17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Buckling-Restrained Braces in Bi-Directional Ductile Diaphragms of Multi-Span Bridges

M. Bruneau[(1)], H. Carrion-Cabrera[(2)],

[(1)] *SUNY Distinguished Professor, Dept. of Civil, Structural, and Env. Engineering, University at Buffalo, bruneau@buffalo.edu*
[(2)] *Graduate Research Assistant, Dept. of Civil, Structural, and Env. Engineering, University at Buffalo, homerofe@buffalo.edu*

Abstract

Multi-span bridges having bi-directional ductile diaphragm consisting of Buckling Restrained Braces (BRBs) can provide resilient bridges with damage-free columns, at low cost, while minimizing displacements demands to levels that can be easily accommodated. Towards the goal of better understanding the behavior of such bridges and developing simple procedures for their design, multi-span bridges having ductile diaphragms, considering various layout and implementation strategies, have been investigated to establish their seismic performance. A parametric study has been conducted using nonlinear time-history analyses considering variations in ratio of substructure-to-superstructure stiffness, span length, period, and other factors. These analyses were performed to determine the level of complexity required to predict adequately the bridge response, with the goal of providing design rules as simple as possible to achieve satisfactory seismic performance. This was assessed by subjecting the resulting designs to suites of ground motions accelerations using non-linear time-history analyses. These dynamic analyses allowed to understand the impact of these parameters on global behavior, as well as the magnitude of the local demands and, more specifically, the extent of bidirectional displacements that the hysteretic devices must be able to accommodate while delivering their ductile response.

Keywords: Buckling Restrained Braces; Ductile Diaphragms; Multi-Span Bridges; Inelastic Analyses; Seismic Response.

1. Introduction

Current state of practice in seismic design of ordinary multi-span bridges relies either on plastic hinging of columns to dissipate earthquake energy, or on base isolation. The first one implies damage to the gravity-carrying columns; the second one requires costly bearings and expansion joints to accommodate displacements that can be extremely large in many cases, as well as a special design procedure (and sometimes peer-review of the design by other engineers). Using the bidirectional ductile diaphragm concept with inexpensive Buckling Restrained Braces (BRBs) can provide resilient bridges with damage-free columns, at low cost, while minimizing displacements demands to levels that can be easily accommodated.

The ductile diaphragm concept was initially proposed by Zahrai and Bruneau in 1999 [1]. The concept was studied for bridges with stiff substructures, using different types of hysteretic dampers and considering movements only in the transverse direction. Further studies included the application of BRBs as the fuse element and the conceptual bidirectional ductile end diaphragm concept was proposed and studied by Celik and Bruneau [2] for stiff substructures. The term "bidirectional ductile diaphragms" is used here to emphasize that energy dissipation is achieved in both horizontal earthquake excitation directions – in this case, using BRBs at the ends of the spans of the superstructure. This innovative approach can be implemented in both concrete bridges and steel bridges. The advantage of implementing BRBs between spans is to avoid damage on substructure elements and to reduce the displacement between spans such that they can be accommodated with regular low cost expansion joints.

However, to make the bidirectional diaphragm concept applicable to multi-span bridges, an analytical understanding must be developed of the behavior of multi-span bridges having simply-supported spans and BRBs tying the spans to each other or to the column bents, and the findings must be formulated into a simple design procedure applicable to general multi-span bridges. The current research investigates application of the bidirectional ductile diaphragm concept in multi span bridges having flexible substructures. The focus of this paper is to report on results obtained from parametric studies conducted using nonlinear time-history analyses considering variations in ratio of substructure-to-superstructure stiffness, span length, period, and other factors. These analyses were performed to determine the level of complexity required to predict adequately the bridge response, with the goal of providing design rules as simple as possible to achieve satisfactory seismic performance. The goal was to obtain relatively similar ductility demands in all BRBs along the bridge longitudinal direction, and to develop a simple design procedure to size BRBs properties. As a simplification, at this stage of the research project, simple supported multi-span bridges were analyzed in the longitudinal direction with different BRBs layout configurations. Findings will be later expanded to revisit previous research results for BRBs used to control transverse direction response.

2. Computational Models

2.1 General

Models used represent multi-span bridges with spans supported at each end by friction-less sliding bearings located on top of bents or abutments. Spans were connected through BRBs at each of these bearing supports, as shown in Fig. 1. This multi degree of freedom system considered lumped masses. The mass of the span was lumped at the center of the span and the mass of the pier caps was considered equal to 10% of the mass of the span and lumped at the top of the pier. Piers were modeled as cantilever elements fixed at their base and BRBs were modeled as truss elements. Abutments located at each the end of the bridge were considered as rigid. For the nonlinear model, the BRBs were modeled using a Menegotto Pinto model without isotropic hardening, and piers consisted of elastic elements. Damping was defined by a Raleigh model with 5% of the critical damping at the first and the third modes; this value was considered to also account indirectly for the additional energy dissipated in the sliding bearings used, which is not explicitly modeled (as idealized friction-less bearings are used in the models). Nonlinear analysis was perform in OpenSees [3] and results were post-processed with MATLAB [4] subroutines.

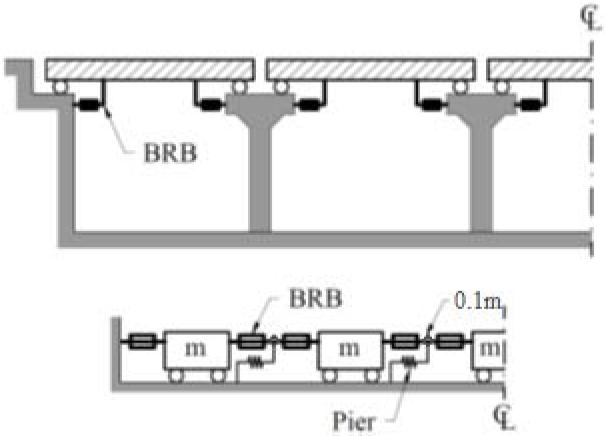

Fig. 1 – Model with BRBs connecting spans to piers and abutment.

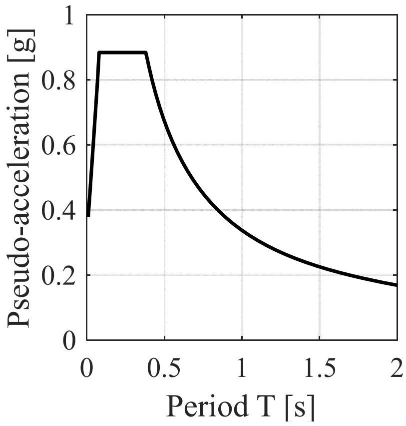

Fig. 2 – Response spectrum

2.2 Seismic hazard and Ground motions

The geographic location considered to obtain the design spectrum shown in Fig. 2 was Memphis, Tennessee. This location was selected to provide continuity with the previous study by Wei and Bruneau [5] (where this city provided the most critical combined axial demands on longitudinal BRBs due to seismic demands and span expansion due to temperature fluctuations). For the nonlinear response history analysis (NL-RHA) performed in this study, the FEMA P695 [6] far-field set of ground motions was used, along with its ground motion scaling procedure; it consist of 22 pair of ground motions selected to represent a variety of locations and seismic hazards. This set was used because it is not site dependent, and the FEMA P695 scaling procedure was used here as it is rational and not overly-conservative. Incidentally, among a number of possible scaling procedures considered, it was found to generally produce the lowest median and variation in ductility demands.

3. Parametric study

Generally, in the longitudinal direction, the geometry of bridges does not necessarily follow a specific pattern. For instance, parameters such as the mass of spans, number of spans, and the stiffness of piers, are determined as function of the topography of the site where it is located. Therefore; there is an infinite number of combinations of those parameters. The complete parametric study will account for this variability, and these results will be reported at a later time. However, at this stage, regular bridges were considered with constant mass span and pier stiffness along the bridge. The mass span values considered ranged from 0.5 kips s^2/in to 3 kips s^2/in, the number of spans were 3, 5, 7, 9, and 11; and the stiffness ranged from 4000 kips/in (representing a rigid pier) to 10 kips/in (representing a flexible pier). Finally, the BRBs yield stress and length were set arbitrarily equal to 50 ksi and 80 in.

4. Design Considerations

4.1 Findings based on elastic results

The AASHTO Guide Specifications for LRFD Seismic Bridge Design [7] provides different seismic design procedures that can be used depending on the complexity of the bridge structure. In the case of regular bridges, the uniform load distribution or the simple mode method can be used, whereas for more complex structures a modal spectrum analysis is required. Here, the bridges under study are regular, but their desired performance level is higher than required by the code. The objective, in addition to avoiding collapse, is to reach a uniform ductility demand along the bridge; therefore, the multi modal analysis (response spectrum analysis, RSA) was used. Additionally, past research [8] has reported a better correlation between RSA and NL-RHA results than when using the simple mode method. With respect to modal combination, in the extreme case where piers are rigid, periods are close each other; thus, the complete-quadratic-combination (CQC) rule was used.

Initially, a target reduction factor (R) was set equal to 5, independently of the period of the structure. The cross-section area of each BRB in each model was obtained using an optimization procedure (implemented in MATLAB) and considering the force in the BRB obtained from RSA to be equal to the BRB yielding force. Results showed that the ratio of BRB cross-section area to mass of the span was a function of ratio between mass of the span to pier stiffness, for models with the same number of spans. Subsequent analysis considered a constant span mass equal to 1 kip s²/in and expressed results as a function of the ratio span mass (M) to pier stiffness (K), defined as $T_p = 2\pi\sqrt{M/K}$.

Initial results revealed that, to achieve logical results from NL-RHA, it was necessary to constrain the design of pairs of BRBs. Two configurations were considered: one for which BRBs connected to the same span have the same cross-section area, and a second for which BRBs connected to the same pier have the same cross-section area. However, from a capacity design point of view, the configuration where BRBs connecting to the same pier have the same cross-section area is the one which develops lower forces on the piers. Therefore, this configuration was used in all subsequent analyses. Results were obtained only for half of the bridge, accounting the symmetry of the model, and in the case of BRBs connected to the same pier, only results for the BRB developing the greatest ductility demand was considered in all subsequent comparisons. Finally, results for the piers were reviewed, to confirm that the piers remained elastic as intended.

4.2 Nonlinear verification of elastic design

NL-RHA was performed on the models for which BRB areas were selected on the basis of the above elastic RSA procedure, to investigate if the objective of constant ductility demand across all BRBs was met. The resulting ductility demand reported below for each BRB in a specific model was calculated as the mean of the maximum ductility demand obtained from each ground motion. The resulting BRB ductility demands were found to vary significantly along the bridge, as shown in Fig. 3 for bridges having different number of spans and different values of pier stiffnesses. As could logically be expected, the demand ductility of BRBs is uniform along the bridge when piers are relatively rigid (lower values of T_p). When piers become flexible, BRBs connected to the abutment and located at the mid-length of the bridge experienced higher ductility demands than BRBs in other locations. Similar trends were observed with different R values.

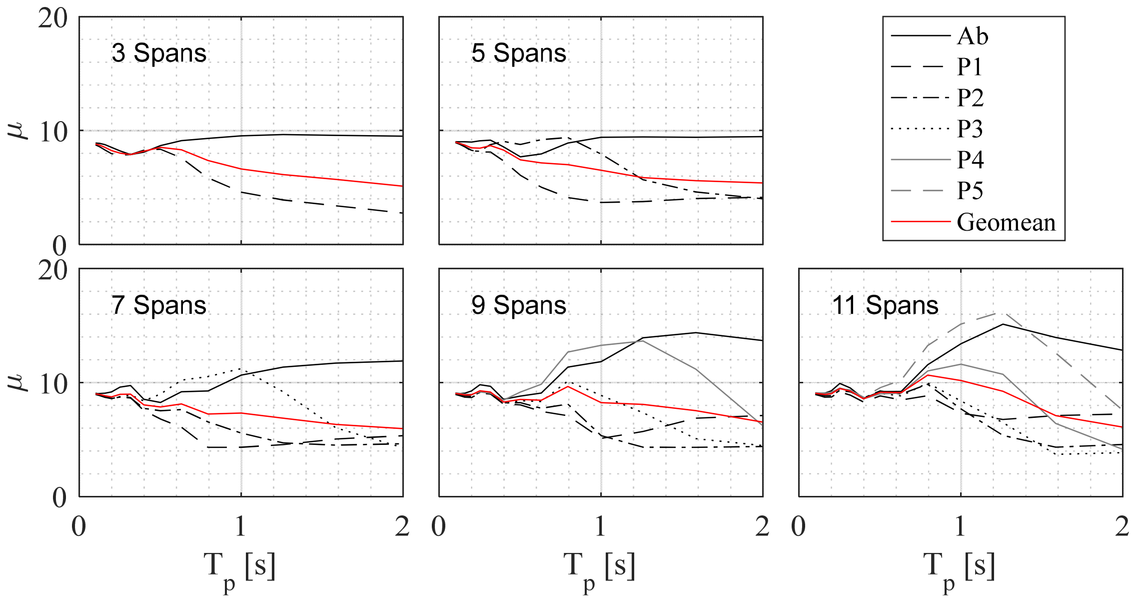

Fig. 3 – Ductility demand for BRBs depending the location along the bridge

5. Nonlinear response history analysis based design

In a subsequent parametric study, the BRBs cross-section area of the bridge models used in Section 4 were re-designed, this time using NL-RHA as the engine behind the optimization procedure, such that all BRBs reached a target demand ductility, arbitrarily set equal to 5. The algorithm modified the cross-section area of each BRB until the target of equal ductility demand in all BRBs along the bridge was reached. Satisfactory results were obtained, but this procedure was most time consuming (in CPU time) because it required several iterations. Each iteration was performed using the complete set of 44 ground motions. In average, 12 iteration per BRB were required to achieve the target design. Results, as expected, reached the desired mean ductility along the bridge in all BRBs at the design level; also, in 90% of the cases, the maximum ductility reached for individual ground motions was less than twice the desire value. This demonstrated that reaching the same ductility demand along the bridge was possible, but still pointed to the need of an easier design procedure, even at the cost of more variability in the results.

6. Design procedure

A design procedure was proposed, seeking simplicity while at the same time relatively and acceptable demand ductilities in BRBs along the bridge. The intent was that the format of the design procedure should be similar in format to the equivalent lateral force (ELF) used in buildings. Note that the ELF method in building design is based on the dominance of first mode and an assumed possible mode shape. For reference, the distribution of forces along the high of a building is defined as:

$$F_i = \frac{W\ Sa(T)}{R} \frac{m_j h_j^k}{\sum_{j=1}^{n_f} m_j h_j^k} \tag{1}$$

where F_i, m_j, and h_j are the lateral force, mass and height of the i floor; W is the total mass; R is the reduction factor; $Sa(T)$ is the spectral acceleration at the fundamental period (T); and k is a factor that is a function of the period of the structure and accounts for the influence of higher order modes. The period of the structure is calculated based on an empirical equation developed based on field measurements of structures under small displacement oscillations. The reduction factor has been defined based on past practices, or, nowadays, conservatively following the FEMA P695 procedure for new structural systems [6].

To apply this procedure to bridges equipped with ductile end diaphragm, the equations for the period and the mode shape were redefined. Some considerations were taken in account to define an equivalent mode shape: for the simplified bridges considered here, the mode shape is symmetric because the bridge is symmetric, and the highest displacement along that mode shape is located at the mid-length of the bridge. Note that the mode shape values should express constant displacement values along the bridge when piers are rigid. Moreover, the mode shape was defined by a linear piecewise function for which each vertex is located where masses for each span are lumped.

The equivalent modal value for each mass span was calculated from bridges designed based on a NL_RHA such that all BRBs yields. Fig. 4a shows the equivalent mode shape normalized for the value at the center of the bridge for a structure with 11 spans, the origin was defined at mid-length of the bridge and the distance from the center of the bridge to any span was normalized for simplicity. The normalized distance (x) goes from zero at the center of the bridge to one at the end of the bridge, and is defined by Eq.(2) where i is the number of span, numbered from left to right, and N_{span} is the total number of spans. Values of equivalent mode shapes were adjusted with Eq. (3) where k accounts for the flexibility of the substructure and is defined by Eq. (4). The fundamental period of the structure for the optimum design was also adjusted and defined by Eq. (5). The R value was calculated as the ratio between the total mass of the structure times the pseudo acceleration obtained from the design spectrum at the predicted period to the the lateral force required to reach yielding in all BRBs. It was observed that the R value obtained changes as function of the period of the pier and the number of spans. In most cases, R is greater than 3 except when T_p is close to 0.4, as shown in Fig. 4b. For simplicity, a constant R value equal to 3 was selected which implies that it is not possible to reach the same ductility demand in all models considered here. Finally, forces applied at each mass are defined by Eq. (6), which is similar in format to Eq. (1).

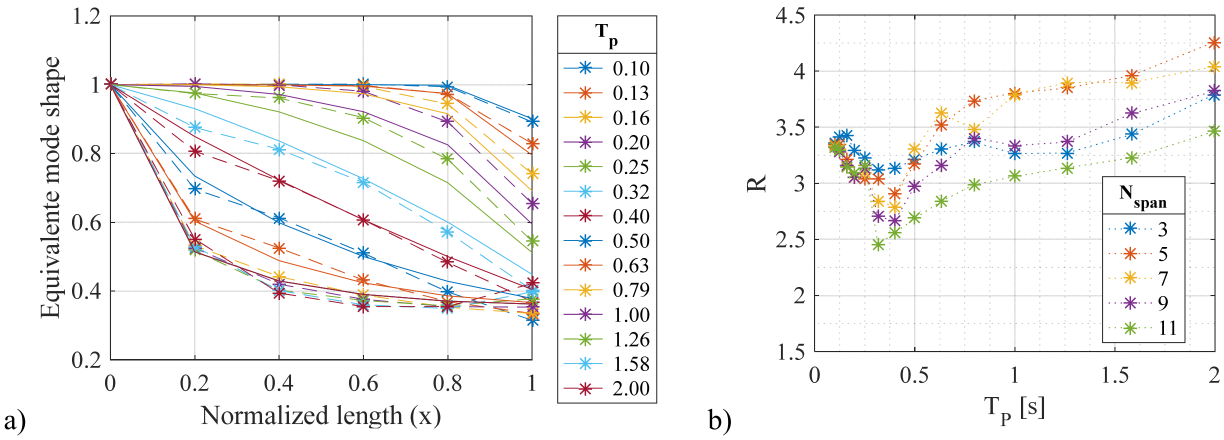

Fig. 4 – a) Equivalent mode shape (dashed line) and predicted mode shape (solid line) defined in each span (asterisk) for a model with 11 spans and different pier stiffness, b) Reduction factor for models with different number of spans

$$x = 1 - 2\frac{i-1}{N_{span} - 1} \tag{2}$$

$$\phi(x) = 0.36 + 0.64 \cdot \left(1 - \frac{x^{1/k}}{1.1}\right)^k \tag{3}$$

$$k = 3.5 \cdot (T_p - 0.08) < 3 \cdot (1 - 0.86^{N_{span}-1}) \tag{4}$$

$$T = 0.24\left[0.3N_{span}\left(1 - \frac{1}{3T_p^2 + 1}\right) + 1\right] \tag{5}$$

$$F_i = \frac{W\ Sa(T)}{R} \frac{m_j\phi(x_i)}{\sum_{j=1}^{n} m_j\phi(x_i)} \tag{6}$$

The proposed design procedure was used to design the set of models used in the NL-RHA based design. Results are show in Fig. 5 for an R value equal to 3. It is observed that mean demand ductilities in BRB are close to the expected ductility of 5 except when T_p is close to 0.4, and that in 90% of the cases, maximum ductilities obtained from individual ground motions are less than twice the target ductility. The upper limit of 90% is used here to ensure that the BRBs can reach such ductility demands of twice the target value, given that all BRBs must be tested to achieve twice their design ductility. The figure also shows result for R equal to 5; this value was used to investigate if the procedure remained valid for another R value that could equally be recommended for design. It is observed that demand ductilities when R is equal to 5 are close to 10 and, again, for most of the bridge models considered, are in 90% of cases less than twice the design ductility.

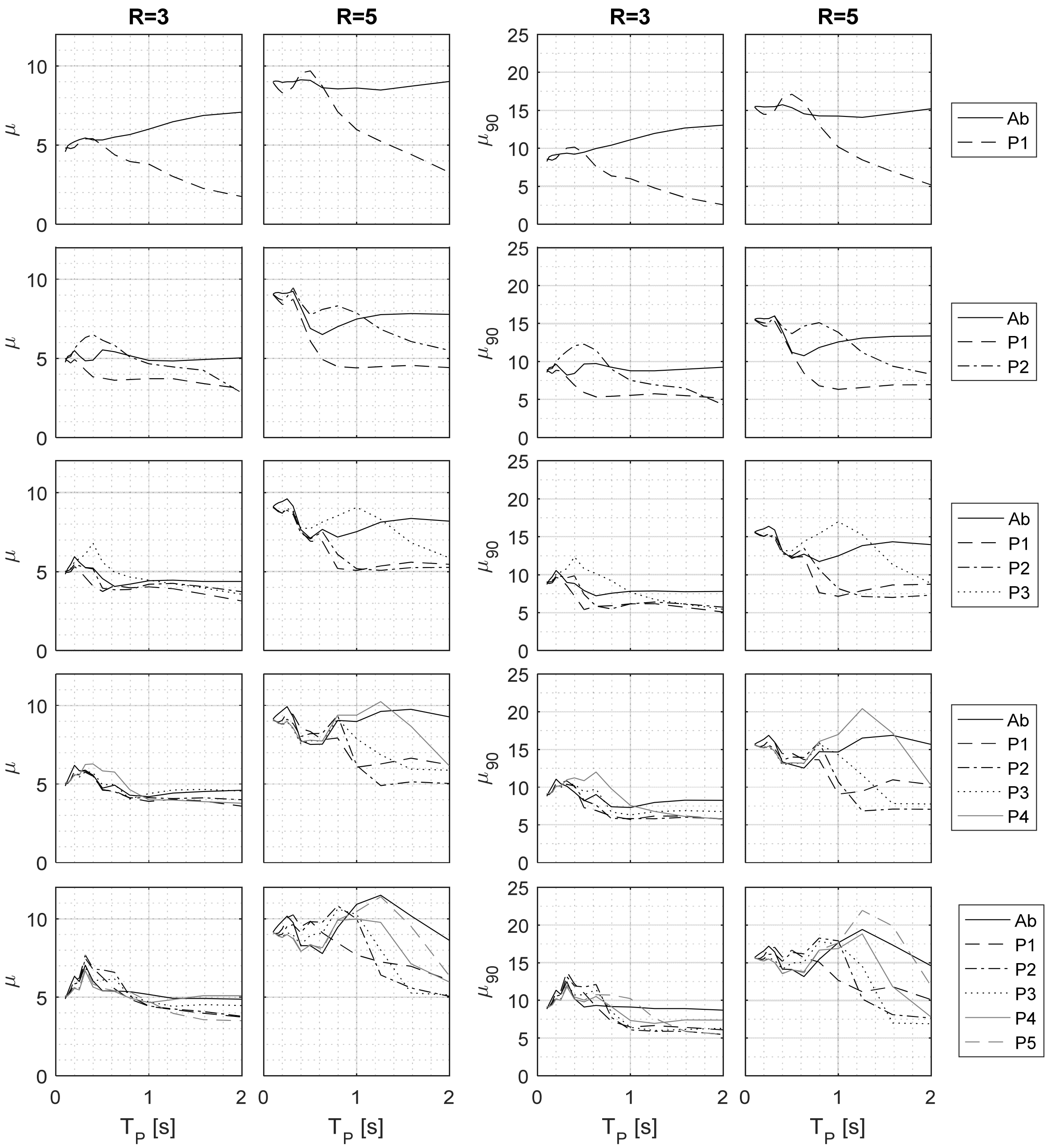

Fig. 5 – Equivalent mode shape (dashed line) and predicted mode shape (solid line) defined in each span (asterisk) for a model with 11 spans

8. Conclusions

Validation of the use of bidirectional ductile end diaphragms in multi-span bridge with flexible substructures was partially demonstrated analytically by studying the behavior of such bridges in the longitudinal direction. The objective to develop equal ductility demands in the BRBs along the bridge, in an average sense, is possible, and an optimum design can be achieved using a NL-RHA based design. However, this procedure is time consuming and computational demanding. Alternately, a simplified design ELF procedure was proposed which can be used to obtain demand ductilities close to 5 and 10 (depending on the R-factor used). Results obtained from the proposed ELF procedure were found to be acceptable, in spite of the method simplicity.

Research is ongoing to improve the design procedure and extend the proposed procedure to irregular bridges. Further stages expand the proposed design procedure to similarly address response in the transverse direction.

9. Acknowledgements

The Fulbright program, SENESCYT Ecuador, and the University of Buffalo, are acknowledged for its financial support through a scholarship for the second author. This study was also sponsored by the Transportation Research Board of the National Academies under the TRB-IDEA Program (NCHRP-215). However, any opinions, findings, conclusions, and recommendations presented are those of the authors and do not necessarily reflect the views of the sponsors.

10. References

[1] Zahrai, S.M. and M. Bruneau, *Ductile end-diaphragms for seismic retrofit of slab-on-girder steel bridges.* Journal of structural engineering, 1999. **125**(1): p. 71-80.

[2] Celik, O.C. and M. Bruneau, *Seismic behavior of bidirectional-resistant ductile end diaphragms with buckling restrained braces in straight steel bridges.* Journal of Engineering Structures, 2009. **31**(2): p. 380-393.

[3] Mazzoni, S., F. McKenna, M.H. Scott, and G.L. Fenves, *OpenSees command language manual.* Pacific Earthquake Engineering Research Center, 2006. **264**.

[4] The_Mathworks_Inc., *MATLAB R2016b*. 2016, Massachusetts.

[5] Wei, X. and M. Bruneau, *Buckling restrained braces applications for superstructure and substructure protection in bridges*. 2016, State University of New York at Buffalo.

[6] FEMA, *Quantification of Building Seismic Performance Factors. FEMA P695Prepared by . Applied Technology Council for the Federal Emergency Management Agency: Redwood City, California, USA*. 2009.

[7] AASHTO, *AASHTO Guide Specifications for LRFD Seismic Bridge Design*. 2nd Edition. Revision 2015. ed. 2011: AASHTO.

[8] Fischinger, M., T. Isakovic, and P. Fajfar. *Seismic Analysis of Viaduct Structures-Which Method to Choose?* in *Proceedings of the International Workshop on Seismic Design Methodologies for the Next Generation of Code*. 1997.

