

Behavior Model of Curved Highway Viaducts under Level II Earthquake Ground Motions

Hokkaido University
Hokkaido University
Hokkaido University
Hokkaido University
Hokkaido University

Fellow member
member
member

Toshiro Hayashikawa
○ Rinna Tanaka
Carlos Mendez Galindo
Takashi Matsumoto
Xingwen He

1. Introduction

Curved alignments offer 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 earthquake¹⁾.

Most existing viaducts are simply single span, which is inexpensive to construct. However the expansion joint makes that traveling performance deteriorated and the noise, vibration and leaked water proceeded. So it takes more costs and time for maintenance. And the repair work often causes tie up. Therefore recently constructed viaducts are adopted continuous span.

To make the span continuous, some devices are needed in the bearings as to prevent concentration of the horizontal seismic force in a single pier and disperse seismic force to the each pier. Also the stretching behavior of the girder length caused by temperature alteration should be reduced.

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 loads²⁾.

LRB bearing makes the viaduct long period and heavy damped. So it is concerned that the amount of horizontal displacement becomes bigger. The displacement may overreach the expansion gap or the maximum permitted value of LRB bearing.

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.

Therefore, the purpose of the present study is to analyze the overall performance of highway viaducts with different sequence of the three kinds of bearings.

The study combines the use of non-linear dynamic analysis with a three-dimensional bridge model to accurately evaluate the seismic demands on kind of bearing in the event of severe earthquakes.

2. Analytical Model of Viaduct

The great complexity related to the seismic analysis of highway viaducts enhances a realistic prediction of the bridge structural responses. This fact provides a valuable 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. Non-linearity is also considered for characterization of the non-linear structural elements of piers and bearings.

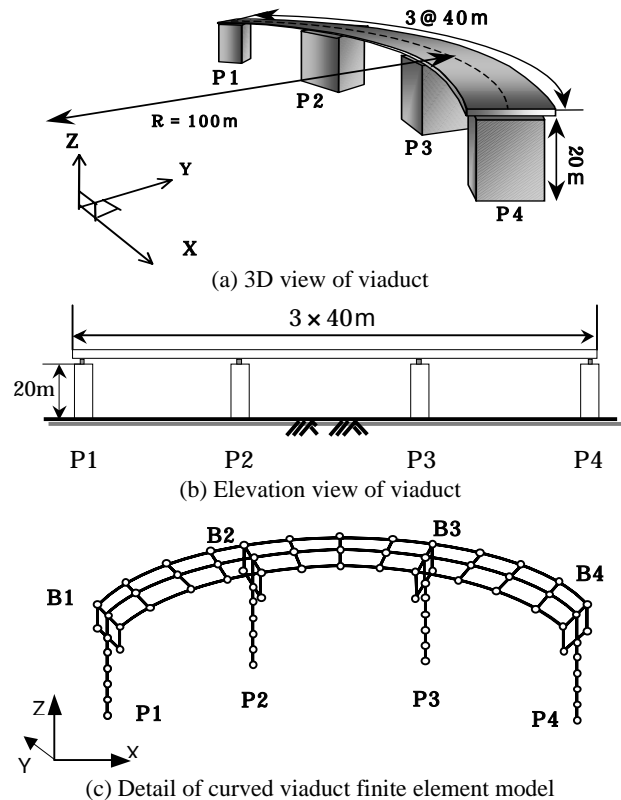


Fig. 1 Model of curved highway viaduct

The highway viaduct considered in the analysis is composed by a three-span continuous seismically isolated section.

The overall viaduct length of 120 m is divided in equal spans of 40m, as represented in Fig. 1. The bridge alignment is horizontally curved in a circular arc. The radius of curvature is 100 m measured from the origin of the circular arc to the centerline 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. 1.

The deck weight is supported on four hollow box section steel piers. The piers are 20m height designed according to the seismic code in Japan¹⁾. 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 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 motions³⁾.

2.2 Bearing supports

The continuous span is supported on four pier units (P1, P2, P3 and P4). The same kinds of bearing supports (**Fig. 2**) are installed across the full width of the pier. In this research, three kinds of bearing and its combinations are compared. The analytical models of bearing supports are shown in **Fig. 2**.

(a) The steel fixed bearing does not allow for movement in any direction. Generally, it imparts the earthquake energy or vibration to the pier. The steel fixed bearing is modeled by using the linear displacement-load relationship as shown in **Fig. 2-a**.

(b) The steel fixed bearing 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. 2-b**.

(c) 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. 2-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_l . The devices are designed for optimum yield force level to superstructure weight ratio ($F_l/W = 0.1$) 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 displacements⁴⁾.

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. The combinations of the bearings in the research are showed in the **Table. 1**.

3. Analytical Method

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%.

Table.1 Bearings comparison

	b1	b2	b3	b4
case1(FMMM)	fix	movable	movable	movable
case2(MFFM)	movable	fix	fix	movable
case3(MFMM)	movable	fix	movable	movable
case4(LRB)	LRB	LRB	LRB	LRB

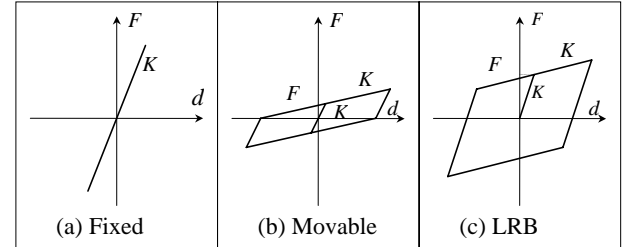


Fig. 2 Analytical models of bearing supports

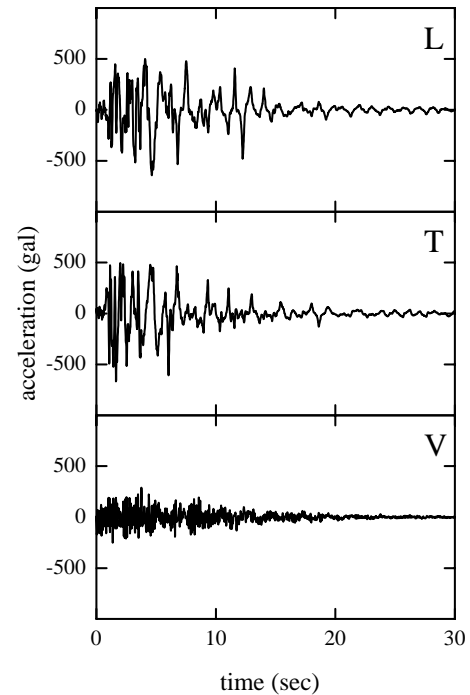


Fig. 3 Input earthquake ground motions

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 as shown in **Fig. 3**. 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 displacements⁵⁾. These exceptionally strong earthquakes have been selected due to the destructive potential of long duration pulses on flexible structures.

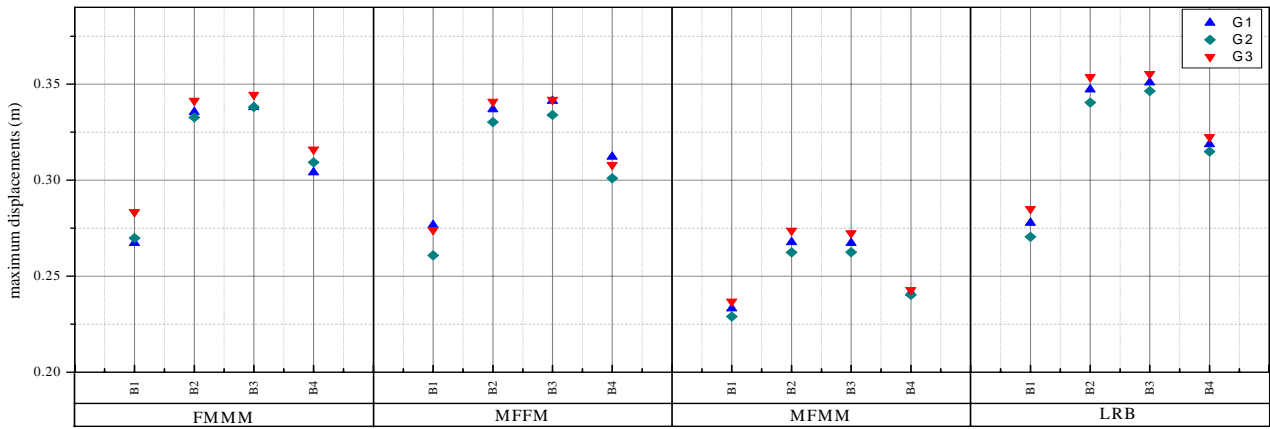


Fig. 4 Maximum displacement on superstructure

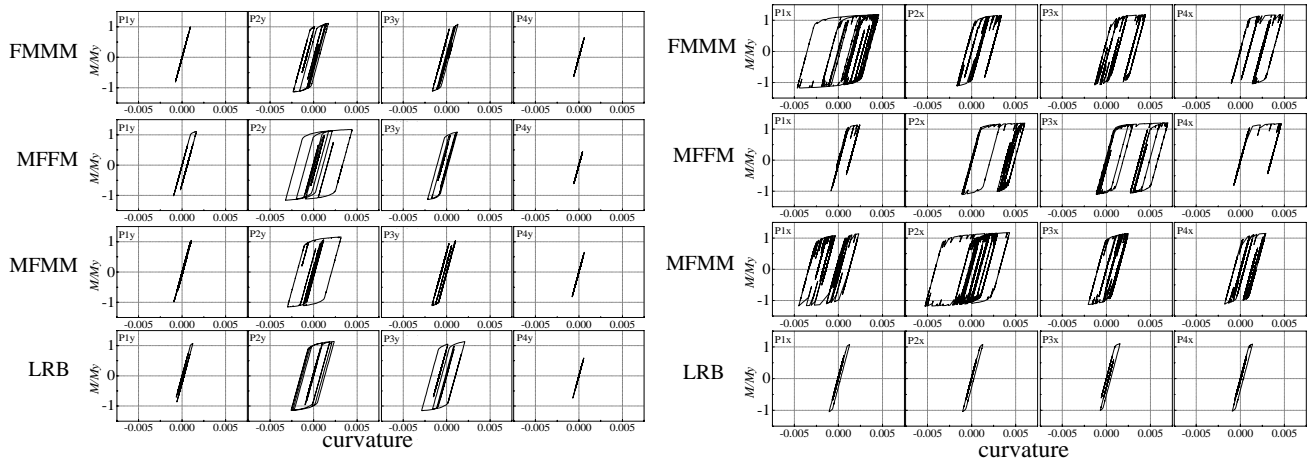


Fig. 5 Moment of pier's bottom

4. Numerical Results

The overall three-dimensional seismic responses of the viaducts are investigated in detail through non-linear dynamic response analysis. In the result, a lot of distinctions caused by the different kind of bearing and the combinations of the bearings are observed.

4.1 Deck superstructure displacement

Firstly, the effect of the kind of bearings on deck displacement is analyzed. The restrained sequence girder viaducts are analyzed in terms of the maximum displacement on the steel roller bearing, the steel fixed bearing and the LRB bearing. The results, shown in Fig. 4, indicate that in the each middle two piers, the maximum displacement of the deck is bigger than in the each outside two piers. And the maximum displacements observed in the middle two piers are much the same values.

In the left side pier, the maximum displacement is the smallest of the four piers. And that is observed in all cases. The result of case MFFM in all four piers, the maximum displacement is the smallest of all the cases. While in the result of case LRB in all piers, the largest displacement is observed. The Case FMMM and the Case MFFM is very similar, slightly the Case MFFM is smaller in all piers.

The differences between the middle piers (observed larger displacement) and the first pier (observed smallest displacement) are about 0.06 m in the all cases. Moreover, difference in the maximum displacement between the first pier (observed smallest displacement) and fourth pier is about 0.03 m in the all cases.

Compared with the 3 girders in the same pier, the girder of G3 (most outside of the girders) is observed the largest displacement except the case MFFM of the both outside

piers. And the value of differences on the same piers observed each girder reaches about 0.01m.

4.2 Moment of pier's bottom

The steel fixed bearing sometimes cause serious damage in the pier suffered by earthquake. The results obtained from the analysis in the combinations of bearings are shown in Fig. 5.

Firstly, on the direction x, obviously the case LRB is different from others. The curvature observed in the case LRB is very small. It means that all the piers, which settle LRB bearings are not influenced in the earthquake, and they do not suffer damage.

On the other hand, the steel fixed bearing causes especially large curvature. The pier settles fixed bearing has large moment and it takes a lot of damage from the earthquake.

At the same time, the piers settling movable bearing is observed reasonable amount of curvature. At the P1 of the case MFFM, the curvature is small. However in other cases, the curvature is middle large amount.

Second, on the direction y, the P1 and the P4 are observed very small curvature and the P2 and P3 are observed some curvature in all cases. And in this direction, the case LRB also shows a little bit different observation from other 3 cases.

While the case LRB is observed both of P2 and P3 similar values of the curvature, other 3 cases are observed the larger amount of the curvature in the P2 than in the P3, especially larger on the pier settling fixed bearing.

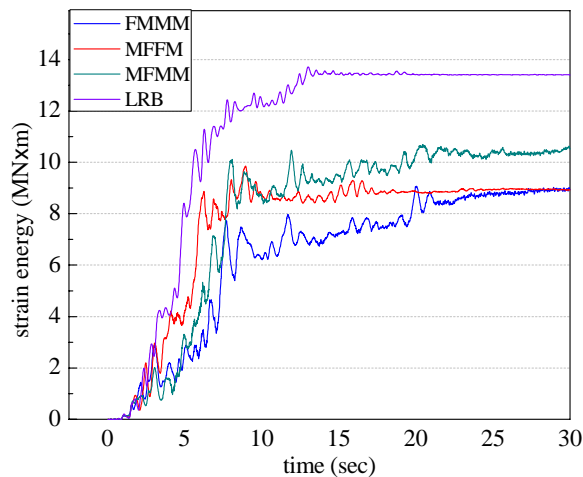


Fig. 6 Strain energy

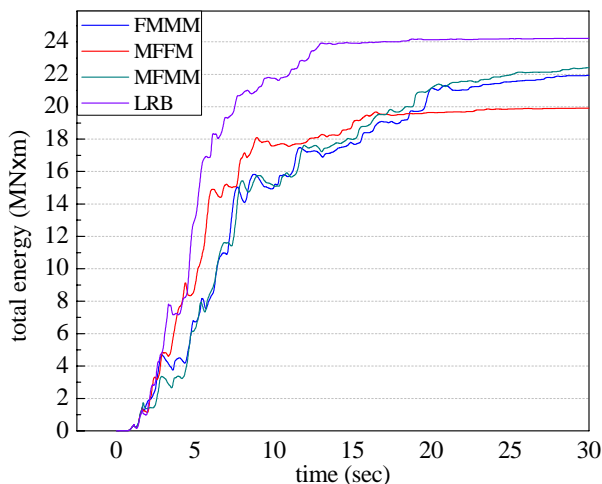


Fig. 7 Total energy

4.3 Energy received from earthquake

The Fig. 6 shows strain energy and the Fig. 7 shows total energy received from the earthquake. The result indicates the effect of the kind of bearing and the combinations of the bearings. Both strain and total energy of the LRB bearing is among others large value. The case FMMM is less value of strain energy than the similar case of MFMM and MFFM. However, on the total energy the case MFFM is observed more value than the similar case of MFMM and FMMM. That result is caused by the combination of the bearings. Both strain energy graph and total energy graph of variants are almost interlocking. The difference between the case LRB and others at the end of the graph is smaller in total energy than strain energy.

5. Conclusions

The effects of the three different kinds of bearing and the combinations of the bearings on nonlinear seismic response of curved highway viaducts have been analyzed.

The effects of the three kinds of bearing and the combinations of the bearings on the deck superstructure movement, the moment of the pier's bottom and the strain and total energies are evaluated.

The effectiveness of bearings for the superstructure and the piers in the amount of earthquake energy on 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.

1) The result shows the maximum displacement of the deck superstructure is very large in the case of LRB. That is because of the capacity of the LRB bearing. The twice weight loaded on the inside two piers makes the displacements of the two bigger than outside of two piers.

In almost all cases were calculated as larger value on G3 than G2 and G1. That is because G3 is the most outside of girder and that is slightly longer, so the girder G3 should move more.

2) The results of the moment of the pier's bottom show the fixed bearing get much curvature. That is why the capacity of the fixed bearing does not accord the superstructure movement. That makes much force of the earthquake reach to the pier. The bearing of movable is allows unidirectional movement for the superstructure. It causes less force reached to the piers. The LRB bearing excuses movement for each direction. So the force of the earthquake does not transmit so much to the pier. The force of the earthquake is taken in the bearing sanction and in the motion energy of the superstructure.

The results of the moment of the pier's bottom on the direction Y indicate that the curvilinear shape effects on the middle two piers (P2, P3) observed moment, bigger than that of outsides (P1, P4). The curved figure restrains movement of the viaducts, and it helps the force be carried to the piers.

The calculation results obviously show these tendencies in the kinds of bearing.

3) Compared on energy of each case, much high energy is observed in the case of LRB than other cases. That is because the bearing LRB takes in much energy depend on the forces produced by the earthquake. That is because the LRB bearing displacement behaves bi-linearly on the forces. So they take in some energy from the earthquake. While Steel bearings displacements act linearly on the forces. That's why they do not get energy from the earthquake. Therefore the case of LRB shows higher energy than others. The calculation results obviously show these tendencies in the kinds of bearing.

The results of less difference between the case LRB and others at the end of the graph are observed in total energy than that in strain energy. That is because the case LRB take less energy on the pier's bottom observed in the calculations than other cases. The calculation results obviously show the relation between the moment and energy.

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