Expansion Joint Damage on Curved Highway Viaducts Equipped with LRB Supports and Unseating Cable Restrainers

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1. INTRODUCTION

During the last decades horizontally curved viaducts have become an important component in modern highway systems as a viable option at complicated interchanges or river crossings where geometric restrictions and constraints of limited site space make extremely complicated the adoption of standard straight superstructures. Curved alignments offer, in addition, the benefits of aesthetically pleasing, traffic sight distance increase, as well as economically competitive construction costs with regard to straight bridges. On the contrary, bridges with curved configurations may sustain severe damage owing to rotation of the superstructure or displacement toward the outside of the curve line due to complex vibrations occurring during an earthquake[1)]. For this reason, curved bridges have suffered severe damage in past earthquakes.

As a result of the implementation of modern seismic protection technologies, bridges can be seismically upgraded through the installation of cable restrainers that provide connection between adjacent spans. The purpose is to prevent the unseating of decks from top of the piers at expansion joints by limiting the relative movements of adjacent bridge superstructures. Moreover, cable restrainers provide a fail-safe function by supporting a fallen girder unseated in the event of a severe earthquake[1)].

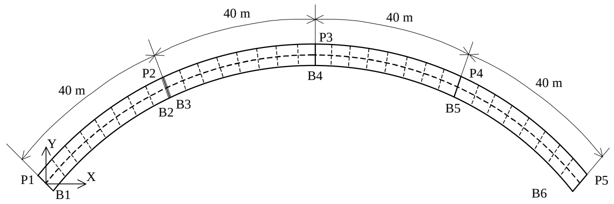
In addition, another commonly adopted earthquake protection strategy consists of replacing the vulnerable steel bearings with isolation devices. Among the great variety of seismic isolation systems, lead-rubber bearing (LRB) has found wide application in bridge structures. This is due to their simplicity and the combined isolation-energy dissipation function in a single compact unit. The LRB bearings are steel reinforced elastomeric bearings in which a lead core is inserted to provide hysteretic damping as well as rigidity against minor earthquakes, wind and service loads[2)].

Even though the application of the mentioned earthquake protection techniques, 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 performance of this kind of structures under great earthquakes presents a variation in the behavior depending on the radius of curvature.

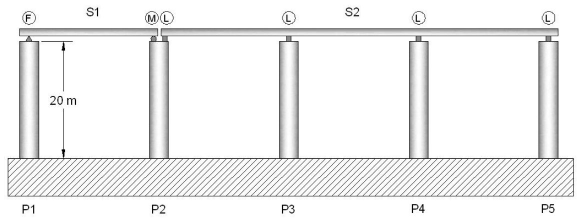
Therefore, the purpose of the present study is to analyze the overall performance of seismically isolated highway viaducts with different radii of curvature. The effect of curvature on deck unseating damage and tangential joint residual damage is analyzed. In addition, a comparison between restrained and unrestrained highway bridges is presented. The study combines the use of non-linear dynamic analysis with a three-dimensional bridge model to accurately evaluate the seismic demands on four radii of curvature in the event of severe earthquakes.

2. ANALYTICAL MODEL OF VIADUCT

The great complexness related to the seismic analysis of highway viaducts enhances a realistic prediction of the bridge structural responses. This fact provides a valuable environment for the non-linear behavior due to material and geometrical non-linearities of the relatively large deflection of the structure on the stresses and forces. Therefore, the seismic analysis of the viaduct employs non-linear computer model that simulates the highly non-linear response due to impacts at the expansion joints. Non-linearities are also considered for characterization of the non-linear structural elements of piers, bearings and cable restrainers.



(a) Plan view of viaduct



(b) Elevation view of equal piers viaduct

Fig. 1 Model of curved highway viaduct

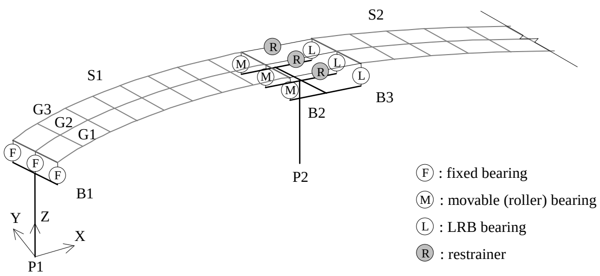


Fig. 2 Detail of curved viaduct finite element model

The highway viaduct considered in the analysis is composed by a three-span continuous seismically isolated section connected to a single simply supported non-isolated span. The overall viaduct length of 160 m is divided in equal spans of 40 m, as represented in **Fig. 1**. The bridge alignment is horizontally curved in a circular arc. Four different radii of curvature are taken into consideration measured from the origin of the circular arc to the centreline of the bridge deck. Tangential configuration for both piers and bearing supports is adopted, respect to the global coordinate system for the bridge, shown in the figure, in which the X- and Y-axes lie in the horizontal plane while the Z-axis is vertical.

2.1 Deck Superstructure and Piers

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 girders 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 superstructure model, which is treated as a three-dimensional grillage beam system shown in **Fig. 2**.

The deck weight is supported on five hollow box section steel piers with equal piers of 20m height designed according to the seismic code in Japan[1)]. Characterization of structural pier elements is based on the fiber element modelization where the inelasticity of the flexure element is accounted by the division of the cross-section into a discrete number of longitudinal and transversal fiber regions with constitutive model based on uniaxial stress-strain relationship for each zone.

The element stress resultants are determined 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. This transverse rigid bar is used to model the interactions between deck and pier motions[3)].

2.2 Bearing Supports

Steel fixed bearing supports (**Fig. 3-a**) are installed across the full width on the left end of the simply-supported span (S1), resting on the Pier 1 (P1). Steel roller bearings at the right end on the Pier 2 (P2) allow for movement in the longitudinal (tangent to the curved superstructure) direction while restrained in the transverse radial direction. Coulomb friction force is taken into account in numerical analysis for roller bearings, which are modeled by using the bilinear rectangle displacement-load relationship, shown in **Fig. 3-b**.

The isolated continuous section (S2) is supported on four pier units (P2, P3, P4 and P5) by LRB bearings. The left end is resting on the same P2 that supports S1, and at the right end on top of P5. Orientation of LRB bearings is such as to allow for longitudinal and transverse movements. LRB bearing supports are represented by the bilinear force-displacement hysteresis loop presented in **Fig. 3-c**.

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. The devices are designed for optimum yield force level to superstructure weight ratio (F_1/W = 0.1) and pre-yield to post-yield stiffness ratio (K_1/ K_2 = 10.0), which provide maximum seismic energy dissipation capacity as well as limited maximum deck displacements[4)].

It is also noted that properties of LRB bearings have been selected depending on the differences in dead load supported from the superstructure. The objective is to attract the appropriate proportion of non-seismic and seismic loads according to the resistance capacity of each substructure ensuring a near equal distribution of ductility demands over all piers. Furthermore, displacements of LRB bearings have been partially limited for all the viaducts, through the installation of lateral side stoppers.

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 between adjacent spans in order to allow for contraction and expansion of the road deck from creep, shrinkage, temperature fluctuations and traffic without generating constraint forces in the structure. In the event of strong earthquakes, the expansion joint gap of 0.1m could close resulting in collision between deck superstructures. The pounding phenomenon, defined as taking place at the three girder ends, is modeled using impact spring elements for which the compression-only bilinear gap element is provided with a spring of stiffness Ki = 980.0 MN/m that acts when the gap between the girders is completely closed.

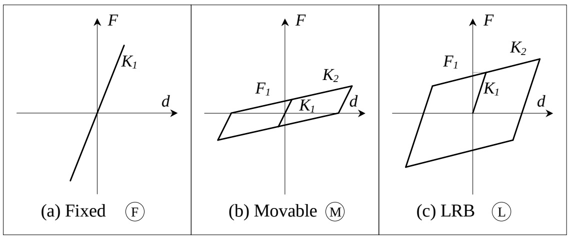


Fig. 3 Analytical models of bearing supports

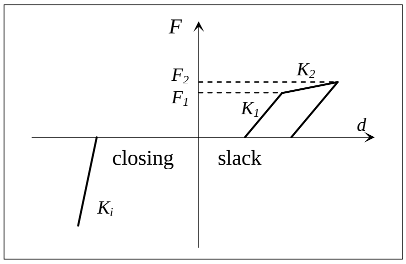


Fig. 4 Analytical model of the cable restrainer

On the other hand, in the analysis of the restrained models, in order to prevent excessive opening of the expansion joint gap, it is provided additional fail-safe protection against extreme seismic loads; for this purpose, unseating cable restrainers units are anchored to the three girder ends (1 unit per girder) connecting both adjacent superstructures across the expansion joint. The seismic restrainers, illustrated in **Fig. 4**, have been modeled as tension-only spring elements provided with a slack of 0.025 m, a value fitted to accommodate the expected deck thermal movements limiting the activation of the system specifically for earthquake loading. Initially, restrainers behave elastically with stiffness K_1, while their plasticity is introduced by the yield force (F_1) and the post-yielding stiffness (K_2=0.05*K_1). Finally, the failure statement is taken into account for ultimate strength F_2, and since then, adjacent spans can separate freely without any action of the unseating prevention device. In order to simplify, the effects of the expansion joint in the transverse direction as well as the shear forces acting on cable restrainers are neglected.

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 bilinear 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%.

To assess the seismic performance of the viaduct, the nonlinear bridge model is subjected to the longitudinal (L), transverse (T), and vertical (V) components of a strong ground motion records from the Takatori (TAK) and Kobe (KOB) Stations during the 1995 Kobe Earthquake, as well as Rinaldi (RIN) Station, from the Northridge 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[5]. These exceptionally strong earthquakes have been selected due to the destructive potential of long duration pulses on flexible structures equipped with isolation systems that can lead to a large isolator displacement, probably exciting the bridge into its non-linear range as well as inducing opening and pounding phenomenon at the expansion joint.

4. NUMERICAL RESULTS

The overall three-dimensional seismic responses of the viaducts are investigated in detail through non-linear dynamic response analysis. Particular emphasis has been focused on the expansion joint behavior due to the extreme complexity associated with connection between isolated and non -isolated sections in curved viaducts. The bridge seismic performance has been evaluated on four different radii of curvature, 100m, 200m, 400m, and 800m, considering two cases: viaducts with and without unseating cable restrainers.

In the analysis of the restrained models, in order to prevent excessive opening of the expansion joint gap, unseating cable restrainers units are anchored to the three girder ends (one unit per girder) connecting both adjacent superstructures across the expansion joint. The seismic restrainers, illustrated in **Fig. 4**, have been modeled as tension-only spring elements provided with a slack of 0.025m, a value fitted to accommodate the expected deck thermal movements limiting the activation of the system specifically for earthquake loading.

4.1 Bearing Supports

Firstly, the effect of curvature radius on deck unseating damage is analyzed. During an earthquake, adjacent spans can vibrate out-of-phase, resulting in relative displacements at expansion joints. In simply-supported spans, the induced relative displacements to steel roller bearings can exceed the seat width at the pier top, causing the dislodgment of the rollers from the bearing assembly and the subsequent collapse due to deck superstructure unseating. The maximum roller bearing displacement in the negative tangential direction has been established as the damage index to evaluate the potential possibility of deck unseating. For this study, a limit of 0.40 m has been fixed to determine the high unseating probability for existing bridges with narrow steel pier caps that provide short seat widths.

First, the unrestrained viaducts are analyzed in terms of the maximum displacement on the steel roller bearing. The results, shown in **Fig. 5**, indicate that all the viaducts supported on steel bearings and subjected to the three earthquake inputs clearly overpass the unseating limit. It can be observer that TAK represents the worst condition for all the curvatures. In the same way, the response obtained from RIN shows extremely high displacements. KOB presents smaller values; however those are still close or even over the unseating limit for the bridges with 400m and 800m curvature

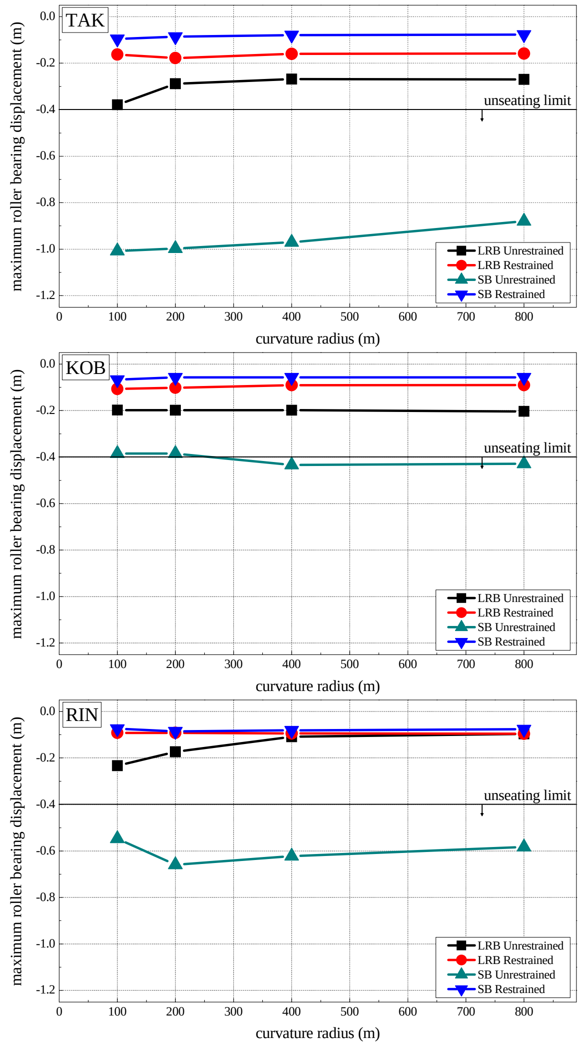


Fig. 5 Curvature effect on deck unseating damage

radius. It can be noticed the excessive vulnerability to unseating damage of curved viaducts equipped with steel bearings. The response of the viaducts equipped with LRB bearing supports is also shown in **Fig. 5**. It can be observed that once the continuous section has been isolated, its seismic response improves significantly in all the curvatures. However, even though the values are remarkable smaller than those from the steel cases, there is still a clear effect of the curvature radius in terms of maximum roller bearing displacements. For restrained viaducts, similar values of maximum displacements on the roller bearing are observed in both, steel and LRB bearings viaducts. Both cases present a remarkable reduction on the maximum displacements in comparison with the obtained in the unrestrained cases; particularly in the bridges with 100m curvature radius. From the results, it can be observed that the input record representing the worst scenario is TAK input, producing significantly higher displacements that put in risk the superstructure of the viaducts.

4.2 Expansion Joint

Permanent tangential offsets at expansion joints cause, in several cases, traffic closure and the disruption of the bridge usability in the aftermath of the earthquakes resulted in a critical problem for rescue activities. This residual joint separation is mainly attributed to the final position of roller bearings supporting the superstructure. The relative inclination between adjacent piers, caused because seismic damages at the bottom of piers are not identical, has been also considered as an additional source of residual opening. The residual joint tangential displacement has been calculated in order to perform the post-earthquake serviceability evaluation on the viaduct. The possibility for vehicles to pass over the tangential gap length, measured as the contact length of a truck tire (0.15m), is suggested as the limit for this damage.

For unrestrained bridges supported on steel bearings, as shown in **Fig. 6**, the results of the residual joint tangential displacement show unacceptable residual displacements at the expansion joint when subjected to TAK and RIN, most of the bridges overpass the separation limit, while KOB input represents less severe damage. It can be seen that TAK produce the most severe condition for the structures, while the other inputs still remain close to the limit. TAK input represents an important damage in the bridge with 100m and 200m curvature radii in both cases, steel and LRB bearings viaducts. In this response, the separation limit has been overpassed, causing by this the disruption of the bridge serviceability. In the viaducts equipped with the LRB bearings, KOB and RIN do not represent significant risk. Regarding the differences on the bearing supports, there is a critical disadvantage in terms of residual displacements presented at the viaducts with steel bearings. The bridges with LRB supports present an important reduction on the possibility of seismic damage. However, even with the use of LRB supports, the bridges with 100m and 200m curvature radii still remain over the separation limit. It is observed that as the curvature radius increases, the behavior of the bridges tends to be less severe.

The results obtained from the analysis of the restrained viaducts are also shown in **Fig. 6**. The application of cable restrainers produces an important variation on the behavior of the bridges in comparison with the cases of unrestrained bridges. This effect is extensive for steel and LRB supports viaducts in all inputs. Firstly, a significant reduction in the tangential offsets of expansion joints is observed. For none of the bridges equipped with unseating prevention systems the separation limit of 0.15m is exceeded. In all the viaducts the residual displacement is observed under 0.08m. Clearly, the use of unseating prevention systems not only provides a residual displacement lower than the separation limit but also maintains these limits in similar values.

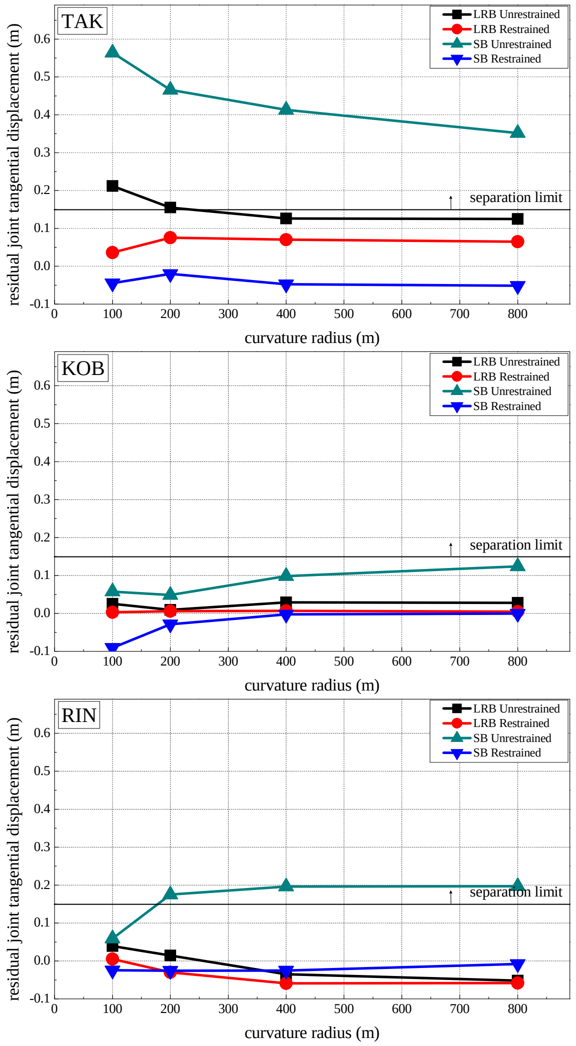


Fig. 6 Curvature effect on tangential joint residual damage

5. CONCLUSIONS

The effectiveness of seismic isolation in order to reduce the possibility of seismic damage on curved highway viaducts has been analyzed. The three-dimensional nonlinear seismic dynamic response has been evaluated. Moreover, the effectiveness of cable restrainers to mitigate earthquake damage through connection between isolated and non-isolated sections of curved steel viaducts is evaluated. The investigation results provide sufficient evidence for the following conclusions:

1) The calculated results clearly demonstrate that curved viaducts are more vulnerable to deck unseating damage. It has been observed that for more curved viaducts, this possibility increase significantly. However, this type of seismic damage is reduced initially by the installation of LRB bearings and subsequently by the installation of cable restrainers.
2) The use of cable restrainers provides to the bridge a similar behavior in case of curved and straight tending bridges, despite of the curvature radii. In terms of tangential joint residual damage, curved viaducts are found particularly vulnerable. This damage was significantly reduced once LRB bearing were installed. In restrained viaducts, an important reduction of the residual joint tangential displacement is appreciated and similar values of residual joint tangential displacement are obtained.
3) Finally, in this analysis, the effectiveness on the use of cable restrainers on curved viaducts is demonstrated, not only by reducing in all cases the possible damage but also by providing a similar behavior in the viaducts despite of curvature radius.

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