Effect of Different Base Isolation Bearings on Nonlinear Seismic Response of Curved Viaducts.

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1. INTRODUCTION

During the last decades horizontally curved viaducts have become an important component in modern highways systems as a viable option at complicated interchanges or river crossing where restrictions and constraints of limited space make extremely complicated the adoption of standard straight superstructures. However, the considerable complexity associated with the analysis of curved viaducts requires a realistic prediction of the structural response, especially under the extreme ground motions generated by earthquakes. Besides, the susceptibility to seismic damage of curved bridges is even more amplified with the rupture of continuity of the superstructure at expansion joints.

In recent years, as a result of the implementation of modern seismic protection technologies, the number of seismic isolated bridges using base isolation bearings has grown considerably. The results show that the performance of this type of earthquake protection system is satisfactory under the action of recent strong earthquakes. These kind of supports protect the bridge from earthquake loads by increasing the fundamental period and dissipating the seismic energy by hysteretic damping. Nevertheless, the performance of this kind of structures under great earthquakes presents a variation in the behavior depending on the specific characteristics of each kind of base isolation bearing.

Therefore, the purpose of the present study is to analyze, through the nonlinear dynamic analysis of a three-dimensional model of a curved highway viaduct, the performance of the bridge under different support conditions. Special attention has been focused on the response of the expansion joint, due to the extreme complexity associated with connections between isolated and non-isolated sections in curved viaducts; and the bridge piers, one of the most vulnerable components in resisting earthquakes, that plays an important role in the serviceability of the structure after an important seismic event. The dynamic behavior of the curved structure equipped with Lead Rubber Bearings, High Damping Rubber Bearings, Friction Pendulum Systems and Friction Sliding Bearings, with different structural and damping properties in each case, has been studied comparing the response of the model under the input of a Level II earthquake ground motion.

2. ANALYTICAL MODEL OF VIADUCT

2.1. Superstructure

The highway viaduct considered in this study is composed by a three-span continuous seismically isolated bridge section connected to a single simply supported non-isolated span. The bridge alignment is horizontally curved in a 100m radii circular arc. The total viaduct length of 160 m is divided in equal spans of 40 m, as shown in **Fig. 1-a**. The bridge superstructure consists of a concrete deck slab that rests on three I-shape steel girders, equally spaced at an interval of 2.1 m. The three girders, that have been called G1, G2 and G3, (being G1 the inner girder, G2 the girder in the middle and G3 the outer girder) are interconnected by end-span diaphragms as well as intermediate diaphragms at uniform spacing of 5.0 m. Full composite action between the slab and the girders is assumed for the deck superstructure model.

2.2. Substructure

The deck weight is supported on five hollow box section steel piers of 20m height (**Fig.1-b**), designed according to the seismic code in Japan[1]. Characterization of structural pier elements is based on the fiber element modeling where the inelasticity of the flexure element is accounted by the division of the cross section into a discrete number of longitudinal and transverse fiber regions, obtaining the element stress resultants by integration of the fiber zone stresses over the cross section of the element. At the pier locations the bridge deck is modeled in the transverse direction as a rigid bar of length equal to the deck width in order to model the interaction between deck and pier motions[2]. Tangential configuration for both piers and bearing supports is adopted respect to the global coordinate system of the bridge, in which the X- and Y-axes lie in the horizontal plane while the Z-axis is vertical.

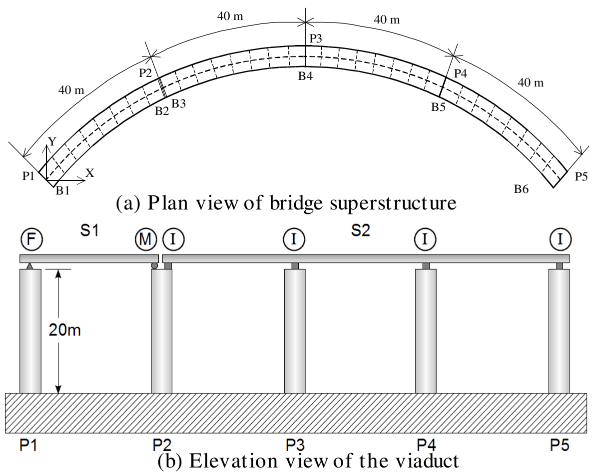

Fig. 1 Model of curved highway viaduct

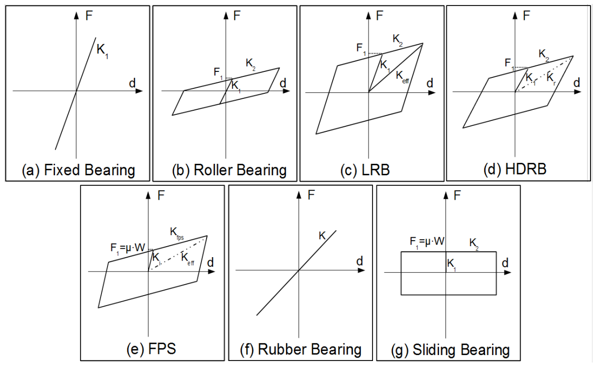

Fig. 2 Analytical models of bearing supports

2.3. Models of Bearings

Four different types of base isolation supports installed between the top of bridge piers and beneath the deck structure are considered in the analysis. The non-isolated simply supported bridge section (S1) is supported by steel fixed (**Fig. 2(a)**) and steel roller (**Fig. 2(b)**) bearings. The isolated continuous section (S2) is supported on top of four pier units (P2, P3, P4 and P5) by the following Base Isolation Bearings:

(1) Lead Rubber Bearings (LRB): The LRB are represented by the bi-linear force displacement hysteresis loop (**Fig. 2(c)**). A pre-yield to post-yield stiffness ratio (K_1/K_2) of 10 is chosen as design parameter to achieve maximum seismic energy dissipation concentrated in the bearings, and to control maximum bearing deformation[3]. Three different types of LRB with 3 different sizes of their lead plug (small (L1), medium (L2) and large (L3)), have been taking in account in this study.

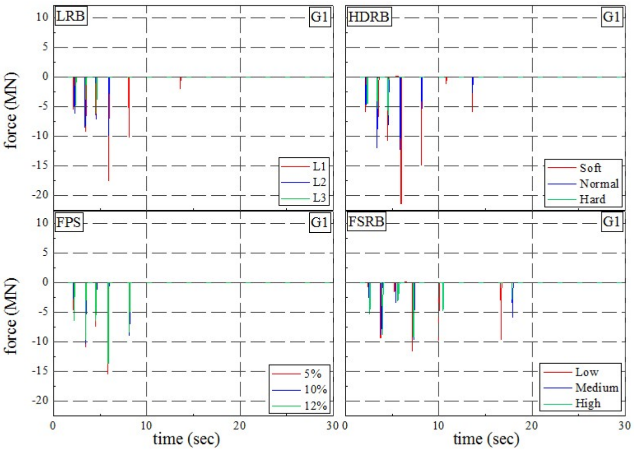

Fig. 3 Impact forces at the expansion joint

(2) High Damping Rubber Bearings (HDRB): the desire damping is achieved by adding fillers (carbon-black) to the rubber. In this study three HDRB isolators, represented by a bi-linear force-displacement loop[4] (**Fig. 2(d)**) have been analyzed, according to three different high dissipating compounds: Soft compound (HDRBS with G=0.4N/mm^2 and 10% equivalent viscous damping); Normal compound (HDRBN with G=0.8N/mm^2 and 10% equivalent viscous damping); and Hard compound (HDRBH with G=1.4N/mm^2 and 16% equivalent viscous compound).

(3) Friction Pendulum System (FPS): in order to reduce lateral forces and shaking movements transmitted, this bearing uses the characteristics of a pendulum to lengthen the natural period of the isolated structure. In the present study three different kinds of FPS have been analyzed (**Fig. 2(e)**), in order to evaluate the effect of the dynamic friction of the sliding surface on the seismic performance of the viaduct. Friction coefficients (μ) of 5%, 10% and 12% have been selected for this purpose.

(4) Friction Sliding Bearings (FSRB): A combination of Friction Sliding Bearings and Rubber Bearings is arranged in the studied model. The Friction Sliding Bearings hold vertical load and dissipates seismic horizontal energy with its friction force, being modeled by a bi-linear force-displacement hysteretic loop (**Fig. 2(g)**). Three different materials for the sliding surface: low friction (FSRBLW), medium friction (FSRBMD) and high friction (FSRBHI) have been taken in account. The Rubber Bearings lead with the horizontal force, control the displacements and have been modeled by using the linear displacement-load relationship with a yield stiffness of 15MN/m (**Fig. 2(f)**). The Friction Sliding Bearings are placed at the outside and inside girder, whereas the Rubber Bearing is placed in the inner girder.

Finally, the radial displacement of the bearings have been limited for all the the studied cases through the installation of lateral side stoppers, in order to control undesirable lateral deck displacements that may have negative consequences in the seismic bridge performance[5].

3. METHOD OF ANALYSIS

The analysis on the highway viaduct model is conducted using an analytical method based on the elasto-plastic finite displacement dynamic response analysis. The tangent stiffness matrix, considering both geometric and material nonlinearities, is adopted in this study, being the cross sectional properties of the nonlinear elements prescribed by using fiber elements. The stress-strain relationship of the beam-column element is modeled as a bi-linear type. The yield stress is 235.4 MPa, the elastic modulus is 200 GPa and the strain hardening in plastic area is 0.01. The implicit time integration Newmark scheme is formulated and used to directly calculate the responses, while the Newton-Raphson iteration method is used to achieve the acceptable accuracy in the response calculations. The damping of the structure is supposed a Rayleigh's type, assuming a damping coefficient of the first two natural modes of 2%.

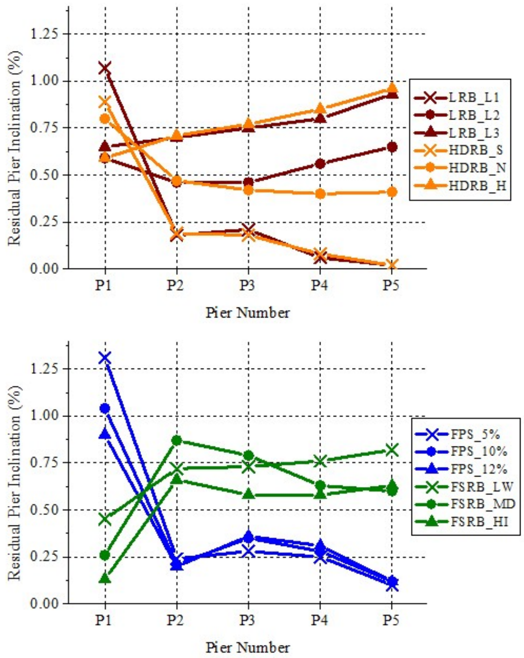

Fig. 4 Residual pier inclination

In order to assess the seismic performance of the viaduct, the non-linear bridge model was subjected to the longitudinal (L), transverse (T) and vertical (V) components of a strong ground motion records from the Takatori station during the 1995 Kobe earthquake. The longitudinal earthquake component shakes the highway viaduct parallel to the X-axis of the global coordinate system, while the transverse and vertical components are acting in the Y- and Z-axes, respectively. The large magnitude records from the 1995 Kobe Earthquake used in this study, classified as near-fault motions, are characterized by the presence of high peak accelerations and strong velocity pulses with a long period component as well as large ground displacements[6]. This exceptionally strong earthquake has been selected due to the destructive potential of long duration pulses on flexible structures.

4. NUMERICAL RESULTS

The overall three-dimensional seismic response of the viaduct is investigated in detail through non-linear dynamic response analysis. Particular emphasis has been focused on the piers behavior due to the important damage that these elements can be suffered during an important seismic event, and the role that this could have in the collapse or temporary lost of post-earthquake serviceability of the structure. The expansion joint response has also been studied, paying special attention to the possibility of pounding damage, due to the amplification of the earthquake damage originated by the rupture of the continuity of the deck superstructure at the expansion joints.

4.1. Pounding damage at the expansion joint

While seismic isolation provided by Base Isolation Bearings beneficially reduces the transmitted forces into the piers, the important added flexibility results in detrimental increase of collisions between adjacent decks. Due to this phenomenon local damage at colliding girders and high and undesirable impact forces transmitted to bearing supports located in the proximity of the expansion joint can be expected. Maximum impact forces higher than the weight of the superstructure (8.84 MN) are considered dangerous, implying significant transmitted forces to the bearing supports and structural damage[1].

According to **Fig. 3** LRB L1 and HDRB with soft compound, show 6 important impacts and two of them (four in the case of HDRB) overpass the proposed damage index.

However, the results reveal that increasing the stiffness of these bearings, improves the behavior of the viaduct in all cases, decreasing the number of impacts, as well as reducing the magnitude of the impact forces to values that reduce the possibility of pounding damage. On the other hand, In the case of FPS increasing the coefficient of friction don´t lead to less number of impacts or a significant reduction of the magnitude of the impact forces. In this case, two impacts overpass the damage index and consequently structural damage is expected. Finally, FSRB show an important number of impacts, even in moments when the rest of the bearings don´t suffer important impact forces. However, increasing the friction of the sliding surface implies a significant reduction on the magnitude of the impact forces and proves to be an effective solution to decrease the possibility of pounding damage for FSRB.

4.2. Residual Pier Inclination

As a consequence of a strong earthquake, piers supporting highway viaducts can be severely damaged due to local inelastic cyclic strains[7]. As a consequence, piers sustain significant residual deformations, that are dependent on the maximum ductility reached during the seismic event. Bridges supported on piers with lare residual inclination may lose their serviceability, becoming largely unsafe and probably irreparable. Therefore, the Residual Pier Inclination (RPI) has been studied in this research as an important damage index, being computed as the final pier position in the orbit of the two horizontal directions at the end of the earthquake. Values greater than 1% have been defined as a cause of severe damage in this study[1].

The results, shown in **Fig.4**, indicate that the variation of the damping characteristics of the bearings leads to different responses of the structure depending on the bearing type and the location of the pier. Firstly, LRB and HDRB show a similar behavior: for Pier 1, equipped with steel bearings, flexible supports arranged in the isolated span lead to higher RPI values on this pier. In the case of LRB L1, the displacement overpasses the damage index. However, the response of the isolated span shows an opposite behavior when the stiffness of LRB and HDRB is increased: LRB L3 and HDRB with a hard rubber compound behave worse than the medium and soft bearings. It can also be noticed that in all the cases the values of the residual displacements of the last four piers show an uniform distribution.

The results obtained for FPS show a similar behavior for all cases, remaining almost independent of the variation of the coefficient of friction, and small residual displacements are observed. Nevertheless, FPS with μ=0.05 and μ=0.10 show a high and undesirable value on P1 displacement, that can be avoided if the friction of the sliding surface is increased until 12%. Moreover, increasing the friction of the FPS decreases the RPI of P1, but has not an important effect on the response of the isolated span. Finally, in the viaducts arranged with FSRB, same behavior is expected for P1, but increasing the friction of the sliding bearing has an important effect on the performance of the isolated span. While low friction and high friction FSRB show a uniform distribution of the residual displacements of the last 4 piers and a RPI lower than 0.80; bearings with a medium coefficient of friction show higher displacements in inner pears that are close to the damage index proposed in this study. Therefore, for this last type of bearing, the FSRB with the highest friction shows the best performance.

4.3. Bending moments at pier´s bottom

During an earthquake, the part of the pier that is more affected by the efforts induced by the ground motion is the bottom section, where the bending moments reach to the highest value. It is well known that maximum curvatures transmitted to the base of the pier can be considered to be an appropriate measure of seismic structural damage, since the plastic strain energy dissipated in the piers is related to inelastic deformations and thus, to structural damage. For this reason it has been adopted as an important response factor in the present study.

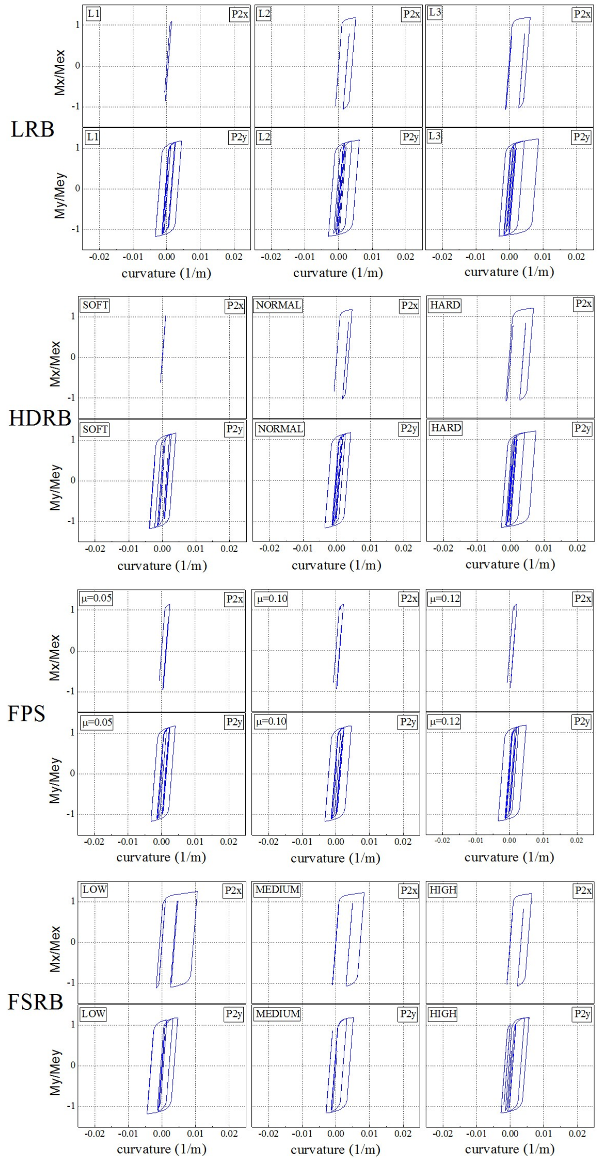

Fig. 5 Bending moment ratio at pier 2 bottom

Fig. 5 helps to visualize the severity of inelastic pier response through the bending moment-curvature relationships at the pier 2 base in X and Y directions subjected to TAK input.

The results obtained from the analysis of the viaduct show that the piers sustain the highest damage in the Y direction, due to the installation of stoppers in order to limit the radial displacements. Moreover, these displacements are higher for pier 2 due to the curvature of the bridge, that concentrates the efforts on the central piers.

According to the results for the X direction, it can be appreciated that among the base isolation bearings the cases of FPS (for all the friction coefficients studied in this research), LRB L1 and HDRBS represent less severe damage to the piers. In the case of LRB increasing the damping characteristics (larger size of the lead plug) involves an important growth of the stiffness of the bearing that implies higher seismic forces transmitted to the bridge piers and higher bending moments for both directions. This effect is extensive for HDRB. It is observed that viaducts equipped with FSRBLW show the worst performance and damage on pier 2 can be expected due to inelastic strain. However, and in contrast to the rest of the bearings, increasing the damping properties of FSRB implies a remarkable reduction on the maximum moment and curvature at the bottom of the pier for X direction, improving the seismic response of the viaducts arranged with this kind of bearing.

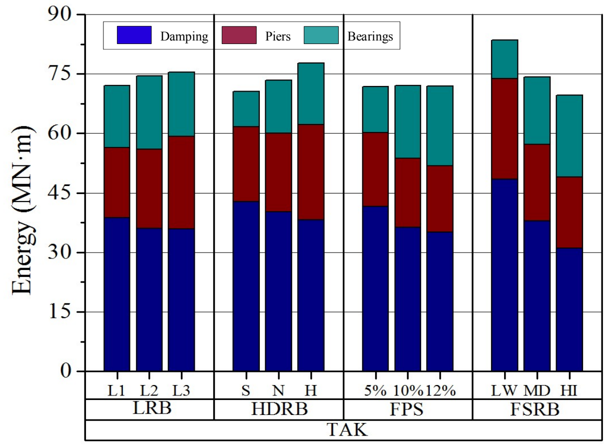

Fig. 6 Energy distribution at the end of the earthquake

4.4. Energetic response

The effectiveness of the installation of the different types of Base Isolation Bearings is studied evaluating the energy dissipated at two different structural elements: the piers and the bearings. The plastic strain energy dissipated in the piers is strictly related to inelastic deformations and, consequently, to structural damage. On the other hand, a great amount of seismic energy dissipated by the bearings implies an effective protection against earthquakes provided by the isolation system.

Figs. 6 clarifies the participation of the different structural elements and mechanisms to dissipate the total energy exerted on the viaduct during the seismic event. Comparing the studied cases, LRB show a high amount of energy dissipated by the bearings, being the support with a medium size of the lead plug (L2) the one who shows a better performance. Increasing the size of the lead plug tends to a larger amount of total seismic energy, but in the case of L3, this increase is not dissipated by the bearings in an important percentage, being the piers the part of the structure that mostly dissipates it. However, L1 and L3 present also a good performance, and important damage of the piers due to inelastic deformations is not expected. For the case of HDRB, HDRBS shows the lower energy dissipated by the bearings; however, increasing the damping characteristics leads to an increase in the total amount of energy, and at the same time a higher amount of energy dissipated by the bearings, thus the piers are protected.

In the case of FPS, increasing the coefficient of friction implies more seismic energy dissipated by the bearings, but not an increase of the total amount of energy. Therefore, the amount of energy dissipated by the piers decreases, resulting in a considerable reduction in seismic damage. This high amount of energy dissipation for all FPS types is related to the large displacements of the supports that lends to a high possibility of pounding damage, as was pointed out in previous sections of this document. Finally, the results show that for FSRB cases, increasing the damping characteristics of these bearings leads to higher amount of energy dissipated by the supports and a decrease of the total amount of seismic energy received by the structure. However, for FSRBLW the amount of energy dissipated by the piers is very important and, as it was advanced during the analysis of the curvature at the bottom piers, this type of bearing results in the highest seismic strain energy dissipated at the bridge piers.

5. CONCLUSIONS

The effects of increasing the damping properties of 4 different types of base isolation bearings on nonlinear seismic response of curved highway viaducts have been analysed. The possibility of pounding damage, the residual displacement at the top of the piers, the moment of the pier´s bottom and the energy response of the viaduct have been evaluated in detail under the action of a near-fault earthquake ground motion. The results provide sufficient evidence for the following conclusions:

1) For LRB, L1 and L2 show lower bearing relative displacements and consequently, the possibility of pounding damage decreases. Furthermore they behave correctly protecting bridge piers against seismic damage. On the other hand, LRB L1 suffer higher bearing relative displacements and because of that, higher risk of pounding damage. Besides, piers situated in the isolated span are protected, however P1 suffers high residual displacement that can affect the serviceability of the bridge after a strong seismic event. Although all the studied LRB types show good energy dissipation properties, LRB L2 and L3 show a better global seismic response.

2) HDRB with high damping characteristics behave correctly against pounding damage, whereas the other two types suffer important impact forces. However, in order to control the seismic forces transmitted to the piers, HDRBS and HDRBN show a better performance. Regarding to energetic response, HDRBS show worse dissipation capacities. Therefore, HDRB with hard compound is recommended according to the results of the studied case.

3) For FPS all the studied cases show similar behaviours. The large displacements suffered by these bearings involve high possibilities of pounding damage and small seismic forces transmitted to the piers. Besides, they show large amount of seismic energy dissipation. However, small values of μ lead to unacceptable values on the residual displacements for P1. Therefore, a high coefficient of friction is recommended for this type of bearing and the installation of cable restrainers or energy dissipation systems at the expansion joint should be studied to avoid structural damage related to this structural element.

4) The variation of the properties of FSRB has an important role in its seismic response: increasing the friction coefficient involves less risk of pounding damage, lower forces transmitted to the piers and a better energetic response. Thus, the bearing with the highest coefficient of friction, FSRBHI, shows the better seismic performance for the the case of Friction Sliding Bearings.

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