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Buckling Restrained Braces to Achieve Resilient Multi-Span Bridges

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ABSTRACT

Resilient multi-span bridges with damage-free columns and displacements demands that can be easily accommodated by conventional expansion joints can be achieved using bi-directional ductile diaphragms consisting of Buckling Restrained Braces (BRBs). To better understanding the behavior of this type of bridges and its advantages, a parametric analysis was performed with regular multi-span simply-supported bridges considering variations in pier stiffness, BRB target displacement, BRB yield displacement, and numbers of spans. The demands of the designed bridges were analyzed to understand the influence of the various parameters considered. It was observed that the proposed system is able to reduce the demands in piers such as to keep them elastic and limit the displacement demands in expansion joints (which makes it easier to prevent unseating in retrofit situations). Satisfactory seismic performance obtained during shake table testing of a 40' long bridge span specimen having various configurations of bi-directional diaphragms experimentally demonstrated that the resilience objective can be achieved using this design strategy.

Keywords: Buckling restrained braces, Multi-span bridges, Inelastic analysis, Resilience, Shake Table testing.

INTRODUCTION

Bidirectional-Ductile End Diaphragm (BDED) consists of hysteretic devices (or fuse elements) located in the diaphragms located at the end of bridge spans. The concept of bidirectional ductile end diaphragm emphasizes the ability to dissipate hysteretic energy in such easily replaceable fuses under both longitudinal and transverse seismic excitations. The use of Buckling Restrained Braces (BRB) in BDED has been studied before [1-3] for the case of rigid piers. Also, a design procedure for this system to resist seismic excitation in the transverse direction of the bridge has been developed earlier [4-6] and included in AASHTO Bridge Seismic Design [7]. The concept in the transverse direction has been experimentally studied by different authors [8-9]. In contrast, only a few studies have considered BRBs in the longitudinal direction: in particular, Lanning et al. [10] studied the implementation of BRBs in the Vincent Thomas suspension bridge, Pantelides et al. [11] considered the implementation of BRBs to avoid pounding of span with abutments, and Carrion-Cabrera and Bruneau [12] studied the longitudinal response of straight multi-span bridges equipped with BRBs in the longitudinal direction and designed using the Multimodal Method. However, there exists no procedure developed to design this kind of system when implemented in the longitudinal direction when piers are not rigid and when the objective is for most of the BRBs to develop the same target ductility.

Therefore, here multi-span simply supported bridges with BRB in BDED are designed and studied in the longitudinal direction with the goal of understanding the influence of pier flexibility on overall behavior and its influence on the design of BRBs. The demands obtained from the resulting bridges are analyzed to verify that this novel system effectively can limit demands in the substructure, and to quantify the displacement demand in expansion joints.

Note that the objective of the BDED concept is to obtain bridges that suffer no damage during an earthquake. As there is no loss of bridge functionality following the earthquake, this design strategy fully meets the broadly accepted resilience objectives of minimizing losses and time to recovery [13-14], both equal to zero in this case.

PARAMETRIC STUDY

Buckling Restrained braces

The reader is assumed here to be familiar with the characteristic of BRBs, which have been described by many authors (e.g., [15-18]. These devices have been popular and used in hundreds of buildings located in seismic regions. Design specifications for Buckling Restrained Braced Frames (BRBFs) in buildings are provided in AISC 341 [19]. There are no equivalent design provisions for BRBs in bridges. Only a few bridges have been equipped with BRBs. Among them are the Vincent Thomas Bridge [10], the Minato Bridge [20], the Auburn-Foresthill Road Bridge [21-22], and the Araku-Bashi Bridge [23] – none of which being multi-span bridges of the type considered here. Details on these and other proposed implementations are provided by Wei and Bruneau [24], together with examples of implementations in buildings and other structures.

Bridges and configuration

This study here focused on regular simply-supported multi-span bridges analyzed in the longitudinal direction. Abutments are considered at each end of the bridges. The spans of the bridges are supported on sliding bearings (i.e., with negligible strength in any horizontal direction), and these bearings are located on the top of piers and abutments. Piers are considered to be cantilever elements fixed at their base. A broad range of pier stiffnesses is considered to encompass the possible stiffness provided by different kinds of substructures (e.g., bents, concrete frames, walls, among others). For simplicity in the numerical models, all spans of the regular bridges considered have the same mass and all piers have the same stiffness. BRBs are located longitudinally at the end of each span and are connecting spans to the top of their adjacent piers (or abutments). Note that several parallel BRBs can be connecting a span end to its adjacent pier or abutment; however, here all those BRBs are represented by one equivalent BRB with the same stiffness and strength as the group of BRBs. Figure 1a shows the schematics of such a bridge. Figure 1b shows one of many possible ways to install a BRBs in the bridge's longitudinal direction.

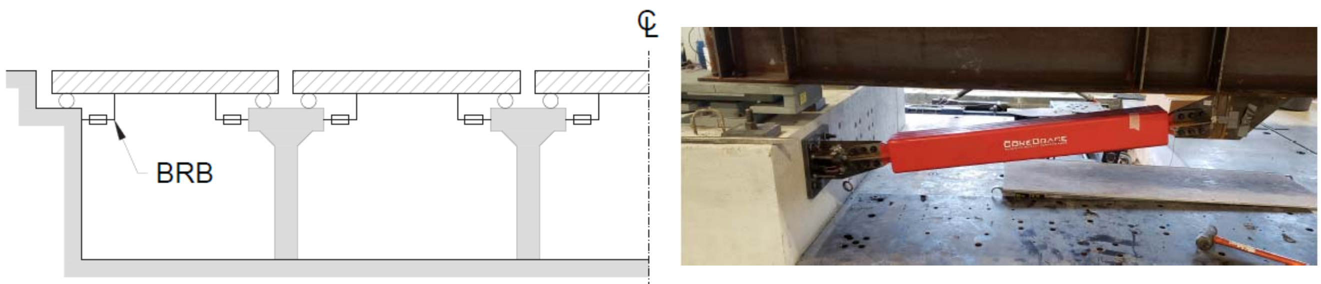


Figure 1: Bridge: a) Scheme, b) Example implementation of a BRB in the longitudinal direction, connecting bridge span to abutment or pier cap

Several constraints were considered to reduce the number of BRBs to be designed, to reduce the number of variables to be considered in their design, and to simplify the study. All BRBs in the bridge are considered to have the same yield displacements and same yielding core material. Additionally, as proven to be more preferable, BRBs were connected to the same pier were constrained to have the same cross-section area and strength [12]. Also, taking advantage of the symmetry of the bridge considered here, only half of the bridge's BRBs were designed. As a result, the number of BRBs to be designed in a bridge with an odd number of spans is equal to half the number of spans plus one.

Bridge behavior and design objectives

The objective of the proposed seismic design concept was to achieve the same ductility demand in as many BRBs along the bridge as possible while the substructure remains elastic. However, due to the wide range of possible pier designs and stiffnesses, in this study, an additional objective was to also reduce demands in the substructure compared with those for a conventional benchmark bridge where the substructure remained elastic. The benchmark elastic bridge considered that one spans is rigidly connected to the abutment and each of the remining spans are rigidly connected to a pier at one of its ends.

The equal target ductility in BRBs was arbitrarily selected to control the extent of hysteretic behavior in these elements, to increase the effective use of BRBs, to have a control of the demands required for the qualification test and parameters to be used for capacity design, and to limit the displacement demand in expansion joints. Note that since the design here is based on using Non Linear Response History Analysis (NL-RHA) for a set of ground motions, demands are defined as the average of the maximum demands in the elements of interest obtained from each ground motion.

Bridge model and analysis approach

A unidimensional model was used to represent bridges since the analysis is performed only in the longitudinal direction. All spans were considered as axially rigid; thus, they were modeled as lumped masses. The reactive pier mass was considered equal to 10% of the mass of the span and lumped at the top of the pier (approximated from bridge drawings provided by the California Department Transportation). Piers were modeled as elastic springs representing a cantilever column (i.e., fixed at their base). The BRBs were modeled as truss elements that connected the lumped masses representing a span, to the top of their adjacent piers or abutments. Only BRBs were modeled as having material nonlinearities, namely a Menegotto Pinto model that has a smooth transition from elastic to plastic behavior and a post-elastic stiffness of 3%. A 5% Rayleigh damping with tangent stiffness was considered anchored at the first and third mode.

Since this system is relatively new, its behavior is unknown. For that reason, several bridges were analyzed. The parameters varied in each bridge are the number of spans, the stiffness of the piers, the BRB yield displacement, and the target BRB displacement as expressed by the target BRB ductility (i.e., normalized by the BRB yielding displacement). These parameters are listed in Table 1.

Table 1: Summary of parameters considered

Parameter	Values
Span mass	175.55 Mg [1 $kip\ s^2/in$]
Number of spans	3, 5, 7, 9, and 11
Pier stiffness range	1.76 to 702.22 kN/mm [10 to 4000 kips/in]
BRB yield displacement	1.753, 3.505, 7.010 mm [0.069, 0.138, 0.276 in]
Target ductility	5 and 10
BRB equivalent length	2032 mm [80 in]

The mass of the span is maintained constant here since the behavior changes based on its ratio to the pier stiffness as expressed by Eq. (1), where m_s is the span mass, and K_{pier} is the stiffness of the pier. More information can be found in Carrion-Cabrera and Bruneau[12].

$$T_p = 2\pi \sqrt{\frac{m_s}{K_{pier}}} \tag{1}$$

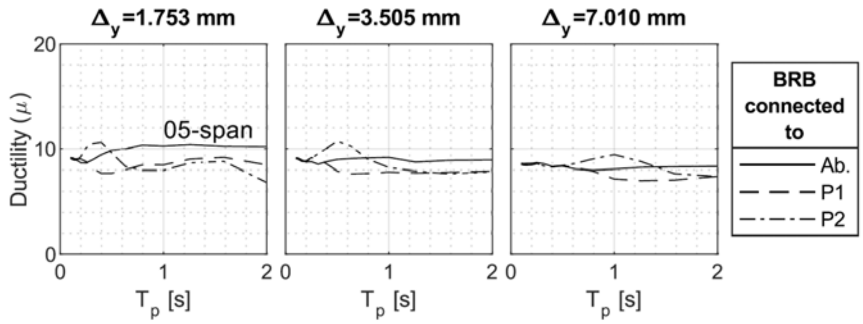
The design spectrum used in this study corresponds to Memphis, Tennessee. This location was selected for consistency with previous work by Wei and Bruneau [24]. For the NL-RHA performed in this study, the FEMA P695 [25] far-field set of ground motions was used, along with its ground motion scaling procedure. All bridges were designed with NL-RHA to reach a given target ductility in as many BRBs along the bridge as possible. Note that the design procedure required several iterations until convergence to a final design where the strength of each BRB is obtained, using an algorithm developed for this purpose.

Selected Results of Nonlinear Response History Analysis based design

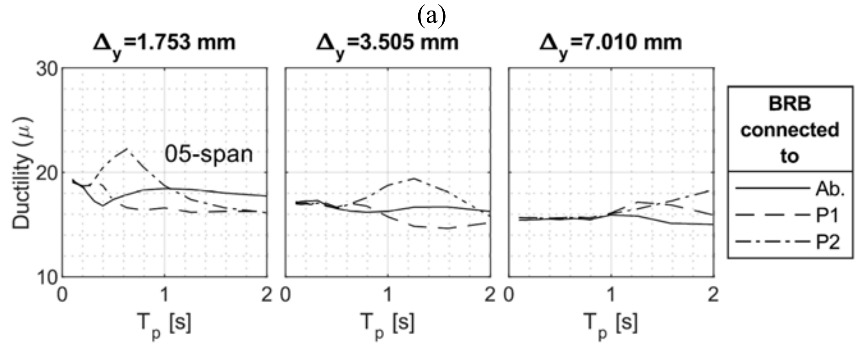
Selected results from NL-RHA based design are summarized here, considering BRBs having different yield displacements and different target ductilities. Due to space constrains, figures show results only for the 5-span bridges considered (similar results were obtained for bridges having 3, 7, 9 and 11 spans). In the figures, abutments are labeled with “Ab.”, and the i^{th} pier next to the abutment is labeled with “P_i”.

Demands in Buckling Restrained Braces

The design procedure described above results in BRBs having an average BRB ductility demand approximately equal to the target ductility. Figures are not shown here due to space constrains. As a byproduct, it was observed that in most of the bridges, the 90th percentile of the ductility demand in BRB is generally less than twice the target ductility, as shown in Figure 2. Note that twice the ductility demand is actually defined as an upper limit for the maximum demand required in qualification testing of BRBs [19]; the fact that results at the 90th percentile level are generally lower than this limit gives more confidence about the expected satisfactory performance of the BRBs.



(a)

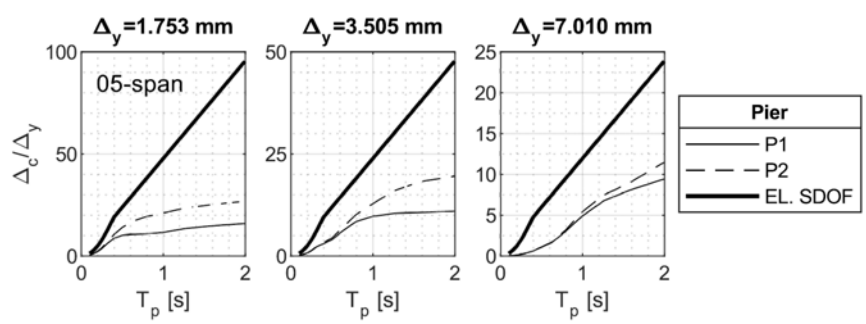


(b)

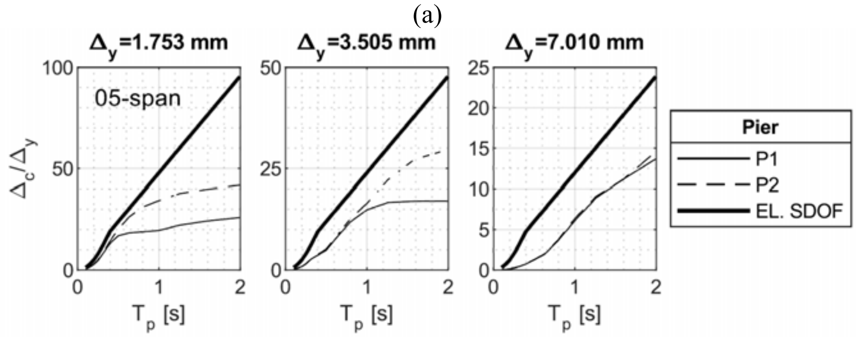
Figure 2: 90th percentile of BRB ductility demands in bridges with target ductilities equal to: a) 5, b) 10

Displacement demands in piers

For the bridges designed above, the resulting pier displacement demands, mean and 90th percentile, are shown in Figure 3, for BRB target ductility of 10. The figure also shows the displacement demands from the design spectrum as a solid bold line, representing demand in an elastic pier (i.e. piers of the elastic conventional benchmark bridge mentioned earlier). It is observed that the mean displacement demands in columns are less than those for elastic piers. However, in some cases, the 90th percentile shows values close to those for the elastic pier, especially for the pier located at the center of the bridge and for bridges having many spans.



(a)

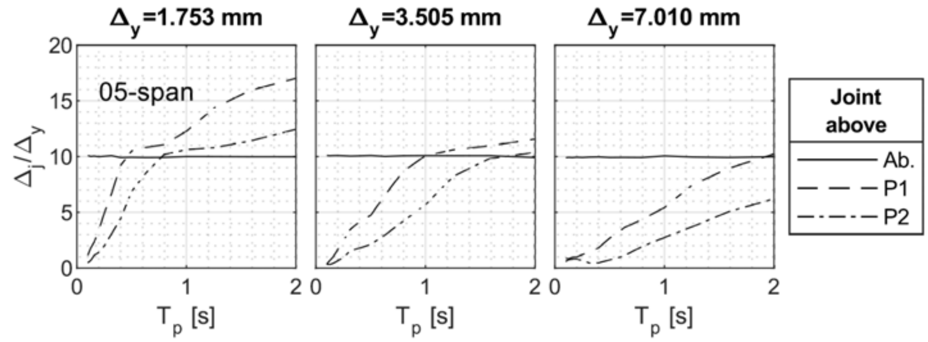


(b)

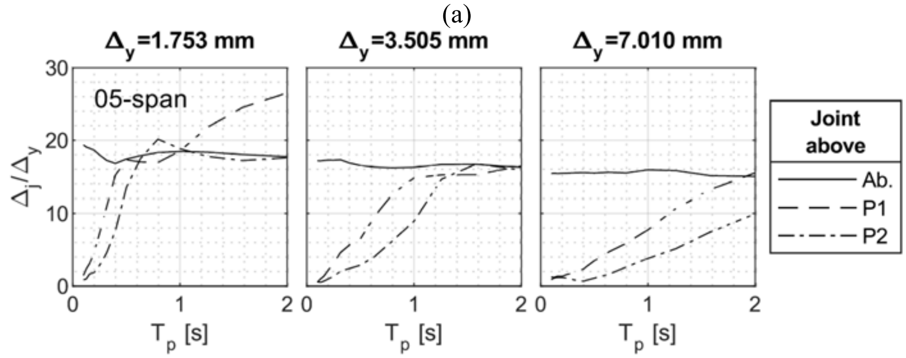
Figure 3: Displacement demand of piers in bridges with target ductility equal to 10: a) mean, b) 90th percentile

Displacement demands in expansion joints

For the bridges designed above, the resulting displacements at the expansion joints are shown in Figure 4 (for target BRB ductility of 10). These figures show that the demand in these elements are effectively limited by the target displacement of the BRBs, and in 90% of the cases, the opening is less than twice the target BRB displacement. The displacement demand in these joints changes when the stiffness of the piers is varied.



(a)



(b)

Figure 4: Expansion Joints demands in bridges with target ductility equal to 10: a) mean, b) 90th percentile

TESTING

A 0.4 scale bridge specimen with bidirectional ductile diaphragms was tested at the University at Buffalo's (UB) Structural Engineering and Earthquake Simulation Laboratory. Four different BRBs configurations were considered. Each configuration was subject to: 1) a sequence of thermal expansion demands to represent their respective life-cycle demands, 2) a sequence of four spectral matched earthquake displacement histories (with components in the longitudinal and transverse direction of the bridge) that represents the design level, 3) a sequence of five strong motions scaled to reach large displacement demands in the BRBs and, at the same time, to represent different types of motions (near field motions, far-field motions, motions with pulses, and motions in soft soils); and in case the bridge does not fail, 4) a sequence of two extreme motions for a bridge with rigid piers that is represented with shake tables moving synchronized. The design of the specimen and the testing protocol made it possible: to provide a more stringent testing protocol than qualification hysteretic test protocol, even expanding it to 3-D; to test various types of connections and BRBs for all the applied earthquake histories; to validate the design for the combination of thermal and seismic life demands, and; to quantify the ultimate hysteretic energy capacity of BRBs in terms of cumulative inelastic deformation. Figure 5 shows the specimen set up on top of both shake tables.

Figure 5: Specimen set up on top of the two shake tables

Example BRB Configuration

Selected results for the bridge specimen with an example BRBs configuration (Configuration I) are summarized here. In the longitudinal direction of Configuration I, BRBs installed were almost horizontal, and BRBs in the transverse direction connected the top of the one girder to the abutment/pier cap, as shown in Figure 6. In the longitudinal direction, the connection of one BRB was bolted and the other was pinned, and in the transverse direction, all BRBs had bolted connections.

a)  b) 

Figure 6: Specimen with BRBs and instrumentation for Configuration I: a) transverse BRB in the west end, b) longitudinal BRB

Selected Results

Figure 7 shows hysteretic loops for all BRBs for ground motions representing the design spectrum and Figure 8 shows a preliminary hysteretic loop of one BRB up to its failure. The force in the BRBs were approximated from strain gauges strategically installed on the BRBs. In this configuration one BRB failed after testing the set of ground motions representing the design level, the history representing temperature cycles, and a few strong ground motions. The two other BRBs failed after testing all motions. The maximum BRB demands obtained are summarized in Table 2.

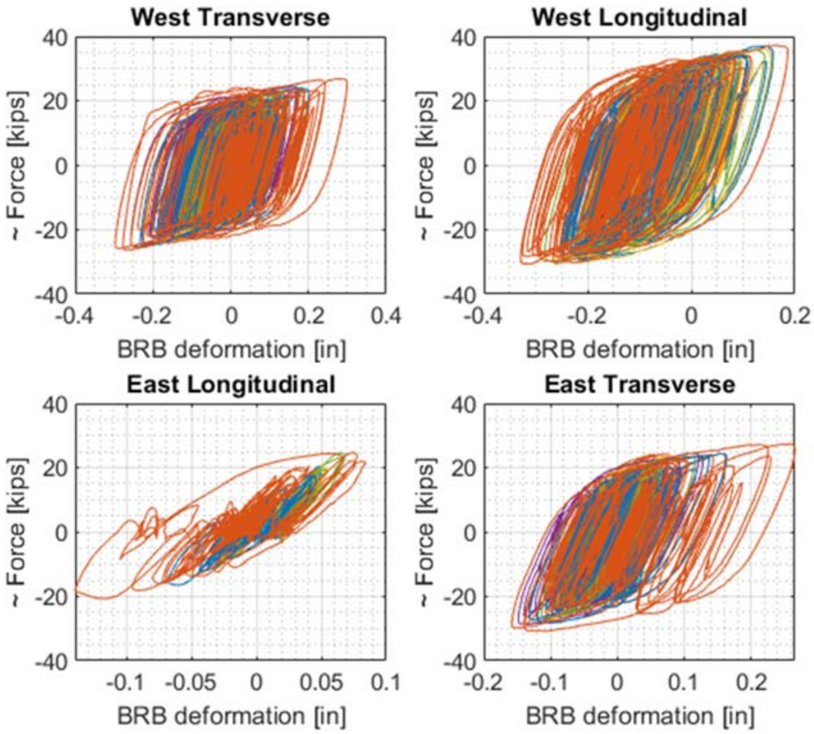


Figure 7: BRB hysteretic loops for the steps 1 – 61 for Configuration I

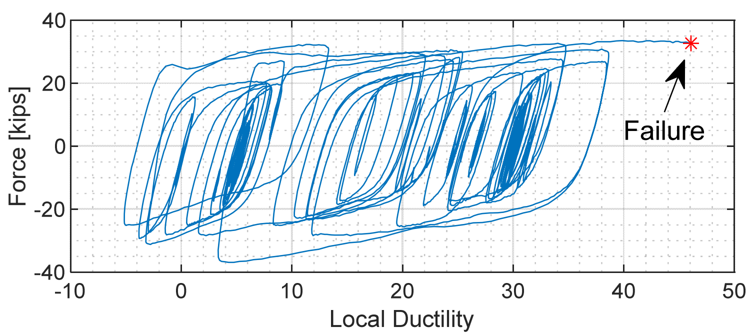


Figure 8: Preliminary hysteretic loop of a BRB from a few ground motions before its failure (note: this is "truncated" data; for clarity, the hysteretic curves corresponding to all the ground motions tests applied to this BRB are not all included in this figure)

Table 2: Summary of maximum BRB demands for Configuration I

Description	WT	WL	EL	ET
BRB number	2a	3a	4a	1a
Max. deformation [in]	0.72	1.94	1.55	1.22
Min. deformation [in]	-0.77	-0.84	-1.59	-0.16
Max def. amplitude [in]	1.49	2.78	3.14	1.38
Max core strain	3.4%	5.5%	4.4%	6.3%
Min core strain	-3.6%	-2.4%	-4.5%	-0.8%
Amplitude core strain	7.0%	7.9%	8.9%	7.1%
Amplitude normalized by core yielding strain	53	60	68	54
Cumulative inelastic deformation	1332	1793	671	664
Max. force (Tension) [kip]	31	46	36	33
Max. force (Compression) [kip]	40	46	40	35
ω	1.63	2.01	1.89	1.73
$\omega\beta$	2.10	2.01	2.01	1.84
Status	Failed	Failed	Failed	----

Note: WT = West transverse BRB, WL = West Longitudinal BRB, ET = East longitudinal BRB, ET = East transverse BRB

CONCLUSION

Several regular multi-span simply-supported bridges with Buckling Restrained Braces (BRBs) in the bidirectional ductile end diaphragm were designed using Nonlinear Response history analysis for seismic excitation in the bridge's longitudinal direction. Bridges were limited to regular bridges were all spans having the same mass and all piers having the same longitudinal stiffness. These designs considered BRBs having different parameters, in order to analyze the behavior of bridges having this proposed lateral-load resisting structural system.

Result shows that, on average, it is possible to reach the same target ductility demand in several BRBs along the bridge and, generally in 90% of the cases, demands are less than twice the target ductility. Considered that BRBs to be used in any structure in the United States would have to pass the AISC 341 qualification testing requirements, this means that in 90% of the cases considered, the BRB displacement demands would remain below those verified by qualification testing. Note that the remaining 10% would not necessarily fail, as well designed BRBs typically have a reserve displacement capacity beyond the range required by qualification testing.

Results also show that the average pier displacement demands can be reduced by up to 10 times the elastic displacement demand for a corresponding conventional benchmark bridge. Also, the demand in expansion joints were on average limited to the target displacement in the BRBs, and in 90% of the cases were less than twice this target displacements. As a result, the expansion joint demands are small, making it possible to use more conventional expansion joint hardware.

Overall, with columns protected from damage, limited displacement demands to prevent unseating or pounding of spans, and relatively no damage to the BRBs, there would be no loss of bridge functionality following an earthquake. As such, the end result is a fully resilient bridge that remains in service throughout and after the earthquake.

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