EXPANSION JOINT SEISMIC DAMAGE EVALUATION ON CURVED BRIDGES EQUIPPED WITH FRICTION PENDULUM SYSTEMS

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ABSTRACT

Since 1995 Kobe Earthquake, a number of occurrences of bridge failures due to severe earthquakes have shown the vulnerability of viaducts with complex configurations to experience important seismic damage. In order to protect these lifeline structures, the use of base isolation systems has been widely implemented. Among the existing variety of these seismic protection devices, the Friction Pendulum System (FPS) has been used as a mean of bridge retrofit in numerous cases. The current research analyses the dynamic behaviour of FPS in curved bridges subjected to strong earthquakes. The main goal is to provide assistance to engineering practice in designing effective earthquake protection strategies for complex structures under critical demands. The specific objectives of the study are (i) to study the performance of curved viaducts equipped with FPS under near-fault motions, (ii) to investigate the influence that the variation of FPS design parameters and restraint of radial displacements have on the bridge response, and (iii) to study the effectiveness of the combination of FPS and unseating prevention cable restrainers to ensure the viaduct safety and serviceability. Special attention has been focused on the expansion joint, evaluating the possibility of pounding damage and the seismic performance of the pier placed under the deck discontinuity. For this purpose, non-linear dynamic analysis and parametric studies are conducted on three dimensional models subjected to near-fault earthquake records. Calculated results reveal the influence of FPS design parameters and restraint of radial displacements on the bridge seismic response. The benefits of the installation of FPS in curved viaducts are demonstrated, effectively reducing the structural damage at the piers. In addition, the structure's vulnerability to suffer seismic damage at the expansion joint, can be effectively reduced by the installation of cable restrainers. However, the ductility demands of the piers as a consequence of this inter-span connection should be carefully evaluated.

Keywords: Nonlinear dynamic response, seismic damage, curved viaducts, near-fault ground motion, friction pendulum system.

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1. INTRODUCTION

In order to reduce the possibility of failure or lost of serviceability of lifeline structures, e.g. highway viaducts, the effort on recent seismic protection of bridges is focused on replacing vulnerable steel bearings with base isolation bearings. These devices are meant to shift the vibrational periods of the structures to avoid the predominant energy-containing periods of the earthquake, and to dissipate seismic energy. Base isolation bearings are basically classified into rubber bearings and sliding bearings. The Friction Pendulum System (FPS) belongs to the second group, dissipating seismic energy through friction, because of the movement of one part of the bearing respect to the other along a curved sliding surface. This movement, that resembles pendulum motion, provides isolated structures with restoring forces by gravity, and makes FPS a viable option for seismic isolation of bridges. However, recent seismic events have demonstrated that the seismic vulnerability of highway viaducts is magnified in curved bridges, due to complex vibrations that occur during strong earthquakes (JRA 2002). This susceptibility is even more amplified with the rupture of continuity of the superstructure at expansion joints (Choi et al. 2004). Therefore, the complexity associated with the seismic response of curved viaducts, especially under near-fault ground motions, requires the conduction of reliable numerical studies. The objective of this research is to provide assistance to current research and engineering practice by analysing the dynamic behaviour of FPS in bridges with complex configurations under critical demands. This paper presents a parametric study to investigate the effect that both the friction coefficient and radial displacements configurations of the FPS have, on the seismic response of the expansion joint. In addition, the effectiveness of combining FPS with unseating prevention cable restrainers is discussed.

2. ANALYTICAL MODEL OF THE VIADUCT

2.1. Deck superstructure and piers

The viaduct considered in this study is composed of 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 100 m radii circular arch, and the total length of 160 m is divided into equal spans of 40 m, as shown in Figure 1(a) and 1(b). 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, designated as G1 (inner girder), G2 (middle girder), and G3 (outer girder) are interconnected by steel diaphragms. Full composite action between the slab and the girders is assumed for the deck superstructure model.

In regards to the substructure, the deck weight is supported by five hollow box section steel piers of 20 m height, designed according to the seismic code in Japan (JRA 2002). Tangential configuration for both pier and bearing supports is adopted with 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.

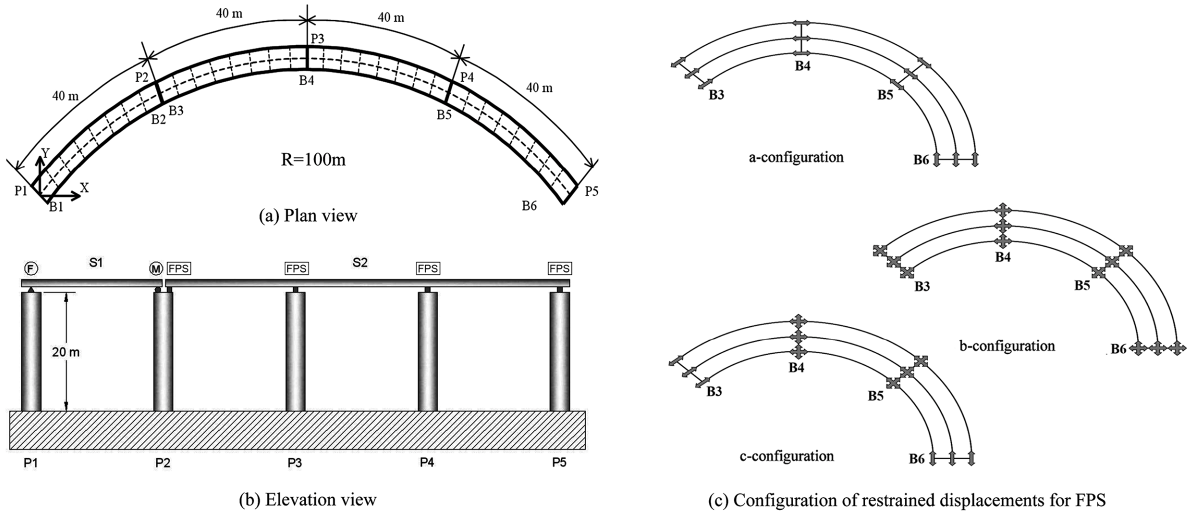

Figure 1: Analytical model of the viaduct.

2.2. Bearing supports

2.2.1. 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 movements 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. The seismic isolation of S2 is achieved by placing FPS supports under each of the three girders above the piers.

On the other hand, in order to examine the effect of different radial displacement restraint configurations on the seismic performance, displacements of the FPS have been partially limited for specific arrangements through the installation of single rail bearings (Figure 1(c)). Out-of-plane radial displacements are restricted in a-configuration for all isolation units, representing the most common bearing configuration for bridges in Japan. In b-configuration, all the isolation bearings are free to move in radial direction. Finally, an intermediate solution, c-configuration, is analysed, consisting of restraining radial displacements to end-span bearings to limit the expansion joint displacements only in the tangential direction.

2.2.2. FPS modelling

The response of FPS is typically modelled by a simplified bilinear force-deformation relationship (Figure 2(a)). The principal parameters that characterize the analytical model of the isolator are the radius of curvature (R_{FPS}) and the coefficient of friction (μ) of the sliding surface of the FPS. Firstly, the radius of curvature of the sliding surface, that controls the period of vibration of the isolation bearing, is set to 1 m in the present paper. Secondly, the selection of the friction coefficient affects the mobilization of the FPS under dynamic forces. Most typical values of μ range from 5% to 20%.

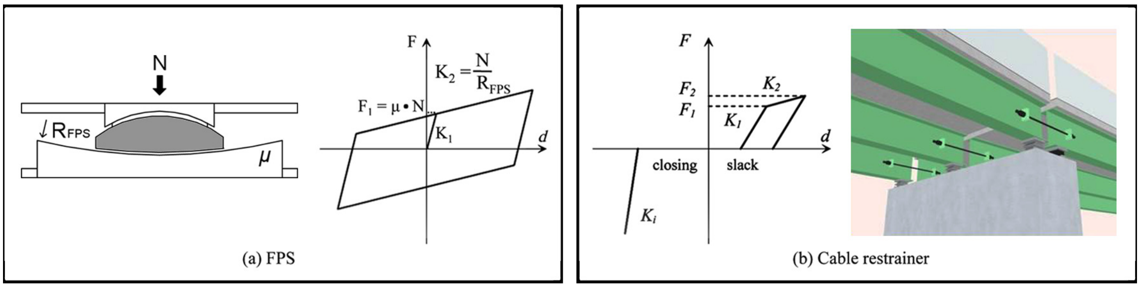

Figure 2: Analytical model of FPS and cable restrainers.

In order to carry out the parametric study, friction coefficients equal to 5%, 12% and 20% are taken in account. Finally, this model is based on the assumptions that: (i) FPS are modelled with a high vertical stiffness; (ii) the normal force acting on each device (*N*) is considered constant, and is taken as the corresponding value after gravity load analysis; and (iii) the response is uncoupled in the orthogonal directions.

2.3. Expansion joint

The isolated and non-isolated sections of the viaduct are separated introducing a gap equal to the width of the expansion joint opening (0.1 m) that could be closed, resulting in collision between deck superstructures. The pounding phenomenon is modelled using impact spring elements with a stiffness *K*=980.0 MN/m. On the other hand, to provide additional fail-safe protection against extreme seismic loads, restrained models where unseating cable restrainers are installed, have been analysed. Cable restrainers units are anchored to the three girder ends (1 unit per girder), connecting both adjacent superstructures across the expansion joint in order to prevent excessive opening. The restrainers have been modelled as nonlinear tension-only spring elements, provided with a slack of 0.025 m to accommodate thermal movements (Figure 2(b)).

3. METHOD OF ANALYSIS

The bridge model has been developed in-house using the Fortran programming language. The analysis is conducted through an analytical method that considers both geometrical and material nonlinearities. Characterization of the non-linear structural elements is based on the fiber flexural element modelling. The damping mechanism is introduced in the analysis through the Rayleigh damping matrix, expressed as a linear combination of the mass matrix and the stiffness matrix. The governing equations of motion are solved in incremental form using Newark's method assuming linear variation of acceleration over small interval of time (β=0.25). In addition, Newton-Raphson iteration method is selected to achieve the acceptable accuracy in the response calculations.

To assess the seismic performance of the viaduct, the non-linear bridge model is subjected to the longitudinal (L), transverse (T), and vertical (V) components of a strong earthquake ground motion record obtained from JR Takatori Station during the 1995 Kobe earthquake. The longitudinal earthquake component shakes the viaduct parallel to the X-axis of the global coordinate system, while the T and V components act following the Y- and Z-axes, respectively.

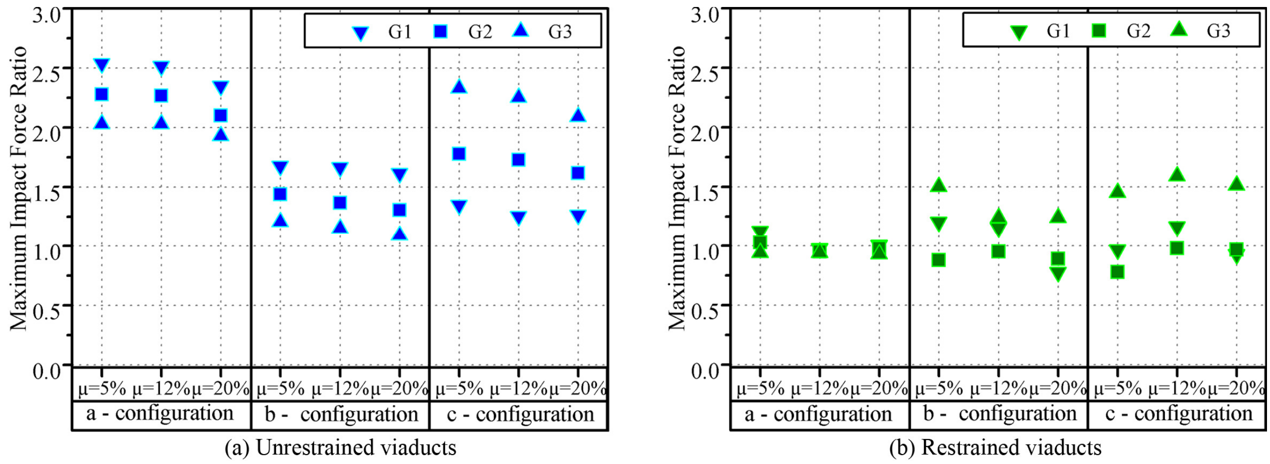

Figure 3: Evaluation of risk of pounding damage.

4. NUMERICAL RESULTS

The present results are focused on the performance of the expansion joint, due to the complexity associated with the connection between isolated and non-isolated sections in curved viaducts. The seismic performance has been evaluated on restrained and unrestrained viaducts equipped with FPS with three different friction coefficient and radial displacement restraint configurations.

4.1. Pounding damage

During a strong earthquake, adjacent spans vibrate out-of-phase, resulting in risk of damage at the expansion joint caused by collisions between adjacent decks. These high impact forces affect the colliding girders and the bearings located near the expansion joint. Isolated viaducts are especially vulnerable to pounding, since the added flexibility will increase these detrimental collisions. Maximum impact forces greater than the weight of the superstructure are considered detrimental for the bearings (Ruiz Julian et al. 2007). Figure 3 shows the maximum impact force ratios for the studied cases. Firstly, it can be noticed that unrestrained viaducts present large impact forces, higher in bridges equipped with low friction FPS. While maximum impact forces generally occur at the interior girder G1 in a- and b- configurations, G3 suffers higher impacts in c- configuration, since this arrangement increases the natural tendency of curved bridges to rotate. Finally, cable restrainers in combination with FPS prove to be very effective in reducing the magnitude of the collisions. Restrained viaducts following a- configuration show the best performance, presenting the lowest magnitude of pounding forces as well a more uniform distribution of the impacts. This fact avoids the detrimental condition that only one girder absorbs most of the energy impact.

4.2. Bending moments at Pier base

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 seismic structural damage.

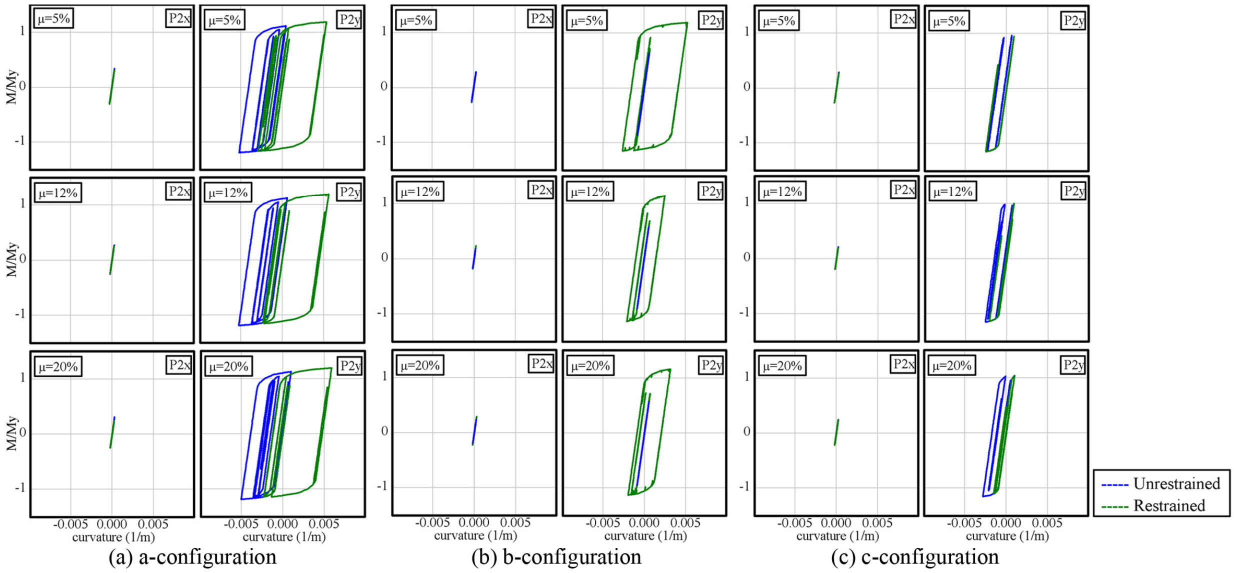

Figure 4: Bending moment ratio at P2 bottom.

Figure 4 helps to visualize the pier response through the bending moment-curvature relationships at the pier placed under the expansion joint (P2) for in-plane (P2x) and out-of-plane (P2y) directions. It can be appreciated that for viaducts equipped with FPS, in-plane bending moments beneficially remain below the elastic limit, avoiding inelastic deformations and thus seismic damage. Out-of-plane bending moments clearly depend on the FPS radial displacement configuration, since the impediment of these movements leads to higher forces transmitted to the substructure during strong earthquakes. By the installation of cable restrainers, viaducts show an increment of the bending moments, which is more pronounced in out-of-plane direction for a- and b- configurations. In comparison with the unrestrained cases, an increment of seismic damage can be expected.

5. CONCLUSIONS

The effectiveness of seismic isolation by FPS in reducing the possibility of seismic damage at the expansion joint has been analyzed. The calculated results demonstrate that curved viaducts are vulnerable to pounding damage. Unrestrained viaducts suffer high impact forces at the expansion joint, especially for those bridges where radial displacements of the bearings are partially or fully restrained. On the other hand, FPS supports beneficially reduce the transmitted forces to the piers of the viaduct, particularly if radial displacements of FPS are not fully restrained. Finally, the use of cable restrainers proves to be very effective in reducing pounding damage. However, curved restrained viaducts present larger out-plane bending moments that should be carefully evaluated.

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