Some Recent Developments in Structures Fitted with Buckling Restrained Braces (BRBS)

Algunos resultados recientes en estructuras equipadas con Contraventeos Restringidos al Pandeo (CRP)

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Abstract

The authors have conducted several numerical and experimental studies aimed at quantifying the benefits of Buckling-Restrained Braces (BRBS) when fitted in frame structures. The most significant experimental studies include shaking table tests on three building models made of concrete or steel. Among the numerical studies are: 1) the proposal of a seismic design method; 2) an evaluation of the economic benefits of BRBS; 3) studies on the residual displacement of structures equipped with BRBS; and 4) the response of structures equipped with BRBs when subjected to seismic aftershocks. This paper presents a summary of the identified benefits of BRBS for frame structures with the intention of encouraging their use in earthquake zones.

Keywords: Buckling-Restrained Braces (BRBS), passive dissipation systems, shaking table tests, seismic analysis and design.

Resumen

El presente trabajo muestra los resultados de varios estudios numéricos y experimentales que han realizado los autores con la finalidad de cuantificar los beneficios de los Contraventeos Restringidos al Pandeo (CRP) al ser introducidos en estructuras de edificios. Los estudios experimentales más relevantes incluyen pruebas, en mesa vibradora, de modelos de acero y concreto reforzado. Dentro de los estudios numéricos, se incluye: 1) la propuesta de un método de diseño, 2) una evaluación de los benefi-

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cios económicos de los CRP, 3) estudios desplazamientos residuales en estructuras equipadas con CRP y 4) respuesta de estructuras equipadas con CRP sometidas a efectos de réplicas sísmicas. Este artículo presenta un resumen de los beneficios identificados de los CRP en estructuras de edificios con la intensión de incentivar su uso en zonas sísmicas.

Palabras clave: *Contraventeos Restringidos al Pandeo (CRP), sistemas de disipación pasiva, análisis y diseño sísmico, pruebas en mesa de agitación, mesa de vibración.*

Introduction

As seen in figure 1, Buckling-Restrained Braces (BRBs) are typically composed of a metallic core (which is weaker in the center and stronger at the ends); a case composed of a steel tube filled with concrete and an unbonding material to prevent direct interaction between the core and the concrete case.

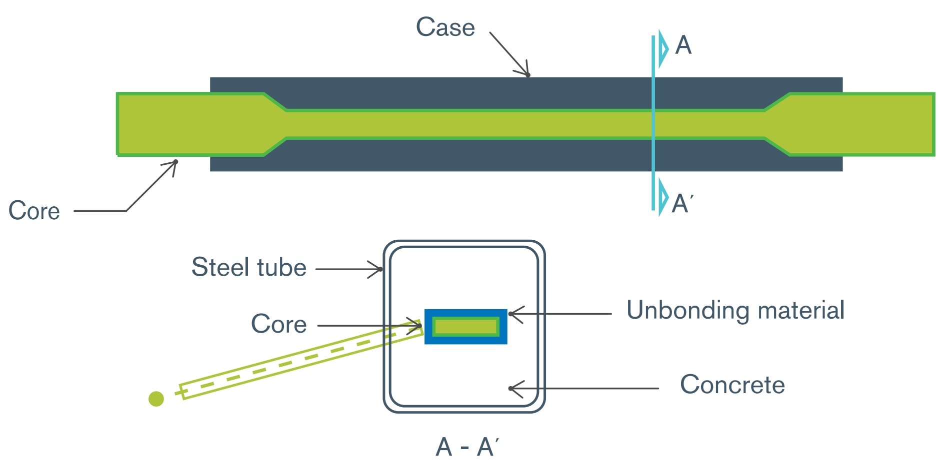

Figure 1: Components of a typical BRB. Image taken from: Héctor Guerrero Bobadilla and others, "Response to Seismic Sequences of Short-Period Structures Equipped with Buckling-Restrained Braces located on the Lakebed Zone of Mexico City." *Journal of Constructional Steel Research* 137, (2017): 37-51.

Figure 2 shows a comparison of BRB performance under cyclic loading versus the performance of conventional braces. It can be clearly seen that BRBs have superior performance as they show a larger area under the curve (that is, they have a larger energy dissipation capacity) and they do not present either stiffness or strength degradation. These advantages are a product of the case, which confines the metallic core and allows for its plastic deformation under tension and compression deformation.

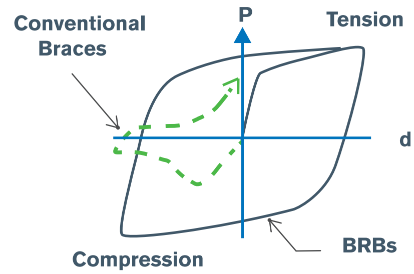

Figure 2: Load-deformation curves for conventional braces and BRBs. Image taken from: Guerrero, Bobadilla and others, "Response to seismic sequences of short-period structures equipped with Buckling-Restrained Braces located on the lakebed zone of Mexico City."

Nowadays, BRBs are popular in earthquake-prone developed nations such as Japan, the United States of America and New Zealand. They are extensively used because of their great efficiency in dissipating large amounts of energy and the fact that they are easy to replace. Unfortunately, their use in poor and developing countries is very rare because most BRBs are privately-made products and their direct and indirect costs are high. Another reason is a lack of awareness of this technology.

The purpose of this paper is to present some recent studies and developments in Mexico on structures equipped with BRBs with the intention of encouraging their use in seismic regions where they are still not implemented widely.

Experimental studies

Shaking table tests on a steel frame model

Figure 3 shows a 1/10 scaled steel frame model tested on a shaking table at the National Autonomous University of Mexico (UNAM).[1]

Figure 4 shows the model's roof displacement relative to its base when subjected to the EW component of the ground motion registered at the SCT-2 station during the April 25, 1989 Mexico earthquake. The ground motion was scaled to reach a Peak Ground Acceleration (PGA) of 0.1g, where *g* is gravitational acceleration. The benefits of BRBs can be clearly seen, as not only were peak displacements reduced but the full total displacement was significantly diminished.

Another significant finding of this experimental study was the observation of an increase in the damping ratio on the model due to the BRBs. This phenomenon occurred even under low-level vibration tests that kept both the BRBs and the frame model within their linear elastic

Figure 3: Héctor Guerrero, *A Steel Frame Model Tested on a Shaking Table at UNAM.* Image taken from: Héctor Guerrero Bobadilla and others, "Experimental studies of a steel frame model with and without buckling-restrained braces."*Ingeniería Sísmica* 95, (2017):33-52.

1 Specific details of the model, experiment setup and results can be found in Héctor Guerrero Bobadilla and others, "Experimental studies of a steel frame model with and without buckling-restrained braces." *Ingeniería Sísmica* 95, (2017): 33-52, where only the most significant results are presented.

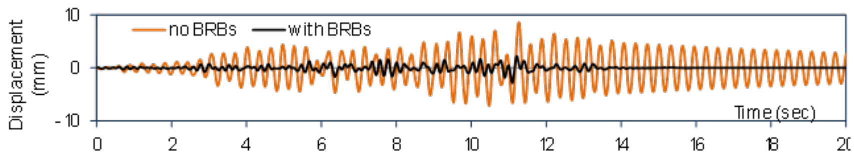

Figure 4: Roof displacement in the model with BRBs when subjected to the SCT2-EW ground motion seen in the April 25, 1989 Mexico earthquake. Image taken from: Héctor Guerrero Bobadilla, and others, "Experimental studies of a steel frame model with and without buckling-restrained braces."

response range. Figure 5 shows an estimation of the damping ratio by means of an energy balance. Figure 5a shows that the model without BRBs had a damping ratio of 0.4% while Figure 5b shows that the damping for the model with BRBs was 7.6%. Using BRBs has the significant benefit of increasing the damping level.

Shaking table tests of two reinforced concrete frame models

Two reinforced concrete frame models, at a scale of 1/3, were tested on a shaking table at UNAM. The first model (model 1) was designed and tested without BRBs, while the second model (model 2) was designed and tested with BRBs. Figure 6 shows a picture of model 2 on the shaking table.

Both models were first subjected to low-intensity white noise motion (WN_{ini}) at the base. Then they were subjected to the EW component of the ground motion registered at the SCT-1 station during the September 19, 1985 Mexico earthquake, scaled to 50%, 100%, 150% and 200%. In the end, the models were subjected once more to low intensity white noise motion (WN_{fin}) in order to determine their final properties after seismic action.

The first outcome of the study was a comparison of the damping level in both models. This was done to verify the increased damping observed in the steel model experiment presented in the previous section.

Again, the damping level was determined by conducting an energy balance. Figure 7 shows the estimated damping for model 1 and model 2 during all conducted tests. Two significant observations are apparent: 1) model 2 (that is, the one with BRBs) had significantly more damping than model 1 in the tests conducted; and 2) the damping level is intensity dependent (the higher the ground motion intensity, the higher the damping ratio).

Another significant observation in this experiment was the level of stiffness degradation in both models. Figure 8 shows the percentage of stiffness degradation in both models after each ground motion. It

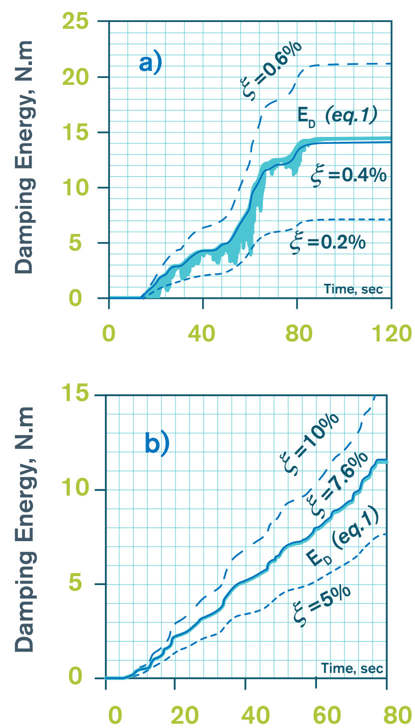

Figure 5: Damping estimate (a) without and (b) with BRBs. Image taken from: Guerrero Bobadilla and others, "Experimental studies of a steel frame model with and without buckling-restrained braces."

was obtained as [1-(f_i/f_{ini})^2], where *fi* is the frequency after the i_{th} test and *fini* is the frequency for the first white noise test (WNini). Here it can be observed that model 1 (that is, without BRBs) has a higher level of stiffness degradation (close to 60%), while model 2 (that is, with BRBs) has about half that (30%). These observations show that BRBs help prevent structural degradation and limit cumulative damage.

Figure 9 shows the dynamic response envelopes for both models when subjected to the SCT ground motion, scaled to 100%. It can be seen that displacement and drift for model 2 is 50% compared to model 1. As the level of structural damage is closely related to displacement and inter-storey drift, this figure shows how BRBs help control lateral displacement and, in turn, damage to structural and non-structural elements. Furthermore, figure 9 explains why stiffness degradation (as observed in figure 8) was lower for model 2 (with BRBs) than for model 1 (without BRBs): BRBs keep lateral deformations lower, which translates to reduced demands on structural elements and cracking.

Figure. 6: Héctor Guerrero Bobadilla, *Reinforced concrete model tested on a shaking table at the UNAM*. Image taken from: Héctor Guerrero Bobadilla, *Seismic Design and Performance of Hospital Structures Equipped with Buckling-Restrained Braces in the Lakebed Zone of Mexico City*. PHD Thesis Dissertation, University of Manchester, UK, 2016.

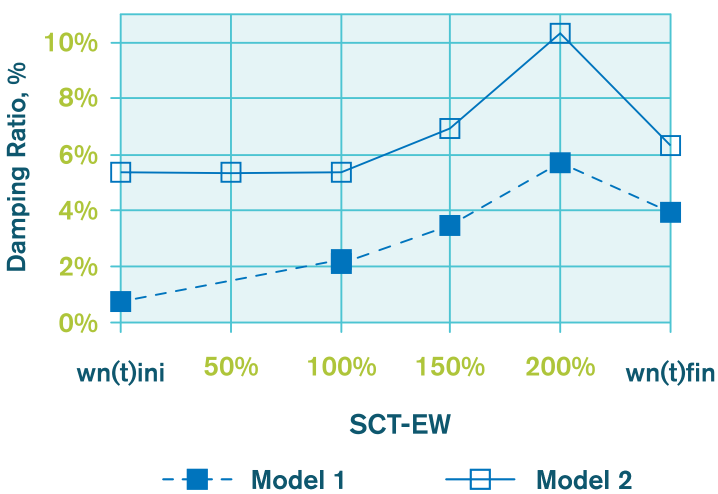

Figure 7: Damping estimate for the reinforced concrete models. Image taken from: Guerrero Bobadilla, *Seismic Design and Performance of Hospital Structures Equipped with Buckling-Restrained Braces in the Lakebed Zone of Mexico City*.

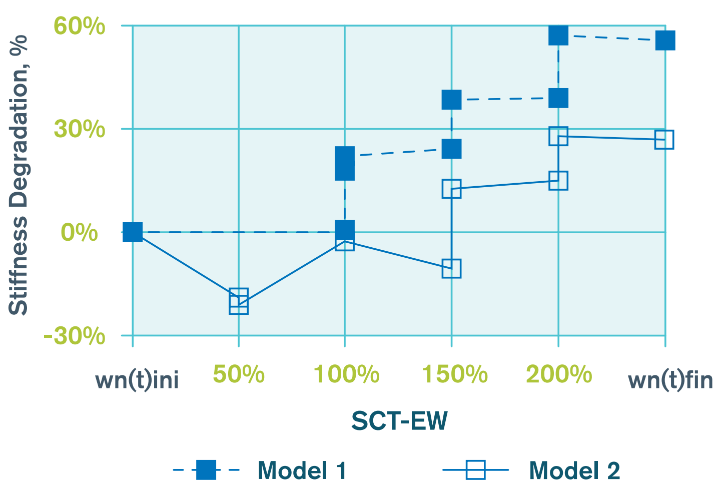

Figure 8: Stiffness degradation estimates for the reinforced concrete models. Image taken from: Guerrero, *Seismic Design and Performance of Hospital Structures Equipped with Buckling-Restrained Braces in the Lakebed Zone of Mexico City*.

Shaking table test of one-story one-bay frames working in parallel

With the intention of further understanding the increase in damping produced by BRBS working within their linear-elastic range, five one-storey one-bay frames, working in parallel, were tested on a shaking table at the UNAM. All of these tests were conducted using low intensity white noise motion to avoid nonlinear response demands.

First, the frames were tested alone, that is, without any BRBS. In the second test, one traditional brace was placed in the central frame. In the third test, the conventional brace was replaced by a BRB. In the fourth test, two BRBS were placed symmetrically. The fifth, sixth and seventh tests were conducted with three, four and five BRBS, respectively. In all of these tests, the BRBS were placed symmetrically.

Figure 11 presents the damping ratios for each test conducted. It can be observed that the first two tests (that is, without BRBS) had a damping ratio lower than 1%, while the tests with BRBS had higher damping ratios (above 6%). Two conclusions are obvious: 1) it can be confirmed that BRBS significantly increase the damping level; and 2) the damping level goes down as the number of BRBS increases. The latter conclusion is attributed to the fact that the axial deformations of BRBS are reduced as the number of BRBS increases. After the experiment, a model was proposed allowing designers to estimate the damping level for structures with inter storey drift. This model is being prepared for publication and will soon be made available.

Figure 10: Héctor Guerrero Bobadilla, *Five one-storey one-bay frames tested on a shaking table.*

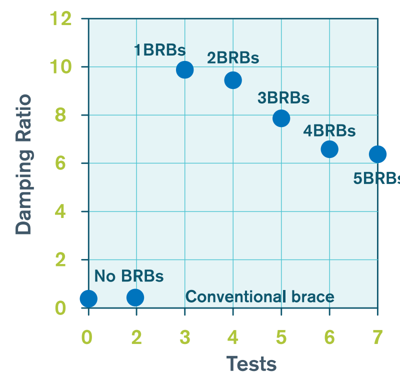

Figure 11: Damping ratio for the tests on the one-storey one-bay frames working in parallel.

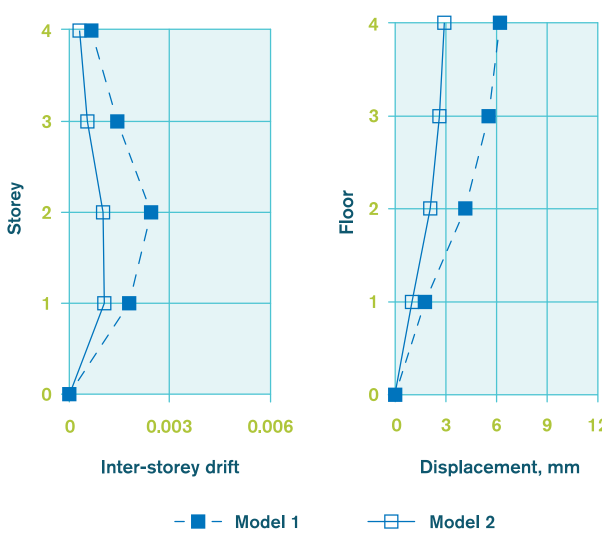

Figure 9: Maximum dynamic response for the model with SCT 100%. Image taken from: Guerrero Bobadilla, *Seismic Design and Performance of Hospital Structures Equipped with Buckling-Restrained Braces in the Lakebed Zone of Mexico City*.

Numeral studies

A method for the seismic design of structures with BRBs

First, a method for the seismic design of structures equipped with BRBs was proposed based on the control of lateral displacements. It assumes, as seen in figures 12 and 13, that: 1) frame structures equipped with BRBs behave as dual structures, namely, as a moment-resisting frame and a braced pinned connected frame; and 2) the dynamic behavior of a dual structure can be represented by a dual single-degree-of-freedom (SDOF) oscillator.

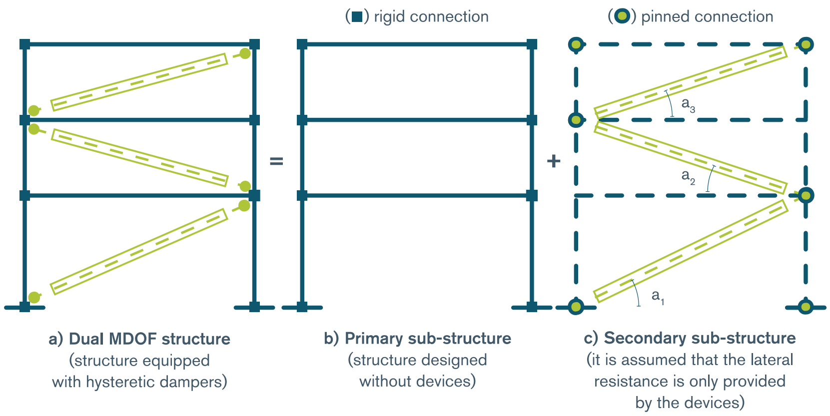

Figure 12: The dual structure subdivided into a moment-resisting frame and a braced pinned connected frame. Image taken from: Héctor Guerrero Bobadilla and others, "A Method for Preliminary Seismic Design and Assessment of Low- Rise Structures Protected with Buckling-Restrained Braces", *Engineering Structures* 123, (2016): 141-84.

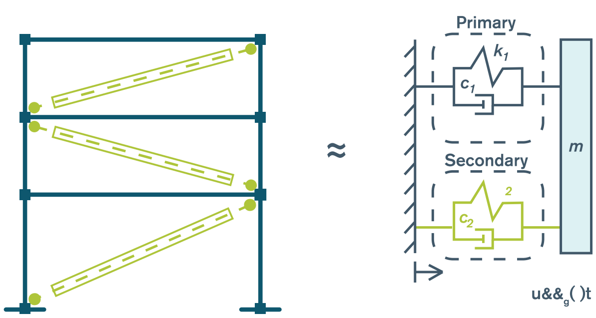

Figure 13: The dual structure represented by a dual SDOF oscillator. Image taken from: Guerrero Bobadilla and others, "A Method for Preliminary Seismic Design and Assessment of Low- Rise Structures Protected with Buckling-Restrained Braces."

Although the method's features are detailed "A Method for Preliminary Seismic Design and Assessment of Low- Rise Structures Protected with Buckling-Restrained Braces".[2] Some of them are described below:

- It allows designers to select the relative contributions of the BRBs and the main structure to total strength capacity. This is significant because designers have the chance to select a balance of contributions from the main structure and the BRBS to create efficient designs.
- It allows for a quick and easy application of the Performance-Based Seismic Design (PBSD) philosophy on structures. This is possible because, during the application of the method, a dual SDOF oscillator, representing a structure equipped with BRBS, is subjected to a set of ground motions scaled to different seismic intensities in order to estimate its dynamic responses (linear and nonlinear). The PEER methodology[3] can then be applied to assess expected performance under different structural scenarios to achieve the best design for stakeholders.

After applying the proposed method, probability distribution functions like those in figure 14 can be obtained. In this figure, three design options are compared by varying the BRBs' cross-sectional areas (A_i) for a case study structure with a seismic intensity of pga=0.2g. Probability distribution functions are useful to stakeholders when deciding which design option is best. For example, in figure 14, it can be seen that the mean repair cost of the structure studied is 0.17C_r , 0.28C_r and 0.50C_r for options 1.5A_i, 1.0A_i and 0.7A_i, respectively, where Ai is the total replacement cost of the structure.

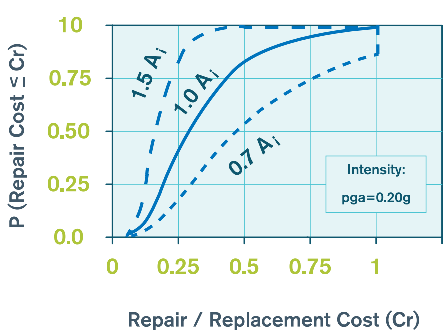

Figure 14: Probability distribution functions for a case study structure equipped with BRBS with different cross-sectional areas. Image taken from: Guerrero and others, "A Method for Preliminary Seismic Design and Assessment of Low-Rise Structures Protected with Buckling-Restrained Braces."

2. Héctor Guerrero Bobadilla and others, "A Method for Preliminary Seismic Design and Assessment of Low-Rise Structures Protected with Buckling-Restrained Braces," *Engineering Structural* 123, (2016): 141-154.
3. FEMA-P58, *Seismic Performance Assessment of Buildings*, Washington D.C. Federal Emergency Managment Agency, 2012.

Evaluation of the economic benefits of BRBs in frame structures

To understand the economic benefits of BRBs in frame structures located in the lakebed zone of Mexico City, three, six and nine-story structures were studied in terms of the varying contribution of BRBs to lateral load capacity. Five cases were studied for each of these structures, as can be schematically seen in figure 15. The cases studied are described below:

- Case 0: A traditional structure (that is, without BRBs) designed to resist full seismic loads. This case serves as reference for the purpose of comparison.
- Case 1: The structure is provided with BRBs. This increases the initial cost but reduces displacement demands on the structure.
- Case 2: For this case, the main frame is redesigned for gravity loads only. BRBs are then provided to match the initial cost of case 0.
- Case 3: Similar to case 2, the main frame is designed to carry gravity loads only. BRBs are then provided to match the same level of displacement demands, as in case 0. This gives us a structure with a lower initial cost than that of case 0, but with a similar dynamic response.
- Case 4: Again, the main frame is designed for gravity loads only. However, in this case, larger BRBs were provided to match the initial cost of case 1.

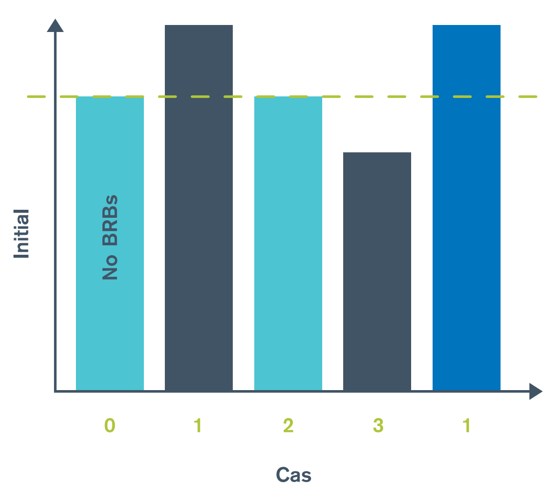

Figure 15: Cases studied for evaluating the economic benefits of BRBs for frame structures. FEMA-P58. *Seismic Performance Assessment of Buildings*.

For this stud y, the FEMA-P58 [4] methodology was applied to assess the performance of the structures and cases under consideration. Several parameters were assessed, such as the probability of collapse, the probability of functionality loss, repair costs and times, etc. For the sake of simplicity, this article only compares initial costs and lifecycle costs, as presented in figure 16.[5] Note that only the results for the six-storey model are shown, as those for the three and nine-storey models were similar. Also, it should be noted that all costs were normalized through the cost of case 0.

From figure 16, the following conclusions can be drawn: 1) in terms of initial cost, the cheapest case is case 3, although the differences between cases 0 to 4 are lower than 5%; 2) in terms of lifecycle costs, all cases with BRBs (cases 1 to 4) were lower than the case without BRBs (case 0) – case 4 was the cheapest, suggesting that the higher the contribution of the BRBs, the lower the lifecycle cost.

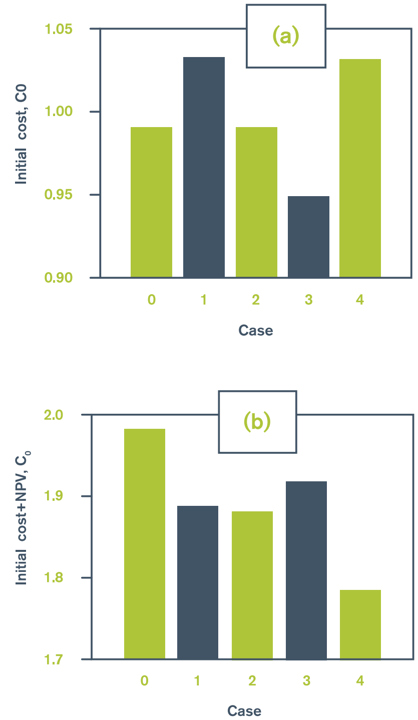

Figure 16: Cost evaluation of the six-story structure: (a) initial costs and (b) life cycle costs. Image taken from: Guerrero Bobadilla and others, "Evaluation of the economic benefits of using Buckling-Restrained Braces in hospital structures located in very soft soils."

The earthquake response of structures equipped with BRBs subjected to seismic sequences

To understand the effects of seismic sequences (mainshock plus aftershocks on steel frames equipped with BRBs, the same buildings and cases seen in the previous section were subjected to three sets of seismic sequences; which are described as follows:

- Set 1: Composed of 28 seismic sequences where the mainshocks and the aftershocks were scaled to the same seismic intensity of *pgv*=61 cm/s, where *pgv* is the peak ground velocity.
- Set 2: Composed of 28 seismic sequences where the mainshocks were scaled to *pgv*=61 cm/s while the aftershocks were scaled to 70% of the mainshocks.
- Set 3: Composed of 28 seismic sequences. The mainshocks were scaled to *pgv*=61 cm/s while the aftershocks were scaled to 35% of the mainshocks.

4 FEMA-P58. *Seismic Performance Assessment of Buildings*.

5 Héctor Guerrero Bobadilla and others, "Evaluation of the economic benefits of using Buckling-Restrained Braces in hospital structures located in very soft soils." *Engineering Structures* 136, (2017): 406-19.

Figure 17 shows, for Case 0 (without BRBs), the heightwise distribution of the mean maximum interstory drift ratios for the six-storey frame subjected to the set 1 seismic sequences. The results for the three and nine-storey frames were similar when subjected to the set 1 seismic sequences. It can be seen that the effects of aftershocks are significant for set 1, in which the mainshocks and aftershocks have the same seismic intensity. The increase in drift demands was not very significant in sets 2 and 3, suggesting that this increase is only relevant when the expected aftershocks have the same intensity as the mainshocks.

Figure 18 shows, for cases 0 to 4, the mean maximum inter-storey drift ratios for the six-storey frame subjected to set 1 sequences. The results for the three and nine-storey frames were similar. Here it can be observed that aftershocks increase interstory drift demands indistinctly, that is, with or without BRBs. Taking this into consideration, an important recommendation can be formulated: when designing structures that may be subjected to seismic sequences, it is important to limit inter-storey drift ratios below a threshold that does not cause undesired damage to the structure. In figure 18, it can be seen that case 4 is the most convenient, as the mean drift demands produced by the full sequences are below 0.01, which is unlikely to cause significant damage to the structure.

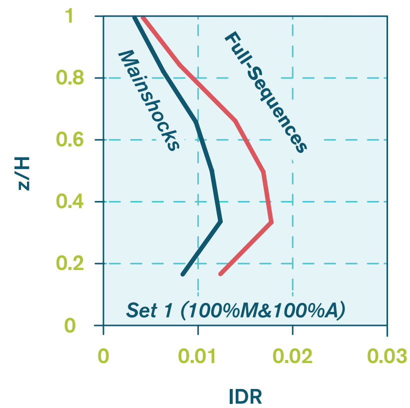

Figure 17: Mean maximum interstory drift ratios for the six-story frame subjected to the set 1 seismic sequences. Image taken from: Guerrero, and others, "Response to seismic sequences of short-period structures equipped with Buckling-Restrained Braces located on the lakebed zone of Mexico City."

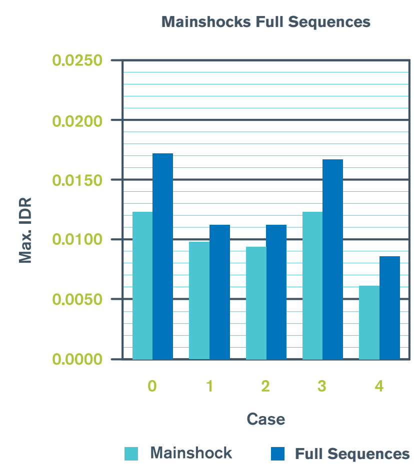

Figure 18: Mean maximum interstory drift ratios by case for the six-story frame subjected to set 1 seismic sequences. Image taken from: Guerrero Bobadilla, and others, "Response to seismic sequences of short-period structures equipped with Buckling-Restrained Braces located on the lakebed zone of Mexico City."

Residual displacement on structures equipped with BRBs

The economic impact of residual displacement (RD) on structures tends to be very high.[6] To understand the residual displacement demands on structures equipped with BRBs, dual SDOF oscillators were therefore subjected to 220 ground motions registered in the lakebed zone of Mexico City.

As can be observed in figure 19, the total capacity of a structure is given by the sum of two curves: the capacity curve of the main (or primary) structure without BRBs plus the capacity curve provided by the BRBs (or secondary structure). As can be anticipated, the residual displacement in structures equipped with BRBs is closely connected to the location of peak displacement demands, which can be located in zone I, II or III. If the peak displacement demand is located in zone I, RD_s is theoretically zero because both the main structure and the BRBs have enough restorative force to bring the structure back to zero deformation. If the peak displacement demand is located in zone II, RD_s may be non-zero because the BRBs undergo plastic deformation. Finally, if peak displacement demand is located in zone III, RD_s may be higher, as both the main structure and the BRBs will undergo plastic deformation.

6 C. Marcelo Ramirez and Eduardo Miranda, "Significance of residual drifts in building earthquake loss estimation", *Earthquake Engineering & Structural Dynamics* 41, (2012): 1477-93.

Figure 20 shows (for a dual SDOF oscillator with a period of 0.5 s, 5% damping and perfectly elastoplastic behavior) the mean residual displacement demand normalized by peak displacement demand. The horizontal axis shows the maximum displacement ductility of the main structure. It can be seen that the normalized RD_s remains low as long as the main structure remain elastic (μ_1<1 and peak displacement demand located in zone 2), but increases dramatically once the main structure starts presenting inelastic behavior (μ 1>1). The recommendation here is to design structures so that the main structure remains elastic while all dissipation is concentrated in the dissipaters.

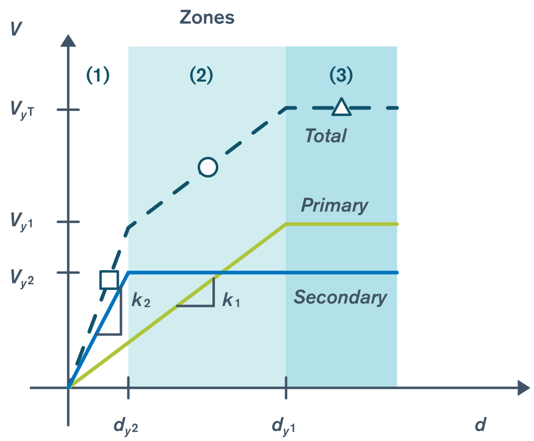

Figure 19: Simplified capacity curve for structures equipped with BRBs. Image taken from: Héctor Guerrero Bobadilla and others, "Residual displacement demands of conventional and dual oscillators subjected to earthquake ground motions characteristic of the soft soils of Mexico City," *Soil Dynamics and Earthquake Engineering* 98, (2017): 206-21.

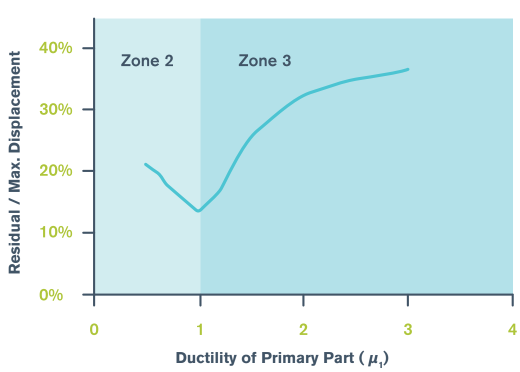

Figure 20: Normalized residual displacement on structures equipped with BRBs. Image taken from: Guerrero Bobadilla and others, "Residual displacement demands of conventional and dual oscillators subjected to earthquake ground motions characteristic of the soft soils of Mexico City."

Figure 21 analyses the effect of a positive, post-yielding stiffness ratio on the main structure (r_1=5%) and on the secondary structure (r_2=5%). The results are compared to those in figure 20. It can be seen that a positive post-yielding stiffness ratio on the main structure does not have a significant effect on the normalized RD. However, a positive post-yielding stiffness ratio on the BRBS (or secondary structure) has a very good effect, as normalized RD is diminished significantly.

Figure 22 analyses the effect of a negative post-yielding stiffness ratio for the main structure (r_1=-5%) and for the secondary structure (r_2=-5%). The results are compared to those in figure 20. Again, it can be seen that a negative post-yielding stiffness ratio for the main structure does not have a significant effect on normalized RD_s. However, a negative post-yielding stiffness ratio for the BRBS (or secondary structure) has a highly detrimental effect, that is, normalized RD_s increases dramatically.

Through an analysis of figures 21 and 22, it can be recommended to provide a positive post-yielding stiffness ratio for BRBS and to never use a negative post-yielding stiffness ratio for them.

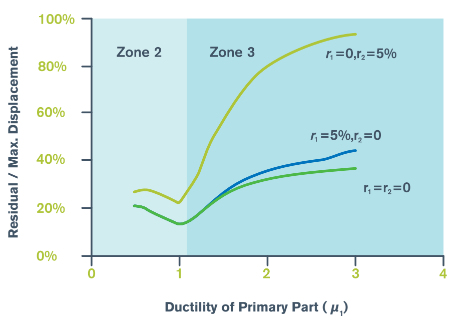

Figure 21: Normalized residual displacement for negative post-yielding stiffness ratios. Image taken from: Guerrero Bobadilla and others, "Residual displacement demands of conventional and dual oscillators subjected to earthquake ground motions characteristic of the soft soils of Mexico City."

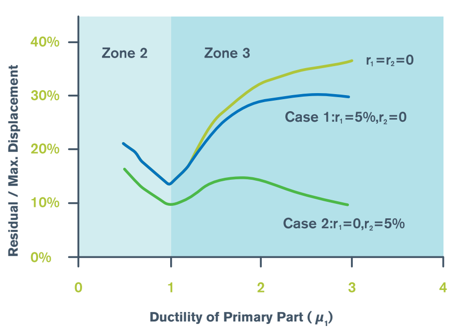

Figure 22: Normalized residual displacement for positive post-yielding stiffness ratios. Image taken from: Guerrero Bobadilla and others, "Residual displacement demands of conventional and dual oscillators subjected to earthquake ground motions characteristic of the soft soils of Mexico City."

Conclusion

A summary of the main studies in which these authors have participated has been presented, including experimental and numerical studies. The main advantages of BRBs are as follows:

- BRBs help to significantly reduce the displacement demand on structures.
- BRBs significantly increase structural damping, even during low intensity motions that do not generate inelastic behavior in either the main structure or in the BRBs.
- BRBs help to reduce stiffness degradation in concrete structures and diminish cumulative damage.
- Using BRBs does not significantly increase the initial cost of a structure (less than 5%), while the lifecycle costs are reduced dramatically.
- Using BRBs in structures prone to seismic aftershocks helps to reduce observed increases in displacement demand. In other words, proper design using BRBs helps to mitigate the problem.
- Structures equipped with BRBs tend to present low levels of residual displacement as long as the main structure remains elastic. If the main structure shows inelastic behavior, a positive post-yielding stiffness ratio for the BRBs must be provided to keep residual displacement low, while negative values must be avoided entirely.

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