The Effect of Superstructure Curvature on the Seismic Performance of Box-Girder Bridges with In-Span Hinges

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Abstract

Curved bridges are commonly constructed at interchange routes as connectors between two main roads in a highway network. Although past earthquakes, particularly the 1971 San Fernando earthquake, revealed the susceptibility of curved bridges to experience considerable damage during earthquakes, the seismic performance of this bridge class has not been investigated thoroughly. To address a part of this deficiency, the current study concentrates on the seismic performance analysis of curved concrete box-girder bridges with in-span hinges. In this bridge class, common potential damage patterns include damage to bearings and expansion joints, which are the most vulnerable components of the system. Hence, curved bridges including, in-span hinges, require particular investigations. As a case study, a highly curved bridge constructed before 1971 and located in California is selected for seismic analysis in this paper. The bridge seismic response is evaluated by performing nonlinear time history analysis in OpenSees on the representative bridge model with two configurations: (i) with an in-span hinge, and (ii) without in-span hinge (i.e. continuous deck). Moreover, the effect of superstructure curvature is evaluated by varying the radius of curvature from low to high (a bridge with a high radius approaches a straight bridge configuration). The analysis results indicate that curvature significantly affects the seismic response of the considered bridge, particularly for the model which includes an in-span hinge.

INTRODUCTION

Multi-frame bridges are constructed with at least one intermediate (or in-span) hinge that is used to release strains triggered by various sources such as temperature and post-tensioning during construction (DesRoches & Fenves, 1997) and to allow relative longitudinal movements of the deck elements. Understanding the effect of expansion joint closure in curved bridges is limited since there are inadequate experimental studies focusing on this phenomenon. During the 1971 San Fernando earthquake in 1971, several curved bridges experienced severe damage such as the collapse of the superstructure in the south overcrossing connector due to the longitudinal displacement of the superstructure and the unseating at the hinge locations (Fung, 1971). Moreover, numerous bridge failures were caused by the superstructure unseating at expansion joints as a result of inadequate seat widths and large relative movements of adjacent frames (Penzien & Thiel, 2003), and in some cases, the decks fell down even though the other bridge elements were not damaged (Housner, 1990). The major interchange at State Route 14 and Interstate Route 5, which is a long curved connector, encountered extensive damage at the intermediate hinge and the collapse of the end spans (Penzien & Thiel, 2003), in the 1994 Northridge earthquake. Post-earthquake investigations of bridge failures induced significant modifications in seismic design codes of bridges. For instance, the seismic bridge design criteria by Caltrans (2006) increased seat widths – 6-8 inches before1971, 12 inches between 1971 and 1994, and 24 inches after 1994 at expansion joint hinges. In addition, restrainers should be installed in hinges in the retrofit process. Although these criteria show improvements in the general performance of regular bridges, additional research is required to test the performance of non-standard bridges with complex alignments such as curved bridges.

Following the 1971 San Fernando earthquake that caused failure of curved bridges, Williams & Godden (1979) performed experimental studies to a long-span curved bridge and discovered that inclusion of intermediate expansion joints in a curved bridge leads to extensive damage. Similar to the intermediate hinge damage, unseating in seat type abutment bridges is also a potential mode of damage in curved bridges with insufficient seat length. In this study, the seismic performance of curved bridges with two different types of deck continuity (i.e., bridge deck (i) with an in-span hinge and (ii) without in-span hinges) is evaluated.

Past studies investigated the effect of curvature on the bridge responses mainly focusing on the steel bridges (Abdel-Salam & Heins, 1988; Galindo, et al., 2009; Seo & Linzell, 2011). These studies demonstrate that as the curvature increases, curved bridges are more susceptible to damage due to deck unseating and pounding. Seo and Linzell (2012) identified parameters including number of spans, span length, and radius of curvature as the significant factors affecting the bearing translations of continuous curved bridges.

More recently, researchers evaluated the performance of concrete curved bridges. Araújo et al. (2014) focused on the pushover analysis of a set of short reinforced concrete curved bridges and explored the influence of various load directions on the seismic analysis. Based on their study, the curved bridges exhibit multi-directional dynamic responses and a higher sensitivity to the earthquake direction compared to the straight bridges. This effect amplified as the curvature increased which proved the need for an accurate seismic assessment of curved bridges to avoid underestimating their seismic response. Tondini and Stojadinovic (2012) examined the seismic behavior of three different prototypes of a curved box-girder bridge. Their study indicated that the transverse column deformation ductility demand increases with increasing the curvature, and that the fragility corresponding to the column drift is affected primarily by the curvature regardless of the height of the columns. Their research focused only on a bridge with a continuous deck, and the only considered seismic demand was the column drift. Instead, the present paper looks into the damage to various structural elements of curved bridges with and without in-span hinges.

Pahlavan, et al. (2015) performed fragility analysis of two-frame curved bridges. They found curvature as the key parameter dominating the fragility of multi-frame bridges. However, their study concentrated on the fragility analysis of the entire bridge rather than the seismic response of the bridge components. Furthermore, only the pounding elements are used to simulate the impacts between the adjacent deck elements, whereas in the current study, the in-span hinge is modeled in detail based on the real bridge plan to capture its actual performance. Besides, their hypothetical bridge configurations were multi-column bents, which are contrary to single column supported bridges considered in this paper since they are found to be more susceptible to the unseating of expansion joints, as observed in the 1971 earthquake (Housner & Thiel, 1995). For the analysis in the current study, uncertainties associated with the ground motion characteristics are considered. However, deterministic values are considered for the bridge geometries and material properties to investigate the variation of the bridge seismic performance with respect to the variations of the curvature and ground motion characteristics.

NUMERICAL MODELING OF CURVED BRIDGE

An existing horizontally curved bridge, S505-E80 CONNECTOR OC, constructed in 1963 and located in Vacaville city in California, is selected for the investigation of this study. This connector bridge is a four-span, three-cell, box-girder bridge, supported on reinforced concrete (RC) single column bents with spread footings, and the abutments are supported by RC piles. Figure 1 provides views of the selected bridge.

This bridge consists of 4 spans with the left span length of 43ft (13.1m) and the remaining three spans of 85ft (25.9m) length. The radius of curvature (R_0) is equal to 250ft (76.2m), and the bridge is divided into two separate frames connected by an intermediate hinge. Similar column heights make the bridge have a balanced stiffness in the frames. More geometric details regarding the plan and elevation views of the as-built bridge are provided in Figure 2. Information about the box-girder section, column dimensions, and cross-sections including the reinforcement arrangements are demonstrated in Figure 3.

Figure 1. Under view of span 4 looking towards abutment 1 (on the left), and Roadway looking back on route (on the right) (source: Caltrans bridge inventory)

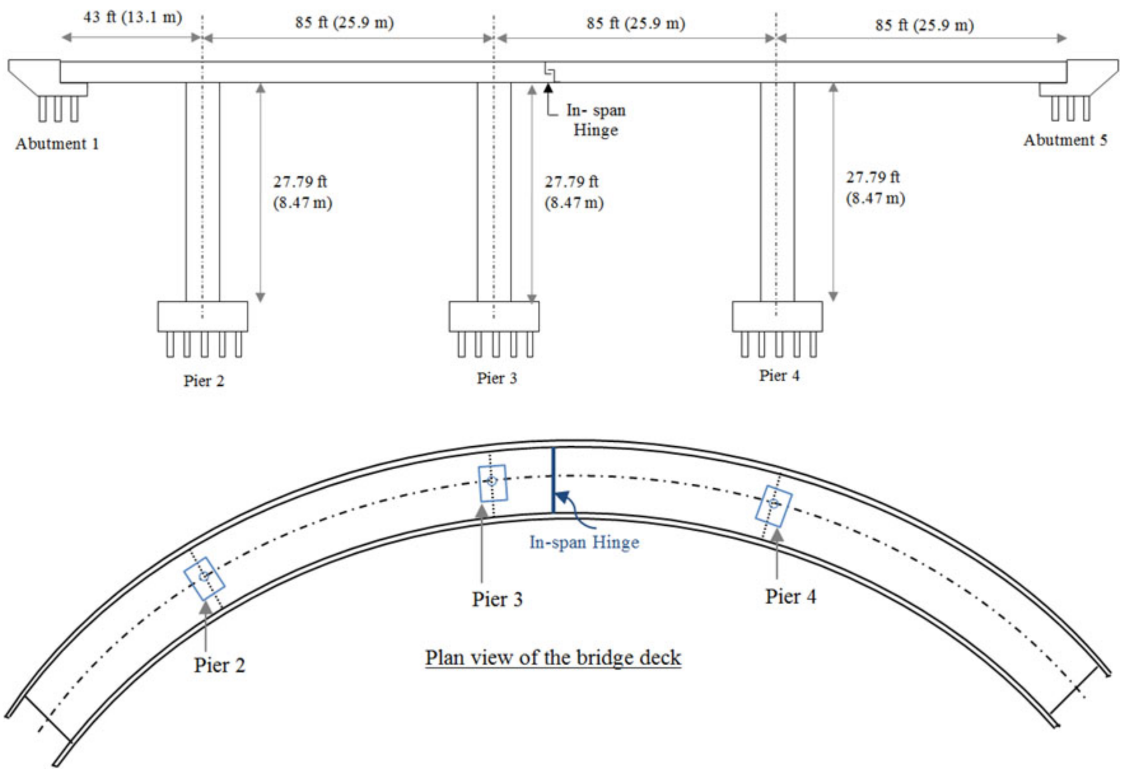

Figure 2. Bridge plan view and elevation

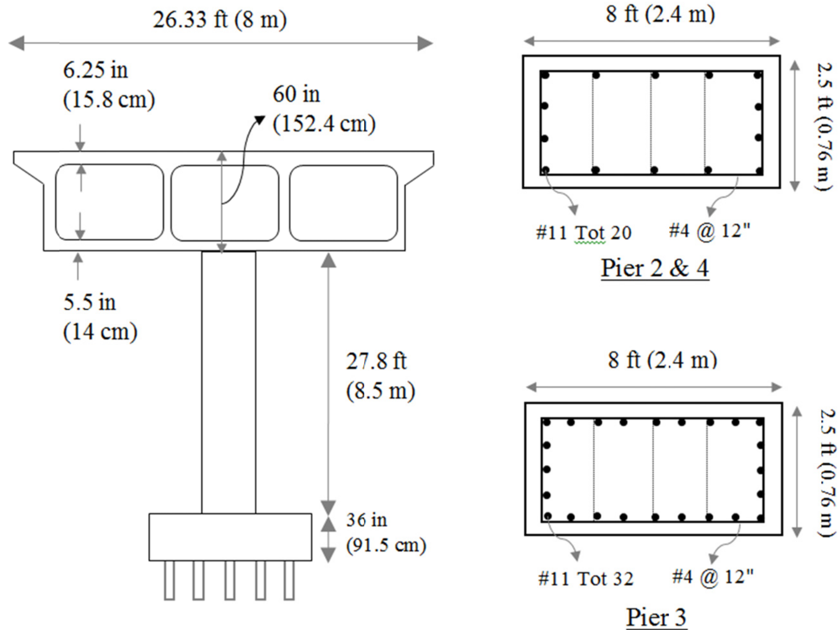

Figure 3. Column detailing and reinforcement arrangements

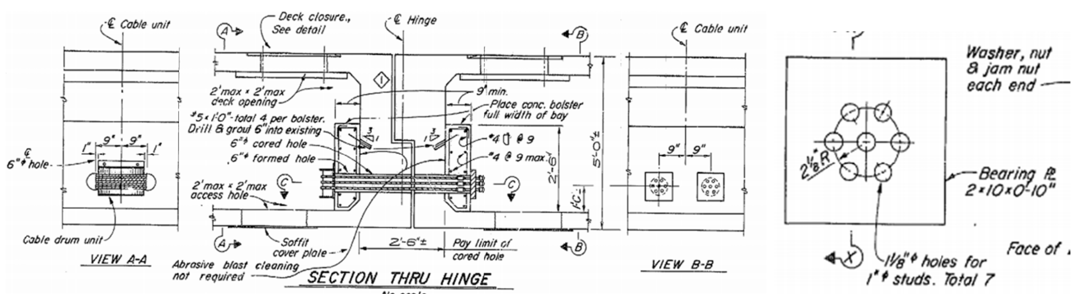

Figure 4. Intermediate hinge arrangement

To generate more realistic simulations, a three-dimensional (3-D) model of the representative bridge is developed in OpenSees (Mazzoni, et al., 2006). The superstructure of the bridge is simulated using elastic beam-column elements with mass lumped along the centerline. The modeling properties of the box-girder cross-section are calculated based on the composite section properties. Bridge columns are simulated using the displacement-based beam-column elements consisting of fiber cross-sections (Soleimani, et al., 2016). Concrete 07 and Steel 02 materials in OpenSees are used to model the concrete and steel components of the column cross-section. The top column elements are connected to the superstructure elements along the bridge deck by rigid link elements. Pounding and bearings are modeled using zero-length elements, and abutment responses including the passive resistance earth pressure and structures resistance are simulated by spring elements. These abutment responses are modeled using the hyperbolic soil model proposed by Shamsabadi and Yan (2008) and the trilinear material model recommended by Ramanathan (2012). As mentioned earlier, this study investigates the effect of curvature in curved bridges with two different types of deck continuity. Therefore, two separate bridge models are generated in OpneSees: one bridge with in-span hinges and the other bridge without in-span hinges. In each of these two bridge types, the bridge models are analyzed for three various radii of curvature: (i) R_0 which is identical to that in the as-built bridge, (ii) ∞ which generates a bridge model with straight (zero curvature) deck elements, and (iii) $2R_0$ that increases the radius of curvature by twice of the original value. The seismic analysis results of these three cases provide an insight into the influence of increasing levels of horizontal curvature on the seismic response of a bridge.

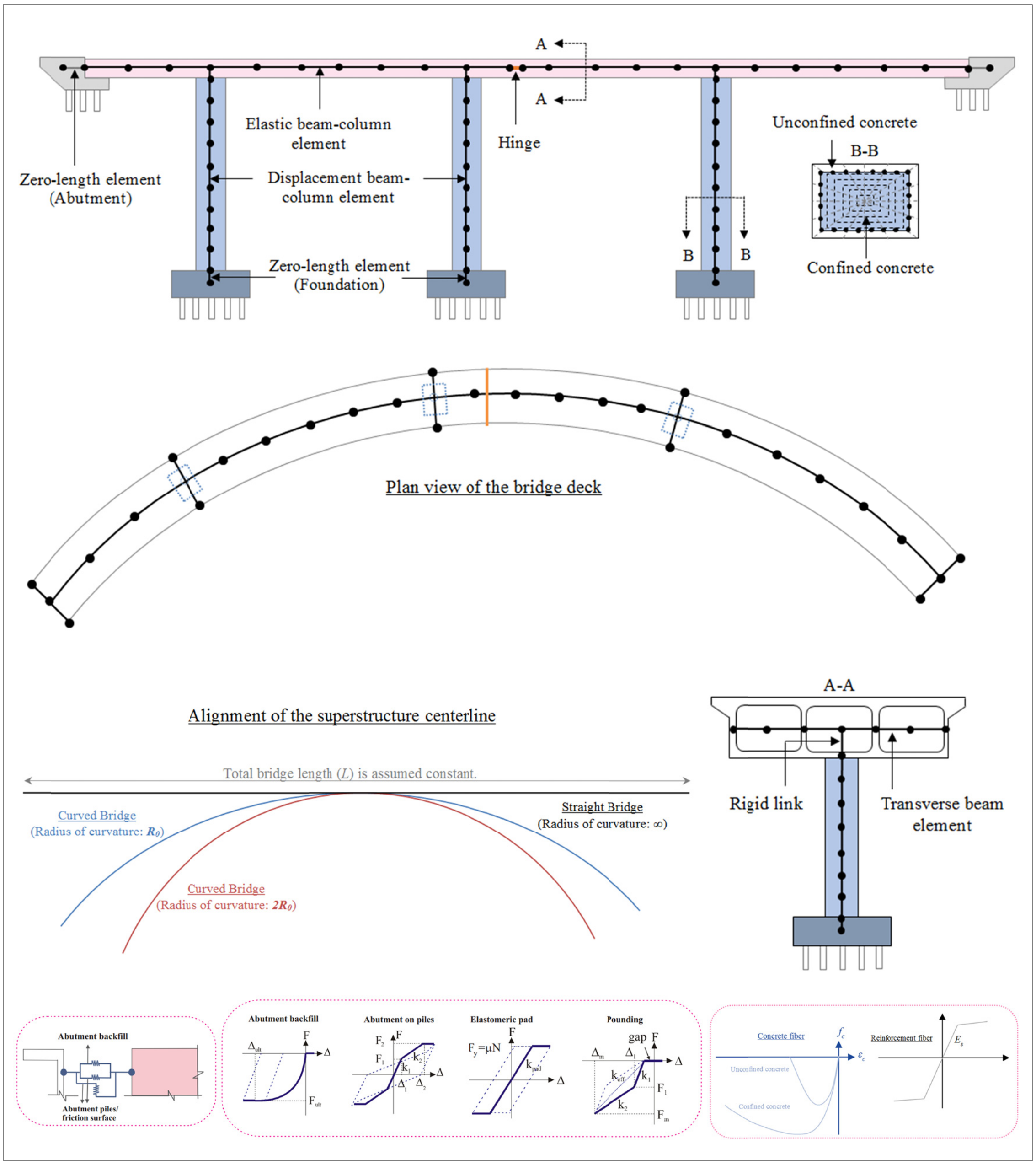

Figure 5. Numerical bridge model

SEISMIC ANALYSIS AND RESULTS

Nonlinear Time History Analysis (NLTHA) is performed on the bridge models using Baker's suite of 160 ground motions (Baker, et al., 2011). These excitations have longitudinal and orthogonal components and are oriented randomly to the longitudinal and transverse directions of the bridge models. The results of this analysis provide the peak seismic response for each of the bridge components during each one of the time history analyses. The peak responses are used to produce probabilistic seismic demand models (PSDM). Probabilistic seismic demand models (PSDM) are regression models expressing the relationship between seismic demands (D) and ground motion intensities (IM) (Cornell, et al., 2002). Based on this regression model, the median value of the seismic demand (S_d) can be estimated for a specific ground motion intensity, as shown in Eq. 1,

$$S_d = a\,(IM^b) \qquad \text{Eq. (1)}$$

where a and b are the regression coefficients that are obtained by performing a regression analysis on $D-IM$ pairs. Dispersion ($\beta_{d|IM}$) is calculated based on Eq. 2.

$$\beta_{d|\mathrm{IM}} = \sqrt{\frac{\sum_{i=1}^{N}\left(\ln(D_i)-\ln(S_d)\right)^2}{N-2}} \quad , N = \text{total number of data points} \qquad \text{Eq. (2)}$$

Comparison of the results is provided in the following presented figures. Figure 6 shows the generated seismic demands versus the ground motion intensities, for the six various bridge types: (1) continuous bridge with straight deck, (2) continuous bridge with curved deck and radius of curvature equal to R_0, (3) continuous bridge with curved deck and radius of curvature equal to $2R_0$, (4) straight bridge with one in-span hinge, (5) curved bridge with one in-span hinge and radius of curvature equal to R_0, and (6) curved bridge with one in-span hinge and radius of curvature equal to $2R_0$. Figure 7 presents the response plots along with the mean values of 160 simulations and helps to observe the general trend of the seismic demands across various cases. Figure 8 illustrates the differences between the seismic response distributions based on the variations of the curvature in bridges with in-span hinges. Figure 9 depicts comparisons of the two-parameter lognormal probability distributions of the bridge deck displacement based on the ground motion intensity measure.

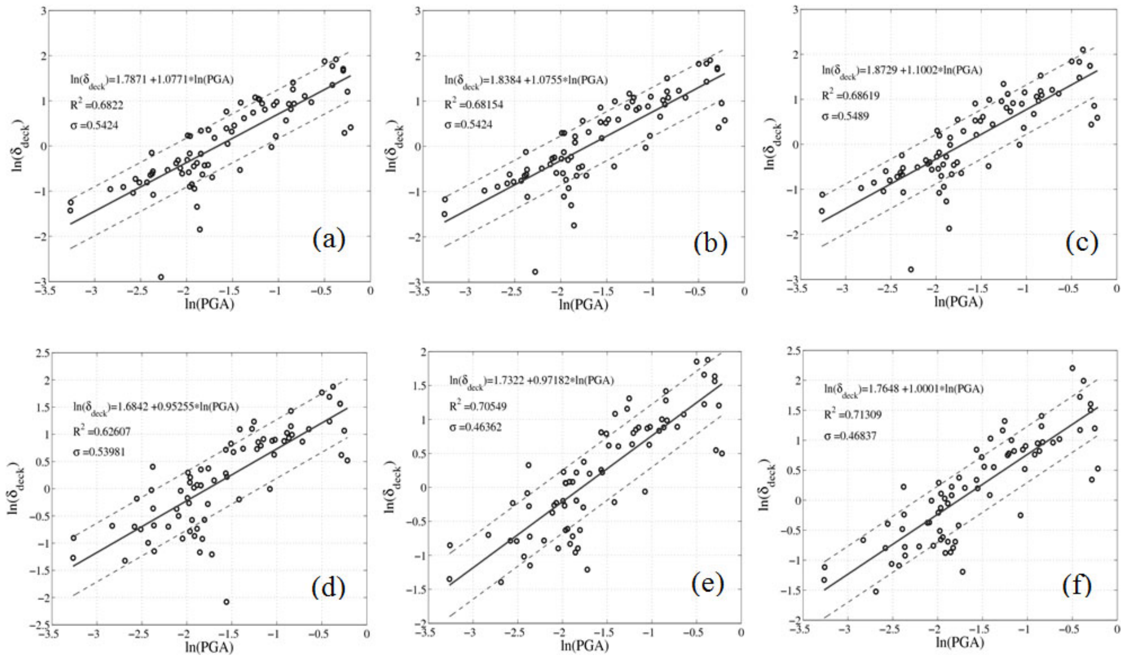

Figure 6. Probabilistic seismic demand models for: (a) straight, (b) curved (R_0), and (c) curved ($2R_0$) continuous bridge; and (d) straight, (b) curved (R_0), and (c) curved ($2R_0$) bridge with in-span hinge

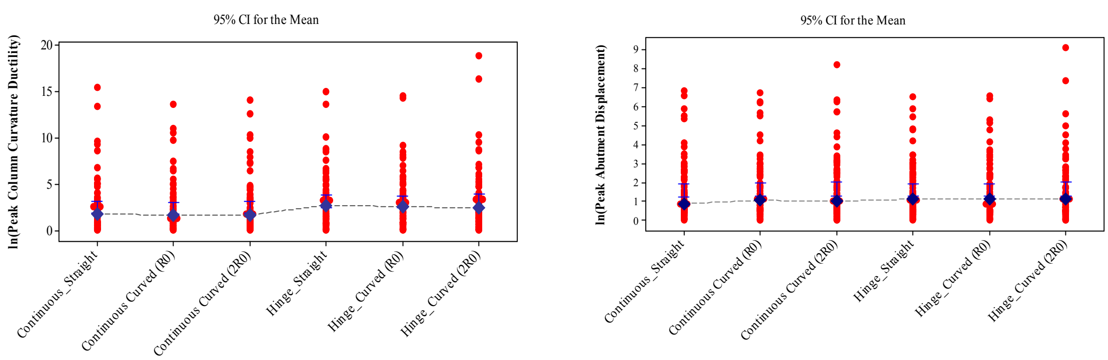

Figure 7. Statistical comparison of the seismic demands

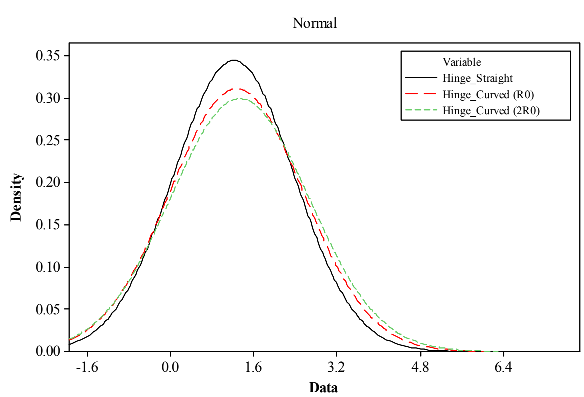

Figure 8. Probability distribution comparison of the demands (deck displacement)

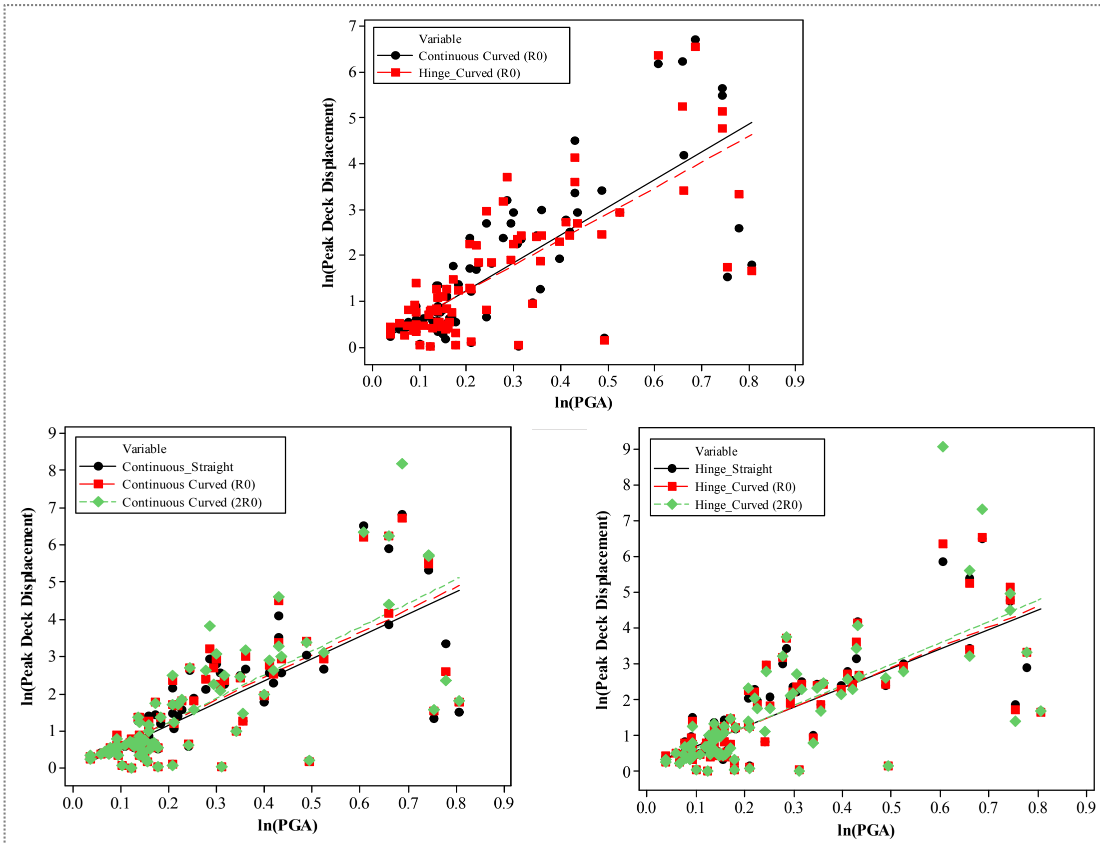

Figure 9. Comparison of the seismic demands

The seismic performance of the bridge models is evaluated by comparing their simulated probabilistic demands including column, deck, and abutment. Assessment of the generated bridge responses indicates the impact of curvature and the existence of the in-span hinge on the bridge seismic response. Among the considered scenarios, the bridge seismic response increases as the curvature increases. In general, the higher seismic demand of curved bridges indicates that this bridge type is more vulnerable than the straight bridge. Although the findings of this paper help to better understand the curved bridge performance, the conclusions of this paper may be limited to the selected box-girder bridge for the purpose of this case study, and hence the findings may not be generalized to all types of curved bridges. In order to broaden the knowledge in this area, the authors are working to expand this study and investigate more curved bridges with a variety of structural configurations.

Following are the summary of the key findings:

- According to the comparison of the seismic responses (e.g. deck displacement), it is observed that curved bridges show higher demands than straight bridges, and the demands increase as the curvature increases.

- Based on the probabilistic seismic demand models of the deck displacements, larger values are noted for the continuous bridges compared to the bridges with in-span hinges. This phenomenon is caused by the in-span hinge that releases strain within the bridge deck.
- Comparison of the probability distribution of the demands illustrates that as the curvature increases, the demands are shifted towards the tails of the distribution and particularly to the right tail that indicates the increase in the demand as the curvature increases.
- The response variations are more notable for the deck displacement and the column curvature ductility than the abutment responses. Based on the previous studies (Ramanathan, 2012) on the bridge fragilities, the deck displacement and the column curvature ductility are more significant than the abutment responses on identifying the vulnerability of a box-girder bridge.

CONCLUSIONS

The experience of past earthquakes revealed that bridges with intermediate hinges had damage, particularly around the expansion joints. Moreover, the bridge curvature leads to a complex dynamic behavior. The combination of curvature with in-span hinges requires more investigation since it can influence the overall bridge sustainability under earthquakes and the seismic performance of curved bridges has not been investigated thoroughly yet. To address a part of this deficiency, this paper attempts to assess the seismic performance of concrete box-girder curved bridges with in-span hinges.

Three-dimensional numerical models of the hypothetical bridge with various curvatures are created in OpenSees. The bridge models are considered with two deck continuity features: one model includes an intermediate hinge, and the other model includes a continuous deck. Using a selected set of ground motions, nonlinear time history analysis is performed on the created models to derive structural responses. The seismic performance of the bridge models is evaluated by comparing their probabilistic seismic demands including column, deck, and abutment. Assessment of the generated curves indicates the impact of curvature and the existence of in-span hinge on the bridge seismic response. Among the considered scenarios, the bridge seismic response increases as the curvature increases.

In general, the higher seismic demand of curved bridges indicates that curved bridges are more vulnerable than straight bridges. However, the findings described in this paper can be limited to the considered box-girder bridge for the case study and may not be generalized to all curved bridges since the research on curved bridges is limited by the time. Therefore, future research of the authors will be focused on the probabilistic assessment of curved bridges with different abutment types, long spans versus short spans, various column heights, and more than one in-span hinge.

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REFERENCES

Abdel-Salam, M. N. & Heins, C. P., 1988. Seismic response of curved steel box girder bridges. *Journal of Structural Engineering,* 114(12), pp. 2790-2800.

Araújo, M., Marques, M. & Delgado, R., 2014. Multidirectional pushover analysis for seismic assessment of irregular-in-plan bridges. *Engineering Structures,* Volume 79, pp. 375-389.

Baker, J. W., Lin, T., Shahi, S. K. & Jayaram, N., 2011. New ground motion selection procedures and selected motions for the PEER transportation research program. *Pacific Earthquake Engineering Research Center.*

Caltrans, 2006. Seismic Design Criteria, Version 1.4.. *California Department of Transportation.*

Cornell, C., Jalayer, F., Hamburger, R. & Foutch, D., 2002. Probabilistic Basis for 2000 SAC Federal Emergency Management Agency Steel Moment Frame Guidelines. *Journal of Structural Engineering,* 128(4), pp. 526-533.

DesRoches, R. & Fenves, G. L., 1997. Evaluation of Recorded Earthquake Response of Curved Highway Bridge. *Earthquake Spectra,* 13(3), pp. 363-386.

Fung, G. G., 1971. Field investigation of bridge damage in the San Fernando earthquake. *State of California, Business and Transportation Agency, Department of Public Works, Division of Highways, Bridge Department.*

Galindo, C. M., Hayashikawa, T. & Belda, J. G., 2009. Damage evaluation of curved steel bridges upgraded with isolation bearings and unseating prevention cable restrainers. *World Acad Sci, Eng Technol,* Volume 35, pp. 11-27.

Housner, G. W., 1990. *Competing Against Time: Report to Governor George Deukmejian from the Governor's Board of Inquiry on the Loma Prieta Earthquake,* Sacramento, CA: George W. Housner Chairman. Governor's Office of Planning and Research.

Housner, G. W. & Thiel, C. C., 1995. The continuing challenge: report on the performance of state bridges in the Northridge earthquake. *Earthquake Spectra,* 11(4), pp. 607-636.

Mazzoni, S., McKenna, F., Scott, M. H. & Fenves, G. L., 2006. OpenSees command language manual. *Pacific Earthquake Engineering Research (PEER) Center.*

Pahlavan, H., Zakeri, B., Amiri, G. G. & Shaianfar, M., 2015. Probabilistic Vulnerability Assessment of Horizontally Curved Multiframe RC Box-Girder Highway Bridges. *Journal of Performance of Constructed Facilities,* p. 04015038.

Penzien, J. & Thiel, C. C., 2003. *The Race to Seismic Safety: Protecting California's Transportation System,* Sacramento, CA: California Department of Transportation.

Ramanathan, K. N., 2012. Next generation seismic fragility curves for California bridges incorporating the evolution in seismic design philosophy.

Seo, J. & Linzell, D. G., 2011. Nonlinear seismic response and parametric examination of horizontally curved steel bridges using 3D computational models. *Journal of Bridge Engineering,* 18(3), pp. 220-231.

Seo, J. & Linzell, D. G., 2012. Influential Curved Steel Bridge Fragility Analysis Parameters. *Sixth Congress on Forensic Engineering.*

Shamsabadi, A. & Yan, L., 2008. Closed-form force-displacement backbone curves for bridge abutment-backfill systems. *Proceedings of the Geotechnical Earthquake and Soil Dynamics IV Congress.*

Soleimani, F. et al., 2016. Cyclic Testing and Assessment of Columns Containing Recycled Concrete Debris. *ACI Structural Journal,* 113(5), pp. 1009-1020.

Tondini, N. & Stojadinovic, B., 2012. Probabilistic seismic demand model for curved reinforced concrete bridges. *Bulletin of Earthquake Engineering,* 10(5), pp. 1455-1479.

Williams, D. & Godden, W., 1979. Seismic response of long curved bridge structures: experimental model studies. *Earthquake Engineering & Structural Dynamics,* 7(2), pp. 107-128.