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Experimental damping on frame structures equipped with buckling-restrained braces (BRBs) working within their linear-elastic response

Héctor Guerrero[a,*], J. Alberto Escobar[a], Amador Teran-Gilmore[b]

[a] Institute of Engineering, Universidad Nacional Autónoma de México, Mexico
[b] Department of Materials, Universidad Autónoma Metropolitana, Mexico

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ABSTRACT

It has been widely recognised that the source of damping on structures is not viscous. However, an equivalent viscous damping, that generates similar dynamic response of structures, is used for simplification purposes. Under such consideration, this paper presents the experimental measurements of damping on structures equipped with Buckling-Restrained Braces (BRBs) working within their linear-elastic range. For comparison purposes, tests were also conducted on bare structures (without BRBs) and on a structure fitted with a conventional brace. All the experiments were conducted on a shaking table. The results show that, while the test with conventional brace did not show increase of the damping ratio, BRBs significantly did. This happened even when both, the main structure and the BRBs, exhibited linear-elastic response. A model is proposed to account for the dissipative forces observed on the experiments. The findings of this study are significant as they show that BRBs start dissipating energy at low levels of displacement; and this energy dissipation must be taken into account in the context of performance-based seismic design, so that the dynamic response demands on such structures are estimated properly.

1. Introduction

Buckling-restrained braces (BRBs) have become increasingly popular in several seismic countries. This is observed on the increasing number of publications related to BRBs. These devices are composed of a metallic core and a case that restrains buckling under compressive loads [1,2]. Although there are diverse types of BRBs, the most popular type is composed of a steel core with a case made of a steel tube, which is filled with concrete. Normally, the core has a smaller area and concentrates plastic deformations and energy dissipation. The core is also referred as the yielding zone. An important component of BRBs is an unbounding material, which is located between the core and the concrete infill in order to avoid direct interaction between them. An extended description of BRBs is detailed in Refs. [1,3], where the reader is referred to for further details.

Diverse experiments show that BRBs are highly effective to dissipate large amounts of energy under cyclic loading (e.g. [1,2,4]). The source of this dissipation capacity is plastic deformation of the metallic core. The first developments and experiments were developed in Japan [5–7]. Then, numerous experiments were carried out in North America, Europe and many other places. Cameron et al. [8] presented the results of a testing program on five isolated BRBs. Displacements, equivalent to inter-storey drift demands of up to 3%, were induced on the devices. Stable hysteretic loops were observed. The authors concluded that BRBs are an attractive alternative to conventional systems. In 2003, Merrit et al. [4] tested six large-size BRBs at the University of California in San Diego. The authors reported stable hysteretic behaviour of the BRBs that included displacement ductility ratios higher than 10, and cumulative ductility levels between 600 and 1400. Similar results were found by Newell et al. [9] after testing two pairs of BRBs with flat and cruciform cross-sections. Significant to note from the tests by Cameron et al. [8], Merrit et al. [4], and Newell et al. [9], is that BRBs have higher load capacity than that predicted with nominal yielding properties of the metallic core, and that the total capacity in compression is higher than that observed on tension. This is attributed to overstrength of the materials, strain hardening, and Poisson effect. Note the latter generates lateral expansion of the steel core and induces compression stresses on the surrounding concrete, resulting in frictional forces between the steel and concrete surfaces.

Regarding testing of BRBs located on frame sub-assemblages, Tremblay et al. [10] tested six BRBs on a single-storey single-bay steel frame. Different yielding lengths and case types were tested. A test using a conventional brace was also included for comparison purposes. The results show that BRB-frame sub-assemblages performed very well

* Corresponding author.
E-mail addresses: hguerrerob@ii.unam.mx (H. Guerrero), jess@pumas.iingen.unam.mx (J.A. Escobar), tga@correo.azc.uam.mx (A. Teran-Gilmore).

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under simulated seismic loads, reaching strain deformations close to 5% and displacement ductility ratios around 8. The results of the test with the conventional brace showed significantly reduced energy dissipation capacity (around 13% of that dissipated by BRBs), although it was seen that the brace specimen withstood the loading protocol without fracture failure. An interesting observation from that study was that the BRB cores, extracted after loading, presented permanent high-mode buckling deformation. Indeed, one of the study conclusions was that high-mode buckling deformation generates frictional forces between the core and the case; leading to higher load capacity in compression than in tension. Certainly, both the lateral expansion produced by Poisson effect and high-mode buckling of the steel core induce compression stresses in the surrounding concrete, generating frictional forces and, as a result, the observed higher capacity in compression than in tension. Fahnestock et al. [11] tested large-scale buckling-restrained braced frame using a hybrid pseudo-dynamic testing method. They found that BRBs exhibit excellent performance, reaching inter-storey drift deformations of up to 5% and maximum ductility demands over 25 with stable behaviour, i.e. with stable hysteretic loops. Mazzonlani et al. [12] conducted experimental studies of full-scale, one-bay, two-story, reinforced concrete (RC) frames upgraded with two types of steel dissipative bracing systems, namely: eccentric braces (EBs) and all-steel BRBs. They found that both systems are simple and effective to retrofitting existing structures; however, BRBs provided better performance than EBs as they presented larger deformation capacity. Di Sarno and Manfredi [13] tested full-scale, two-bay, two-storey, reinforced concrete (RC) frames with and without BRBs. After subjecting the structures to cyclic loading, the authors concluded that BRBs are a viable solution to improve the lateral load capacity and energy absorption capacity on structures. An interesting observation from this study was the reported values for the equivalent damping ratios, which included the displacement-dependent hysteretic damping of the frames. The values averaged 13.2% for the bare frames and 19.0% for the retrofitted frames. These values did not include velocity-dependent damping, as the tests were conducted quasi-statically. More recently, Della Corte et al. [14] conducted inelastic cyclic quasi-static tests of a full-scale, existing damaged, RC building retrofitted using all-steel dismountable BRBs, i.e. BRBs made of a steel core and a steel case that allows inspection after the occurrence of an earthquake. The reported results showed that, even when the existing structure was heavily damaged, a peak inter-storey drift ratio of 3% was reached, showing that BRBs are a feasible and practical solution for retrofitting damaged structures. Again, this study reported high-mode deformation of the BRB cores, which generated large stress levels and local deformations on the steel case.

The studies described in the previous paragraphs show that BRBs are an effective solution to dissipate large amounts of seismic energy. However, dynamic tests of structures equipped with BRBs, on shaking tables, are desirable because they provide more reliable means of assessing the response of structures subjected to loads in similar conditions to actual earthquakes (e.g. [15,16]). Unfortunately, the number of shaking table tests is reduced; mainly because of the cost that they represent. Only few tests are available on the literature; which are described as follows. Special attention is paid to the reported damping, which is the main topic of this paper. Experiments of steel and concrete building models on a shaking table by Guerrero et al. [17,18] showed that BRBs increase damping significantly, even under linear-elastic demand levels. In the USA, Vargas and Bruneau [19] conducted shaking table tests, using a synthetic ground motion, of a three-storey one-bay steel framed model on a scale of 1/3, with and without BRBs. Significant reductions of the inter-storey drifts were seen (by 70%). A significant observation was that the viscous-dependent damping ratio, in the first mode, increased from 2% in the bare model to 5% in the fully-equipped model. In Japan, Kasai et al. [20] conducted a shaking table testing programme of a full-scale five-storey steel framed building. Tests with and without BRBs were included. The results showed that the inclusion of BRBs reduced displacements, shears and accelerations demands. Interestingly, similar damping ratios (of less than 2%) were reported in the models with and without BRBs for white-noise ground motions; while values between 4% and 9% were reported under seismic action on the model with BRBs. These values showed to be intensity-dependent. In China, tests of a full-scale pin-connected steel frame equipped with BRBs were conducted by Hu et al. [21]; who observed adequate performance of BRBs under seismic ground motion. Unfortunately, damping values were not given. Yamaguchi et al. [22] and Hikino et al. [23] conducted shaking table tests of sub-assemblages with BRBs. In the former study, the damping ratios with and without one BRB were 2.3% and 1.7%, respectively; while the latter study reported a damping ratio of 3% for the case with one BRB.

From the literature review, it can be observed on one hand that, although some studies have reported values of the damping on structures equipped with BRBs, there is still no consensus on the level of increase produced by BRBs. Moreover, understanding how this increase occurs is still a knowledge gap that needs to be filled. On the other hand, most studies have focused on assessing the response of structures equipped with BRBs under severe inelastic behaviour; however, no significant attention has been paid to their response at linear-elastic deformation demands. Therefore, the focus of this paper is in the experimental response of structures equipped with BRBs subjected to linear-elastic demands; because, as it will be observed later, for example on Fig. 10, such structures start dissipating large amounts of energy way before the BRB cores reach their yielding strength capacity. This is absolutely significant in the context of performance-based seismic design, as estimation of the expected behaviour and demands on structures needs to be estimated with reliability, so that expected economic impacts or losses are determined as accurate as possible.

This paper presents the results of shaking table experimental tests of concrete and steel framed models equipped with BRBs conducted under linear-elastic response demands. The attention has been focused on the levels of damping with and without BRBs. The main contributions of the paper are: 1) it has been found that BRBs increase the level of damping on structures; 2) it is shown that this increase depends on the ground motion intensity, and the level of axial deformation of the BRBs; 3) the damping dissipation can be assumed to have a source on frictional forces generated by interaction between the core and the case concrete; 4) an equation has been proposed so that equivalent frictional forces can be calculated as a function of the level of axial deformation of the BRBs; and 5) with the help of a test with a conventional brace, it has been shown that, contrary to the effect of BRBs, conventional braces do not increase damping.

2. Experimental tests of a multi-storey building

A four-storey building was tested on a shaking table with and without BRBs. It was a reinforced concrete structure made of precast elements. Fig. 1 shows the structure model and dimensions. It had a total height of 4.40 m with inter-storey height of 1.10 m. The model had one bay on each horizontal direction with a length of 3.30 m each from centre to centre. The columns cross-sections were 0.20 m × 0.20 m, while those of the beams were 0.15 m × 0.27 m. Regarding the materials, the concrete had a nominal resistance of $f'_c = 50$ MPa; while that of the steel was $f_y = 420$ MPa. The masses of the model were 420 kg/m^2 on floors 1–3 and 410 kg/m^2 on the top floor. More details of the experiment can be found in ref. [18].

The BRBs used in the experiment are shown in Fig. 2. They consisted of a steel core, an unbonding material, and a case made of three steel tubes filled with concrete (see shaded areas). The core had a weaker zone in the middle of 800 mm and two stronger connecting ends of 713 mm each. The core thickness was 6 mm for the BRBs of storeys 1 and 2, and 3 mm for those of storeys 3 and 4. The steel nominal resistance was $f_y = 250$ MPa. The unbonding material consisted of a polytetrafluoroethylene (PTFE) film with a thickness of 0.4 mm. The