Effect of Bearing Supports on Nonlinear Dynamic Behavior of Highway Viaducts under Great Earthquake Ground Motions

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1. INTRODUCTION

In recent years, the number of bridge seismic isolation applications using elastomeric bearings has grown considerably. The performance of this type of earthquake protective system has been proven satisfactorily under the action of recent strong earthquakes.

The objective of this study is to evaluate the seismic performance of highway viaducts under different support conditions. For this purpose, nonlinear dynamic analysis of a two dimensional model of highway viaduct is carried out. The dynamic response of the same model of viaduct under the same input earthquake wave is compared when different types of bearing supports are used.

Steel bearings are particularly vulnerable to damage to earthquakes. Therefore, the model of viaduct is equipped with rubber bearing supports to reduce the seismic forces acting on piers and foundations. Originally, rubber bearings were designed to accommodate thermal expansion of bridge deck structures, but by means of their low lateral stiffness the seismic performance of the bridge can be improved. As final step, specific base isolation bearings are used. Lead rubber bearing supports protect the bridge from earthquake loads by increasing the fundamental period and dissipating the seismic energy by hysteretic damping.

2. ANALYTICAL MODEL OF VIADUCT

2.1 Superstructure and Substructure

The lateral side view of a highway viaduct used in dynamic analysis is shown in Fig. 1. The model is a three-span continuous viaduct having equal spans of 40m. Superstructure is supported on four steel piers of 20m of height. The dead load of the steel reinforced concrete deck, assumed to be uniformly distributed, is 8.84MN. Structural properties of cross sections of piers and deck superstructure are shown in Table 1 and Fig. 2.

2.2 Models of Bearings

Three different types of bearing supports installed between the top of bridge piers and beneath the deck structure are considered in the analysis. Steel bearing supported model is constituted by one pier, P2, with steel fixed bearing support (Fig. 3-a), and three piers, P1, P3 and P4, with steel roller bearings (Fig. 3-b), taking friction force into account. For the rubber bearing supported model, the bearings are modeled with a bilinear element, as it is shown in Fig. 3-c. In order to prevent excessive displacements of the superstructure, side stoppers with a clearance of 10cm and 3.5cm, for steel roller and rubber bearings respectively, are placed at each side of bearing supports. The lead rubber bearings (LRB) installed in the base isolation model are characterized with bilinear force-displacement hysteretic loop, as it is represented in Fig. 3-d.

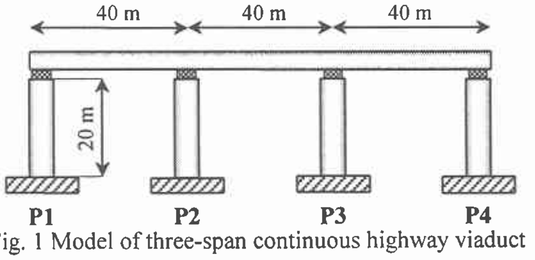


Fig. 1 Model of three-span continuous highway viaduct

Table 1 Structural properties of cross section

	b (m)	t (m)	A (m^2)	I (m^4)
Pier 1	2.20	0.05	0.4300	0.3314
Pier 2	2.30	0.05	0.4500	0.3798
Pier 3	2.30	0.05	0.4500	0.3798
Pier 4	2.20	0.05	0.4300	0.3314
Deck	1.61	0.082	0.5013	0.1963

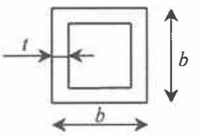
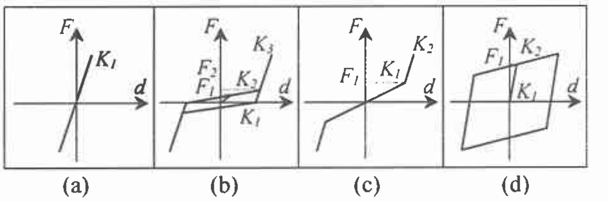


Fig. 2 Cross section of piers and superstructure



(a)　(b)　(c)　(d)

Fig. 3 Models of bearings

Table 2 Structural characteristics of bearing supports

Type of bearings	Type of piers	K_1	K_2	F_1	K_3	F_2
		MN/m	MN/m	MN	MN/m	MN
Steel	P1, P3, P4	49.0	0.01	0.118	980.0	0.119
	P2	980.0	-	-	-	-
Rubber Type-a	P1, P4	12.3	588.0	0.429	-	-
	P2, P3	14.7	588.0	0.515	-	-
Rubber Type-b	P1, P4	24.5	588.0	0.858	-	-
	P2, P3	29.4	588.0	1.029	-	-
LRB-1	P1, P4	26.6	11.0	0.409	-	-
	P2, P3	52.6	29.5	0.737	-	-
LRB-2	P1, P4	15.7	2.0	0.196	-	-
	P2, P3	18.6	2.9	0.235	-	-

Five cases of study have been analyzed: the basic steel supported model, two rubber supported models (Type-a and Type-b) and two lead rubber supported models (LRB-1 and LRB-2). Structural characteristics of these five models are summarized in Table 2.

3. METHOD OF ANALYSIS

In this study, the analytical method is based on the elasto-plastic finite displacement dynamic response analysis composed by finite element method, Newmark β method and Newton-Raphson method. This finite element method is considered the beam-column element with material yield and geometrical nonlinearity. The tangent stiffness matrix considering material and geometrical nonlinearities in-plane of bending deformation is adopted in this study. The stress-strain relationship of the beam-column element is modeled as a bilinear type. The yield stress is 235.4MPa, the elastic coefficient is 200GPa and the strain hardening in plastic area is 0.01. The damping of the structure is supposed a mass proportion type and the damping coefficient to the first natural mode of structures is 5%. The number of divisional elements of the bridge is 40.

Table 3 Natural periods of highway viaduct model

Type of bearings	1st mode (sec)	2nd mode (sec)	3rd mode (sec)	4th mode (sec)	5th mode (sec)
Steel	1.148	0.440	0.345	0.239	0.160
Rubber Type-a	1.008	0.440	0.345	0.239	0.133
Rubber Type-b	0.827	0.440	0.345	0.239	0.117
LRB-1	0.893	0.440	0.345	0.239	0.133
LRB-2	1.852	0.440	0.345	0.239	0.153

4. NATURAL VIBRATION ANALYSIS

In Table 3 are summarized the calculated natural periods for all cases of study. It is noted that same values for the second, third and fourth modes of vibration have been obtained because they are dominated by vertical movement of the superstructure, which is the same for all configurations. For the first and the fifth mode of vibration, movement of piers is predominant with respect to the vertical displacements of superstructure, and consequently the type of bearings used for the model takes special relevance.

For rubber supported models elastic stiffness is the parameter that determines the vibration modes. These bearings need a relatively high initial stiffness to offer rigidity under service and low lateral loads, and therefore low first natural period is obtained.

When isolation bearings are installed, different behaviors are observed for the two models. LRB-1 type is designed to dissipate seismic energy by hysteretic damping simultaneously that control the displacements by means of its relatively high stiffness, and therefore its first natural period of vibration is low. In contrast, LRB-2 type bearings are very flexible so that the base isolation system is able to reduce significantly seismic accelerations due to period shift as well as hysteretic energy is dissipated at bearing level. First natural period of LRB-2 model is increased from 1.15 to 1.85 seconds with respect to the basic steel supported model.

5. NONLINEAR DYNAMIC ANALYSIS

5-1 Input Earthquake Wave

To assess the performance of the multi-span continuous bridge, the nonlinear model is subjected to the action of "Standard Earthquake Wave, Ground Type II" with a peak ground acceleration (PGA) of 686.83 gal. Time-history acceleration data is given in Fig. 4.

5-2 Reaction Forces at Bearings

Large inertial forces of the superstructure are applied directly on steel bearings due to the limitation of displacements imposed by the lateral stoppers. The replacement of the original steel bearings with rubber bearing supports causes a significant reduction in terms of reaction forces acting on bearings. Approximately, a 25% of reduction can be observed for Type-a, and 35-55% for Type-b rubber bearings. This reduction is due to the increase of horizontal flexibility using rubber material. When, in its movement, the bearing reaches the stoppers, smaller forces are transmitted to them.

In case of base isolation models, the longitudinal displacement of bearings is not limited by stoppers, and consequently larger reduction in forces is observed: 45-70% for LRB-1 and 50-65% for LRB-2 type, as it can be appreciated in Table 4 and Fig. 5 (notice that the scale used for LRB type bearings is different). Maximum displacements of more than 44cm for LRB-2 type are observed because the isolator displacements increases as the isolation period increases.

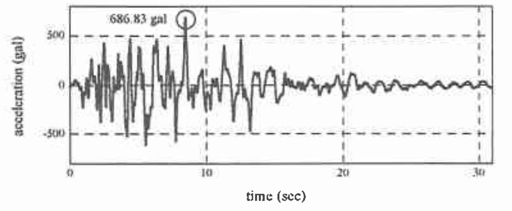


Fig. 4 Input earthquake wave

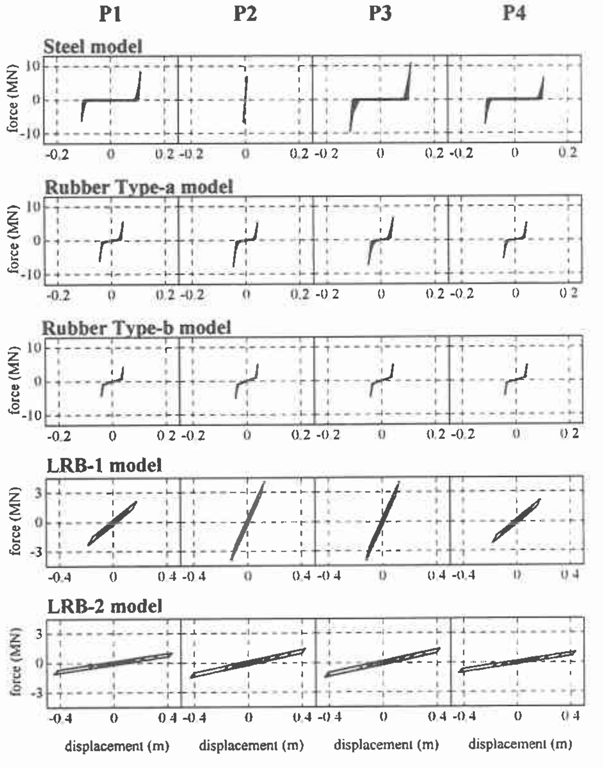


Fig. 5 Force-displacement relationship at bearings

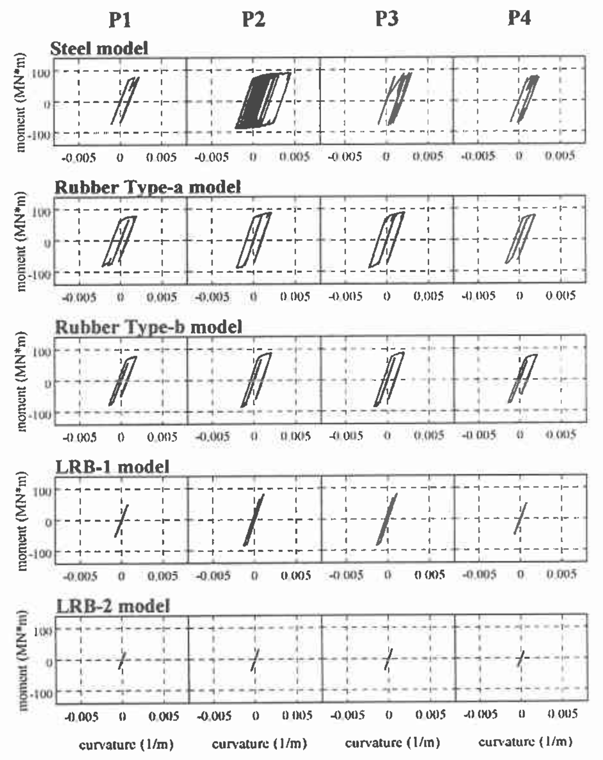


Fig. 6 Moment-curvature relationship at base of piers

Table 4 Maximum reaction forces on bearings (MN)

Type of bearings	P1	P2	P3	P4
Steel	8.52	7.01	10.84	7.36
Rubber Type-a	6.09	7.80	7.38	5.61
Rubber Type-b	4.28	5.05	4.94	4.64
LRB-1	2.28	4.06	4.04	2.23
LRB-2	1.07	1.46	1.47	1.06

Table 5 Maximum bending moment at base of piers (MN*m)

Type of bearings	P1	P2	P3	P4
Steel	80.11	91.36	89.57	79.86
Rubber Type-a	80.10	87.76	87.81	78.94
Rubber Type-b	78.91	87.68	87.48	79.73
LRB-1	51.82	82.90	83.27	50.75
LRB-2	27.80	34.76	34.87	27.62

Table 6 Maximum curvature at base of piers (1/m)

Type of bearings	P1	P2	P3	P4
Steel	0.0022	0.0046	0.0030	0.0022
Rubber Type-a	0.0022	0.0021	0.0021	0.0019
Rubber Type-b	0.0019	0.0021	0.0020	0.0021
LRB-1	0.0008	0.0013	0.0013	0.0007
LRB-2	0.0004	0.0004	0.0004	0.0004

5-3 Moment-Curvature at Base of Piers

Fig. 6 shows the relationship between bending moment and curvature at base of piers. Maximum values for all cases of study are listed in Tables 5 and 6. When steel bearings are replaced with rubber bearing supports, due to reduction of reaction forces at bearing level, damage affecting piers decreases. For the model supported by steel bearings most of damage is concentrated on fixed pier, P2. This design is based on providing safety against collapse, but it tends to be costly due to the difficulties of repairing and restoring permanent deflections after an earthquake. In contrast, for models supported by rubber bearings, all piers suffers almost the same small damage, therefore the serviceability of the bridge after an earthquake is not affected.

The use of lead rubber bearings can substantially reduce the seismic forces on piers. The linearity between bending moment and curvature is observed at base of piers. This indicates that isolation bearings are evidently effective decoupling the movement of the superstructure from the substructure.

5-4 Time-history Analysis

The response of each model of highway viaduct to the input earthquake wave is computed for the first 30sec of the input ground motion. Time-history displacement responses of deck superstructure and piers are drawn in Fig. 7. Maximum and residual displacements are listed in Tables 7 and 8 respectively. From the analysis it is possible to observe how the assembly P2-Deck of steel supported model undergoes large displacements resulting in significant residual displacement for all piers. Displacements at piers top decreases considerably when base isolation bearings are used, but almost 0.5m of maximum displacement of deck can be observed for LRB-2 model. LRB-1 type is not much flexible, so that the response of displacements is more controlled, and maximum displacement of deck is only 27cm.

Maximum velocities of top of piers and deck are analyzed in Table 9. It is noted an appreciable reduction of velocity at top of pier when steel bearings are replaced with rubber and lead rubber bearings. The increment of horizontal flexibility at the bearing level causes a significant reduction in the velocities transmitted from ground to the structural system.

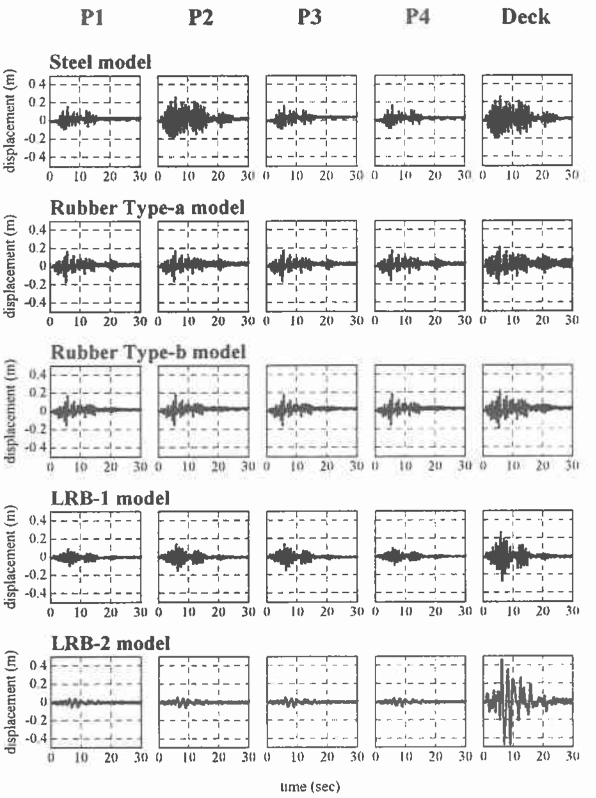


Fig. 7 Displacement time-history

Table 7 Maximum displacement at piers top and deck (cm)

Type of bearings	P1	P2	P3	P4	Deck
Steel	15.70	26.27	16.15	16.82	26.47
Rubber Type-a	16.67	17.21	16.96	17.31	21.03
Rubber Type-b	17.42	17.87	17.67	18.12	21.80
LRB-1	9.78	14.90	15.06	9.61	27.22
LRB-2	5.27	5.79	5.81	5.22	47.25

Table 8 Residual displacement at piers top and deck (cm)

Type of bearings	P1	P2	P3	P4	Deck
Steel	2.67	2.19	3.69	2.90	1.98
Rubber Type-a	1.44	1.83	1.78	1.70	1.28
Rubber Type-b	0.96	1.30	1.22	1.29	1.14
LRB-1	0.31	0.66	1.07	0.10	0.84
LRB-2	0.17	0.16	0.16	0.18	0.42

Table 9 Maximum velocities at piers top and deck (m/sec)

Type of bearings	Pier 1	Pier 2	Pier 3	Pier 4	Deck
Steel	3.86	2.26	4.25	3.06	1.82
Rubber Type-a	2.69	2.65	3.47	2.12	1.64
Rubber Type-b	1.83	1.82	1.70	1.93	1.50
LRB-1	0.87	1.01	1.00	0.86	1.65
LRB-2	0.73	0.88	0.88	0.72	1.72

Similar behavior is observed for accelerations. Two amplification factors have been summarized in Table 10, considering amplification factor as the relationship between maximum accelerations of the consideredstructural elements. Calculated deck/ground amplification factors are always less than one which indicates that the peak input acceleration of earthquake has been reduced. But in case of pier top/ground amplification factor, the accelerations increase with height to reach at piers top a maximum about 2.5 times that of the input acceleration for the steel bearing supported model. The lead rubber bearing supported model in contrast behaves essentially as a rigid body moving with small accelerations.

Table 10 Dynamic amplification factors of acceleration

Type of bearings	deck/ ground	pier top/ ground
Steel	0.42	
Rubber Type-a	0.20	0.90
Rubber Type-b	0.05	0.39
LRB-1	0.02	0.04
LRB-2	0.01	0.04

5-5 Energetic Analysis

Energy-time history for all cases of study is given in Fig. 8. In Fig. 9, the distribution of every type of energy for each model of viaduct is summarized. Analyzing the obtained results for all models, and comparing the different types of energy it is possible to obtain several conclusions. The kinetic energy at the instant when the earthquake motions finishes does not have special relevance since their values are small compared with the other types of energy. The consumed energy due to viscous damping mechanism of the system does not vary significantly. The cumulative strain energy is quite large for steel supported model because great ammount of plastic strain energy appears at base of piers due to plastic hinge by bending damage. Strain energy is also large for base isolation models, but in this case, this energy corresponds to hysteretic energy dissipated by deformation of bearings. Rubber bearings do not have capability to dissipate energy, therefore the strain energy is due to smaller plastic zone that appears at base of piers.

The base isolation system, by means of the hysteretic behavior of the lead core, is able to absorb some of the earthquake input energy before this energy can be transmitted to the structure. Great part of possible seismic damage that it could affect the structural elements of the viaduct is reduced, and even in some cases it is eliminated.

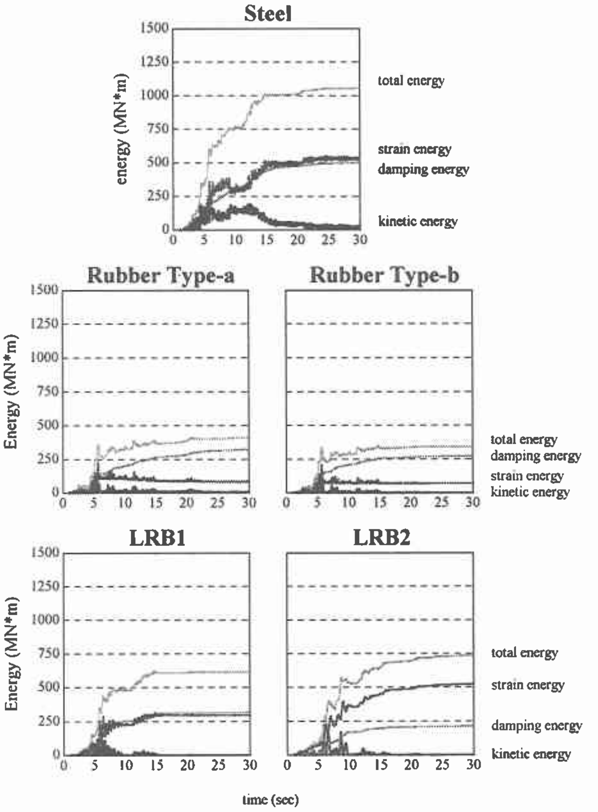


Fig. 8 Energy time history

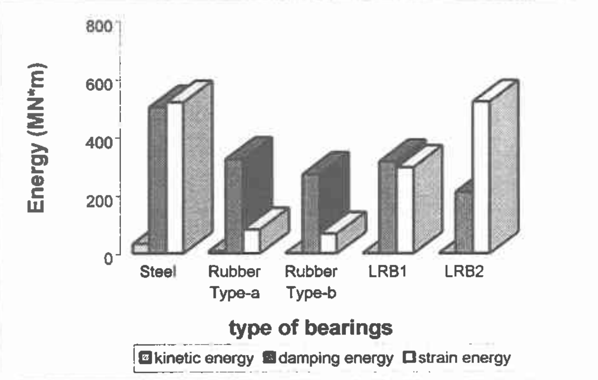


Fig. 9 Distribution of seismic energy

6. CONCLUSIONS

The results of the dynamic analysis of the highway viaduct model, under the action of great earthquake motions, show how the replacement of vulnerable steel bearings with isolation bearings (LRB) causes a significant improvement in the seismic response of the viaduct. Reaction forces acting on bearings decreases, and therefore a considerable reduction of damage affecting at base of piers can be observed. All piers undergo almost the same small damage ensuring apropriate serviceability of the bridge after an earthquake occurs. Using rubber bearings, flexibility at bearing level is added, and damage is reduced, and for areas of low-medium seismic risk they could be enough to prevent the rocking of the structure in case of earthquake.

As expected, due to the flexibility of lead rubber bearing supports, deck structure of the base isolation model undergoes larger displacements than that in non-isolated viaducts. It must be taken into account, because large reaction forces can be appear at the abutments or damage could be caused at the expansion joints.

Energetic analysis is very effective to explain the seismic behavior of the structure. Analyzing separately the different types of energy it is possible to understand how energy of earthquakes is dissipated by each one of the structural elements of the highway viaduct. Using energetic analysis it can be distinguised where structural damage is located and therefore neccesary measures can be taken to protect the structure against earthquake ground motions.

Base isolation bearings distribute and reduce the seismic accelerations acting on piers. Long continuous multi-span viaducts supported by lead rubber bearings behaves well under the action of great earthquake loads, allowing a greater comfort for vehicle travel because less expansion joints are needed, and by the same reason, lower maintenance is required.

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