316, +34 60 6807733; fax: +34 93 4016320.
  E-mail address: francesc.lopez-almansa@upc.edu (F. López-Almansa).

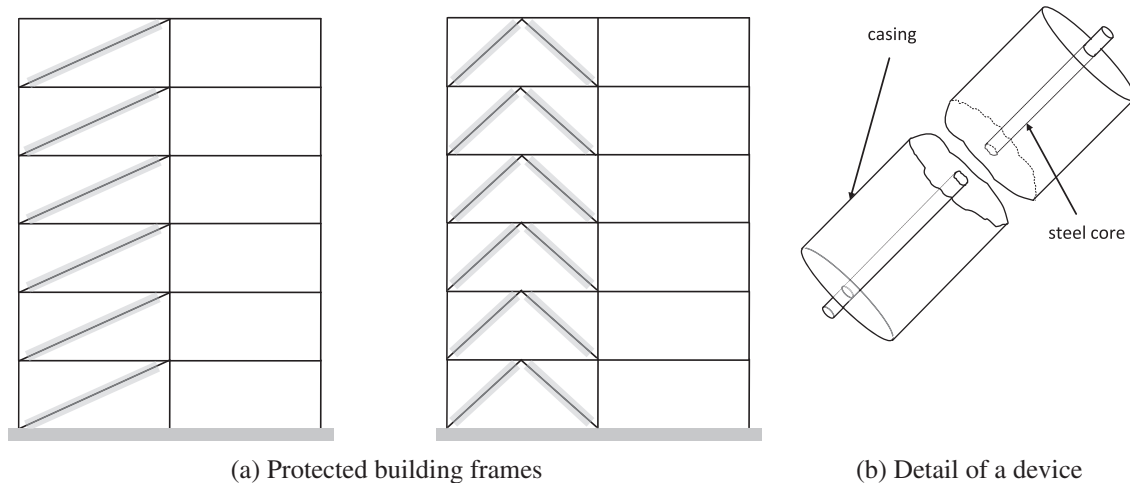(a) Protected building frames　　　　　　　　　　(b) Detail of a device

Fig. 1. Buckling-restrained braces.

In spite of the aforementioned relevant existing background about the buckling-restrained braces, there are still some open questions dealing mainly with the numerical modeling of the buckling behavior of these devices. The buckling design of the mortar-steel coating is based usually in simplified second-order formulations [7,42] whose parameters usually are not selected from the actual characteristics of the device but mainly from semi-empirical considerations; hence, such models are not highly accurate and might yield unsafe results. In Refs. [29,30], approximate expressions of the critical axial force and maximum bending moment in the casing are derived in terms of the actual axial force and the initial eccentricities the core and of the casing; the accuracy of this formulation is checked by comparison with experimental results. Ref. [10] presents a similar study for buckling-restrained braces whose sliding interface consists of a small air gap. In that work, a finite element model of the cyclic behavior of the considered devices is derived; this model is implemented in the computer program Abaqus [1]. The von Mises yielding criterion was considered in the steel core and restraining members; the cyclic effects were described by a combined isotropic and kinematic hardening model. The behavior of the concrete was assumed to be elastic. The sliding interaction between the steel core and the restraining members was modeled as a hard contact behavior, allowing separation of the interface in tension and no penetration in compression; a friction coefficient equal to 0.1 was adopted to simulate greasy steel interfaces.

Apart from these rather simplified models, an accurate and comprehensive numerical model of the coupled nonlinear behavior of all the involved elements (steel core, casing and sliding interface) has not yet been proposed. This lack hinders the deep understanding of the structural behavior of these devices, compels that the design is based on uncertain and over-conservative approaches and prevents the proposal of innovative and daring solutions. This work aims to close this gap by proposing an accurate and reliable numerical finite element model of the structural behavior of buckling-restrained braces composed of a steel core surrounded by a mortar and steel casing. This model considers the joint behavior of the involved materials (inner and outer steel, mortar and sliding interface) and accounts for the partial sliding between the core and the encasing mortar. The buckling behavior of the steel core is described by a coupled damage and plasticity model formulated for large displacements; the behavior of the mortar casing is described by an isotropic damage model and the sliding behavior of the interface is described by a contact penalty model. These three models are jointly implemented in the Abaqus software package

[1] following an explicit formulation; the resulting combined model is aimed to describe the structural behavior of buckling-restrained braces and constitutes the main contribution of this work. The ability of the three individual models to simulate the corresponding behaviors and the capacity of the combined model to reproduce the cyclic behavior of buckling-restrained braces are verified in a number of simple yet representative situations. The accuracy of the proposed algorithm is checked by comparison with two sets of available experimental results [29,25]; satisfactory agreements are obtained. Arising from these studies, relevant conclusions are issued and further research needs are identified.

This work belongs to a research project that aims to promote the mass use of patent-free buckling-restrained braces for seismic protection of buildings in developing countries. The research approach consists of: (i) designing, producing and testing individually short length dissipators (about 400 mm long) [27,30], (ii) taking profit of the gained experience to design, produce and test individually larger prototype devices (near 3000 mm long) [29], (iii) deriving a simplified model of the buckling behavior of these devices [29], (iv) developing an accurate numerical model of their structural behavior, (v) designing, producing and testing on sub-assemblies a number of full scale dissipators and (vi) performing a numerical parametric study about the seismic efficiency of such devices. The first three stages are completed while the last three ones are still in progress; this paper deals mainly with the fourth stage. It is expected that the proposed model will allow designing devices that are more slender than the currently available ones; such devices might be less costly and, hence, more suitable for mass use in developing countries.

2. Isotropic damage model for the mortar casing

The behavior of the mortar casing is described by a triaxial isotropic damage model. Damage models [23] consist basically of describing the degradation of the material by a scalar damage index d ranging between 0 (no damage) and 1 (destruction):

$$\boldsymbol{\sigma} = (1-d)\,\boldsymbol{\sigma}_0 = (1-d)\,\mathbf{E}_0 : \boldsymbol{\varepsilon} \tag{1}$$

In this constitutive relation tensors $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ represent stresses and strains, respectively; $\boldsymbol{\sigma}_0$ is the undamaged stress tensor and $\mathbf{E}_0$ contains the undamaged values of the constitutive parameters. Eq. (1) shows that the undamaged behavior is described by a linear elastic multiaxial model; damage arises when $F(\tau, r) = G(\tau) - G(r)$