SEISMIC RESPONSE ANALYSIS OF CURVED GRILLAGE VIADUCT WITH STEEL BEARING SUPPORTS AND HEIGHT PIERS

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ABSTRACT

Strong earthquakes have repeatedly demonstrated the seismic vulnerability of highway viaducts. The poor seismic performance of traditional steel bearing supports has been highlighted due to the disastrous consequences for the overall bridge seismic performance. Recently in order to improve the seismic behavior of viaducts, stopper, due to its cheap price and simple installation method, is installed on side of roller bearing. This paper presents analysis to evaluate the efficiency of using roller bearing equipped with different stopper values. The bridge model is developed in-house using the Fortran programming language. Seismic wave is measured by the Takatori (TAK) stations during the 1995 Kobe earthquake. In order to get accurate seismic response, the study combines non-linear dynamic analysis with a three-dimensional bridge model considering material and geometrical nonlinearities. The advantage of using stopper, reducing residual tangential displacement at expansion joint and pounding force between superstructures, is obviously proved.

Keywords: Curved grillage viaduct; Stopper; Roller bearing; Cable restrainer; Seismic response.

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. 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 (Japan Road Association 2002).

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 (Watanabe et al. 1998; Scawthorn and Yanev 1995). Moreover, traffic vehicle flow was impeded in some cases by superstructure falling on to the surface of the substructure. This severe 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

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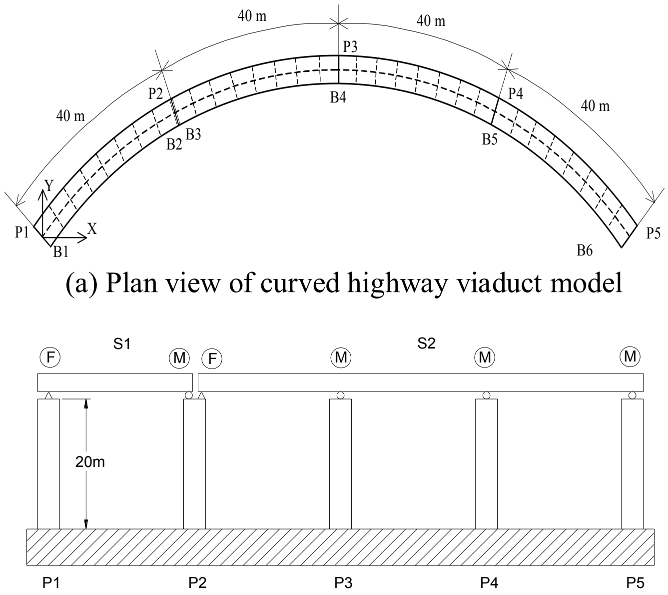


(a) Plan view of curved highway viaduct model

(b) Elevation view of curved highway viaduct model

Figure 1: Analytical model of viaduct.

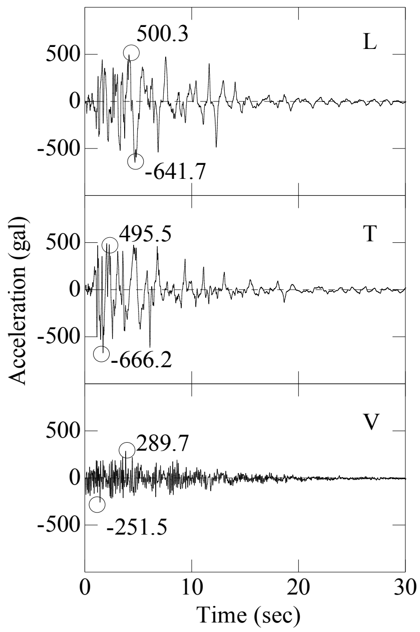


Figure 2: JR Takatori St. record 1995 Kobe earthquake.

roller bearings equipped with stopper are installed on top of piers. Since 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 roller bearing supports equipped with stoppers. Then obtain the relationship between different stopper values and the calculation results, at the same time evaluate the calculation results. According to the calculation results, provide advice for the seismic design of viaduct based on the appropriate stopper values at last.

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. The non-linear bridge model was subjected to the longitudinal (L), transverse (T) and vertical (V) components of three strong ground motion records (Fig. 2) measured by the Takatori (TAK) stations during the 1995 Kobe earthquake (Mendez Galindo et al. 2010).

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

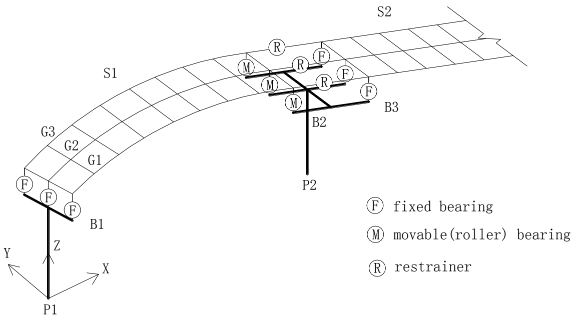
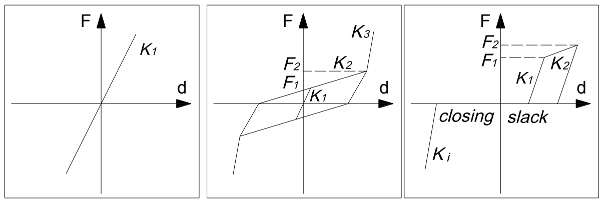


Figure 3: Finite element model for viaduct.



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

Figure 4: Models of bearing and restrainer.

action between slab and 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. 3. The deck weight is supported on four hollow box section steel piers 20 m high designed according to the Japanese seismic code. 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.

2.2. Bearing supports

In the viaduct, fixed bearing supports (Fig. 4a) are installed across the full width at the left end of the continuous span, resting on pier 2. Roller bearings at the top of the other piers allow for movement in longitudinal direction and provide restraint in transverse radial direction. For simple supported span, fixed bearing supports are installed at the left end, and roller bearing supports are installed at the right end. Table 2 shows the structural properties of the steel bearings. Roller bearings are represented by using a trilinear element shown in Fig. 4b. Coulomb friction force is taken into account in numerical analysis. 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 roller bearings 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.

2.3. Expansion joint

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 is modeled using impact spring elements, and the spring stiffness is K_i = 980.0 MN/m as shown in Fig. 4c. Cable restrainers units are anchored to the three girder ends connecting both adjacent superstructures across the expansion joint. The seismic restrainers, illustrated in Fig. 4c, 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. 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). 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 unseating prevention device (Ruiz Julian et al. 2007). Structural properties of cable restrainers are shown in Table 2.

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 and cable restrainer

	Component	K_1 (MN/m)	K_2 (MN/m)	K_3 (MN/m)	F_1 (MN)	F_2 (MN)
Fixed Bearing	Longitudinal	980.0	–	–	–	–
	Transverse	980.0	–	–	–	–
Roller Bearing	Longitudinal	49	0.0098	980	0.0735	Variable
	Transverse	980	–	–	–	–
Cable Restrainer 4	Longitudinal	204.058	10.203	-	2.584	3.04
	Transverse	-	-	-	-	-

2.4. 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 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%.

3. 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.

3.1. Tangential and radial horizontal joint residual opening

The residual joint tangential displacement (RJTD) has been calculated in order to evaluate post-earthquake serviceability of the viaduct. 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 of the

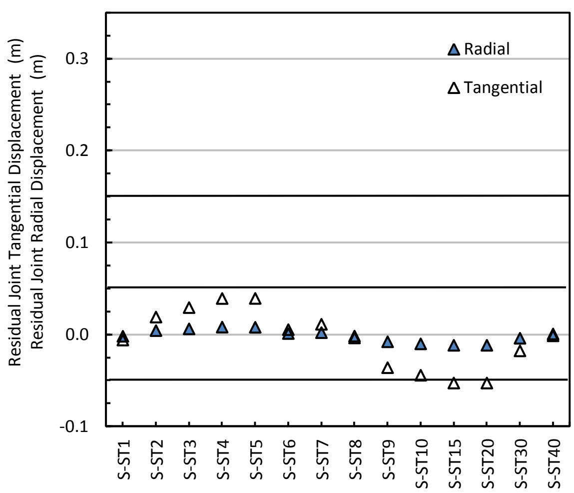


Figure 5: Tangential and radial residual displacement.

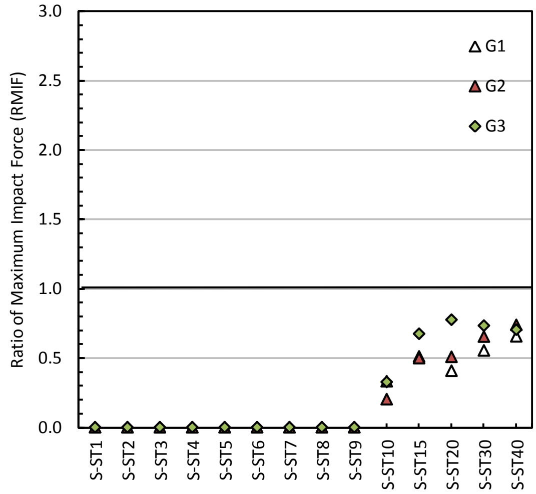


Figure 6: Pounding damage.

damage index (Zhu et al. 2004). According to the experiences obtained from previous earthquake damages, residual joint radial displacement (RJRD) greater than 0.05 m is able to eliminate the usability of one complete traffic lane, being suggested as the limit of the damage index. RJTD and RJRD are all under the limit line for all cases in Fig. 5, so there is no damage for RJTD and RJRD in earthquakes.

As stopper value is from 1 cm to 4 cm, RJTD presents increasing trend in Fig. 5. Because the slack value of cable restrainer is 4 cm which is larger than above stopper value. In addition, expansion joint gap of 10 cm is also larger than stopper value. So cable restrainer does not work and pounding phenomenon between superstructures also does not happen. Finally, under the influence of the pounding force between roller bearing and stopper, RJTD presents increasing trend.

As stopper value is from 5 cm to 10 cm, RJTD presents decreasing trend. Pounding phenomenon between superstructures does not happen because of large expansion joint gap of 10 cm which is larger than stopper value, but positive pounding phenomenon between roller bearing and stopper happens that induces RJTD increasing trend. However, RJTD does not presents increasing trend. The main reason is that, at the same time, cable restrainer also begins to work because of its small slack 4 cm which is smaller than stopper value. Restrainer tension pulse times are almost same with positive pounding force times of bearing 2, but restrainer tension peak is larger than pounding force peak. So under the cable restrainer's tension effect, joint tangential displacement becomes small.

When stopper value is larger than 10 cm, RJTD presents increasing trend. Roller bearing 2 does not impact on stopper, but directive pounding phenomenon between superstructures happens because expansion joint gap of 10 cm which is smaller than stopper value. So cable restrainer and pounding phenomenon between superstructures affect RJTD. Although pounding times between superstructures are almost same with cable restrainer tension times, pounding force is larger than cable restrainer tension. Finally, RJTD shows increasing trend. Since radical direction of all bearings is restraint, residual joint radial displacement (RJRD) is near zero as shown in Fig. 5.

3.2. Pounding damage

Large pounding force between superstructures can lead to large local damage at colliding area. Besides high impact forces are transmitted to bearing supports, make bearing supports particularly vulnerable to failure, which could result in the collapse of the bridge. Ratios of maximum impact force to the deck weight greater than 1.0 have been observed to provide a good estimation.

According to the presented results in Fig. 6, ratio of maximum impact forces are smaller than 1 in all cases. As stopper values are smaller than 10 cm, pounding forces between girders are zero. Since expansion joint gap is 10 cm which is larger than stopper value in above cases, it is stopper that resists the impact force.

As stopper value is larger than 10 cm, there is impact force between girders. There is a sharp increased trend in the cases that stopper value is 10 cm. When stopper value is larger than 15 cm, the curve is becoming smooth and steady. Considering bridge curve alignment, the deck irregularly translates because it does not concentrate movement exclusively in the tangential direction. Impacts are observed to be non-uniformly distributed across the expansion joint, thus particular girders, especially G3, resist most of the impact force.

3.3. Bridge pier damage

Bridges supported on piers with large residual inclination may lose their serviceability, becoming largely unsafe and probably irreparable. Due to this fact, the 1996 Japanese specifications imposed the limitation of 1% maximum inclination of the bridge pier height in post-earthquake pier demolition for important bridges (Japan Road Association 2002). It is also noted that residual pier inclination values greater than 0.5% and less than 1% have been defined as moderate to severe damage in the study.

According to the previously analyzed seismic damages, it could be concluded that generally stoppers and cable restrainers are very effective to protect the bridge from damage. So bridge pier damage evaluation becomes very important. However, calculated results presented in Fig. 7 shows that pier inclination damage happens in some cases.

The installation of lateral stoppers to roller bearings is found relatively effective since the 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 large residual displacement extended to all top of piers in Fig. 7. Because large impact forces acting on stoppers of roller bearings are transferred to the piers with a sharp increment of bending moment at those pier bottoms. Consequently, all piers have residual pier inclination. In addition, residual pier inclination and residual curvature have almost same change trend as shown in Fig. 7 and Fig. 8. Residual curvature is determined by curvature time-history, especially, those curvatures which are larger than yield curvature. Maximum positive and negative curvatures have a great influence on residual pier inclination to some extent.

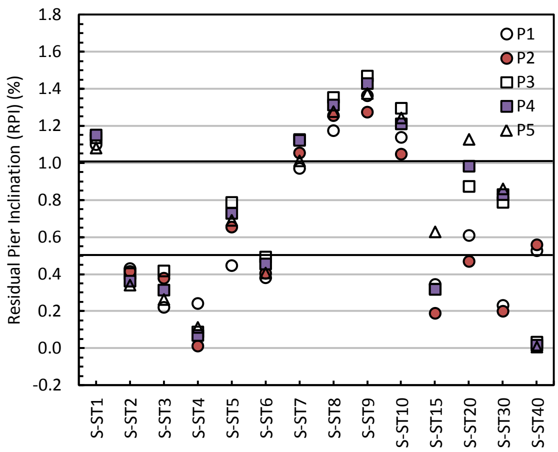


Figure 7: Evaluation of pier inclination damage.

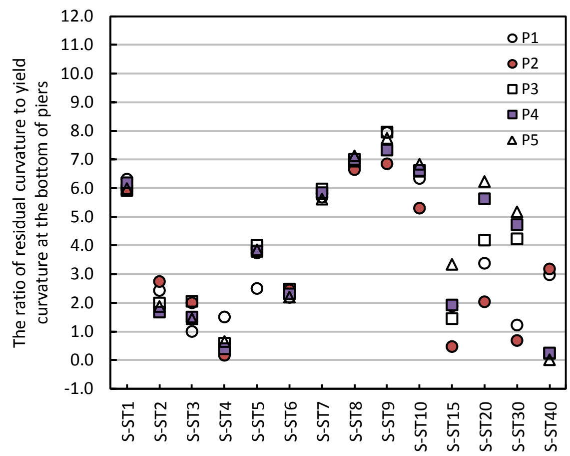


Figure 8: The ratio of residual curvature to yield curvature at the bottom of piers.

When stopper value is from 1 cm to 4 cm, residual pier inclination decreased with stopper value increasing as shown in Fig. 7. Slack value of cable restrainer and closing value between superstructures are all larger than stopper value. So it is stopper resisting external force. From beginning, top of piers has positive direction trend for TAK input. As stopper value increased, both maximum positive pounding force and positive pounding times between stopper and roller bearing decreased. However, pounding times of negative direction between roller bearing and stopper increased. Then maximum positive bending moment and curvature are all becoming small. The residual curvature at the bottom of piers also decreases, as shown in Fig. 8. So, residual displacements on the top of piers decreased for positive direction in Fig. 7.

When stopper value is from 5 cm to 9 cm, residual pier inclination increased as shown in Fig. 7. It is stopper and cable restrainer work together to resist external force. From beginning, top of piers has positive direction trend for TAK input. When simple supported span move toward negative direction, cable restrainer resists the force instead of stopper. Cable restrainer transfer the negative pounding force to continuous span, do not directly apply on the pier 2. Besides as stopper value increased, maximum positive bending moment and positive curvature of pier bottom also increased. Then it results in residual curvature at the bottom of piers increasing, as shown in Fig. 8. At last residual displacement on the top of piers increased in Fig. 7.

As stopper value is larger than 10 cm, residual pier inclination presents fluctuating curve in Fig. 7. Since stopper value is larger than 10 cm, there is no pounding force between stopper and roller bearing for bearing 2. In other words, there is no directive pounding force between simple supported span and pier 2. Then simple supported span and continuous span shall present respective different behavior because of different masses. In addition, the variation degree of different behavior shall increases because of directive pounding force between superstructures. Then the residual curvature at the bottom of piers respectively presents different values for simple supported span and continuous span, as shown in Fig. 8. So the piers of simple supported span and continuous span present obviously different residual pier inclination in Fig. 7.

Fortunately, when stopper value is 2 cm, 3 cm, 4 cm and 6 cm, residual pier inclination is under 0.5% presenting no damage. And stopper value is 5 cm, residual pier inclination indicates less moderate damage which is acceptable to a certain degree. However, it presents more moderate or serious damage in other cases. Conclusively, the region, stopper value of nearby 4 cm which equal to slack value of cable restrainer, shows moderate or no damage.

4. CONCLUSIONS

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 roller bearings are equipped with different stopper values. The presented results provide sufficient evidence for the following conclusions:

(1) The calculated results clearly demonstrate that stopper of roller bearing provide an effective means for overcoming the potential problems associated with residual tangential and radial displacement at expansion joint.

(2) It is additionally highlighted that when stopper value is larger than 10 cm, there is obvious impact force between girders, but the ratio of maximum impact force is below 1 which is not problem for the bridge’s safety. Therefore, stopper is appropriate device for reducing the ratio of maximum impact force between girders.

(3) According to evaluation of pier inclination damage, the region, stopper value of nearby 4 cm which equal to slack value of cable restrainer, shows moderate or no damage. In addition, residual pier inclination and residual curvature at the bottom of piers have almost same trend in the case of different stoppers. In other words, residual curvature at the bottom of piers has important influence on residual pier inclination.

REFERENCES

Japan Road Association (2002). Specifications for Highway Bridges – Part V Seismic Design, Maruzen, Tokyo.

Watanabe E, Sugiura K, Nagata K, and Kitane Y (1998). Performances and damages to steel structures during the 1995 Hyogoken-Nanbu earthquake. Eng. Struct., 20 (4-6), pp. 282-290.

Scawthorn C and Yanev PI (1995). Preliminary report 17 January 1995, Hyogo-ken Nambu, Japanese earthquake. Eng. Struct., 17 (3), pp. 146-157.

Mendez Galindo C, Gil Belda J, and Hayashikawa T (2010). Non-linear seismic dynamic response of curved steel bridges equipped with LRB supports. Steel Construction. 3 (1), pp. 34-41.

Ruiz Julian FD, Hayashikawa T, and Obata T (2007). Seismic performance of isolated curved steel viaducts equipped with deck unseating prevention cable restrainers. Journal of Constructional Steel Research. 63(2), pp. 237-253.

Zhu P, Abe M, and Fujino Y (2004). Evaluation of pounding countermeasures and serviceability of elevated bridges during seismic excitation using 3D modeling. Earthquake Engineering & Structural Dynamics. 33(5). pp. 591–609.