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Seismic response of bridges with sliding and elastomeric isolation bearings

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ABSTRACT: During the last decades, the need for safer bridges has led to high level aseismatic design of bridges including the use of seismic isolation bearings. This study numerically evaluates the seismic responses of a curved bridge equipped with either elastomeric-type or with sliding-type isolation bearings under strong earthquakes. The Spring Confined Pb High Rubber Bearing (SPR-S) and the Friction Pendulum System (FPS) are selected as the representative devices for this study. Nonlinear dynamic analyses are conducted with three-dimensional models subjected to near-fault earthquakes. The results show that, when allowing these devices to move in both horizontal directions, the seismic damage at the piers is clearly reduced. Viaducts equipped with FPS are more flexible and, in the majority of the cases, present higher bearing displacements and lower deck accelerations. On the other hand, the installation of SPR-S provides similar reductions in piers demands and lower deck displacements.

1 INTRODUCTION

Past and recent severe earthquakes, such as the 1994 Northridge earthquake, the 1995 Kobe earthquake, or the 1999 Chi-Chi earthquake have exposed the seismic vulnerability of highway bridges. The collapse or lose of serviceability of these lifeline structures is an important issue that can detrimentally affect the rescue and evacuation activities in the aftermath of a seismic disaster. According to these past experiences, such vulnerability may be magnified in structures with irregular and complex geometries like curved viaducts (Watanabe et. al. 1998). During the last decades, the use of base isolation bearings has been implemented to improve the seismic performance of bridges, changing their fundamental frequencies to avoid resonant vibration with the predominant energy-containing frequencies of the earthquake.

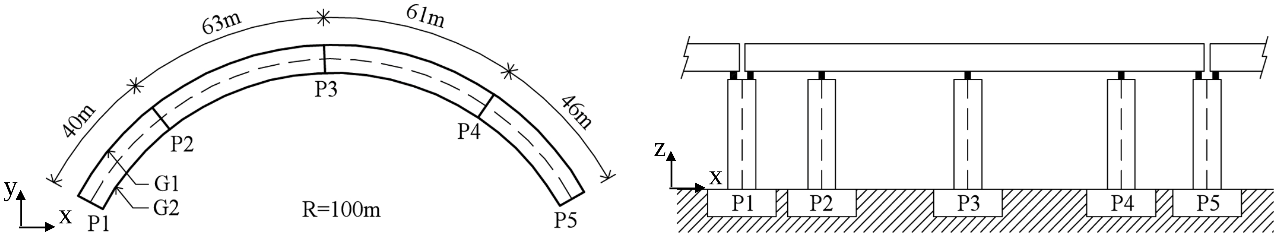
Isolation bearings are basically classified into elastomeric and sliding bearings. In order to achieve seismic isolation, elastomeric bearings make use of the mechanical characteristics of the rubber. On the other hand, sliding bearings utilize the low friction between interfaces to achieve low horizontal stiffness and lengthen the period of the structure. Throughout the last decades rubber bearings have been extensively used as seismic isolators, but recently sliding supports have been successfully applied in the seismic isolation of bridges and buildings (Jangid 2005). For this research the most representative devices inside each group of seismic isolators, the confined lead rubber bearing and the friction pendulum system, are selected as the object of the study.

The individual response of these isolators has been widely researched, but there is a necessity of a better understanding of the impact of different seismic isolators on the seismic response of seismically isolated bridges. In the current research, the nonlinear seismic response of a curved viaduct subjected to near-fault earthquake ground motions, and isolated in one case with the lead rubber bearings and in another case with the friction pendulum system is analyzed. The obtained results are compared, and the relative benefits of each isolator type discussed, in order to withdraw conclusions which can assist engineering practice in designing effective protection strategies against strong earthquakes.

2 NUMERICAL MODEL OF THE VIADUCT

2.1 *Superstructure, Piers and Foundations*

The three-dimensional bridge model object of this study is based on a section of an existing viaduct located in Fukuoka (Japan), which has been given a curved alignment in a 100 m radius circular arc. Tangential configuration for both piers and bearing supports is adopted with respect to the global coordinate system, in which the



(a) Plan view of the viaduct (b) Elevated view of the viaduct

Figure 1. Description of the viaduct model

Table 1. Properties of the piers of the viaduct.

Steel piers						Reinforced concrete piers					
	Plate dimensions in tangential direction		Plate dimensions in radial direction				Properties in the tangential direction		Properties in the radial direction		
Pier	Width (mm)	Thickness (mm)	Width (mm)	Thickness (mm)	Pier Height (m)	Pier	Width (mm)	Longitudinal Reinforcement	Width (mm)	Longitudinal Reinforcement	Pier height (m)
P2	3000	31	2250	31	10.3	P1	4000	ϕ51	3500	ϕ38	13
P3	3000	34	2250	34	10.3	P4	4000	ϕ51	3500	ϕ38	11
						P5	4000	ϕ38	4000	ϕ35	10

X- and Y-axes lie in the horizontal plane while the Z-axis is vertical. The overall viaduct length of 210 m is divided into four spans of 40 m, 63 m, 61 m, and 43 m, as described in Figure 1. The bridge superstructure consists of a concrete slab resting on two trapezoidal steel sections. The total width of the deck is 20.3 m, and the bearings supporting each steel section are separated 10.2 m. The superstructure is expected to remain inside the elastic range and therefore, the deck elements have been modeled using elastic beam elements. The superstructures adjacent to the model have been partially modelled. The end-span bearings of these superstructures have been represented as nodes where their tributary dead load has been applied. Each adjacent superstructure presents six isolation bearings placed on top of the first and last pier of the model.

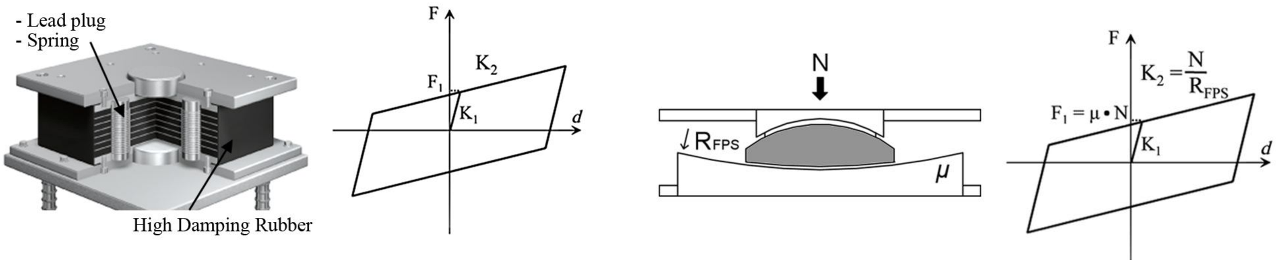
The superstructure weight is supported by five rectangular piers. There are two piers, i.e. P2 and P3, which are hollow box sections steel piers that have been partially filled with concrete. The remaining piers (P1, P4, and P5) are reinforced concrete piers. The geometric characteristics of the substructure units are described in Table 1. Characterization of the non-linearity of the piers is achieved by using three-dimensional fiber elements, with the corresponding constitutive models for the concrete, the structural steel, and the steel reinforcement. For the steel piers, the structural steel is modeled using a bilinear model with yield strength of 355 MPa, elastic modulus of 2×10^8 kN/m^2, and a strain-hardening ratio of 0.01. The filling concrete presents a characteristic strength of 16 Mpa. On the other hand, the concrete of the reinforced concrete piers has a characteristic strength equal to 27 Mpa. Finally, the reinforcing steel presents yield strength of 345 MPa, an elastic modulus of 2×10^8 kN/m^2, and no strain-hardening.

The bridge rests on medium soil conditions, classified as ground type II according to the Japanese specifications of highway bridges (JRA 2002), and has rectangular footings. The interaction between the soil and the foundations is modeled by using vertical, horizontal, and rotational spring nodes.

2.2 *Bearing Supports*

The seismic isolation of the viaduct is achieved by placing 2 units of isolation bearings on top of each pier. As described in the introduction, two different types of bearings are taking into account in this study: the Spring Confined Pb High Rubber Bearing (SPR-S), and the Friction Pendulum System (FPS). Figure 2 describes the characteristics of both isolation bearings.

The SPR-S is a high damping rubber bearing with a lead core surrounded by a spring and press-fit into one or four cavities. The spring is vulcanized to the surface rubber improving the transmission of forces between the lead plug and the rubber material. The dimensions of the supports are obtained according to the manual of bearings for highway bridges (JRA 2004). The correspondent design earthquakes are applied to the model in the global X- and Y-axis alternatively, to verify that the designed bearings do not exceed a shear strain limit of 250%. The SPR-S bearings are modelled by a bilinear force-deformation relationship, as described in the manual of bearings for highway bridges (JRA 2004). The principal parameters that characterize the analytical model are the pre-yield stiffness K_1, corresponding to combined stiffness of the rubber bearing and the lead core, the stiffness of the rubber K_2 and the yield force of the lead core F_1.



(a) SPR-S support (a) FPS support

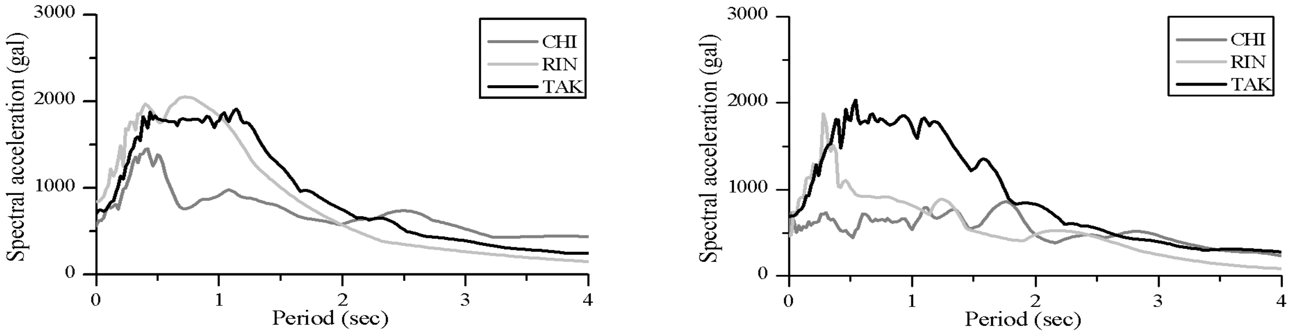
Figure 2. Analytical model of the seismic isolation bearings

The FPS is a sliding isolation bearing that dissipates energy through friction and has re-center capability. This is due to the relative movement of the bearing along to a curved sliding surface which resembles pendulum motion. FPS bearings are modeled with a high vertical stiffness, and the normal force acting on each device (N) is considered as a constant value obtained after gravity load analysis. Similarly to the SPR-S, FPS isolators have been modeled by a simplified bilinear force-deformation relationship (Zayas 1990). The two main design parameters of the FPS are the radius of curvature of the sliding surface (R_{FPS}), which controls the period of vibration, and the coefficient of friction (μ) of the sliding surface. The radius of curvature is selected to achieve the minimum period shift, but ensuring that the maximum displacements remain lower than the displacement capacity of the bearing ($d_{max}/R_{FPS} \leq 0.15$). The coefficient of friction is selected equal to 12%, which seems appropriate for bridge structures subjected to near-fault earthquakes (Jangid 2005).

3 METHOD OF ANALYSIS

The three-dimensional model of the seismic isolated curved bridge was developed in TDAPIII, a software widely used in Japan to carry out nonlinear seismic analysis of structures. In order to analyze the elasto-plastic dynamic response, as well as to assess seismic damage of bridge frame structures when subjected to strong earthquakes, the analysis is conducted through a numerical method that considers material nonlinearities. The characterization of the non-linear structural elements is based on the fiber flexural element modeling. The damping mechanism is introduced in the analysis through the Rayleigh damping matrix. Additionally, the governing equations of motion are solved in incremental form using Newmark's method ($\beta=0.25$), and Newton-Raphson iteration method is selected to achieve the acceptable accuracy in the response calculations. Before conducting the nonlinear time history analyses, the initial values of stresses and displacements of the elements are obtained subjecting the model to nonlinear static analysis, applying the dead weight load gradually.

To assess the seismic performance of the viaduct, the bridge model is subjected to the longitudinal and transverse components of different strong earthquake ground motions. The longitudinal earthquake component shakes the viaduct parallel to the global X-axis, while the transverse component acts in the Y-axis. Since the seismic performance of a structure can be strongly influenced by the properties of the applied wave, a group of near-fault ground motion records has been employed for simulations, to ensure the applicability of the conclusions of this study. Three different earthquake records characterized by their high intensity and low probability of occurrence, and considered as level II earthquakes in the Japanese seismic code (JRA 2002), have been selected. The first earthquake record, named as CHI in this study, belongs to 1999 Chi-Chi earthquake and was obtained from the recording station TCU068. The second record (RIN) was recorded in the Rinaldi station



(a) Longitudinal component (b) Transverse component

Figure 3. 5%-damped earthquake acceleration spectra

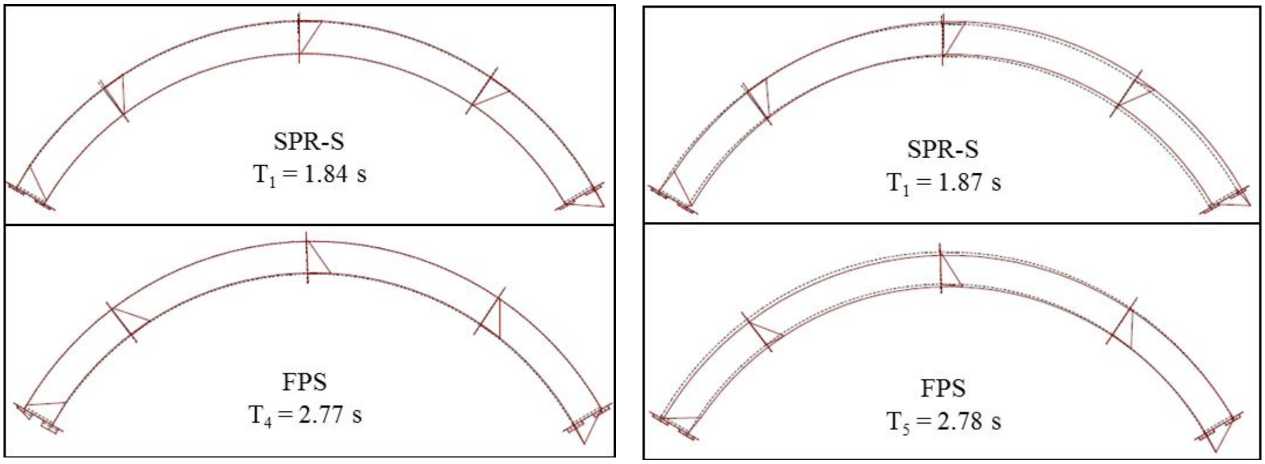
during the 1994 Northridge earthquake. Finally, the longitudinal and transverse accelerograms from JR Takatori station (TAK) obtained during the 1995 Kobe earthquake are also applied to the model. These last accelerograms are the modified records to fit the design code spectrum described in the Japanese seismic specifications. As it can be observed in the 5%-damped earthquake acceleration spectra presented in Figure 3, both longitudinal and transverse components of the selected earthquake records present remarkably high spectral accelerations in large periods. These records would be expected to develop extensive damage to structures with longer natural periods, such those using base isolation systems or with increasing size of the spans.

4 NUMERICAL RESULTS

The overall three-dimensional seismic response of the bridge is examined in detail through non-linear dynamic response analysis. The above described viaduct model is analyzed first when SPR-S isolation bearings are installed on top of each pier. These results are compared with the ones obtained when FPS supports are used as seismic isolators. In addition, two different cases are taken into account to evaluate the effect that the restraint of bearing displacements has in the seismic performance of the curved viaduct. In Case 1, bearings are allowed to move only in the tangential direction, while restrained in the radial one. This is achieved by placing side blocks on the sides of the SPR-S, or by using single-rail FPS supports. On the other hand, Case II allows bearings to move in both horizontal directions. The overall seismic response of the viaduct is evaluated analyzing first the bridge mode shapes and fundamental periods. After that the maximum bearing displacements and deck accelerations, and finally the response of the piers of the viaduct are also evaluated.

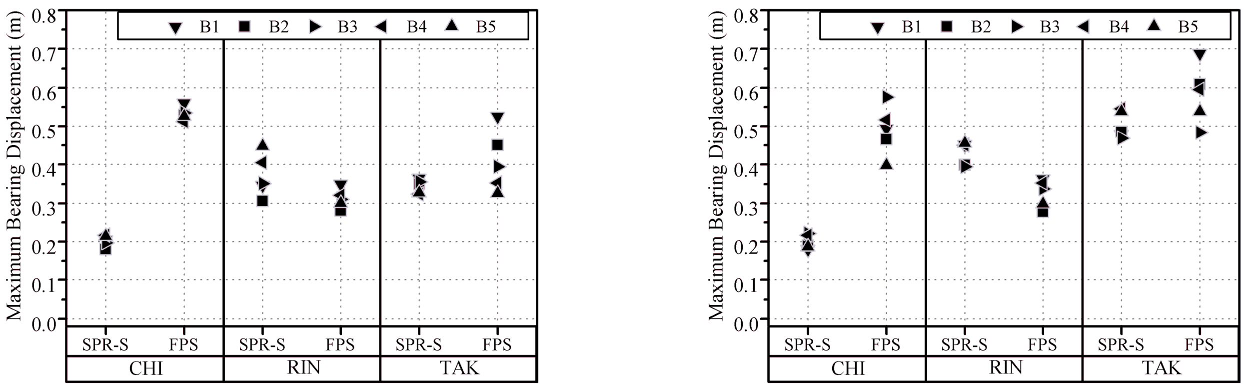
4.1 *Eigenvalue Analysis*

An eigenvalue analysis is carried out including the equivalent stiffness of the isolation bearings under the displacements obtained during the design stage. The representative natural modes for the isolated viaducts differentiating between Case 1 and Case 2 are presented in Figure 4. For viaducts equipped with SPR-S isolators, the first modes correspond to longitudinal displacements. The fundamental periods of these viaducts are slightly larger than 2 times the period of the structure when considering fixed supports. This is one of the principles of the Japanese Menshin seismic design (Kawashima 2004), which aims for moderate changes on the fundamental periods. Viaducts equipped with FPS supports are more flexible, and present a fundamental period larger than 2.75 seconds. The first modes of vibration for these models are related to the movement of the bearings of the approach span, but they present values almost identical to the ones presented in Figure 4. By comparing the obtained values with the earthquake acceleration spectra presented above, it can be concluded that for viaducts equipped with SPR-S, TAK and RIN record inputs could present the highest damage potential. On the other hand, the remarkably high predominant periods of CHI input would make viaducts equipped with FPS supports especially vulnerable to its large pulses. Finally, due to the specific characteristics of FPS supports, those bearings supporting lower vertical load will be more flexible. Consequently, the supports located under the inner girder (G2) are expected to undergo larger displacements than the bearings supporting the outer girder. This fact can be observed in the presented mode shapes for the FPS viaducts. Viaducts equipped with SPR-S supports show the opposite tendency, since in this case bearings located on top of the outside girder G1 are the ones which are expected to undergo larger displacements.



(a) Case 1
(b) Case 2

Figure 4. Natural mode shapes of the isolated viaducts



(a) Case 1

(b) Case 2

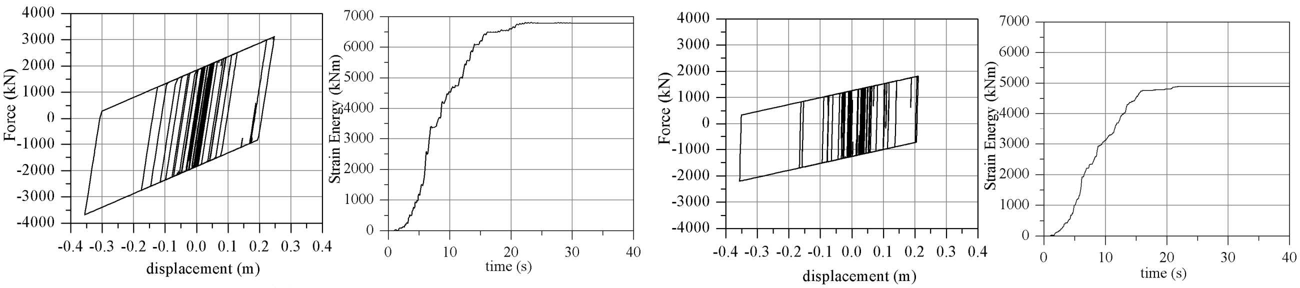
Figure 5. Maximum bearing displacements

The natural tendency of curved bridges to rotate, which appears in all the study cases, will have negative consequences in case of impacts between adjacent spans, since one girder will be the one that absorbs most of the energy impact.

4.2 *Bearing Displacements and Energy Dissipation*

In this section a comparison between the maximum displacements that the isolation bearings undergo in viaducts equipped with SPR-S and FPS supports is carried out. Figure 5(a) shows the maximum displacements of each line of bearings in viaducts where the supports can move only in the tangential direction. B1 makes reference to those bearings located on top of P1, B2 to those located on top of P2, etc. In Figure 5(b) the maximum displacement of each line of bearings evaluating both horizontal directions are plotted. The analysis of the presented data highlights how the specific characteristics of each earthquake record affect the seismic response of each isolated structure. Viaducts equipped with FPS show, in the majority of the cases, larger displacements than those equipped with SPR-S isolators. Only under the action of RIN input, an earthquake wave which characteristics make viaducts with lower vibrational periods more vulnerable, the FPS viaducts which present higher fundamental periods of vibration, shows slightly lower displacements than the SPR-S cases. Viaducts where bearings are installed according to Case 2 configuration show the largest bearing deformations when subjected to TAK input, which highlights the severe conditions that this earthquake record represents for isolated viaducts. The obtained displacements are higher than those obtained during the design stage, when these accelerograms were applied alternately.

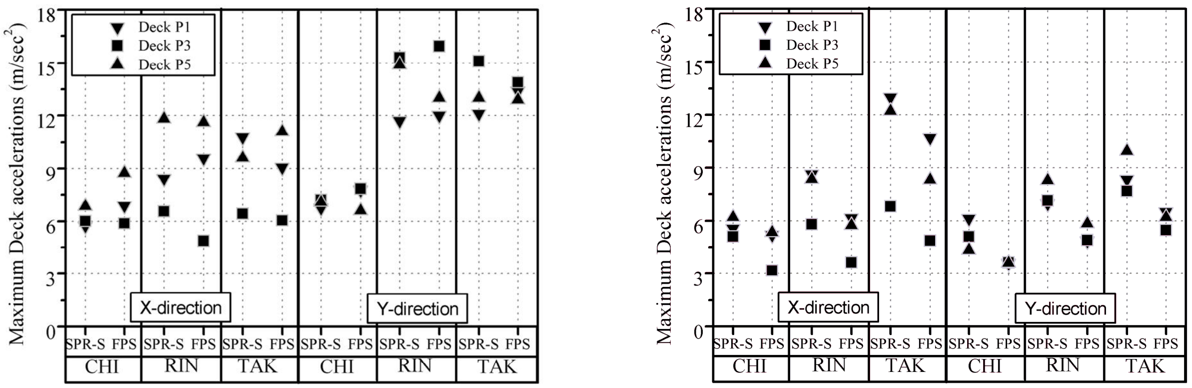
In order to complete this analysis, Figure 6 presents the force-displacements relationships and strain energy dissipation time histories for a specific isolator. The bearing located on top of P3 under the outer girder G2, following the configuration of Case 1 has been selected for comparison. Under TAK input this bearing presents similar maximum displacements for both study cases, which makes it suitable for this comparison. Examining both hysteresis loops it can be observed that SPR-S bearings present larger values of the yielding force (F_1), and post-yielding stiffness (K_2), which leads to lower strain energy dissipation under similar maximum displacements. These two parameters are related, in the case of FPS, to the supported vertical load, and are lower than the correspondent SPR-S designs, especially for end-span bearings. Increasing the coefficient of friction or reducing the radius of curvature of the sliding surface of the FPS, will increment F_1 and K_2 in the supports. However, very high values of μ will reduce the restoring capacity of the FPS (Quaglini et al. 2014), and low R_{FPS} will increase the vertical displacements of the isolators and reduce their displacement capacity.



(a) SPR-S

(b) FPS

Figure 6. Bearing hysteretic loops and strain energy dissipation time histories (Case 1) under TAK input



(a) Case 1 (b) Case 2

Figure 7. Maximum values of deck acceleration

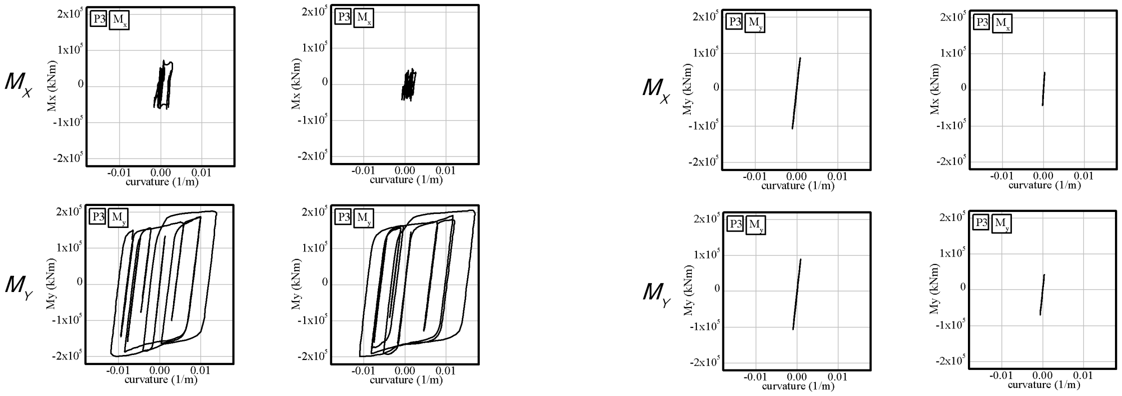
4.3 *Deck Accelerations*

In the present section, the maximum accelerations in the global X- and Y- axes directions are evaluated for different points of the deck, located on top of P1, P2, and P3. Firstly, it can be observed that viaducts following Case 1 configuration shows higher accelerations in the majority of the study cases. This can be related to the restrain of bearings displacements in the radial direction, which reduces the benefits of seismic isolation. Focusing on Figure 7 (b), which presents the maximum acceleration values for those viaducts where isolators can move in both horizontal directions, a clear difference between viaducts equipped with FPS and SPR-S supports can be observed. Viaducts equipped with FPS isolators, which suffered higher deck displacements, present in this case a better performance, showing lower deck accelerations in all the studied cases.

4.4 *Piers Response*

The seismic performance of the piers of the viaducts is evaluated in terms of maximum curvatures transmitted to the substructure. Figure 8 presents the bending moments – curvature relationships at the bottom of P3, the central pier of the viaduct. The bending moments are shown in two directions according to the tangential and radial axis of the pier. In the first row, results related to the in-plane bending moments (M_X) are presented, while the graphs located in the lower row display the out-of-plane bending moments (M_Y). Viaduct models where bearing supports have been arranged following the configuration of Case 1 show large plastic deformations in the out-of-plane direction, regardless the bearing type used for the seismic isolation of the structure. This seems to be related to the restraint of radial displacements of the bearing supports, which increases the seismic forces transmitted to the piers in the radial direction.

The results observed for the viaducts following Case 2 configuration, presented in Figure 8 (b) show a remarkable difference. No plastic deformation can be observed in either viaducts equipped with FPS or SPR-S bearings, and the piers remain elastic even under the demanding conditions imposed by TAK record input. Re-



SPR-S FPS SPR-S FPS

(a) Case 1 (b) Case 2

Figure 8. Pier bottom bending moment – curvature relationships of P3 under TAK input

garding the difference between bending supports, SPR-S bearings transmit higher forces to the piers of the viaduct due to their larger restoring forces. The lower restoring forces that characterize FPS supports are beneficial in this aspect, since they reduce the seismic demands at the piers which show lower values of bending moments and curvatures. In any case, when allowed to move in both horizontal directions, both types of isolators are effective in mitigating the seismic damage at the substructure units imposed by these strong earthquake ground motions.

5 CONCLUSIONS

The seismic response of curved viaduct models isolated by elastomeric-type and sliding-type isolation bearings and subjected to great earthquake ground motions has been analyzed. The overall seismic performance of the isolated viaducts has been analyzed focusing on their fundamental periods and mode shapes, bearing displacements, deck accelerations, and piers response, and considering two different cases depending on the configuration of the isolators. The obtained results provide sufficient evidence for the following conclusions.

Allowing isolation bearings to move in both horizontal directions increases the beneficial effects of the seismic isolation, improving the seismic response of the viaduct regardless the type of isolator.

When compared to viaducts equipped with SPR-S supports, FPS viaducts present larger periods of vibrations. In the event of near-fault earthquakes characterized by high peak accelerations and large predominant periods, these viaducts present larger displacements but lower deck accelerations. The lower restoring forces of the FPS supports imply lower energy dissipation capacity but, at the same time, reduce the transmitted forces to the piers of the viaduct.

Bridge models equipped with SPR-S supports showed lower bearing displacements, but larger deck accelerations in the majority of the cases. SPR-S isolators present remarkably high energy dissipation capacity and, when allowed to move in both horizontal directions, protect the piers from seismic damage under the action of the strong earthquake ground motions taken into account in the current study.

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