Dynamic response analysis of curved viaduct equipped with steel bearing supports under great earthquake ground motion

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1. INTRODUCTION

Horizontally curved viaducts have become an important component in modern highway systems in past decades. They represent a viable option at complicated interchanges or river crossings. In addition, curved alignments result in better aesthetic, an increase in traffic sight distances and economically competitive construction costs compared with straight bridges. On the other hand, bridges with curved configurations may sustain severe damage owing to rotation of the superstructure or displacement towards the outside of the curve due to the complex vibrations that occur during an earthquake [1].

Recent strong earthquakes have repeatedly demonstrated the seismic vulnerability of highway viaducts. The poor seismic performance of steel bearing supports has been highlighted due to the disastrous consequences for the overall bridge seismic performance. Failure of steel bearings resulted in collapse of highway viaducts during the 1995 Kobe earthquake [2, 3]. Moreover, traffic vehicle flow was impeded in some cases by superstructure falling on to the surface of the substructure, large differences in levels of the road surface, or damaged superstructure ends, making the bridge unusable and irreparable after the earthquake. This severe and extensive damage to highway viaducts that resulted from inadequate performance of bearing supports emphasizes the need to carefully evaluate the role of bearings as important bridge structural elements.

Traditional steel bearings are very common, but they are easy to be broken in earthquakes. Recently roller bearings equipped with stopper are installed on top of piers. Because stopper can be easily installed and the price is not expensive, so it has wide application prospect in future. Therefore, the purpose of the present study is to analyze the response of curved steel viaduct, based on steel bearing supports equipped with stopper. The study combines non-linear dynamic analysis with a three-dimensional bridge model in order to evaluate the seismic response accurately.

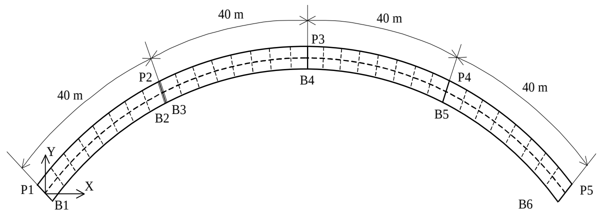
2. ANALYTICAL MODEL OF VIADUCT

The highway viaduct considered in the analysis is composed by a three-span continuous span connected to a single simply-supported 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 with a radius of curvature of 200 m, measured from the origin of the circular arc to the centre-line of the deck superstructure. Piers and bearing supports adopt a tangential configuration with respect to the global coordinate system, in which the X and Y -axes lie in the horizontal plane while the Z-axis is vertical.

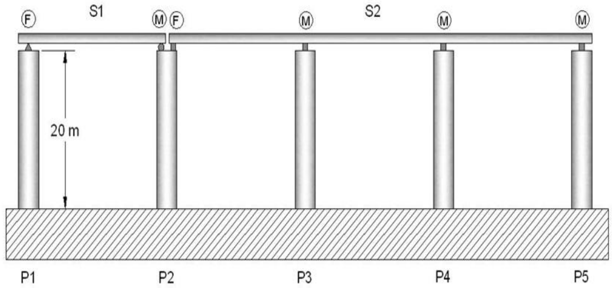
2.1 Deck superstructure and piers

The bridge superstructure consists of a concrete deck slab that rests on three I-section steel girders (G1, G2 and G3) equally spaced at a distance of 2.1 m. The girders are inter - connected by end-span diaphragms as well as intermediate diaphragms at a uniform spacing of 5.0 m. Full composite action between the slab and the girders is assumed for the linear elastic elements of the superstructure model, which is represented by the three dimensional grillage beam system shown in **Fig. 2**. The deck weight is supported on four hollow box section steel piers 20 m high designed according to the Japanese seismic code[1]. The cross-sectional properties of the deck and bridge piers are summarized in **Table 1**. Steel and concrete densities are 7850 kg/m^3 and 2500 kg/m^3 respectively.

Characterization of structural pier elements is based on fiber element modeling where the inelasticity of the flexure element is accounted for by the division of the cross-section into a discrete number of longitudinal and transverse fiber regions with the constitutive model based on uniaxial stress-strain relationship for each zone [4].



(a) Plan view of curved highway viaduct model



(b) Elevation view of curved highway viaduct model

Fig. 1 Analytical model of viaduct

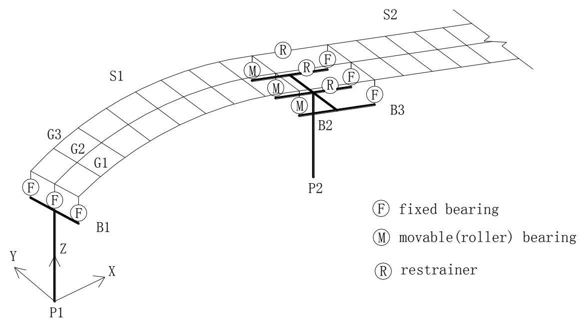
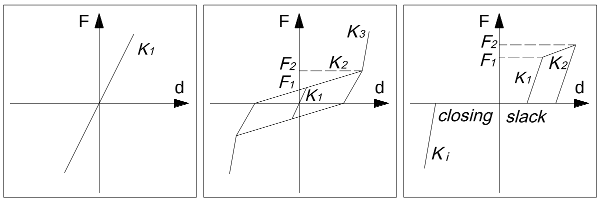


Fig. 2 Detail of curved viaduct finite element model



(a) Fixed bearing　(b) Roller bearing　(c) Restrainer

Fig. 3 Analytical models of steel bearing supports and restrainer

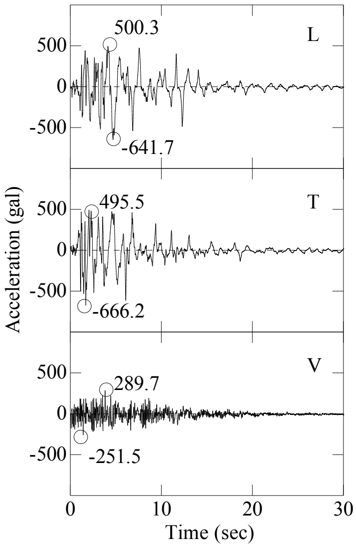


Fig. 4 JR Takatori St. record 1995 Hyogoken Nanbu earthquake

2.2 Bearing supports

In the viaduct equipped with steel bearing (S), steel fixed bearing supports (**Fig. 3a**) are installed across the full width at the left end of the continuous span, resting on pier 2 (P2). Steel roller bearings at the top of the other piers (P3, P4 and P5) allow for movement in the longitudinal direction (tangential to the curved superstructure) and provide restraint in the transverse radial direction. For simple supported span, steel fixed bearing supports are installed at the left end (resting on pier 1), and steel roller bearing supports are installed at the right end (resting on pier 2). **Table 2** shows the structural properties of the steel bearings. Steel roller bearings are represented by using a trilinear element shown in **Fig. 3b**. Coulomb friction force is taken into account in numerical analysis and represented by a rectangle displacement-load relationship. The frictional force of a roller support is obtained by multiplying the vertical reaction due to the dead load acting on the support by the coefficient of friction assumed to be 0.05. In addition, lateral steel stoppers are provided at each side of the bearing in order to prevent rollers to be dislodged from the bearing assembly. The effect of stoppers is introduced in the analytical model by the high third stiffness slope, K_3, related to impact reaction forces transmitted due to collision with the stopper.

2.3 Expansion joint

The continuous span and single simply-supported span of the viaduct are separated, introducing a gap of 10 cm that 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 (**Fig. 3c**) that acts when the gap between the girders is completely closed.

Table 1 Cross-sectional properties of deck and piers

	A (m^2)	I_x (m^4)	I_y (m^4)^a
P1	0.4500	0.3798	0.3798
P2	0.4700	0.4329	0.4329
P3	0.4700	0.4329	0.4329
P4	0.4700	0.4329	0.4329
P5	0.4500	0.3798	0.3798
G1	0.2100	0.1005	0.0994
G2	0.4200	0.1609	0.2182
G3	0.2100	0.1005	0.0994

^{a} I_z in case of G1, G2 and G3.

Table 2 Structural properties of steel bearing supports

Bearing type	Component	K_1 (MN/m)	K_2 (MN/m)	K_3 (MN/m)	F_1 (MN)	F_2 (MN)
Fixed	Longitudinal	980.0	–	–	–	–
	Transverse	980.0	–	–	–	–
Roller	Longitudinal	49.0	0.0098	980.0	0.0735	Variable
	Transverse	980.0	–	–	–	–

Table 3 Structural properties of cable restrainers

Cable restrainer	K_1 (MN/m)	K_2 (MN/m)	F_1 (MN)	F_2 (MN)
Restrainer 4 (R4)	204.058	10.203	2.584	3.040

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. 3c**, have been tangentially modeled as tension-only spring elements provided with a slack of 4 cm, 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[5]. Structural properties of cable restrainers are summarized in **Table 3**.

3. METHOD OF ANALYSIS

The bridge model was developed in-house using the Fortran programming language. The analysis of the highway bridge model was conducted using an analytical method based on elasto-plastic finite displacement dynamic response analysis.

The incremental equation of motion accounts for both geometrical and material non-linearities. Material nonlinearity is introduced through the bilinear elastic-plastic stress-strain relationship of the beam-column element, incorporating a uniaxial yield criterion and kinematic strain-hardening rule. The yield stress is 235.4 MPa, elastic modulus is 200 GPa and

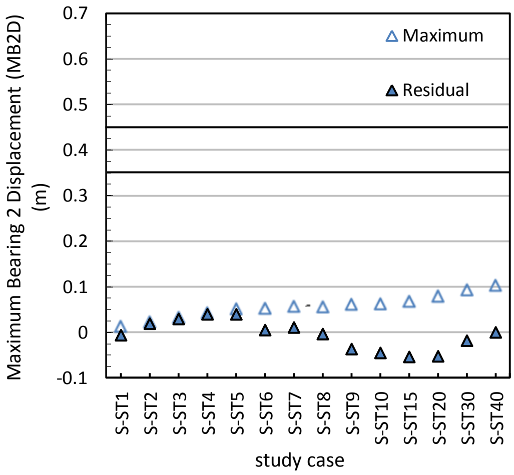


Fig. 5 Evaluation of deck unseating damage for TAK input

the strain-hardening in the plastic zone is 0.01. Newmark's step-by-step method of constant acceleration was formulated for the integration of the equation of motion. Newmark's integration parameters (β = 1/4, γ = 1/2) were selected to give the required integration stability and optimum result accuracy. The equation of motion was solved for the incremental displacement using the Newton-Raphson iteration scheme where the stiffness matrix is updated at each increment to consider geometrical and material non-linearities and to speed to convergence rate. The damping mechanism was introduced into the analysis through the Rayleigh damping matrix, expressed as a linear combination of mass matrix and stiffness as a linear combination of mass matrix and stiffness matrix. The particular values of damping coefficients were set to ensure a relative damping value of 2 % in the first two natural modes of the structure.

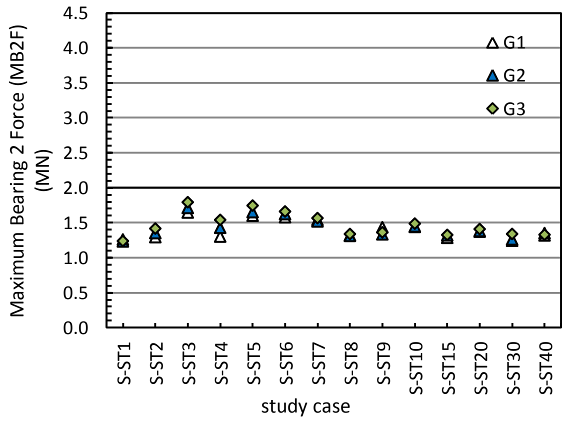
In order to assess the seismic performance of the viaduct, the non-linear bridge model was subjected to the longitudinal (L), transverse (T) and vertical (V) components of three strong ground motion records (**Fig. 4**) measured by the Takatori (TAK) stations during the 1995 Kobe earthquake[6]. The longitudinal earthquake component shakes the highway viaduct parallel to the X-axis of the global coordinate system, whereas the transverse and vertical components act in the Y- and Z-axes respectively.

4. NUMERICAL RESULTS

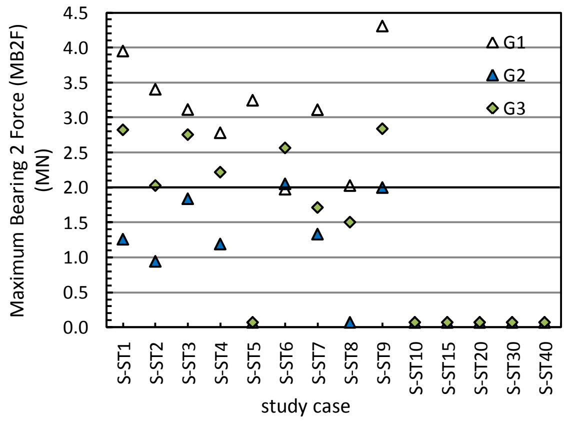
For an easy identification of the different study cases, a specific nomenclature is adopted in this research: “S” refers to the steel bearing, while “ST” refers to stopper of roller bearing. So “ST5” indicates that the stopper value is 5 cm.

4.1 Deck unseating

One of the most catastrophic seismic damages to bridge structures is the failure due to deck unseating. 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 (B2) displacement in the negative tangential direction has been established as the damage index to evaluate the potential possibility of deck unseating. A limit of 0.45 m has been established to determine the relatively low unseating susceptibility for new construction bridges. An additional limit of 0.35 m is also considered to indicate the high unseating probability for existing bridges with narrow steel pier



(a) Maximum bearing 2 force in radical direction



(b) Maximum bearing 2 force in tangential direction

Fig. 6 Maximum bearing 2 force

caps that provide short seat widths.

Collapse due to deck unseating does not take place for all cases, as can be seen in **Fig. 5**. In the cases that stopper values are 1 cm, 2 cm and 3 cm, the maximum steel bearing displacement is same with stopper values respectively. Because the cable restrainer slack value is 4 cm which is larger than stopper values in these cases. So cable restrainer does not work when earthquake happens. In above cases, the stopper values determine the maximum steel bearing 2 movements.

In the cases that stopper values are from 4 cm to 9 cm, cable restrainer and stopper work together to resist the external force. So the maximum bearing displacements are determined by all of them.

In other cases that stopper values are larger than 10 cm, the roller bearing 2 does not impact stopper, cable restrainers and roller bearings on top of other piers resisting the external force. So the maximum negative displacements are determined by the cable restrainers' performance and the roller bearing of other piers impact effect when earthquake happens.

4.2 Bearing supports

The vulnerability of highway viaducts supported on steel bearings has been demonstrated in several recent strong earthquakes. Deficient seismic performance is generally identified as a consequence of the brittle behavior of bearing supports. Steel bearings, supporting the adjacent span, are characterized by the lack of strength or deformation capacity required during earthquakes. For this reason, the maximum bearing 2 force (MB2F) is calculated in order to evaluate excessive radial and tangential reaction forces, which have been the cause of brittle failure of steel roller bearings in recent earthquakes. This failure occurs when the tangential or radial seismic forces exceed shear capacity of anchor bolts (2.0 MN)

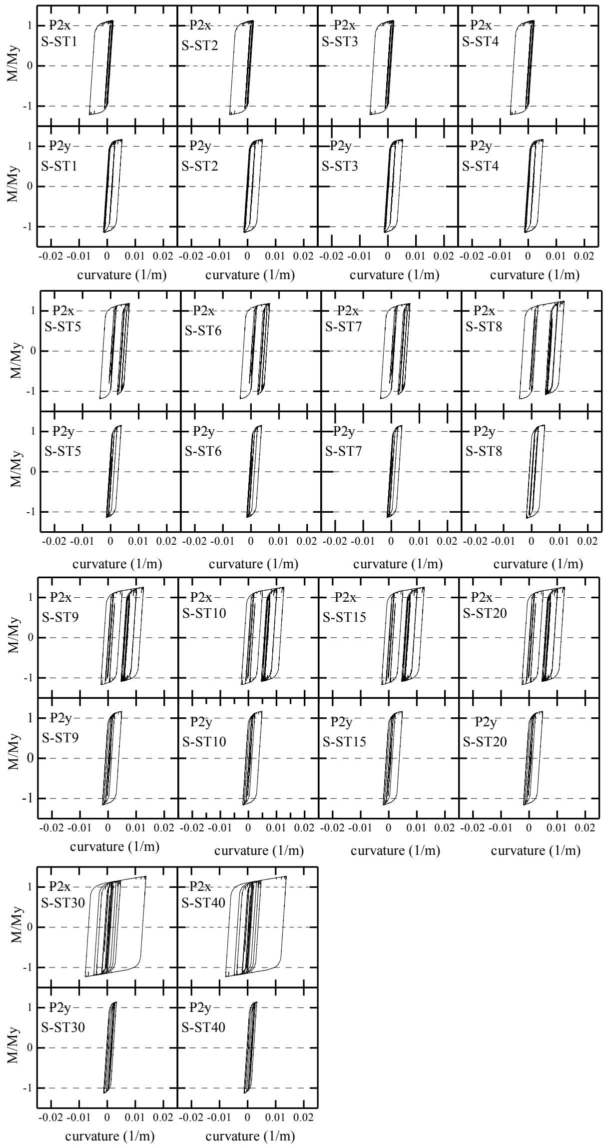


Fig. 7 Bending moment ratio at pier 2 bottom

that provide connection between the bearing top plate and the superstructure, causing vertical gaps of several centimeters.

The installation of lateral stoppers to roller bearings is found relatively effective since maximum bending moment acting on the pier with fixed bearings tends to be reduced. However, adverse effects are appreciated for piers with roller supports, being the possibility of seismic damage extended to all substructures. Radial force of steel bearing 2, in all cases, is smaller than 2 MN in **Fig .6a**. However, tangential force of steel 2 is larger than 2 MN when stopper value is smaller than10 cm in **Fig .6b**. As stoppers are positioned more than 10 cm, the tangential force is very small, because the external force in positive direction is resisted by the simple-supported and continuous spans directly pounding phenomenon, with the expansion joint gap of 10 cm. For negative direction, external force is afforded by cable restrainer with the slack of 4 cm.

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 considerate as an appropriate measure of seismic structural damage. Bending moment curvature relationships at the pier placed under the expansion joint (p2) in X and Y directions are shown in **Fig. 7**.

According to the results for the bending moments (P2x and P2y) in plane, the absolute value of M/My overpasses 1 in all cases as shown in **Fig. 7**. It indicates that there is plastic deformation in x and y direction, results in plastic damage at pier 2 bottom.

As the stopper value increased, the maximum curvature increased in x direction and decreased in y direction in **Fig. 7**. When stopper value is smaller, the roller bearings at the top of other piers can afford more impact force. So the roller bearings of pier 2 need resist smaller force, inducing smaller curvature value in x direction.

On the opposite side, when the stopper value is very large, the pounding forces of roller bearings on the top of other piers become small, moreover, on the top of pier 2 there is a fixed bearing which can transmit force to substructure, then pier 2 need afford larger force. So the maximum curvature is larger in above mentioned cases.

5. CONCLUSIONS

The effectiveness of roller bearing stopper as preventing roller bearing excessive movement is evaluated in this study. In order to perform a complete investigation of its role on the seismic performance of the viaduct, the dynamic behavior of the structure has been analyzed when the steel bearings are equipped with different stopper values. The presented results provide sufficient evidence for the following conclusions:

1) The calculated results clearly demonstrate that appropriate roller bearing stopper provide an effective means for overcoming the potential problems associated with deck unseating. The fixed steel bearings and roller steel bearings arrangement can reduce deck unseating damage obviously.
2) During an earthquake, it is also obvious that the steel bearings arrangement could lead to the roller bearing tangential seismic force exceed the shear capacity of the anchor bolts, increasing the vulnerable broken possibility of the roller bearing. But the bearing damage is less important than deck unseating damage and pier damage. So comparing with other damage forms, bearing damage is acceptable to some extent.
3) As the roller bearing stopper value becomes larger, maximum bending moments increase in x direction and decrease in y direction for pier 2. Besides maximum bending moments in x direction is larger than y direction. So choosing a large stopper value is not appropriate method to reduce the maximum bending moments in x direction.

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