3 - Dimensional Nonlinear Dynamic Analysis of Curved Viaduct with Various Bearing Conditions under Great Earthquake Ground Motion

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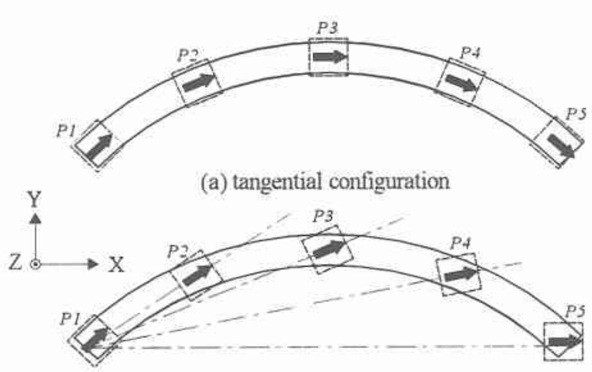
1. INTRODUCTION

During the last three decades, a large number of seismic isolation systems have been developed to meet the need of an innovative seismic design approach ensures the safety of the structure by reducing the seismic forces near to the elastic capacity and thus reducing the plastic deformations during an earthquake. The wide variety of these systems is a combination of elastomeric bearings and energy dissipaters such as lead plugs.

While a large number of high way viaduct systems utilizing conventional bearings suffered unexpected severe damage and collapse in the last earthquake of Hyogoken Nanbu 1995, it was reported that the viaduct systems utilizing base isolation devices suffered much less damage. So, It has become with much importance to reconsider using conventional bearings and investigate the behavior of such viaduct systems using base isolations.

The purpose of this study is to evaluate the 3-dimensional nonlinear seismic response of the continuous curved viaduct systems utilizing either conventional steel bearings or seismic isolation bearings such as rubber or lead rubber. Two configurations of bearings are investigated, tangential and radial.

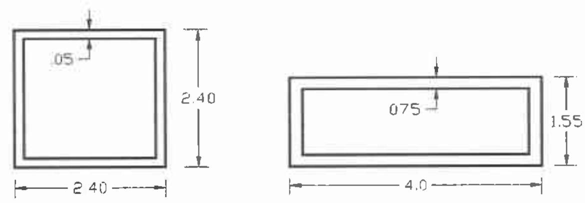
It can be concluded that the replacing the conventional steel bearings with LRB, has sufficient stiffness, greatly enhance the seismic response of the curved viaduct and that the response of the radial configuration is better than the radial one.



(a) tangential configuration

(b) radial configuration

Fig. 1 Plan of the studied system



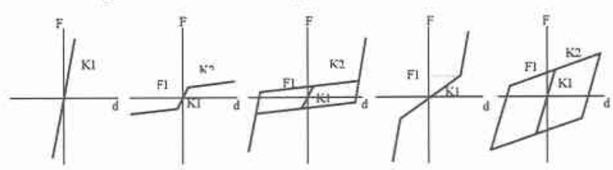
(a) pier　　　(b) deck

Fig. 2 Cross Sec. of the elements of the viaduct

2. DESCRIPTION OF THE VIADUCT SYSTEM

2.1 Viaduct deck and piers

The studied curved viaduct has a continuous steel four spans deck of total length equal 160 m (40 m each span) and radius of curvature equal 100 m. Two pier configurations are studied, radial and tangential. The length of all piers is kept equal to 20 m. The plan of the studied system is shown in Fig. 1 while the cross sections of deck and piers are shown in Fig. 2.



(a)　(b)　(c)　(d)　(e)

Fig. 3 Modeling of the bearings

2.2 Bearings

In this study, the bearings are allowed to have their horizontal motion only in the direction of configuration while the perpendicular direction is kept fixed. All bearings are allowed to rotate freely. Following a brief description of the behavior of each bearing:

(1) Steel bearing (SI, SII) ; Two cases of steel bearing are studied, SI and SII, for both cases the first bearing is considered as fixed support , Fig. 3 (a) while the other bearings are considered as roller bearings without using stoppers for case SI, Fig. 3 (b), and with stoppers for case SII, Fig. 3 (c). The stoppers allow a displacement of 10 cm.

(2) Rubber bearing (R) ; The rubber bearing is consisted of layers of steel and rubber, the modeling of this device assumes the existence of stopper which allows displacement of 3.5 cm., Fig. 3 (d).

(3) LRB (LRBI, LRBII) ; The studied lead rubber bearing consists of layers of steel and rubber with lead plug. LRBI is designed as flexible bearing while LRBII is considered stiff one. The model of LRB is shown in Fig. 3 (e). For both cases the strain hardening ratio is nominally equal 0.15[1,2]. The characteristic parameters of the studied cases of bearings are shown in Table 1.

Table 1 Characteristic stiffness and strength of the studied bearings

Case	Pier number	Initial stiffness (K1)	Post yielding stiffness (K2)	Yielding strength (F1)
		MN/m	MN/m	MN
SI	P1	1000	1000	1000
SII	P2-P5	5000	1.00	0.115
R	P1,P5	47.33	588.00	1.66
	P2,P3,P4	52.92	588.00	1.86
LRBI	P1,P5	32.00	4.80	0.40
	P2,P3,P4	38.00	5.80	0.48
LRB II	P1,P5	64.00	9.60	0.80
	P2,P3,P4	76.00	11.60	0.96

3. FINITE ELEMENT ANALYSIS

A three dimensional time history analysis is carried out using Newmark β method. Both girder and piers are modeled as flexural fiber element. The bearings are modeled as spring elements in the three dimensions. The material behavior is modeled by an elasto-plastic constitutive model with strain hardening in the plastic range equal to 0.01, The yield stress and the elastic modulus are equal to 240 MPa and 200 GPa respectively. Damping of the structure is taken 5% of the first mode. The earthquake input motion adopted in this study is the three components (N-S, E-W, U-D) of the JR Takatori wave, ground Type 2.

4. NATURAL VIBRATION ANALYSIS

Natural vibration analysis for the studied cases is carried out using consistent mass method. The values of the first mode of natural period for the studied cases are mentioned in Table 2, from which it can be observed that no shift in the period is obtained when using rubber or lead rubber bearings, this is related to the strategy of Menshin design which is adopted for the design of bridges in Japan. This strategy uses seismic isolation bearings as element to dissipate energy and distribute the lateral forces to elements of the substructure, rather than as elements to shift the period of the bridge. This is because that Level 2 bridge design spectra for Japan are characterized by a constant spectral region that extends up to between 1.4 sec and 2.0 sec. For effective seismic isolation it is necessary to lengthen the period to values beyond 3.0 sec [3] which is very difficult to obtain and if possible will lead to undesirable excessive displacement and hence the requirement of large expansion joints.

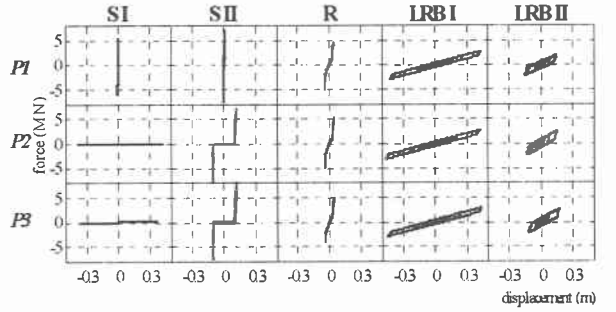
Table 2 Natural period of the first mode of the studied cases

Case	SI, SII	R	LRBI	LRB II
Tangential	1.55	0.81	1.65	1.26
Radial	1.52	0.81	1.65	1.26

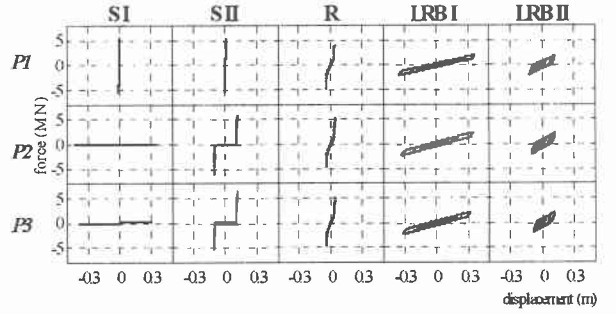
5. NONLINEAR SEISMIC ANALYSIS

5.1 Force-displacement of bearings

The behavior of each bearing type can be observed clearly from Fig. 4. While the roller bearings undergo large displacement, the stoppers restrict the horizontal motion according to the clearance of the stopper resulting in high values of the corresponding forces.



(a) tangential configuration



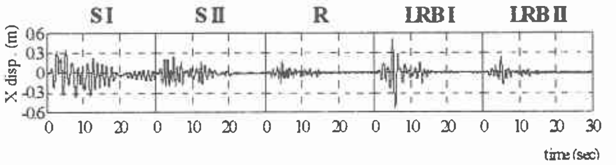
(b) radial configuration

Fig.4 Force displacement for the bearings

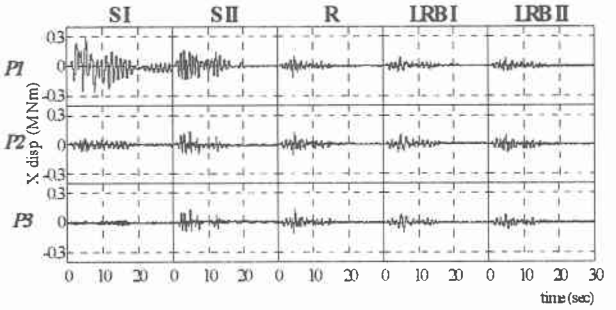
Although using stopper for the rubber bearings, the experienced values for the forces are less than those of case SII. The observed forces of the LRB are small and their behavior depends on their characteristic stiffness and strength.

5.2 Deck and top piers displacement

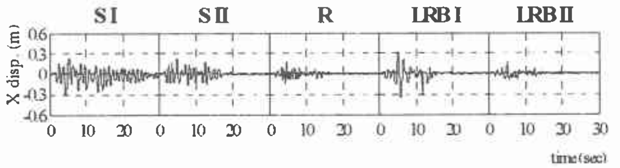
The response of both deck and top of piers are shown in Fig. 5, from which it is clear that the radial configuration is better than that of the tangential one. For this configuration the best response is observed for the cases R and LRB II which displayed a deck displacement about 0.17 m, while for the cases SI and SII it is about 0.32 and .0.22 m respectively.



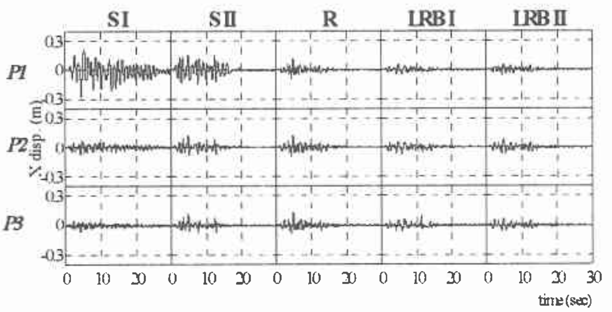
(a) X displacement of the deck (tangential configuration)



(b) X displacement of top of piers (tangential configuration)



(c) X displacement of the deck (radial configuration)



(d) X displacement of top of piers (radial configuration)

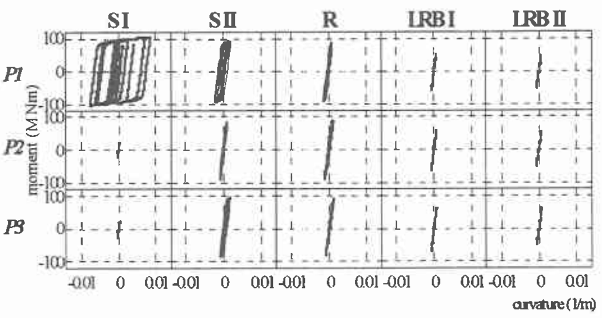
Fig. 5 X displacement response of deck and top of piers

The response of piers top displacement is almost similar for all cases except for the fixed piers of SI and SII.

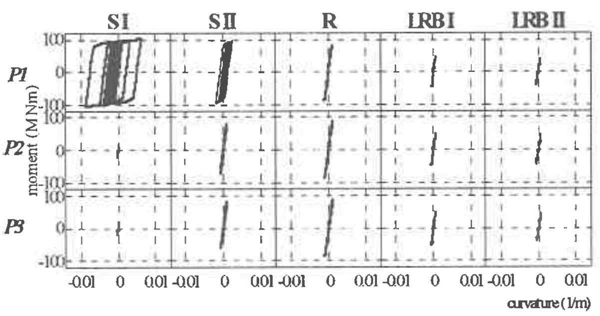
5.3 Moment curvature

The response of the in and out of plane moment curvatures for base of piers is shown in Figs. 6 and 7, from which it can be observed that in case SI, the in plane moment is concentrated in the fixed pier which suffered large moment curvature hysteretic loop. For both SII and R, the observed values of moment are high for all piers. Using LRB yields to more than 50 % reduction in the values of in plane bending moment in comparison with other cases, this means that all piers are still in the elastic range.

The out of plane stiffness for all bearings is kept fixed, so that almost all piers suffered from relatively high values of out of plane moment with slight improvement for the cases R and LRB II. The radial configuration is still considered better in reducing the moment and curvature for the curved viaduct.

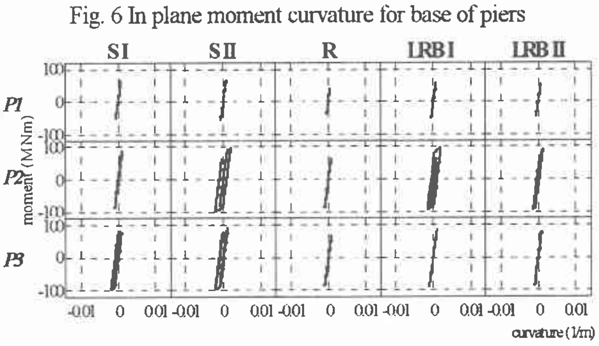


(a) tangential configuration

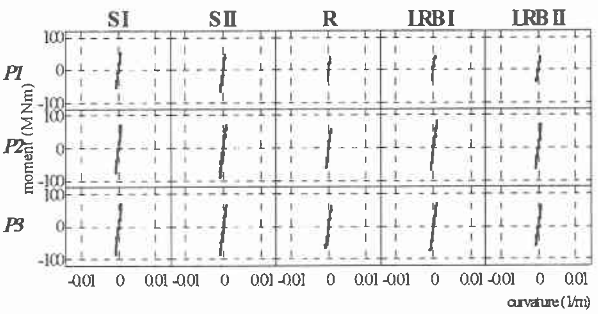


(b) radial configuration

Fig. 6 In plane moment curvature for base of piers



(a) tangential configuration

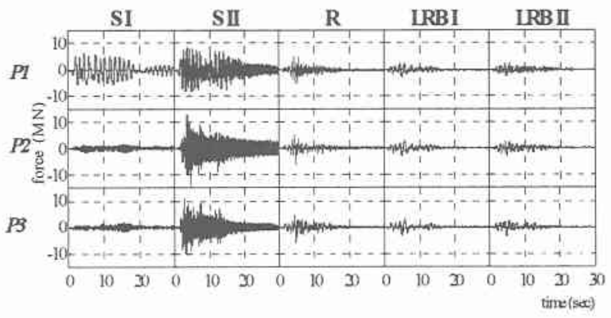


(b) radial configuration

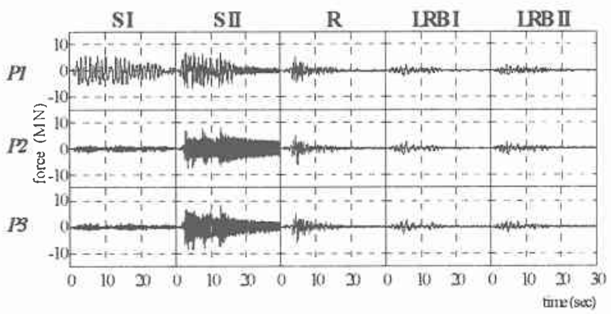
Fig. 7 Out of plane moment curvature for base of piers

5.4 Base shear

In Fig 8, it can be observed that using either rubber or LRB highly reduces the values of base shear in comparison with the conventional steel bearings. For SII all piers undergo frequently high base shear, this is due to the effect of stoppers, the colliding of the bearing with the stopper results in high values for the response of shearing forces. For the case of steel roller support without stopper, the first bearing is considered as fixed pier. This pier suffered from high values of base shear.

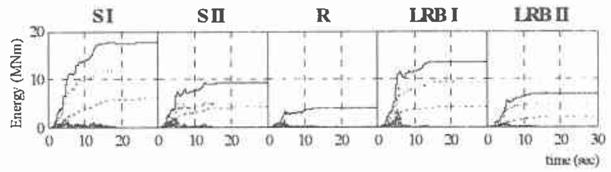


(a) tangential configuration

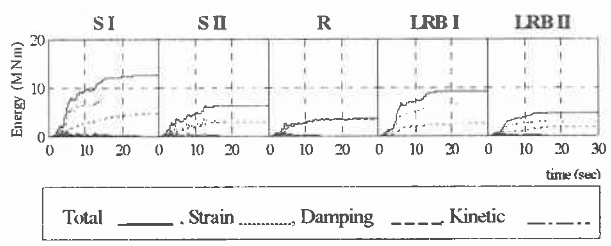


(b) radial configuration

Fig. 8 In plane base shear



(a) tangential configuration



(b) radial configuration

Fig. 9 Time history of energy

5.5 Energy

The time history analysis of the absorbed energy for the studied cases is shown in Fig. 9, for each case the kinetic, damping, strain and total input energy are studied. For all cases the kinetic energy are so small and therefore has no significant consideration. The damping energy represents the viscous damping characteristics of the studied cases. The dissipated strain energy involves the energy dissipated due to the formation of plastic hinge at base of piers and the deformations of bearings. While almost all studied cases experienced similar values of damping energy, there is a difference in the values of the strain energy according to each studied case. Case SI experienced the highest values of strain energy, this is related to the formation of high plastic deformations in the base of piers. High values of strain energy are observed for the cases of steel bearings due to suffering from large plastic hinges at the base of piers. The energy behavior of the lead rubber bearing depends on the chosen stiffness, flexible stiffness leads to higher values of strain energy. The rubber does not have the capability of dissipating energy through bearing deformations, so most of the energy is dissipated through viscous damping. For all studied cases, it is clear that using radial configuration leads to a significant reduction in the values of the energy leading to better performance of the viaduct.

5. CONCLUIONS

From the 3 - dimensional nonlinear dynamic analysis of the viaduct system with different configurations, it is clear that the radial configuration for piers and bearings lead to results in a better seismic behavior than the tangential configuration.

Using the conventional steel bearings without stopper yields to excessive increase in the deck horizontal displacement and unexpected high values of plastic deformations are concentrated in the base of the fixed pier which makes the retrofit of such piers difficult after the earthquake.

The use of the stopper for steel bearings is effective in reducing the displacement response of the deck, but in contrarily the collide of the bearing with the stopper results in high response of base shear and moment for all piers.

The rubber bearings are effective in eliminating the hysteretic loops observed for the cases of steel bearings, but the obtained response for the moment in the base of piers are still high.

Replacing the conventional steel bearing with LRB leads to the enhancement of the overall behavior of the seismic response of the curved viaduct system and eliminated all plastic deformations of the substructure, the displacement response relies on the stiffness of the LRB, sufficient stiffness of LRB highly control this response.

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