Nonlinear Seismic Response of Curved Viaducts Isolated with Friction Pendulum Systems under Level II Earthquake Ground Motions

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1. INTRODUCTION

Recent seismic events, such as the 1994 Northridge earthquake in California, the 1995 Kobe earthquake in Japan and the 1999 Chi-Chi earthquake in Taiwan have demonstrated the seismic vulnerability of highway bridges, which is magnified in structures with irregular and complex geometries like curved viaducts[1)], especially in those equipped with expansion joint[2)].

To protect and improve the seismic performance of these lifeline structures, the use of base isolation system has been widely implemented, replacing the steel fixed and roller bearings supports, that previous research indentified as significantly vulnerable to seismic loads. Although rubber bearings have been extensively used in base isolation systems, sliding bearings have found more and more applications in numerous cases around the world. These systems filter out the imparting earthquake forces through the frictional interfaces and rarely possess re-centering capability, except the Friction Pendulum System (FPS)[3)]. Due to its curved sliding surface, movement of one part of the FPS bearing with respect to the others resembles pendulum motion, providing isolated structures with restoring forces by gravity[4)].

Since FPS is a common isolation bearing equipped with all the desirable features of this earthquake protection technology, the current research is devoted towards the necessary study of its dynamic behavior in bridges with complex configurations subjected to severe ground motions, and also to investigate the optimum design parameters and configurations for FPS under these demanding conditions.

2. ANALYTICAL MODEL OF VIADUCT

2.1 Superstructure

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

2.2 Substructure

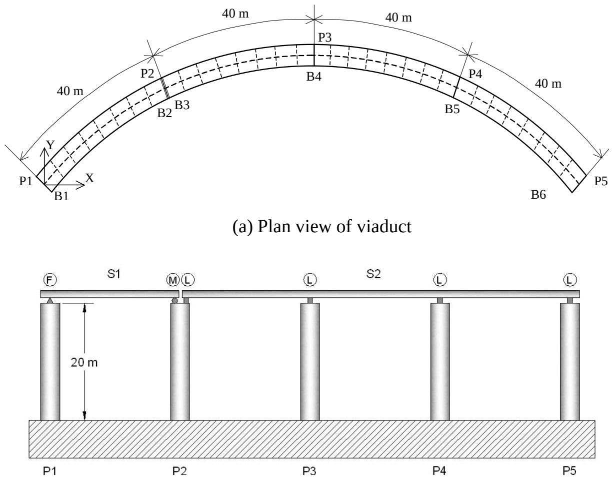
The deck weight is supported on five hollow box section steel piers of 20m height, designed according to the seismic code in Japan[1)]. Tangential configuration for both piers and bearings supports is adopted respect to the global coordinate system of the bridge, in which the X-axis and Y-axis lie on the horizontal plane while the Z-axis is vertical.

2.3 Bearing Supports

(1) ***Bearing Supports Configuration:*** The non-isolated simply supported span approach (S1) is supported by steel fixed bearings resting on Pier 1 (P1), whereas steel roller bearings are placed at the right end on Pier 2 (P2), allowing for movement in the in-plane tangent direction while restrained by stoppers in the out-of-plane radial direction. The isolated continuous superstructure (S2) is supported on four pier units (P2, P3, P4 and P5) by seismic isolation bearings. Regarding to the isolation system two different cases are considered in this manner. For 3FPS case the seismic isolation of S2 is achieved by placing FPS supports under each of the three girders above the piers.

On the other hand, FPS+R acronym denotes the case where FPS and Rubber Bearings are combined as a function-separated bearing, following a common trend to prevent isolated structures equipped with sliding bearings from over-displacing. For this configuration, FPS bearings are placed at the outer and inner girder, whereas the Rubber Bearing supports the middle girder.

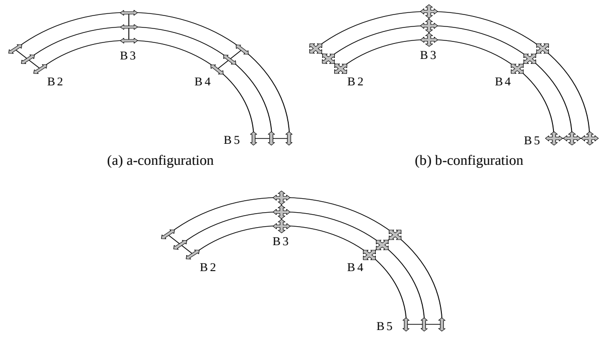
Finally, in order to examine the effect of different radial restraint configurations on the seismic performance, displacements of the isolation bearings have been partially limited for some arrangements through the installation of lateral side stoppers as follows (**Fig.2**). Out-of-plane radial displacements are restricted in a-configuration for all isolation units. In b-configuration all the isolation bearings are free to move in radial direction. Finally, an intermediate solution c-configuration is analyzed, consisting in providing stoppers only to end-span bearings to limit the joint displacements exclusively in the tangential direction.[5)]



(a) Plan view of viaduct

(b) Elevation view of the viaduct

Fig. 1 Model of curved highway viaduct



(a) a-configuration

(b) b-configuration

(c) c-configuration

Fig. 2 Radial restraint configurations for the isolated span

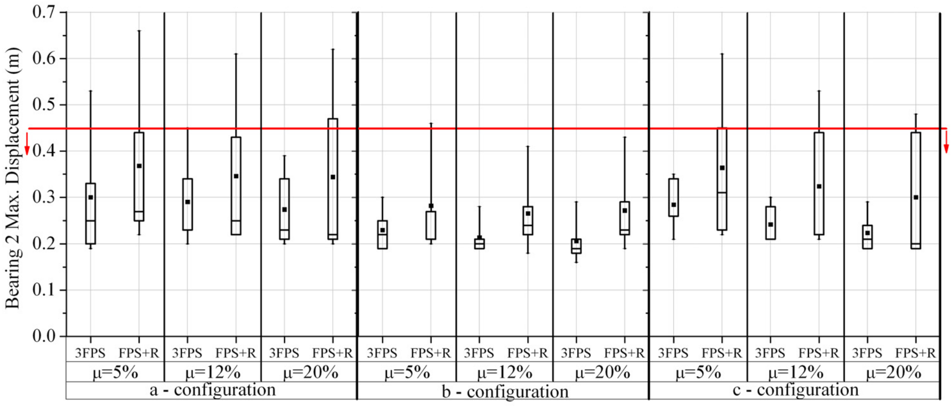


Fig. 3 Evaluation of risk of unseating damage

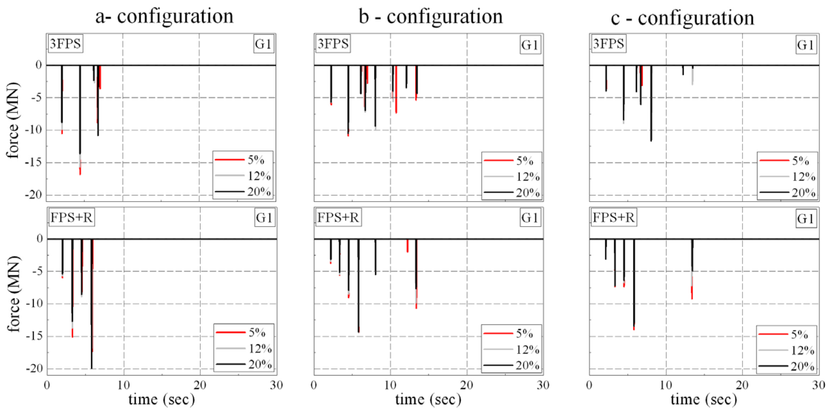


Fig. 4 Impact forces at the expansion joint

(2) ***Bearing Supports Modeling:*** The response of FPS is modeled by a simplified bilinear force-deformation relationship. When the earthquake forces are below the friction force level (F_1=μ•N), the structure responds like a conventional supported structure with the pre-yield stiffness K_1. Once F_1 is exceeded the dynamic response is controlled by the stiffness of the FPS isolators (K_2=N/R). The FPS bearings analyzed in this paper have a radius of curvature of the sliding surface R=1m, while the value of the supported weight by each device (N) is taken as the corresponding value after gravity load analysis. Three different coefficients of friction (μ) are taken in account to carry out a parametric analysis adopting three different values: μ=5%, 12% and 20%. Finally, Rubber Bearings are modeled by using the linear-displacement load relationship with a yield stiffness of 10MN/m.

3. METHOD OF ANALYSIS

The bridge model has been developed in-house using the Fortran programming language and its analysis is conducted through an analytical method, that considers both geometric and material nonlinearities, and prescribes the cross sectional properties of the nonlinear elements by using fiber elements. The steel is modeled as a bilinear material with yield strength of 235.4MPa, elastic modulus of 200GPa and a strain-hardening ratio of 0.01. The governing equations of motion are solved in the incremental form using Newmark's step-by-step method assuming linear variation of acceleration over small interval of time (β=0.25), while the Newton-Raphson iteration method is selected to achieve the acceptable accuracy in the response calculations.

To ensure that the conclusions are applicable to different near-fault earthquake ground motions 5 different three dimensional records, such as Northridge Earthquake (Rinaldi and Sylmar Receiving Stations), Kobe earthquake (JR Takatori Station and Kobe Observatory of Japan Meteorological Agency) and Chi-Chi earthquake, are employed for simulations. Since these large magnitude records are characterized by the presence of high peak accelerations, strong pulses with a long period component, as well as large ground displacements, flexible structures are especially exposed to its destructive potential

4. NUMERICAL RESULTS

The overall three-dimensional seismic response of the viaduct is investigated in detail through non-linear dynamic response analysis. Particular emphasis have been focused on the expansion joint and the piers seismic response, due to the important damage they can suffer, and the role that this could have in the collapse or lost of serviceability of the structure after an important seismic event.

4.1 Deck Unseating

One of the most catastrophic seismic damages to bridge superstructures is the failure due to deck unseating. During an earthquake, adjacent spans can vibrate out of phase, resulting in relative displacements at the expansion joints which can exceed the seat width at the pier top, causing the dislodgement of the rollers from the bearing assembly and subsequently collapse due to deck superstructure unseating. The maximum roller bearing displacement in the negative tangential direction has been established as the damage index, fixing a limit of 0,45m to determine the high unseating probability for existing bridges with narrow steel pier caps that provide short seat widths.

In **Fig. 3**, the effect of seismic isolation configuration, radial restraint of the bearings and friction coefficient of the FPS on the reduction of the possibility of deck unseating is evaluated. The results of the analysis of the viaduct subjected to the five near-fault earthquake motion records above mentioned, are represented by using box-whisker plots.

Firstly, regarding to the isolation system configuration it can be observed that compared to FPS+R cases, viaducts equipped only with FPS show less risk of unseating damage, and also less variability in the dynamic response results, especially for those cases where radial displacements of the supports are not fully restrained. On the other hand, increments of the coefficient of friction μ, slightly reduce the maximum tangential displacements at the roller bearing. This trend of variation is more appreciable for the combination of friction and rubber bearings or paying attention to the peak values of the obtained results, which correspond to the Takatori Station and Chi-Chi earthquake records. Regarding to the different configurations of radial stoppers, radially non-restrained viaducts effectively eliminate the risk of unseating damage for the vast majority of studied cases, being b-configuration particularly effective in this regard.

4.2 Pounding Damage

While the flexibility provided by base isolation bearings beneficially limits the transmitted forces into the piers, the considerable added flexibility results in detrimental increase of collisions between adjacent decks, which could cause local damage at colliding girders and high impact forces transmitted to bearing supports located in the proximity of the expansion joint. Maximum impact force greater than the weight of the superstructure (8,82MN) have been observed to provide a good estimation of significant transmitted forces to bearing supports[1)]. **Fig. 4** presents the time histories of impact forces at the expansion joint for Takatori Station input, and helps to visualize the importance of this problem for curved viaducts equipped with Friction Pendulum System when subjected to near-fault earthquake ground motions.

In general, for viaducts exclusively isolated with FPS supports (3FPS cases) the number of impacts is greater than the ones appreciated for FPS+R cases. However, the installation of Rubber bearings seems ineffective in reducing the magnitude of the impact forces, which remain remarkably higher than the proposed damage index. None of the proposed bearing configurations is able to decrease the acceleration of the superstructure, or the displacements of the isolators to values that could lead to smaller impact forces and thus to a lower risk of pounding damage.

Analyzing the displayed time histories it can be appreciated that, in some cases it is possible to eliminate some of the impacts, and reduce the magnitude of the remaining ones by increasing the coefficient of friction of the isolators until 20%, although peak values still remain over the damage index. Lastly, it seems remarkable the effect that radial stoppers have in the seismic response of the viaduct regarding to this aspect. While the restriction of radial displacements is effective in reducing the impacts, the reduction of the magnitude of the forces can only be achieved by allowing the bearing supports to move in both horizontal directions. Once again, this design alternative is not enough to completely eliminate the risk of pounding damage in the event of the destructive earthquake ground motions taken in account in this study.

4.3 Bending moment at pier's bottom

During an earthquake, the section of the pier that suffers higher demands is the bottom one, where the bending moments reach to the highest value. The maximum curvatures transmitted to the base of the pier can be considered as an appropriate measure of structural seismic damage, since the plastic strain energy dissipated in the substructures is related to inelastic deformations and thus, to structural damage. **Fig. 5** presents the bending moment-curvature relationships at one of the central piers (P4) in X and Y directions, when the viaduct

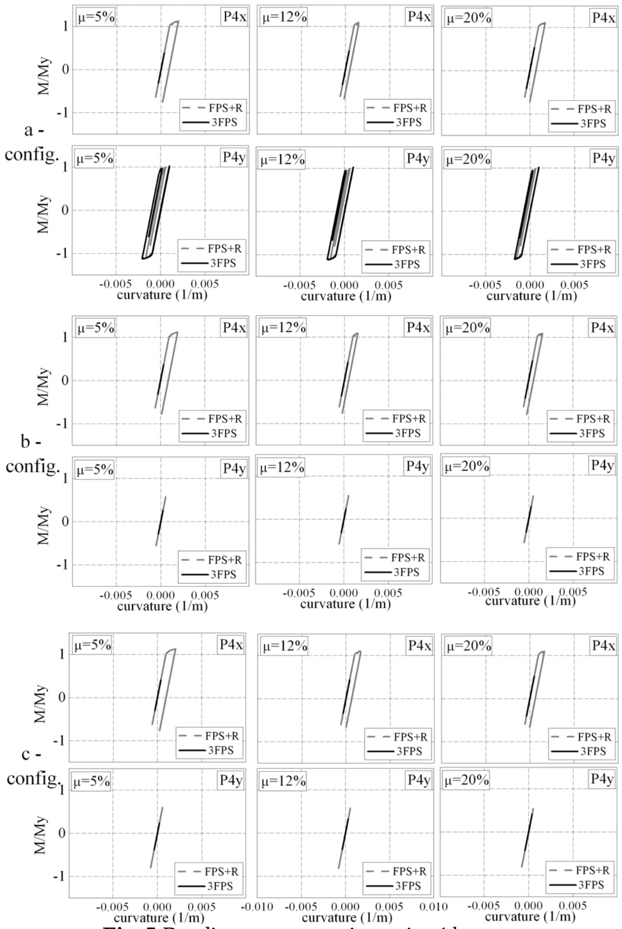


Fig. 5 Bending moment ratio at pier 4 bottom

is subjected to the Northridge Earthquake records registered in Rinaldi Station.

According to the results for the in-plane bending moments (P4x), it can be appreciated that for viaducts equipped exclusively with FPS supports, bending moments beneficially remain below the yield force, which evidences the effectiveness of this isolation device to minimize the seismic forces carried out by the piers, through the disconnection of the bridge deck form the substructure during the seismic event. The installation of Rubber bearings in combination with FPS, increases the stiffness of the isolation system, and thus higher seismic forces are transmitted to the piers and consequently values that slightly overpass the yield force can be observed. On the other hand, increments in the magnitude of the friction coefficient μ cause slightly higher values of bending moment at the pier bottom, since the isolated system remains more time in the non-sliding phase.

Finally, analyzing the effect of the restriction of radial displacements at the isolation bearings, we can conclude that a-configuration leads to higher values of the bending moment in the out-of-plane direction, since the presence of stoppers leads to high shear forces transmitted to the substructure, increasing bending moments in the out-of-plane direction. However by the installation of isolation bearings following b- and c-configurations, the benefits of seismic isolation in reducing seismic forces transmitted to the substructure, can be observed in both horizontal directions. Furthermore, for 3FPS cases with possibility of radial displacement, elastic behavior of P4 in both in plane and out-of-plane directions can be appreciated, fact that beneficially eliminates the energy dissipated by the pier due to inelastic deformations and thus, improves the seismic performance of the viaduct.

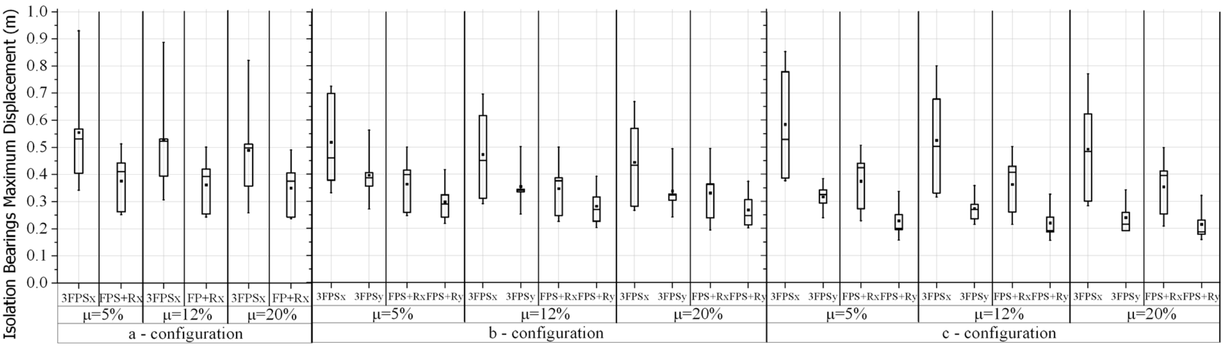


Fig. 6 Maximum displacements of isolation bearings

4.4 Base Isolation Bearings Displacements

In this section the relative displacements of the base isolation supports are analysed in terms of maximum displacements in the tangential direction (designated with the subscript x) and radial direction (y). In **Fig.6** the maximum isolation bearing displacements for all the studied cases are plotted by using box-whisker plots, in order to clarify the variation of results associated to each near-fault ground motion and to be able to provide more general and widely applicable conclusions.

The combination of Rubber bearings and FPS (FPS+R case) is effective to reduce the large bearing displacements of the viaducts equipped only with FPS isolators, and is also capable of controlling the range of variation of these large relative displacements which, otherwise, will lead to requirement of very large supports. This performance is also perceived comparing the values of the radial displacements for b- and c-configurations. Increments in the friction coefficient have also a similar effect, because for higher friction values the isolator system becomes relatively stiff and, as a result, the bearing displacements are reduced. Regarding to the radial stoppers configurations, once the bearings are free to move in both directions, the peak values of the tangential displacements are reduced and the average value of these displacements remains approximately constant. Observed maximum radial displacements of the isolators present moderate values.

5. CONCLUSIONS

The effects that different bearing supports configurations involving the use of Friction Pendulum systems, have in the overall seismic performance of curved highway viaducts subjected to strong near-fault earthquake ground motions have been analyzed. The consequences that the use of Rubber bearings as part of the isolation system, the role of the friction coefficient of the sliding surface of FPS and the inference of radial stoppers on the dynamic behavior of the bridge have been studied. The results of the analysis of the risk of unseating damage, pounding damage at the expansion joint, bending moment at the bottom of a central pier, and maximum displacements registered at the base-isolation supports, provide sufficient evidence for the following conclusions:

1) The calculated results clearly demonstrate that the combination of FPS and Rubber bearings in an integrated sliding bearing configuration, effectively reduces the large displacements of FPS supports when installed in curved viaducts under the effect of strong ground motions. However, this bearing combination shows a poor performance regarding to the expansion joint seismic performance, since the risk of unseating and pounding damage is clearly increased in comparison with the case where only FPS are installed as isolation system.

2) Under near-fault ground motions, the increase of friction coefficient of FPS may reduce the bearing displacements significantly without much alteration to the peak superstructure accelerations, but slightly increasing the seismic forces transmitted to the piers. Therefore, through a detailed parametric study it is possible to obtain the most suitable value for the coefficient of friction of FPS to optimize the seismic performance of curved viaducts subjected to strong ground motions.

3) For the studied cases, models where bearing displacements in the radial direction of the isolated span are not completely restrained, a better performance is observed in the majority of the studied seismic responses. By allowing FPS to move in both horizontal directions, we can increase the benefits offered by this seismic isolation system.

4) Finally, curved viaducts equipped with FPS are clearly vulnerable to suffer seismic damage due to pounding between adjacent spans at the expansion joint during a strong seismic event. None of the design alternatives described in this paper is able to fully reduce the risk of damage and other possibilities, like the installation of restrainers at the expansion joint should be studied in order to avoid seismic damage. This high flexibility of FPS viaducts that detrimentally affects the performance of the expansion joint, is, at the same time beneficial for the protection of the piers. The presented results are satisfactory regarding to this aspect, with values that remain inside or near the elastic range for the vast majority of studied cases, demonstrating that with a suitable solution to reduce the impacts at the expansion joint, FPS have potential to become a suitable alternative for seismic isolation of curved viaducts subjected to strong earthquake ground motions.

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