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Evaluation of Seismic Performance for Bridges Isolated with Lead-Rubber Seismic Isolator Bearing

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ABSTRACT

Lead rubber bearing (LRB) is the most developed and the most common seismic isolator in the world that can reduce 60-80 percent of the seismic force to structures. Isolators are applied in bridge design to achieve maximum energy absorption (relative to the period in isolated buildings). Therefore, isolators with high damping should be used. In this regard, lead rubber seismic isolators, abbreviated LRB, have the inherent properties of 30 percent (independent of vibration frequency, temperature and environmental conditions). The objective of isolation in bridges is very different from building. In a building, isolators are installed to reduce the energy forces exerted on the superstructure in order to reduce stress on structural elements. However, seismic isolators are installed to protect the elements under the isolator (abutments and bases) to reduce the transmitted energy, and displace superstructures (deck) to substructures (abutments and bases). This study introduces lead rubber bearing (LRB) and its advantages compared to elastomeric bearings. Then, the design for replacement of those bearings in four important bridges in the country with seismic isolators, and its impact on reducing the stress on bases and abutments are discussed.
KEYWORDS: lead-rubber seismic isolator, elastomeric bearings, seismic isolation.

1. INTRODUCTION

Several studies have been conducted on the effect on seismic isolators on seismic behavior of bridges, and their seismic design in bridges. Hwang and Shang [1] calculated effective stiffness and effective damping ratio for an equivalent elastic system of bridges isolated with lead rubber seismic isolators, and presented empirical relationships to calculate the change in effective period and the effective damping ratio. Hwang and Chiou [2] and Hwang et al. [3] obtained a linear model for seismic analysis of bridges isolated with lead rubber isolators using a characteristic method. Ghobarah and Ali [4] showed that lead rubber isolators are highly efficient in reducing seismic response of highway bridges. Pagnini and Solari [5] obtained random response of a three-span bridge with seismic isolation system includes rubber seat and hysteretic damper using linear equations techniques.

Saiidi et al. [6] evaluated the effect of seismic isolation on the reduction and displacement of the superstructure in a six-span bridge, and concluded that the use of the isolators does not necessarily increase the displacement in the deck. Chaudhary et al. [7] carried out the research on determining system parameters of seismic accelerations recorded on an isolated bridge, and performance of various components of bridges. All the studies mentioned above were carried out assuming bi-linear force-displacement behavior and non-correlated with isolator, considering only one earthquake excitation component. In recent years, only in three cases, it has been tried to evaluate the seismic response under effect of a bi-directional excitation and correlated behavior of isolator, and its comparison with unidirectional excitation and non-correlated isolator were carried out, and different researchers with different methods obtained different results, so further research is clearly required. Jangid [8] conducted parametric studies by changing the parameters of stiffness of bridge bases and primary and secondary stiffness of the isolator, and lead-rubber isolators strength in order to study the effects of seismic isolators on the maximum displacement values of bridge decks, as well as to evaluate bi-directional interaction effects of seismic isolators forces. The results showed significant effects of the bidirectional interaction of forces on the behavior and performance of bridges. If these effects are not considered, the maximum deformation of isolator will be less estimated, that damages the isolation system design. Ryan and Chopra (2004) [9] proposed a new plan to estimate the precise deformations and isolator forces, where correction factor of 1.13 is used to consider the bi-directional effects. Warn and Whittaker [10] also carried out research on a simple span bridges with the objective of controlling the validity of the design elations and testing AASHTO instructions [11], as well as determining the amount of the increased displacement by bi-directional excitation. These researchers used circular fluidity level rule to adjust correlation effect, and suggested corrective coefficient of 1.2 on displacement isolator design based on AASHTO instructions. Currently, most of the highway bridge in Iran have metal, concrete and elastomeric bearings, and elastomeric bearings are the main bearings used in bridges for technical and economic reasons [12]. The shear behavior of these bearings are linear until failure, and thus have no hysteresis damping. Replacement of the elastomeric bearings with lead rubber seismic isolators bearings can be a good option for seismic development of the bridge structure. Since

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the use of seismic isolators increases deck displacement, more accurate estimate of deck displacement is necessary to estimate free space required at the end of the bridge girders.

2. Introduction of lead-rubber isolators

The use of isolators in bridge design aims to achieve maximum energy absorption (relative to the period in isolated structures). Therefore, isolators with high damping should be used. In this regard, lead rubber seismic isolators, abbreviated LRB, have the inherent properties of 30 percent (independent of vibration frequency, temperature and environmental conditions). this isolator consists of several layers of normal rubber and steal, as well as one or more lead cores. Lead has a high initial shear stiffness and low fluidity shear strength. it shows perfect elastic behavior and properties of appropriate tirelessness in plastic cycles. These properties of lead cause the lead -rubber seismic isolators to have high horizontal stiffness against the service loads and high energy dissipation against strong seismic loads. Lead cores deform at about 10 MPa shear stress, and cause a bilinear response in the seat. These isolators also have alternate rubber and steel plates. Steel plates are involved both in vertical service loads and horizontal loads. In vertical service loads, steel plates prevent the expansion of side rubber parts, and significantly increase the seat vertical stiffness, while have no impact on seat vertical stiffness that is controlled with elastomer low shear module. In horizontal seismic loads, steel plates cause deformation of lead core in shear.

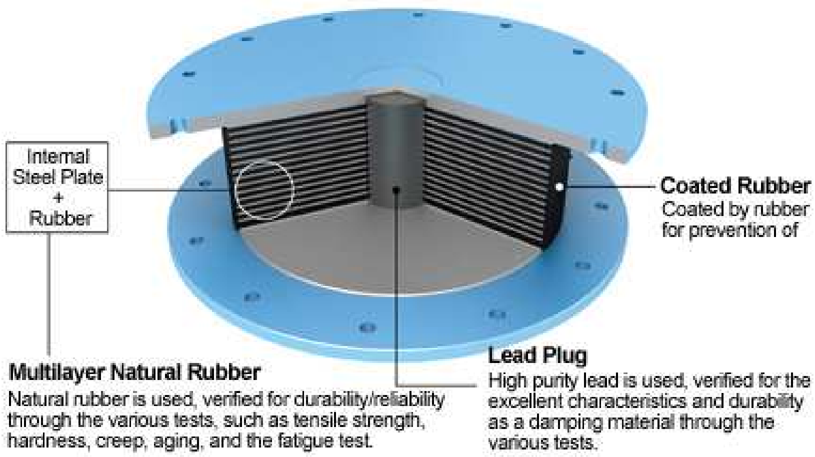


Figure 1. Components of lead-rubber seismic isolators

For the design of bridges, due to limitation of displacement, the effect of increased period in most projects is low. However, the effect of damping in bridge is higher than building projects. Since the seismic isolator is tested before installation in terms of long-term permanent loads and thermal conditions, and according to its philosophy, that is resistance to earthquake forces that are much larger than the service loads, the buckling stability of isolator is controlled against the forces. Thus, its design principles is based on gravity and lateral loads of earthquake. As a result, the main objective is to use LRB with 30% damping, compared to 10% damping of HDRB for bridges. The effect of LRB seismic isolator on width and length displacements, and the forces applied to base depend on energy absorption, and increased period of isolators depends on the displacement. In terms of limited longitudinal displacement of the deck (prevent collision of deck to abutments during an earthquake), optimized amount of energy absorbed by LRB against the performance of increased period is the main issue in designing LRB elements. Given that the element that affects LRB energy absorption performance is the size of its lead core, and the element that affects increased period of superstructure is the height to width ratio of LRB.

3. Comparing LRB and HDRB seismic isolators

Rubber isolators (HDRB) are composed only of rubber, while in similar seismic lead-rubber isolators, there are rubber seats with low damping, but with a lead core and a hole in the middle. LRB has 30% damping, while HDRB has 10% to 15% damping. To start the movement, LRB has more delay than HDRB, since the lead should change its phase from stiffness to fluidity. HDRB has less physical endurance against weaker earthquakes and winds than LRB, for initial stiffness of lead. HDRB is more sensitive to environmental vibrations than LRB. LRB performance against earthquake is far better than HDRB. We reviewed applications of LRB and HDRB in the bridges in countries New Zealand, the United States, and Japan until 1995, and found that in New Zealand all 35 bridges were constructed using LRB, and HDRB was not used in any case. In the United States, LRB was used in 90 bridges, and HDRB only in 2 bridges, and in Japan, LRB was used in 27 bridges, and HDRB only in 7 bridges. It should be noted that in these 3 countries, application of LRB than HDRB in buildings is far more than the bridges. HDRB is generally applied only to reservoirs.

4. Basics of isolation in bridges

The main objective of seismic isolation is to reduce the vibration frequency of the structure base, to a value lower than the prevailing earthquake energy frequencies. In other words, seismic isolation increases structural and bridge vibration period, and so forced exercised to the base caused by the earthquake, will be reduced using seismic isolation. Another advantage of seismic isolation is providing a means to energy loss, so that energy exercised into the structure will be lost at several points in a controlled manner. Thus, the destruction and damage will be concentrated in specific locations, that can be replaced after the earthquake. In general, the design of seismic isolation will decrease the response of structures subjected to an earthquake with the help of these factors:

1. Increasing main period
2. Increasing the relative damping (energy dissipation)

The objective of isolation in bridges is very different from building. In a building, isolators are installed to reduce the energy forces exerted on the superstructure in order to reduce stress on structural elements. However, seismic isolators are installed to protect the elements under the isolator (abutments and bases) to reduce the transmitted energy, and displace superstructures (deck) to substructures (abutments and bases).

Adding a seismic isolator to a bridge with the mass m_0, base stiffness k_0, and viscous damping coefficient C_0, is similar to adding a spring with a spring constant k_i, and a viscous damping with coefficient c_i. (Figure 2).

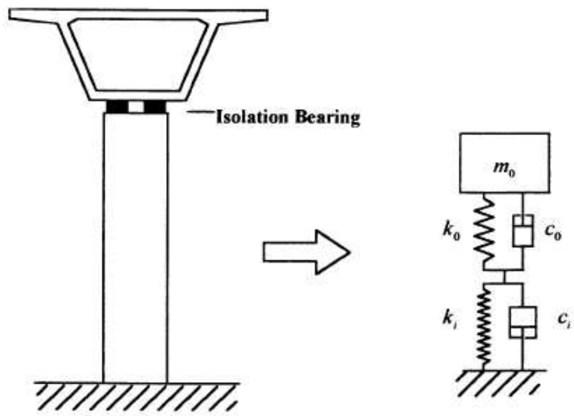


Figure 2. Isolated bridge structure and a simplified model of a degree of freedom [12]

Thus, the total stiffness of the isolated set is calculated from the following equation, which is the familiar equation of stiffness of the series springs.

$$k = \frac{k_0 k_i}{k_0 + k_i} \quad (1)$$

So the movement equation of this new system with a degree of freedom under earthquake excitation is expressed by equation 2:

$$m_0 x + (c_0 + c_i)x + kx = -m_0 x_g \quad (2)$$

The normal period of the structure T (3) is explained with equation 3:

$$T = 2\pi \sqrt{\frac{m_0(k_0 + k_i)}{k_0 k_i}} \quad (3)$$

Since isolator stiffness is always selected to be lower than base stiffness, k will be smaller than k_0, and normal period of isolated system is higher than non-isolated one. This will lead to a decrease acceleration entered into the system caused by earthquake (Figure 3), that means reduced seismic base shear, and on the other hand increases structure displacement caused by the earthquake (Figure 4). Since adding seismic isolators increases structural damping, some of the displacement is reduced by increasing the structural damping (Figure 4), and subsequently, the acceleration entered into the system caused by earthquake will be reduced.

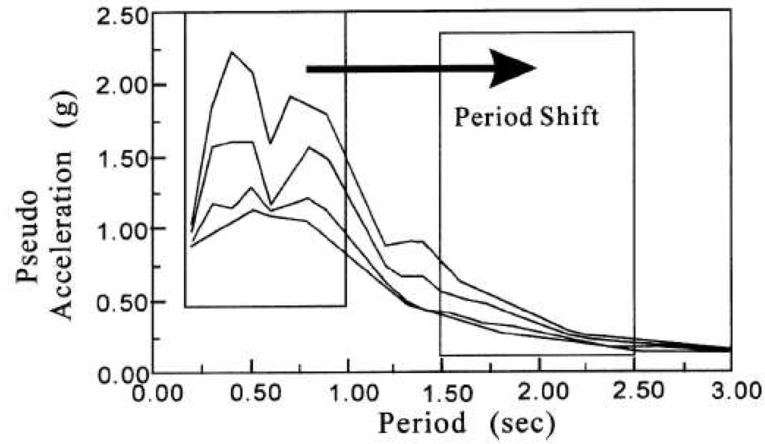


Figure 3 – Decreased pseudo acceleration with increased period [14]

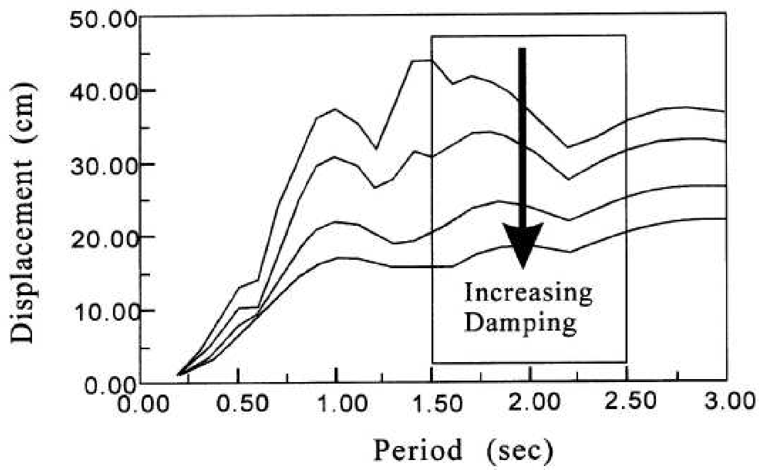


Figure 4 - Reduced structural displacement with increased damping [14]

This damping in isolated structures is provided from two sources: the viscous energy loss, and hysteresis energy loss. Viscous energy loss is directly associated with the speed, but hysteresis energy loss is resulted from the distance between loading and unloading branches of curve under cyclic loading [15].

In Figure 5 a bilinear curve behavior of a seismic isolator is shown. In displacement d_y, the isolator reaches to the force F_y, and passes through displacement d_max and force F_max. The first part of the route is passed with slope k_u (elastic stiffness) and the second part with the slope k_d (plastic stiffness). The inside part of the curve, which represents the hysteresis energy dissipated during a full displacement cycle.

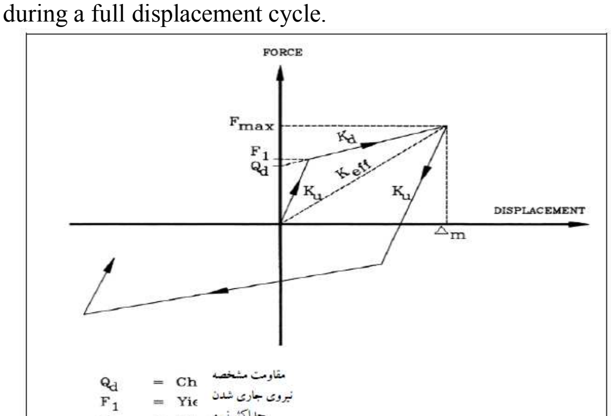


Figure 5 – The bilinear behavior curve of a lead rubber seismic isolator [15]

5. Replacing the bearing seats in the four bridges under study

Replace the seats with lead-rubber seismic isolators can be a good choice for seismic rehabilitation of bridges in the country. Figure 6-A shows a structure bridge with elastomeric bearing, and 6-B shows deformation profiles of the structure caused by seismic demand in current and limit conditions. As shown in figures 6-C and 6-D, the hysteresis behavior is focused on the bridge base, that means damage or failure of the substructure.

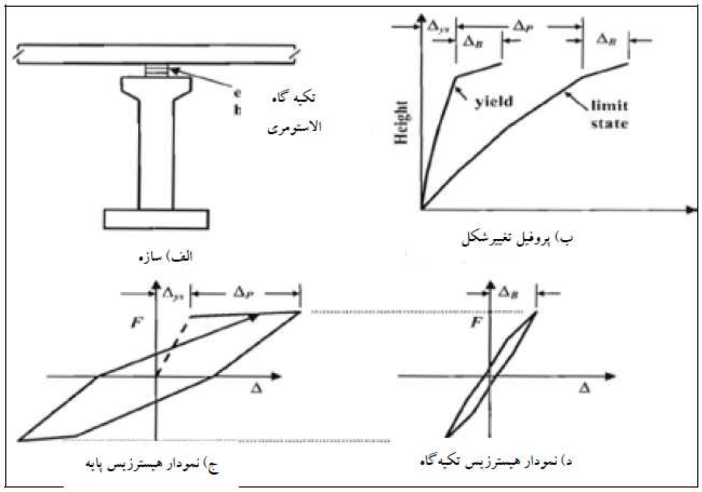


Figure (6) – Non-isolated bridge with elastomeric bearings [16]

Figure 6-A shows a structure bridge with lead-rubber bearing, and 6-B shows deformation profiles of the structure caused by seismic demand in current and limit conditions. As shown in figures 6-C and 6-D, the hysteresis behavior is focused on the seismic isolator, that means survival of the substructure.

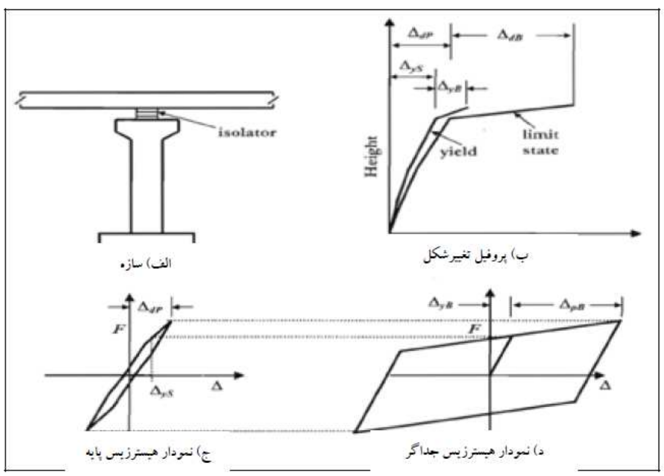


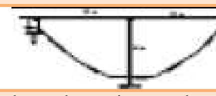
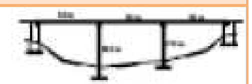
Figure (7) - Isolated bridge with lead-rubber seismic isolators [16]

However, since the use seismic isolation increases the amount of displacement in superstructure, the more accurate estimate of the amount of displacement of seismic isolators is essential to estimate the free space required at the end of bridges girder. If such a space is not provided, there is possibility of collision of girder with abutment (at the side bearing) or each other (in a discontinuous central bearing). As a result, seismic isolation is not only ineffective, but also causes more damage on the bridge, such as abutment rotation in the side bearing or fall of girders from the abutment and base in discontinuous side and middle bearings.

In order to more accurate estimate of this displacement, four highway bridges in the country have been studied. The bearing seat of these bridges are elastomeric bearings with synthetic rubber (Neoprene). Safety and vulnerability assessment have shown that the middle bases of these bridges do not have sufficient seismic against earthquake, and operations to strengthen and improve seismic behavior are required. Replacing existing seats with seismic isolation is the cheapest, fastest and most convenient option to implement, since it reduces seismic demand of superstructure, and substructure will be exempted from the need to strengthen. Thus, to estimate more accurately the free space required at the end of the four bridges girders, with assumption of replacement of existing bearings, nonlinear time history analysis dynamic under bi-directional earthquake excitation, and correlated nonlinear behavior of seismic isolators is used and compared to unidirectional earthquake excitation, and non-correlated nonlinear behavior of seismic isolators commonly used by engineers [17].

Four highway bridges have been studied in this section. The first bridge is Sayed Abad, located in the Roodehen-Firoozkooh axis, the second bridge is Hoseiniha located in the Ramhormoz- Behbahan axis, the third bridge is Miandoroud located in the Ramsar-Langrood axis, and the fourth bridge is the bridge located in 300 + 30 km of Tehran-Roodehen road. Full details of the four bridges along with their overall schema is shown in Table 1. Due to lower base height, bridges 1 and 3 have higher lateral stiffness compared to bridge 2 and 4. It should be noted that none of the bridges have tilt.

Table 1 - Profile of the studied bridges [17]

	Bridge NU1	**Bridge NU2**	**Bridge NU3**	**Bridge NU4**
Name of bridge	Sayed Abad	Hoseiniha	Miandoroud	Located in 300 + 30 km
Overview of bridge				
Location of bridge	located in the Roodehen-Firoozkooh axis	located in the Ramhormoz- Behbahan axis	located in the Ramsar-Langrood axis	Tehran-Roodehen road
Type of bridge	Simple span	Simple span	Simple span	Simple span
Nu. Of spans	2 spans	2 spans	3 spans	3 spans
Length of span	36m	30m	20m	33m
Width of bridge	11.8m	11.8m	11.8m	11.8m
Type of deck	Beam - Slab	Beam - Slab	Beam - Slab	Beam - Slab
Thickness of deck slab	20cm	20cm	20cm	20cm
Type of girder	Prefabricated reinforced concrete beams	Beam steel plate	Prefabricated reinforced concrete beams	Prefabricated reinforced concrete beams
Nu. Of girders	8	4	8	5
Space of girders	1.45m	3m	1.4m	2.5m
Dimension of web girder	1.4 * 0.2 m	2000 * 12 mm	1.4 * 0.2 m	1.8 * 0.2 m
Dimension of flange girder	0.6 * 0.2 m	500 * 30 mm	0.6 * 0.15 m	Top flange 1.0*0.15m Below flange 0.7*0.25m
Type of middle base	Multi-column	Multi-column	Multi-column	Multi-column
The number of columns per base	2	3	3	4
Base high	11.3m	30m	5.1m	A row 17.5m Another row 21.2m
The shape and dimensions of the section in the column	Circle with diameter of 1.5m	Circle with diameter of 1.5m	Circle with diameter of 1.2m	Rectangular with sides 2.5 * 1.5 m
Types of backpacks	Packages with reciprocating wall	Packages with reciprocating wall	Packages with reciprocating wall	Packages with reciprocating wall
Type of foundation	Surface	Depth	Depth	Surface
Bell beam height	2.5m	1.4m	1.15m	2.5m
Beam width capital	2m	1.9m	2m	2.5m
Diagram intervals transverse	12m	10m	10m	11m
Weight deck	11000 KN	5000 KN	9000 KN	14000 KN

For each bridge under study, based on the AASHTO uniform load method [15], four isolators a, b, c, and d are designed. In the design of the isolators, it is assumed that the bridges are located in areas with high seismic risk, and the soil is relatively hard. So, according to AASHTO regulations, effective acceleration value is 0.4 and the S_i amount is 1.5. Full details of the design of these isolators is discussed in [14]. In this study, in order to eliminate the effects of isolator characteristics in the analytical results, only isolator type a is used to better compare the results. The approximate analytical profiles are summarized in Table (2).

Table 2 - The approximate analytical profiles for isolator type a [17]

Type of damper	Shear modulus (G) (Kn/m^2)	Initial stiffness (K_n) (Kn/m)	F_y (Kn)	ratio of secondary to primary stiffness ($\frac{K_d}{K_u}$)	Vertical stiffness (K_v) (Kn/m)
a	700	1000	40	0.2	400/000

6. Conclusion

Since the most important factor in designing the seismic isolation system in bridges is deck (superstructure) displacement, and what determines this displacement is deformation of the isolator, a more realistic estimate is essential to avoid collision of bridge deck with each other or the abutments. The most common procedures on seismic isolation system design is currently AASHTO instruction manual. Designers of seismic isolator systems in bridges, first design the isolator, and then using the uniform load method in the instruction, evaluate the performance of systems with a nonlinear time history analysis process [17].

In this study, it was shown that lead-rubber seismic isolators, while reducing the displacement of bridge superstructure, lead to a significant increase in damping. The reason for reduced displacement of superstructure (deck) can depend on the ratio of height to width at isolator, and the amount of damping depends on the diameter of the lead core. Therefore, due to restrictions on displacement of the deck, using lead-rubber seismic isolators with minimum ratio of height to width is optimizing. Certainly, to waste more energy caused by the earthquake, the lead core diameter in isolators used in bridges should be increased.

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