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Effects of Buckling-Restrained Braces on reinforced concrete precast models subjected to shaking table excitation

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

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

A R T I C L E I N F O

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A B S T R A C T

To examine the effects of Buckling-Restrained Braces (BRBs) on precast, reinforced concrete (RC) models, shaking table experiments were conducted on two four-storey frames at a scale of 1/3. One model was without BRBs and designed according to common practice in Mexico (Model 1), while the other (Model 2) was equipped with BRBs and designed according to a displacement-based methodology. This paper presents several comparisons between the two models to illustrate the benefits of the BRBs. The fundamental frequencies, damping ratios and seismic response of the models were monitored. The models were subjected to two types of ground motion: low-intensity white noise, and the SCT-EW record of the M8.1 Michoacán earthquake of 19/09/1985 scaled to 50, 100, 150 and 200%. The most significant findings of this study were: (1) for the linear-elastic response, the BRBs increased the damping ratios significantly; and (2) improvements of the seismic response, due to the BRBs, were quantified in terms of several parameters. Retrofitting was also explored by replacing the BRBs in Model 2 after the original model had been subjected to the seismic tests.

1. Introduction

Reinforced Concrete (RC) precast structures are attractive to builders and developers because such systems can be assembled quickly, and provide cost savings on formwork, materials and the workforce [1]. While some countries have devoted important research and development efforts to provide them with stable plastic behaviour [2], and even, self-centering capacity [3]; other countries still view the use of RC precast structures in seismic zones with scepticism [4]. Particularly, engineers in developing countries consider that the complications involved in providing them with stable earthquake resistance counteracts the advantages they offer, and this has discouraged their extensive use in ample geographic regions. Despite the risks involved, precast structures with standard detailing (as opposed to ductile) are being built in earthquake-prone zones. Combining the benefits of precast concrete industry with protection systems, such as Buckling-Restrained Braces (BRBs), can help to overcome this scepticism and provide many countries with the possibility of using, in an extensive, efficient and safe manner, precast systems.

Buckling-Restrained Braces (BRBs) are an effective way of reducing damage and collapse due to earthquake action. They have a high energy dissipation capacity, because their seismic behaviour is characterised by stable and symmetric hysteretic loops [5,6]. Numerous studies on individual BRB members [6,7], sub-assemblages [8–10], and braced frames [11,12] indicate that these devices work well if they are properly designed and detailed. For retrofitting existing damaged structures, BRBs are also very effective. Proof of that are several successful tests conducted by Della Corte et al. [13] and Mazzolani et al. [14] on reinforced concrete buildings; which demonstrates the capacity of the devices. While Della Corte et al. [13] used an innovative all-steel dismountable type of BRB that allowed reaching interstorey drift ratios of 0.03 with stable response, Mazzolani et al. [14] conducted experiments using eccentric braces (EBs) and all-steel BRBs. Their results showed that both EBs and BRBs are effective to improve the seismic performance of the tested structures; however, BRBs showed to be superior as they provided larger displacement capacity, and the increase of stiffness and strength can be better controlled. The above advantages help to avoid damage to existing structural elements.

Shaking table tests provide a reliable means of assessing the response of structures to dynamic loads (e.g. [15,16]). In this regard, several tests have been conducted on steel frames equipped with BRBs. For example, Vargas and Bruneau [12] tested a 1/3 scale model of a three-storey one-bay steel frame with, and without, BRBs, on a shaking table in the USA. They reported that the lateral displacements and inter-

* Corresponding author.
E-mail address: hguerrerob@ii.unam.mx (H. Guerrero).

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storey drifts were reduced by 70% in the braced frame, while floor accelerations remained almost unchanged. An increase in the damping ratio in the fundamental mode, from 2% in the bare model to 5% in the fully-equipped model, was reported. Kasai et al. [17] tested a full-scale five-storey steel framed building, equipped with four different types of energy dissipaters (including BRBs), on a shaking table in Japan. The frame was tested without, and with, the devices in four of the five storeys. It was subjected to low-intensity white noise and the Takatori motion of the 1995 Kobe earthquake, scaled to different intensity levels. The results showed that the inclusion of BRBs reduced the displacements, storey shears and absolute floor accelerations. For the low-intensity tests, similar damping ratios (of less than 2%) were reported in the models with, and without, BRBs, which is different to the findings in the study by Vargas and Bruneau [12]. However, damping ratios between 4% and 9% were reported in the model with BRBs, for the seismic tests. It was also observed that the damping ratios were intensity-dependent. In China, Hu et al. [18] tested a full-scale pin-connected steel frame equipped with BRBs. They found that the BRBs performed well under high-intensity seismic ground motion; drift demands were well controlled and no damage was encountered in the structural elements of the frame. However, no damping values were reported. Yamaguchi et al. [19] tested a steel sub-assemblage composed of one column, a beam and a BRB as a diagonal brace. Shaking table tests with, and without, the BRB, showed that lateral displacements were reduced by 65% when the BRB was included. The damping ratios with, and without, the BRB were 2.3% and 1.7%. Hikino et al. [20] performed shaking table tests on a single-storey single-bay steel frame, with two BRBs in chevron configuration. Good behaviour was observed if out-of-plane buckling of the brace-beam connection was prevented. A damping ratio of 3% was reported for the frame with BRBs.

From the literature review, two main gaps have been identified: (1) while some researchers have reported increased damping ratios due to the BRBs, for low intensity excitation, others have not; and (2) only steel models equipped with BRBs have been tested on shaking tables. The latter finding is especially significant for RC precast systems, since experimental studies on beam-column sub-assemblages have shown that, when complicated detailing and construction measures are not carried out, they exhibit different behaviour in comparison with conventional concrete structures, [1,21,22]. Therefore, it is of interest to examine, within the context of damage-tolerant structures [23], the performance of RC precast structures equipped with BRBs to assess the combination of the traditional advantages of precast construction and the efficiency and reliability of BRBs. This is important because significant human and economic losses have occurred in earthquakes [24,25], and developing countries can't afford the risks of building precast systems with standard detailing in high seismicity zones.

The objective of this work was to compare the dynamic properties and seismic response of two RC precast frame building models with, and without, BRBs. The experiments presented in this paper are indicated in Fig. 1. Two types of input were used to excite the models; low-intensity white noise, and horizontal seismic ground motion with different intensities. While no BRBs were used in the first model, hereafter referred to as Model 1, the second model (Model 2) was tested with, and without, BRBs. White noise was used in all tests to assess the models' dynamic characteristics; whilst seismic input was used in three cases to evaluate seismic response. Note that Model 2 was re-tested following the seismic action after replacing the BRBs by a new set. This simulates retrofitting the structure following earthquake loading and assuming that some devices may present internal damage. It also helps to explore the feasibility of the fuse concept, i.e. easy replacing of the devices after severe demands that brings the structure to its pre-earthquake state. The dynamic behaviour and seismic response of the models were assessed and they are compared in this paper.

2. Models

A prototype structure was selected for this project. It was assumed to be located on the lakebed zone of Mexico City, which is characterised by soft soils that generate long-duration narrow-banded ground motions with well-defined and long predominant periods of motion. The structure had four storeys and one bay in each horizontal direction. For comparison, two test models were constructed. The first model (Model 1) was designed according to the strength-based procedure required by the Mexico City Building code [26], and did not have BRBs. Details of the design are provided in Section 2.2. The second model (Model 2) was equipped with BRBs and designed using the methodology proposed by Guerrero et al. [27], which is based on controlling the lateral displacements. The experimentally based examination of the two different design approaches enables some interesting comparisons to be made.

Because of the capacity of the shaking table [28], the two models were first designed at full scale and then built at a linear scale of 1/3. The full-scale models had a square base of 10 × 10 m and a height of 13.2 m. Fig. 2 gives the model dimensions and a photograph of Model 2. The total masses of the models were 420 kg/m^2 on floors 1–3 and 410 kg/m^2 on the top floor. A factor of mass per area of 1/2 was also used due to weight constraints of the testing platform. Similitude laws were developed accordingly, and are presented in Table 1 together with the relationships used to calculate the scaled properties from the full-scale values. As an example, the fundamental period of vibration of Model 1, at full-scale, was estimated to be $T_f = 0.5$ s, which is equivalent to $T_s = 0.5/\sqrt{6} = 0.20$ s for the scaled model. However, in Table 1 it is noted that the material properties (modulus of elasticity and stress) are at a scale of 1/1, but other parameters (such as the period of vibration, time step and acceleration) are affected by diverse factors. This was considered for the ground motions used in the experiment by scaling their time and amplitude by $1/\sqrt{6}$ and 2, respectively.

2.1. Precast system

The system, which is currently used in some regions of Mexico, consists of precast beams and columns joined at the nodes using a wet connection (Fig. 3). The connection is similar in many ways to that in [21,29,30], but different because: (a) the precast beams were not introduced into the column windows, instead they were supported by temporary metallic supports which were removed after the cast-in-situ concrete had reached its nominal resistance; and (b) the floor system was supported by concrete corbels located at the bearing beams, so that the floor did not reduce the size of the beams or their capacities.

In addition, column-to-column connections were used, which enabled erection of two or more consecutive storeys. The connections were made at the mid-height of the columns using high-strength grout and connecting steel bars.

During construction, two consecutive storeys were assembled, and the column-to-column connections were made in the middle of the third storey. The models were fabricated in the following order: (1) two storeys were fabricated away from the shaking table; (2) they were then mounted on the table; and (3) the third and fourth storeys were assembled whilst on the table. The finished models were similar to that shown in Fig. 2.

2.2. Design

Initially, a design for a full-scale building was undertaken. Then the model properties and parameters were determined using the scale similitude laws shown in Table 1. It was assumed that the building would be located at the lakebed zone of Mexico City (zone IIIb) and was to be used for residential occupancy. A brief summary of the design basis is given here; further details can be found in Ref. [31].

Model 1 (without BRBs). A strength-based design was conducted as