STUDY ON SHAKING TABLE TESTS OF ISOLATED BRIDGE MODEL WITH LRB

Q.Han [1,2*], X.L. Du [2] and J.B.Liu [1]

[1] *Dept. of Civil Engineering, Tsinghua University, Beijing. China*
[2] *The Key Lab. Of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing. China*
**Email: qhan@yahoo.cn*

ABSTRACT :

With the growth of the application of the seismic isolation technique to civil structures, a large variety of isolation systems has been developed during the past several decades. In order to investigate the vibration properties and isolated effect of continuous girder isolated bridges with lead rubber bearings (LRB) under multi-directional excitation, the simulated earthquake test of a seismically isolated bridge model consisting of two-span continuous deck is carried out on a shaking table. The acceleration response, displacement response in the deck, and restoring force relationship and vertical deformation of LRB are tested and analyzed in different earthquake intensity excitation. The isolated bridge stability will be secure and good isolation effect will be obtained under minor earthquake excitation if the design for LRB is reasonable. The response and relativity of various effect of seismically isolated bridge are tested and analyzed in multi-directional earthquake excitation. As a result, deck acceleration almost is equal on condition that unidirectional or bi-directional earthquake wave input, but deck acceleration is increase when input vertical earthquake wave. Comparison with unidirectional earthquake wave input, deck displacement is increase when bi-directional horizontal earthquake wave input, however, deck displacement is almost invariable when input vertical earthquake wave simultaneously. Horizontal force-deformation relationship in orthogonally horizontal direction and vertical force characteristic of LRB has been studied. Some reasonable and valuable conclusions are obtained to design of continuous girder isolated bridges.

KEYWORDS: shaking table test, seismic isolation, bridge model, lead rubber bearings, multi-directional earthquake

1. INTRODUCTION

Seismic isolation is a strategy which attempts to reduce the seismic forces to or near the elastic capacity of a bridge, thus eliminating or reducing inelastic deformation and damage to the substructure. This technique also permits distribution of the lateral forces to the various elements of the substructure. Seismic isolation systems have been employed in bridges in Japan and the United States (Naeim 1999). The isolation system of the majority of these bridges consists of lead-rubber bearings (Hwang 1996), the rest being sliding isolation systems. There had been several studies in the past investigating the effectiveness of isolation devices for the aseismic design of bridges. Constantinou et al. (Constantinou 1992, 1998), and Tsopelas et al. (Tsopelas 1996) conducted experimental and analytical studies on the seismic response of bridges isolated by sliding isolation systems, and found that such devices are quite effective. Saiidi et al.(1999) studied the effectiveness of seismic isolators in reducing the force and displacement of the superstructure of a six-span bridge, and found that the use of isolators does not necessarily increase the displacement of the superstructure. Wang and Yan et al. (2002) studied nonlinear time history analyses of isolated bridges with the input of large numbers of seismic waves, where the nonlinear behavior of LRB and ductile plastic hinges of piers are taken into account by using nonlinear spring element. Jangid (2004) analyzed the seismic response of isolated bridges by LRB under bidirectional earthquake excitation regarding the restoring forces relations in two orthogonal horizontal directions as Park model.

For the present study, the LRB consisting of alternating layers of steel shims and rubber is considered as the isolation device. The LRB is very stiff in the vertical direction and flexible in the horizontal direction. The horizontal flexibility and damping characteristics of the bearing provide the desired isolation effects in the system. The horizontal flexibility transmits relatively limited earthquake forces from the piers to the superstructure. On the other hand, the damping of the bearing dissipates the seismic energy, thereby reducing the design displacement of the bridge. In addition, the inelastic deformation of the lead plug provides the hysteretic damping in the system.

Currently, the seismically isolated bridge with LRB is few and no bridge design codes for seismic isolation include specific requirements for the testing of isolation bearings, so experimental study of bridge seismic isolation systems with LRB is important and essential in order to apply and develop bridge seismic isolation technology in China. The simulated earthquake tests of a seismically isolated bridge model consisting of two-span continuous deck are carried out on a shaking table in this paper. The specific purpose is in order to investigate the vibration properties and the nonlinear seismic responses of isolated bridges with LRB under multi-directional horizontal earthquake excitation, and researchers hope it is helpful to the current engineering practice of seismic isolation of highway bridges and to the future guideline of bridge seismic isolation design in China.

2. OUTLINE OF SHAKING TABLE TESTS OF ISOLATED BRIDGE MODEL

2.1. Scaled Bridge Model

A bridge model consisting of a two-span continuous steel girder deck supported by LRB has been constructed for the shaking table test, as shown in Figure1. The bridge model is isolated by the LRB installed on the top of each pier. The substructure of bridge model consists of two rigid abutments and a circular column. The total span length and deck width of the prototype bridge are equal to 60 m and 9 m, respectively. The total pier height is equal to 10 m, including the cap beam.

Considering the shaking table capacity, a scaling factor of 1/10 is determined for the bridge model. Since the bridge deck is expected to exhibit rigid-body motion under horizontal excitations, the mass similarity is the major concern for the deck model. The plan dimensions of the deck model are determined to be 3 m in length and 0.9m in width. Concrete blocks are placed on the rigid steel girder to result in a total weight of 90 kN for the deck model.

To preclude stiffness degradation due to possible concrete cracks, concrete-filled portal frame steel columns are used and designed based on stiffness similarity for the pier models. The thickness and exterior diameter of the steel pipe are determined to be 8 mm and 120 cm, respectively, from a scaled equivalent transformed section. Also, the steel cap beams are jacketed with steel plates to prevent cracks. Correspondences similitude ratio of the bridge model to the prototype are shown in Table 1.

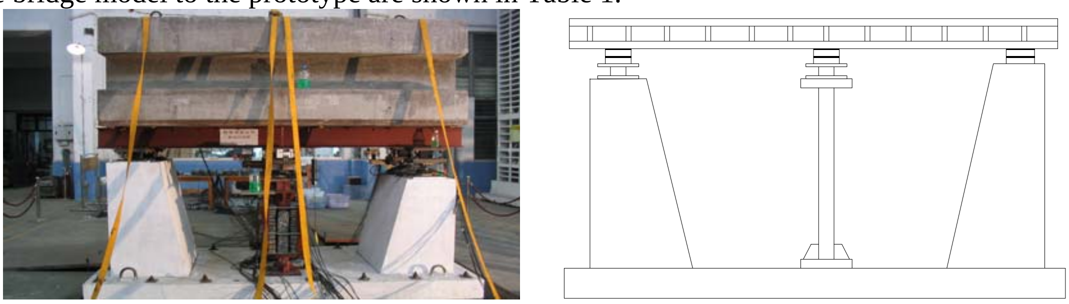


Figure1 The 1/10 isolated bridge model

Table1 Similitude ratio of the bridge model to the prototype

Items	Similitude ratio	Items	Similitude ratio
length	1/10	Acceleration	1.0
Stress	1.0	Displacement	1/10
Time	1/3.16	Velocity	1/3.16
Density	25/2	Weight	1/80

2.2. The Characteristic of LRB

The LR bearings are foursquare and constructed with a 16mm diameter central lead core, and the length of these foursquare bearings is 100mm. The shear modulus of the elastomer used these experimental bearings is 0.8N/mm^2. The bearing is composed of 9 layers of 3mm thick rubber and 8 layers of 1.5mm thick steel shims with an outer (bonded) length of foursquare of 90mm. The total rubber thickness in this bearing is 27mm, and the first shape factor, S1, is 8.5. The top and bottom steel end plated are 79mm thick. Characteristic parameter of LRB is shown in Table 2.

Table2 Characteristic parameter of LRB

NO.	Parameter of LRB	Value	NO.	Parameter of LRB	Value
1	Length of square (mm)	90	10	G (N/mm^2)	0.8
2	Total high (mm)	79	11	S1	8.3
3	Thickness of a rubber layer (mm)	3.0	12	S2	3.7
4	Total rubber layer	9	13	Area of a LBR (mm^2)	7899
5	Total thickness of rubber layer (mm)	27	14	Surface pressure (MPa)	1.90
6	Diameter of LRB(mm)	16	15	Vertical force (KN)	15
7	Thickness of a steel layer (mm)	1.5	16	Horizontal stiffness (KN/mm)	0.234
8	Total steel layer	8	17	Vertical stiffness (KN/mm)	73
9	Total thickness of steel layer (mm)	12	18	H_p/D_p	2.2

2.3. Property of Input Earthquake Wave

The isolated bridge model system is tested for the three real earthquake excitations. The peak acceleration of these earthquake ground motions is shown in Table 3. The specific components of these ground motions applied in the longitudinal and transverse directions are also indicated in Table 3. The test wave is obtained and used in experiment by compressing original real earthquake wave. Namely, the compression ratio of the test wave to the original real earthquake wave is 1/3.16, and the amplitude of acceleration is modified to 0.2g, 0.4g and 0.6g. In experiment, 1Dx, 2Dxy, 3Dxyz represent longitudinal, horizontal bidirectional (longitudinal and transverse), and multi-directional (horizontal and vertical) earthquake wave input of bridge model, respectively.

These tests have been carried out on the shaking table that manufactured MTS company in Earthquake Engineering and Test Research Center of Guangzhou University in China.

Table3 Peak Ground Acceleration of Various Earthquake Ground Motions

Earthquake	Recording station	Waves length (s)	Peak acceleration (g)		
			EW	NS	UD
El Centro, 1940	Imperial	50	0.214	0.349	0.211
Kobe, 1995	KJMA	50	0.821	0.599	0.343
Chi-Chi, 1999	CHY015	160	0.145	0.157	0.032

3. EXPERIMENTAL RESULT AND ANALYSIS

3.1. Deck Acceleration Response

The deck acceleration time-history curves are shown in Figure2 under the 0.6g 2Dxy El Centro record. The reducing of deck longitudinal peak acceleration is 70 percent, 69.6 percent, and 65 percent under longitudinal earthquake wave input, longitudinal and transverse earthquake wave input, and longitudinal, transverse and vertical earthquake wave input at the same time, respectively. The reducing of deck transverse peak acceleration is 50 percent and 46 percent under longitudinal and longitudinal, transverse and vertical earthquake wave input at the same time, respectively. So seismic isolation is effective to reduce deck acceleration response, and the tendency of acceleration response of deck and pier-cap are in-phase and same shape.

The deck acceleration time-history curves are shown in Figure3 under the 0.4g 2Dxy Chi-Chi record. The reducing of deck longitudinal peak acceleration is 32 percent, 36 percent, and 31 percent under longitudinal earthquake wave input, longitudinal and transverse earthquake wave input, and longitudinal, transverse and vertical earthquake wave input at the same time, respectively. The reducing of deck transverse peak acceleration is 32 percent and 31 percent under longitudinal and transverse earthquake wave input, longitudinal, transverse and vertical earthquake wave input at the same time, respectively. Seismic isolation is effective to reduce deck acceleration response, however, the tendency of acceleration response of deck and piercap are same shape but out-phase. The peak acceleration is float and local magnification, so seismic isolation technology shouldn't be adopted in soft soil site and should be prudent.

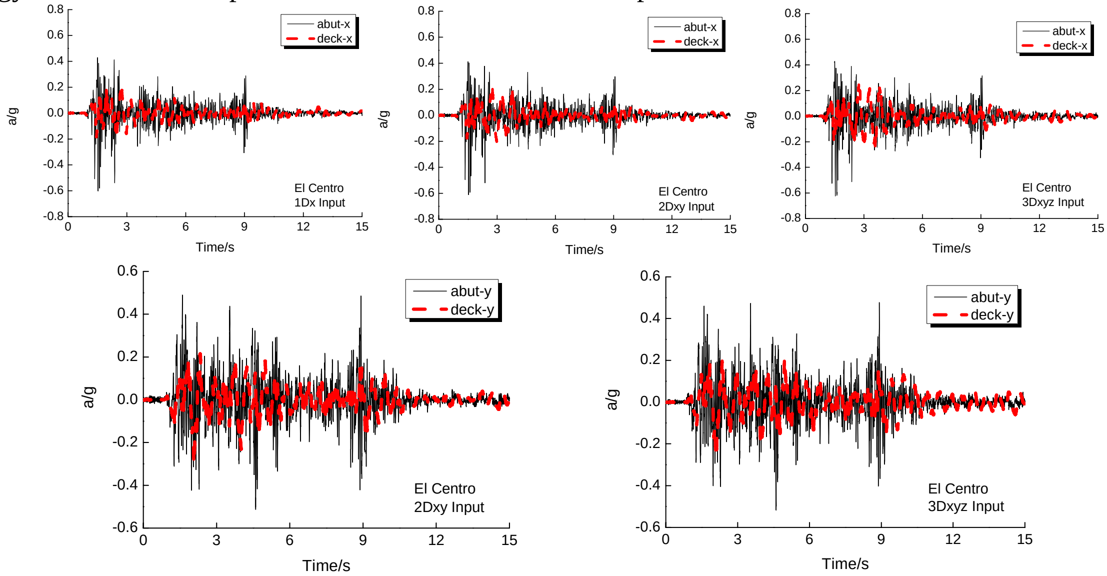


Figure 2 Acceleration time history curve of pier and corresponding deck under multi-directional earthquake input (El Centro, peak acceleration:0.6g)

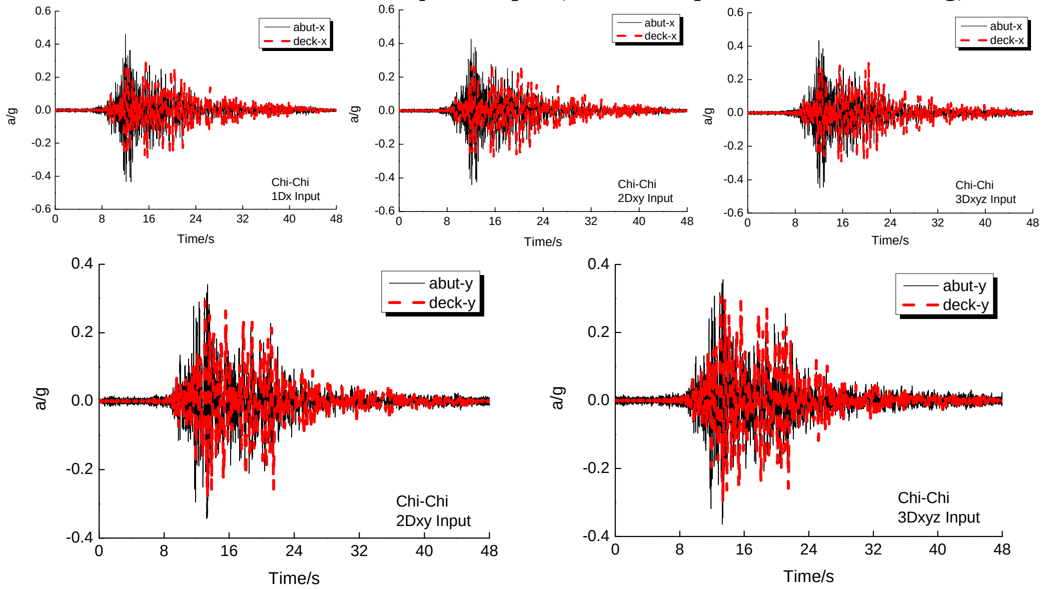


Figure3 Acceleration time history curve of pier and corresponding deck under multi-directional earthquake input (Chi-Chi, peak acceleration:0.4g)

3.2. Deck Displacement Response

The deck displacement time-history curves are shown in Figure 4 under the 0.4g 1Dx, 2Dxy and 3Dxyz Kobe record input. The peak displacement of piercap and deck under multi-directional earthquake input are shown in Table 4. From Fig.4 and Table 4, it is also observed that the deck longitudinal peak displacement under longitudinal earthquake input is smaller than under longitudinal and transverse earthquake wave input. The deck peak displacement will increase obviously under longitudinal, transverse and vertical Kobe earthquake wave input at the same time, but deck peak displacement is almost equal under longitudinal, transverse and vertical El Centro earthquake wave input at the same time. The reason is that Kobe earthquake wave is near fault earthquake record, and near fault earthquake has important influence on seismic response of bridges.

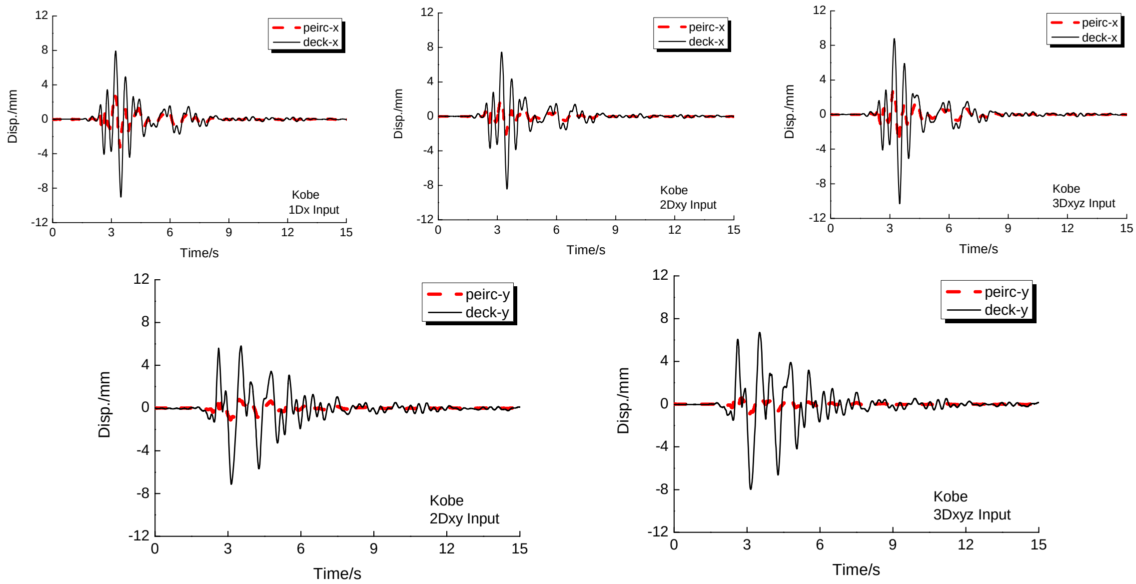


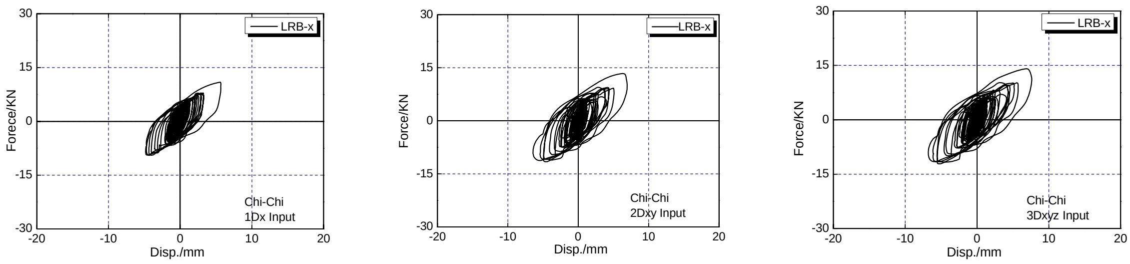
Figure 4 Displacement time history curve under multi-directional earthquake input (Kobe,peak acceleration:0.4g)

Table 4 Peak displacement of piercap and deck under multi-directional earthquake input

Earthquake waves	Longitude (mm)		Horizontal bi-direction (mm)				Horizontal and vertical (mm)			
	x-direction		x-direction		y-direction		x-direction		y-direction	
	Pier-cap	deck	Pier-cap	deck	Pier-cap	deck	Pier-cap	deck	Pier-cap	deck
Kobe(0.2g)	1.10	3.76	0.94	4.02	0.71	3.16	0.92	5.01	0.72	3.78
Kobe(0.4g)	3.05	8.94	1.84	8.47	1.06	7.13	3.24	10.2	1.07	7.97
Chi-Chi(0.2g)	2.07	5.78	2.31	7.91	1.54	8.34	2.28	8.65	2.07	9.22
Chi-Chi(0.4g)	5.57	14.61	3.32	18.4	3.61	21.10	3.5	17.89	3.13	19.86

3.2. Force-Deformation Relationship of LRB

The area of the hysteretic loop of the LRB implies energy dissipation capacity of isolated layer, and restoring force model depends upon the curve of the force-deformation behavior of the LRB. The force-deformation behavior of LRB is plotted in Figure5 under the Chi-Chi earthquake wave input. The hysteretic curve shape has bilinear behavior according to experimental results. For the selected three pairs of recorded earthquake ground motions, it is observed that bearing restoring force curve are less irregular in bidirectional earthquake wave input than unidirectional earthquake wave input. The reason is that the interaction between the restoring forces in two orthogonal horizontal directions of LRB significantly influences the response of isolated bridges. The bidirectional behavior of LRB is different from unidirectional behavior (Han, 2006).



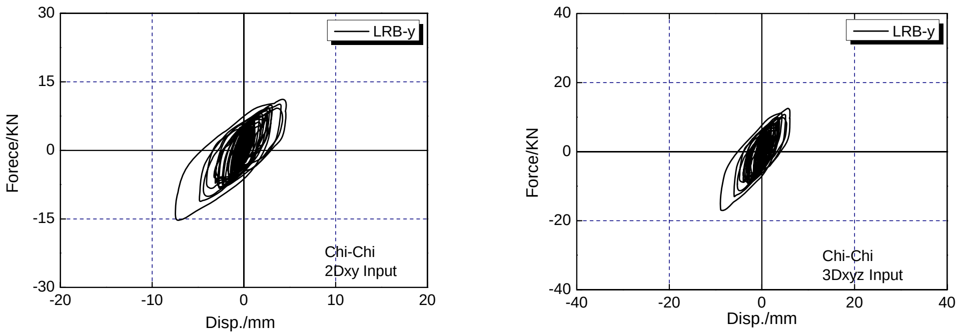


Figure 5 Force-displacement relationship curve in multi-directional Chi-Chi earthquake wave input

3.3. Vertical Force Response of LRB

The tensile force of LRB rarely arises in design region, therefore the studies on the tensile force of isolator is few. But the shear properties are significantly influenced by bearing tension state (Han 2006). Fig.6 shows the vertical force of LRB time-history curve under the 0.6g El Centro record. From Figure 6, it is also observed that the tensile force of LRB will come into being if the peak acceleration quantities are bigger, especially, the vertical component of earthquake ground motion is bigger.

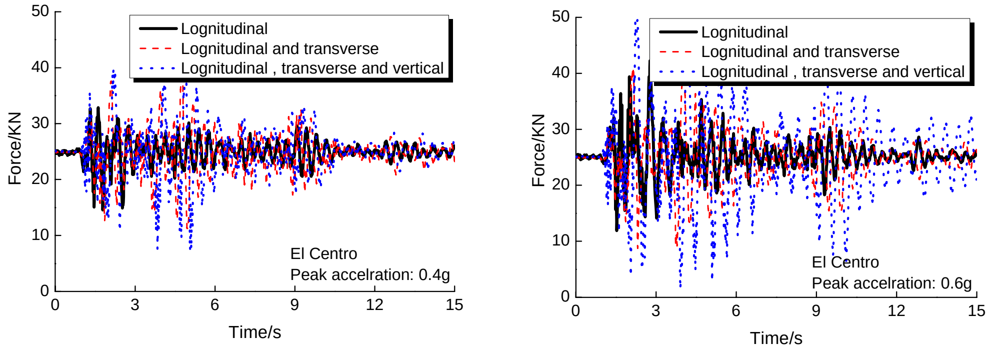


Figure 6 Vertical force time history of single isolator

3.4. Bridge Pier Strain Response

The steel pier axial strain time history curve under multi-directional earthquake input are shown in Figure7. From in Figure7, it is shown that the steel pier peak axial strain increases along with peak acceleration of earthquake wave input. The steel pier peak axial strain will almost equal under longitudinal, transverse and vertical El Centro earthquake wave input at the same time if peak acceleration of earthquake wave input are equal.

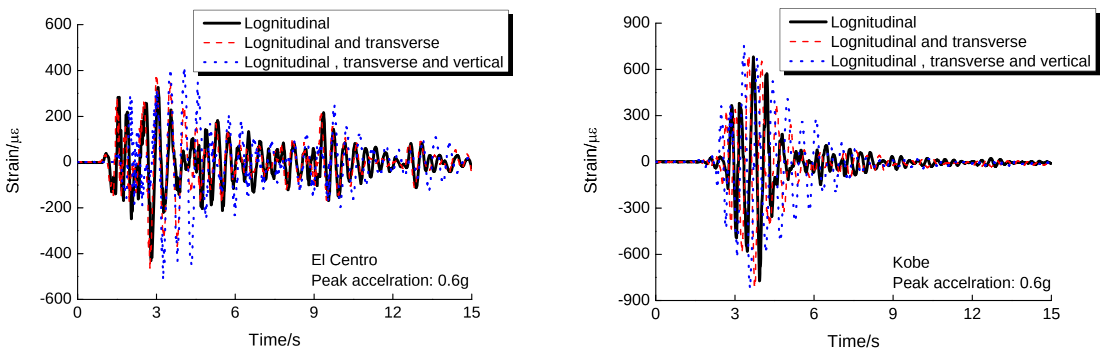


Figure7 Axial strain time history curve under multi-directional earthquake input

4. CONCLUSIONS

The shaking table tests of continuous girder isolated bridges model with LRB under multi-directional earthquake excitation were carried out. From trends of results of the experimental study following conclusions may be drawn:

(1) Seismic isolation is effective to reduce deck acceleration response, however, seismic isolation technology shouldn't be adopted in soft soil site and should be prudent.

(2) The tensile force of LRB will come into being if the peak acceleration quantities are bigger, especially, the vertical components of earthquake ground motion is bigger. So the tensile force of LRB should be considered in design isolator if the vertical component of earthquake ground motion is bigger.

(3) The interaction between the restoring forces in two orthogonal horizontal directions of LRB has significant effect on the response of isolated bridges.

ACKNOWLEGMENTS

The study presented in this paper was supported by National Science Fund Council of China under Grants NSFC No.50325826 and NSFC No.90715032. The support is gratefully acknowledged.

REFERENCES

Constantinou, M. C., Kartoum, A., Reinhorn, A. M., and Bradford, P. (1992). Sliding isolation system for bridges: Experimental study. *Earthquake Spectra* 8:3, 321-344.

Constantinou, M. C., and Tadjbakhsh, I. G. (1998).Hysteretic dampers in base isolation: Random approach. *J. Struct. Eng.*111:4,705-721.

Han, Q., Du, X.L., Liu, W.G. (2006). Research on tension property of rubber isolators. *Journal of Beijing University of Technology* 3:208-212. (in Chinese)

Hwang, J. S., and Chiou, J. M. (1996). An equivalent linear model of lead-rubber seismic isolation bearings. *Eng. Struct* 7:528-536.

Hwang, J. S., Chiou, J. M., Sheng, L. H., and Gates, J. H. (1996).A refined model for base isolated bridges with bi-linear hysteretic bearings. *Earthquake Spectra* 2:245-273.

Naeim, F., and Kelly, J. M. (1999). Design of Seismic Isolated Structures. New York: John Wiley and Sons Inc.

P. S. Jangid. (2004). Seismic Response of Isolated Bridges. *Journal of Bridge Engineering. ASCE,*2:156-165.

Saiidi, M., Maragakis, E., and Griffin, G. (1999).Effect of base isolation on seismic response of multi-column bridges. *Struct. Eng. Mech* 8:4,411-419.

Soong, T. T. and Constantinou, M. C. (1994). Passive and active structural vibration control in civil engineering, Springer-Verlag, Vienna, New York,

Tsopelas, P., Constantinou, M. C., Kim, Y. S., and Okamota, S. (1996).Experimental study of FPS system in bridge seismic isolation.Earthquake *Eng. Struct. Dyn*.25:1, 65-78.

WANG, L., YAN, G.P. and FANG, Y, L.(2002).Analysis of seismic response of isolated bridges with LRB. *Engineering Mechanics*1:80-84. (in Chinese)