

# Effects of Curvature Radius on Nonlinear Seismic Response of Curved Highway Viaducts with Piers of Unequal Heights Equipped with 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<sup>1)</sup>. 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<sup>1)</sup>.

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<sup>2)</sup>.

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 highway viaducts with different radii of curvature. The effect of curvature on deck unseating damage and pounding 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

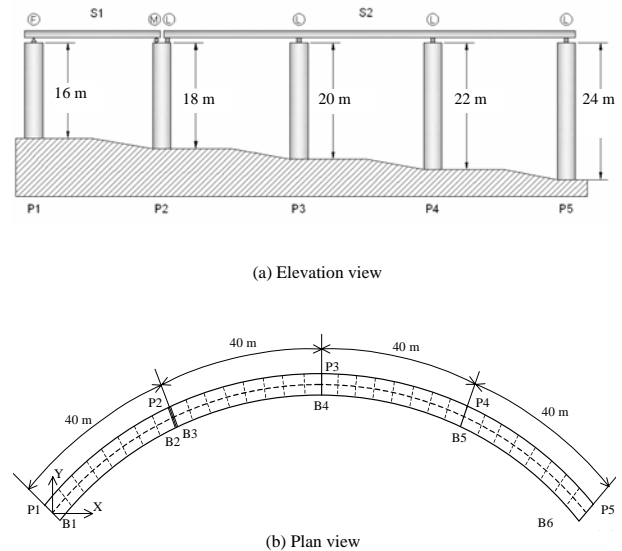


Fig. 1 Model of curved highway viaduct

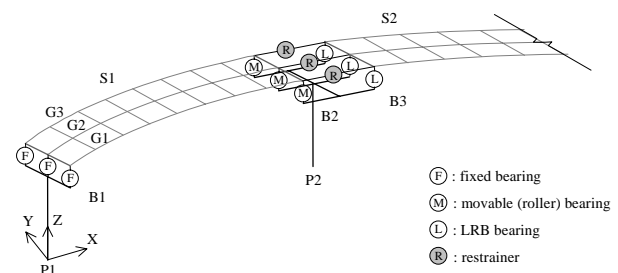


Fig. 2 Detail of curved viaduct finite element model

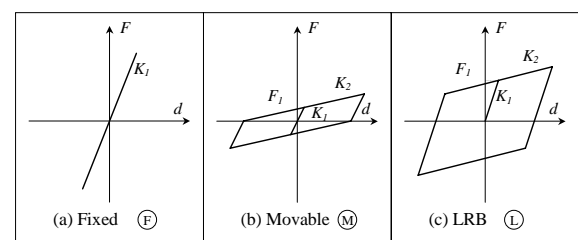


Fig. 3 Analytical models of bearing supports

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.

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 of 16m, 18m, 20m, 22m and 24m of height, as is shown in Fig. 1, designed according to the seismic code in Japan<sup>1)</sup>. 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<sup>3)</sup>.

## 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 the 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<sup>4)</sup>.

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.

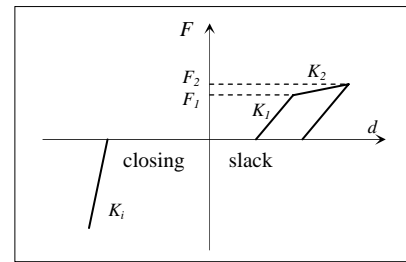


Fig. 4 Analytical model of the cable restrainer

## 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  $K_i = 980.0$  MN/m that acts when the gap between the girders is completely closed.

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 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<sup>5)</sup>. 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 response of the viaduct is 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, 100 m, 200 m, 400 m, and 800 m, considering two cases: restrained and unrestrained curved viaducts. For this study, the structural properties of the cable restrainers are as follows: cross sectional area of  $1.765 \times 10^{-3} \text{ m}^2$ , a total length of 1.73 m and modulus of elasticity of 200 GPa.

##### 4.1 Bearing Supports

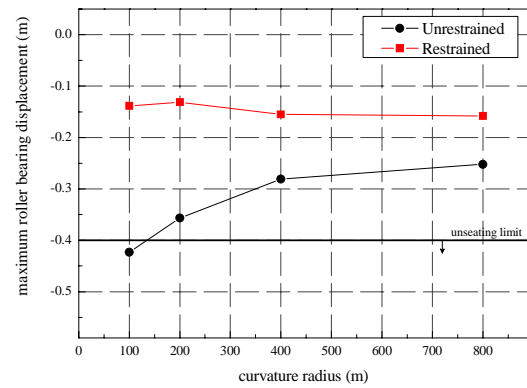
Firstly, the effect of curvature radius on deck unseating damage is analyzed. For this study, a limit of 0.40 m has been fixed to determine the high unseating probability for existing bridges with narrow steel pier caps that provide short seat widths. First, the unrestrained viaduct is analyzed in terms of the maximum displacement in the steel roller bearing. The results indicate that in this case, only the viaduct with a curvature radius of 100m overpass the unseating limit. However, a close to limit maximum roller bearing displacement is observed in the bridge with radius of 200m, presenting a maximum displacement of 0.356m. For the two remaining bridges, an acceptable displacement is observed, which have a roller bearing displacement of 0.280m in the bridge with a curvature radius of 400 m, and 0.252m in the bridge with 800 m of curvature radius, as is shown in **Fig. 5**. It is clear that in case of more curved viaducts; the possibility of unseating damage is higher, especially in the bridge with the curvature radius of 100 m. Therefore, it is possible to observe the significant reduction on the maximum displacements in the case of the bridges tending to the straight alignment.

In the case of restrained viaducts, similar values of maximum displacements on the roller bearing are observed. For the bridge with 100 m radius, the maximum displacement is 0.138m, very similar to the values obtained in the bridges with 200 m, 400 m and 800 m of curvature radius, which are 0.131m, 0.154m and 0.157m respectively. For the restrained viaduct, an important reduction on the displacements is observed, especially in the bridge with 100 m curvature radius.

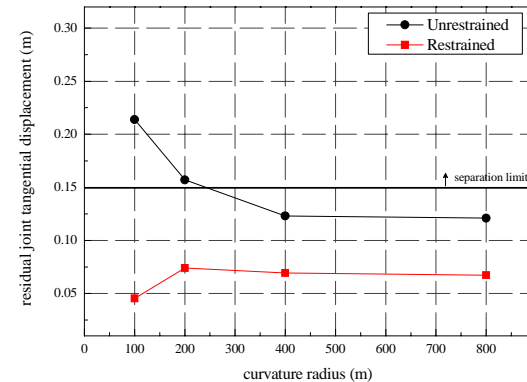
##### 4.2 Expansion Joint

Permanent tangential offsets of expansion joints observed at the end of recent earthquakes have substantially interfered in the post-earthquake serviceability of highway viaducts. The possibility for vehicles to pass over the tangential gap length, measured as the contact length of a truck tire (0.15 m), is suggested as the limit for this damage.

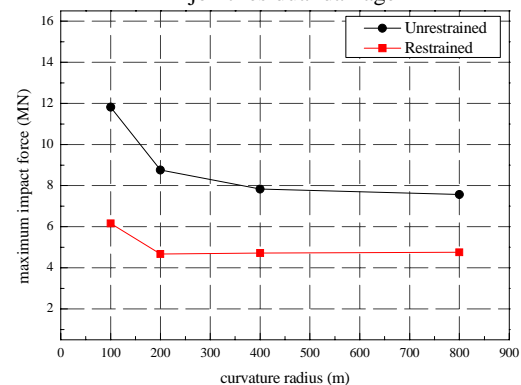
For unrestrained viaducts, as is illustrated in **Fig. 6**, the results of the residual joint tangential displacement show an important damage in the bridge with 100m and 200m curvature radii. In both bridges, the separation limit has been



**Fig. 5** Effect of curvature radius on deck unseating damage



**Fig. 6** Effect of curvature radius on tangential joint residual damage



**Fig. 7** Effect of curvature radius on pounding damage

over passed. The bridge with 100m of curvature radius presents a separation in the expansion joint of 0.214m. Meanwhile, in the bridge with 200m radius a separation of 0.157m is observed. However, the bridges with radius of curvature of 400m and 800m present a separation under the limit. In those cases the separation is 0.123m and 0.121m respectively. It is clear the effect of the curvature on the residual joint tangential displacements. It is observed that as the curvature radius is increased, the behavior of the bridges tends to be less severe in terms of damage.

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. 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 four viaducts the residual displacement is observed under 0.08m. The restrained viaduct with 100m of curvature radius presents a displacement of 0.045m. For this bridge, the difference between having or

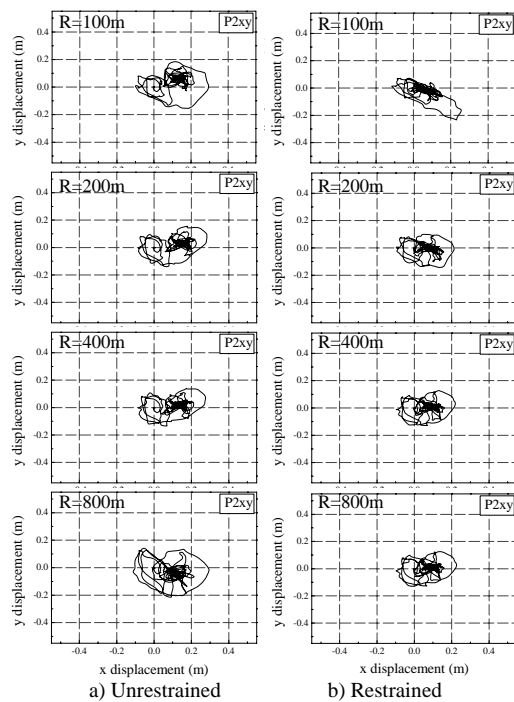


Fig. 8 Pier top displacements at P2 in local coordinates

not cable restrainers is 0.168m. For the other viaducts, 200m, 400m and 800m, the residual joint tangential displacement are 0.074m, 0.069m and 0.067m respectively. Clearly, the use of unseating prevention systems provide not only a residual displacement lower than the separation limit but also maintain these limits in similar values. The analytical results for the unrestrained viaducts show that the maximum impact force is presented in the viaduct with radius of curvature of 100m, which presents an impact force of 11.82 MN. As for the bridge with 200m of curvature radius, its maximum impact force is 8.761 MN. The last two viaducts with 400m and 800m of curvature radii have impact forces of 7.83 MN and 7.57 MN respectively. It is clear the uniform impact forces in the less curved viaducts, as is illustrated in Fig. 7.

In case of the viaducts equipped with cable restrainers, the reduction in the possibility of pounding damage is significant. Firstly, the use of restrainers reduces the maximum impact forces in all viaducts. Even in the bridge with a radius of curvature of 100 m, the maximum impact force is reduce to only 6.164 MN, clearly less that the obtained in the unrestrained case of 11.82 MN. This effect applies as well to the other bridges with 200m, 400m and 800m of curvature radii. The 200m radius bridge presents a maximum impact force of 4.67 MN, very similar to the values obtained for the 400m and 800m viaducts, 4.71MN and 4.75 respectively, as presented in Fig. 7.

#### 4.3 Pier at Expansion Joint

The pier top displacements at P2 in local coordinates, presented in Fig. 8, show that in case of unrestrained viaducts, the displacements remain among the same values even though the difference on the radius of curvature. On the other hand, for restrained bridges, a significant reduction on the maximum displacements due to the installation of cable restrainers, especially in the bridges with a straight tending alignment, is observed. However, the 100m viaduct still presents an important displacement even though the use of the unseating prevention system. This is due to the transmission of seismic forces from the long span to the short span that results in more severe demands for curved viaducts.

#### 5. CONCLUSIONS

The effects of curvature radius on nonlinear seismic response of curved highway viaducts equipped with unseating prevention cable restrainers have been analyzed. The effect of the curvature radius on the unseating damage, tangential residual damage at the expansion joint and pounding damage has been evaluated.

The effectiveness of cable restrainers to mitigate earthquake damage through connection between isolated and non-isolated sections of curved steel viaducts is evaluated. For this purpose, important bridge elements as well as the global structural response have been examined in detail under the action of near-fault earthquake ground motions. The effect of the use of piers with unequal heights and its impact on the expansion joint is specially emphasized. 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. However, the possibility of deck unseating is reduced by increasing the curvature radius or by the use of restrainers. Moreover, the use of cable restrainers provide to the bridge a similar behaviour in case of curved and straight bridges, despite of the curvature radii and the differences on pier heights.
- 2) Curved viaducts are found vulnerable to tangential joint residual damage. The possibility of this kind of damage increases by reducing the curvature radius. In case of restrained viaducts, a significant reduction of the residual joint tangential displacement is appreciated and similar values of residual joint tangential displacement are obtained despite of the unequal pier heights.
- 3) In this study, the results show that in case of curved bridges, pounding damage is presented. A significant reduction in the impact forces at the expansion joint is observed by increasing the curvature radius. Furthermore, even though the differences on the radii of curvature in the viaducts, the application of cable restrainers reduces the possibility of pounding damage. However, for viaducts with unequal heights, the effect of curvature is observed even though the use of cable restrainers.
- 4) The effect of the curvature radius on the displacements at the top of the pier supporting the expansion joint is reduced by the use of an unseating prevention system based on cable restrainers. However, the transmission of seismic forces from the long span to the short span results in high displacements in case of more curved viaducts.

#### REFERENCES

- 1) Japan Road Association (JRA), Specifications for Highway Bridges – Part V Seismic Design, Maruzen, Tokyo, 2002.
- 2) Robinson, W. H., Lead-rubber hysteretic bearings suitable for protecting structures during earthquakes, Earthquake Engineering Structures, Vol. 10, pp. 593-604, 1982.
- 3) Maleki, S., Effect of deck and support stiffness on seismic response of slab-girder bridges, Engineering Structures, Vol. 24, No. 2, pp. 219-226, 2002.
- 4) Ruiz Julian, F. D. and Hayashikawa, Study on seismic response of curved highway viaducts with different cable restrainers, Journal of Structural Engineering, JSCE, Vol. 51A, pp. 701-712, 2005.
- 5) Ali HM, Abdel-Ghaffar AM. Modeling the nonlinear seismic behavior of cable-stayed bridges with passive control bearings. Computer & Structures, Vol. 54, No.3, pp. 461-92, 1995.