

Influence of Passive Isolator Parameters on Seismic Response Control of Multi-Span Bridges

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Abstract- The seismic response of bridges seismically isolated by elastomeric bearings to earthquake excitation is presented in this paper. The specific objective of the study is to identify the various parameters affecting the response of the isolated bridge and to assess the effects of seismic isolation on peak responses of the bridge. The seismic response of the lumped mass model of continuous span isolated bridges is obtained by solving the governing equations of motion in the state space form. To study the effectiveness of bearings, the seismic response of isolated bridges subjected to various near field and far field earthquakes is compared with the response of corresponding non isolated bridges (i.e. bridges without isolation devices). The specific objectives of the study are to investigate the performance of bridge isolated by LRB and to investigate the optimum parameters of the LRB bearing for minimum earthquake response of the isolated bridge under different near field and far field earthquake ground motions.

Index Terms- isolation, lumped mass, elastomeric bearings, earthquake

I. INTRODUCTION

Bridges constitute an important component of the transportation network and form a vital link in the lifelines of a nation in managing emergencies caused by man-made or natural disasters. Historically, bridges have suffered extensive damage all over the world, during moderate to strong earthquakes in the past three decades resulting in huge direct and indirect economic losses besides causing inconvenience and hardship to the communities.

Typical earthquake accelerations have dominant periods of about 0.1 to 1 seconds with maximum severity often in the range 0.2 to 0.6 seconds. Structures whose natural periods of vibration lie within the range 0.1 to 1 seconds are therefore, particularly vulnerable to seismic attack because they may resonate. The fundamental period of vibration of a majority of bridges is in the range of 0.2 to 1.2 second. In this range, the structural response is high because it is close to the predominant periods of earthquake-induced ground motions. The seismic forces on bridges can be reduced, if the fundamental period of a bridge is lengthened or its energy dissipating capability is increased. The most important feature of seismic isolation is that it shifts or lengthens the natural time period of the structure beyond the pre-dominant periods of earthquake. Therefore, the seismic isolation is a promising alternative for earthquake-resistant design of bridges.

Seismic isolation is an innovative aseismic design approach aimed at protecting structures against damage from earthquakes by limiting the earthquake attack rather than resisting it. Seismic isolation limits the effect of the earthquake attack by decoupling the structure from the horizontal motion of the ground and thereby reducing the structural responses. A range of isolation devices including elastomeric bearings, lead rubber bearings, frictional/sliding bearings have been developed and used in aseismic design of buildings and bridges during the last 20 years in many countries [1, 4, 7, 9]. Basically there are two categories of bearings: elastomeric and sliding bearings. Amongst all the isolators laminated rubber bearing is most commonly used elastomeric base isolation system. The second category of elastomeric bearings is lead rubber bearing (LRB) which is very similar to laminated rubber bearing. It is also generally referred to as N-Z bearing since it's widely used in New Zealand.

The present study focuses on the seismic response of bridges isolated with the LRB isolation systems. These systems have found extensive application in both buildings and bridges [1, 10, 12, 13, and 17]. There have been several studies investigating the effectiveness of isolation devices for seismic design of bridges. Ghobarah and Ali [2], and Turkington et al. [17] have shown that the lead-rubber bearings are quite effective in reducing the seismic response of bridges. The influence of the shape of isolator force-deformation loop on the response of isolated structure was studied under the variation of important system parameters. Hameed et al [3] conducted a parametric study to investigate the effect of lead rubber bearing (LRB) isolator and ground motion characteristics on the response of seismic isolated bridges and found that there exists a particular range of values for which the responses of the structure will be minimum. In 2004 Jangid [5] studied the bidirectional response of bridges isolated by lead-rubber bearings, showing that the bidirectional interaction of bearing restoring forces had considerable effects on the seismic response of isolated bridges. Matsagar et al [10] had investigated the influence of isolator characteristics on the seismic response of multi-story base-isolated structure. Similarly [6, 13,] has studied the effect of LRB and its parameters on the response of the structure. From the research related to LRB for seismic isolation of bridges, it is found that extensive research is done to evaluate the performance of LRB isolated bridge. However, the research related to optimum design of LRB for seismic isolation of bridges is scarce.

The present study is focused on the performance of the bridges isolated using LRB. The specific objectives of the study are: to investigate the performance of bridge isolated by the LRB isolators when subjected to different near-field and far-field earthquakes, to study the effect of the isolator parameters on the seismic response of the isolated bridge and to investigate the optimum parameters of the LRB for minimum earthquake response of the isolated bridge under different ground motions. The parameters investigated for LRB are: (a) isolation period T_b , (b) damping ratio ξ_b and (c) normalized yield strength and (d) ratio of post to pre-yielding stiffness (α).

II. MODELLING OF BASE-ISOLATED BRIDGE USING LRB BEARING

The LRB isolator is a multilayered laminated rubber bearing along with a central lead-core to add damping to the isolation system. The LRB isolator provides the combined features of vertical load support, horizontal flexibility, restoring force and damping in a single unit. The schematic diagram of the combined mechanism is shown in Figure 1(b). The ideal force-deformation behavior of the LRB system is generally represented by non-linear characteristics following a hysteretic nature as shown in Figure 1(c). One of the most important parameter of LRB isolator is F_0 . The yield strength of the bearing is normalized with respect to the total weight of the isolated structure and expressed by the parameter F_0 defined as:

$$F_0 = \frac{Q_d}{W} \quad (1)$$

where $W = Mg$ is the total weight of the isolated structure; and g is the acceleration due to gravity. This parameter is largely related to the responses of the structure under earthquake.

The second parameter is the post-yield stiffness k_b of the LRB bearing which is designed in such a way as to provide the specific value of the isolation period T_b , expressed as:

$$T_b = 2\pi \sqrt{\frac{M}{k_b}} \quad (2)$$

Another important parameter is the viscous damping (c_b) in the bearing due to the rubber which is evaluated by the damping ratio, ξ_b , expressed as:

$$\xi_b = \frac{c_b}{2M\omega_b} \quad (3)$$

where, $\omega_b = 2\pi/T_b$ is the base isolation frequency. The mathematical modeling is done with the help of a non-linear Bouc-Wen model to characterize the hysteretic behavior of the LRB systems. The restoring force developed in the isolation bearing is given by,

$$F_b = c_b \dot{x}_b + \alpha k_b x_b + (1 - \alpha) F_y Z \quad (4)$$

where, F_y is the yield strength of the bearing; α is an index which represent the ratio of post to pre-yielding stiffness; k_b is the initial stiffness of the bearing; c_b is the viscous damping of the bearing; and Z is the non-dimensional hysteretic displacement component satisfying the following non-linear first order differential equation expressed as,

$$q\dot{Z} = A\dot{x}_b - \beta|\dot{x}_b|Z|Z|^{n-1} - \tau x_b|Z|^n \quad (5)$$

where, q is the yield displacement; dimensionless parameters β , τ , A and n are selected such that predicted response from the model closely matches with the experimental results. The parameter n is an integer constant, which controls smoothness of transition from elastic to plastic response.

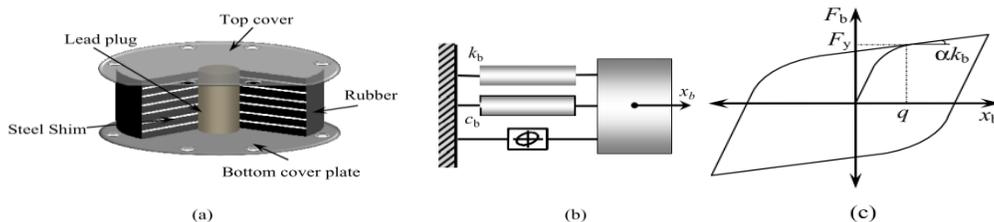


Figure 1: Lead Rubber bearing: (a) Sectional view of LRB ;(b) Schematic of LRB and (c) Force-deformation behavior of LRB

The mathematical modeling of the bridge is done as a lumped mass model idealizing the deck and piers as beam elements. In this model the flexibility of the pier alone is taken into account and the deck is made to act as a rigid mass. This model is consistent with the bridge models used by Tsopelas et al. [16], and Jangid et al. [5] in the seismic analyses of bridges.

The governing equations of motion for the isolated bridge system under single horizontal component of ground motion are expressed in matrix form as:

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} + [D]\{F\} = -[M][r]\{\ddot{X}_g\} \quad (6)$$

$$\{X\} = \{X_1, X_2, \dots, X_n, X_d\}^T$$

where, $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrices, respectively, of the bridge structure of the order $N \times N$; $\{X\}$, $\{\dot{X}\}$, $\{\ddot{X}\}$ are structural acceleration, structural velocity and structural displacement vectors, respectively; X_d is the displacement of

the bridge deck relative to ground; [D] is the location matrix for the restoring forces of isolator; {F} is vector containing the restoring forces of isolator; {r} = {1,1,.....,1}^T is influence coefficient vector; {X_g^{''}} is earthquake ground acceleration. The equation of motion is solved using state space.

III. NUMERICAL STUDY

In the present study a three span continuous bridge is selected from the literature [18] and a lumped mass model of the bridge is numerically modeled using Matlab. The properties of the three-span bridge taken from Ref. [18] are: deck mass = 771.12×10³ kg; mass of each pier = 39.26 × 10³ kg; moment of inertia of piers = 0.64 m⁴; Young's modules of elasticity = 20.67 × 10⁹ (N/m²); pier height = 8 m; and total length of bridge = 90 m. These properties correspond to the bridge studied by Wang et al [18] using the sliding isolation system. The numerical modeling of the isolated bridge is done by considering the lumped mass model and the performance of the bridge is studied by subjecting it to different near-field and far-field earthquake ground motions.

In order to choose the optimum parameters for the isolation system, a better understanding of the effect of these parameters on the seismic behavior of the isolated bridge is required. Different researchers had attempted to investigate the different parameters for LRB. However, none of the papers investigated the optimum values of all the parameters for the isolators. Based on the literatures available, the range of the different parameters of the study were selected. The different parameters considered for the study are:

- (a) Isolation time period (T_b) (1.5-4 sec),
- (b) Normalized yield strength ratio given by F_o=Q_d/W (0.03 to 0.50)
- (c) Damping ratio (ξ_b) (0.025 to 0.12)
- (d) The ratio of Elastic Stiffness to Post Yield Stiffness (α=K_e/K_d) (0.1 to 0.5).

The seismic response of the isolated bridge is investigated for three near-field: Kobe, Northridge, and Chichi and three far-field Imperial Valley, Coalinga and Sanfernando earthquake ground motions. Table 1 shows the details of the ground motion characteristics.

Table 1. Characteristics of the earthquake ground motions considered in the study.

Earthquake	PGA(m/s ²)	PGV(m/s)	PGA/PGV
Kobe	8.3692	0.9575	8.740679
Chichi	8.1438	1.2955	6.286222
Northridge	5.6448	0.7709	7.32235
Imperial Valley	1.127	0.1247	9.03769
Coalinga	0.3822	0.0422	9.056872
Sanfernando	0.245	0.0382	6.413613

IV. RESULTS AND DISCUSSION

In order to study the performance of the LRB, the responses of the isolated bridge, subjected to different near-field and far-field earthquake ground motions, are compared with those of non-isolated bridge. The variation of the responses namely maximum isolator displacement, deck acceleration and base shear are considered in evaluating the performance.

Table 2 shows the percentage control of deck acceleration and base shear of the isolated bridge (T_b=2.5secs) subjected to different earthquake ground motions. Maximum control of 81% for deck acceleration and 92% for pier base shear is observed for Kobe earthquake. The results indicate that the isolation system is effective in reducing the deck acceleration and pier base shear for both far field and near field earthquakes. The percentage control however, is different for different earthquakes and hence, it can be inferred that the performance of the isolator depends on the ground motion characteristics. It is observed that in case of the earthquakes with higher PGA/PGV ratio the control of responses is better.

Figure 2(a) shows the isolator displacement time history of the bridge subjected to earthquake ground motion. In Figure 2(b) the absolute deck acceleration time histories of the non-isolated and isolated bridges subjected to earthquake are compared. The figure shows that the deck acceleration is effectively reduced by the LRB isolator.

Table 2. Percentage control of deck acceleration and base shear of the isolated bridge ($T_b=2.5$ secs)

Earthquake ground motion	Deck Acceleration(m/s^2)		%Control	Base shear(W_d)		%Control
	Non-isolated	Isolated		Non-isolated	Isolated	
Kobe	23.78	4.32	81.83	2.86	0.23	92.12
Chichi	8.22	3.47	57.85	1.01	0.15	85.16
Northridge	7.49	3.94	47.38	0.87	0.19	77.72
Imperial Valley	3.13	0.70	77.66	0.39	0.03	91.17
Coalinga	1.36	0.43	67.99	0.16	0.03	82.06
Sanfernando	0.49	0.26	46.39	0.06	0.02	71.31

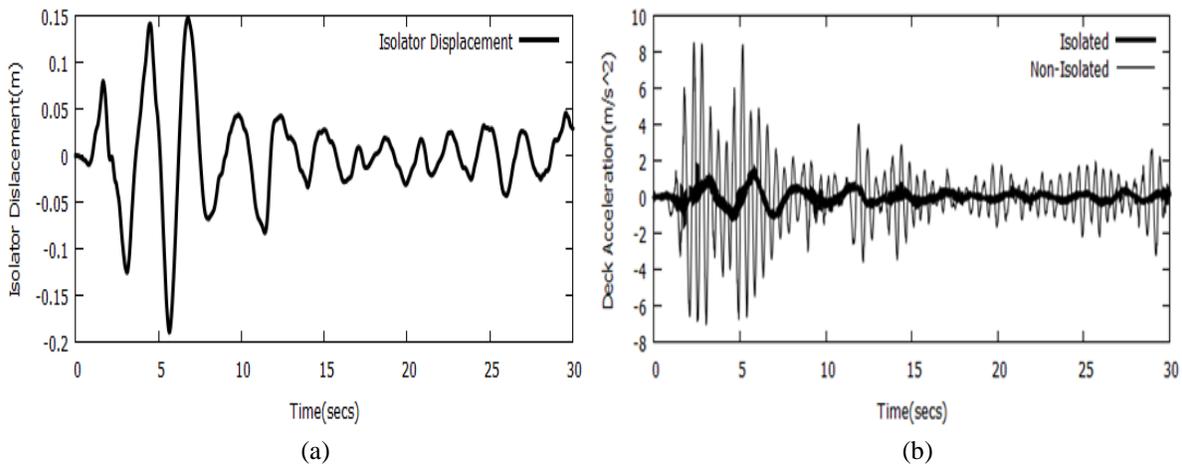


Figure 2. Time history response of (a) isolator displacement and (b) deck acceleration of LRB isolated bridge

A. Effect of Normalized yield strength

In order to study the effect of normalized yield strength for different isolation time period values, the responses of the isolated bridge are plotted in Figure 3 against normalized yield strength for different values of isolation time period (T_b). For the near-field earthquakes, it is observed that with the increase in F_0 , the isolator displacement decreases. In case of far-field earthquakes it is observed that, with the increase in F_0 , the isolator displacement follows a general trend of decreasing however, the values are observed to fluctuate with the increase in flexibility of the structure. For all the six earthquakes, the minimum isolator displacement is observed for a higher F_0 value. The plots also explain that, with the increase in time period the isolator displacement is increasing. For a given yield strength, the lower the isolation time period, the stiffer the system and the lower is the isolator displacement. With the increase in flexibility of the structure, the isolator displacement increases.

Fig 4. shows the variation of deck acceleration against normalized yield strength F_0 for various values of time period (T_b) subjected to far-field earthquakes and near-field earthquakes. The figure explains that with the increase in F_0 the deck acceleration increases for both near field and far field earthquakes. With the increase in isolation time period, the deck acceleration decreases. So a flexible system has better control of deck acceleration. In order to get maximum control of deck acceleration a lower value of F_0 and a flexible system is preferred for both near-field and far field earthquakes.

The variation of base shear (Fig 5) with increase in F_0 for different time periods shows similar nature of variation of deck acceleration. Hence lower value of F_0 and a flexible system is preferred for both near-field and far field earthquakes.

The results indicate that at higher yield strength, the isolator displacement decreases. The better performance can be attributed due to stiffening of the isolator caused by the higher yield strength under ground motions. The increase in stiffness of the isolator reduces the bearing displacement however, the pier base shear and deck acceleration initially decreases and then increases which states that there exists an optimum value of the yield strength for which the responses will attain a minimum value. The minimum value of the pier base shear and deck acceleration occurs for the value of F_0 in the range of 0.1–0.15 for different values of the isolation periods.

It was observed that all the three responses considered (displacement, acceleration and base shear) are, in general, 10 times greater in case of near-field earthquakes than those in case of far-field earthquakes. In order to investigate whether this is due to the difference in the pga values of the ground accelerations chosen or due to the difference in the frequency characteristics between the near-field and far-field ground motions, all the earthquakes are scaled in such a way that they have the same pga value, namely, that of Northridge earthquake($pga=0.5112g$). The responses corresponding to these scaled ground motions, when compared, are then found to be in same range of magnitude as shown in figure 6, figure 7, figure 8.

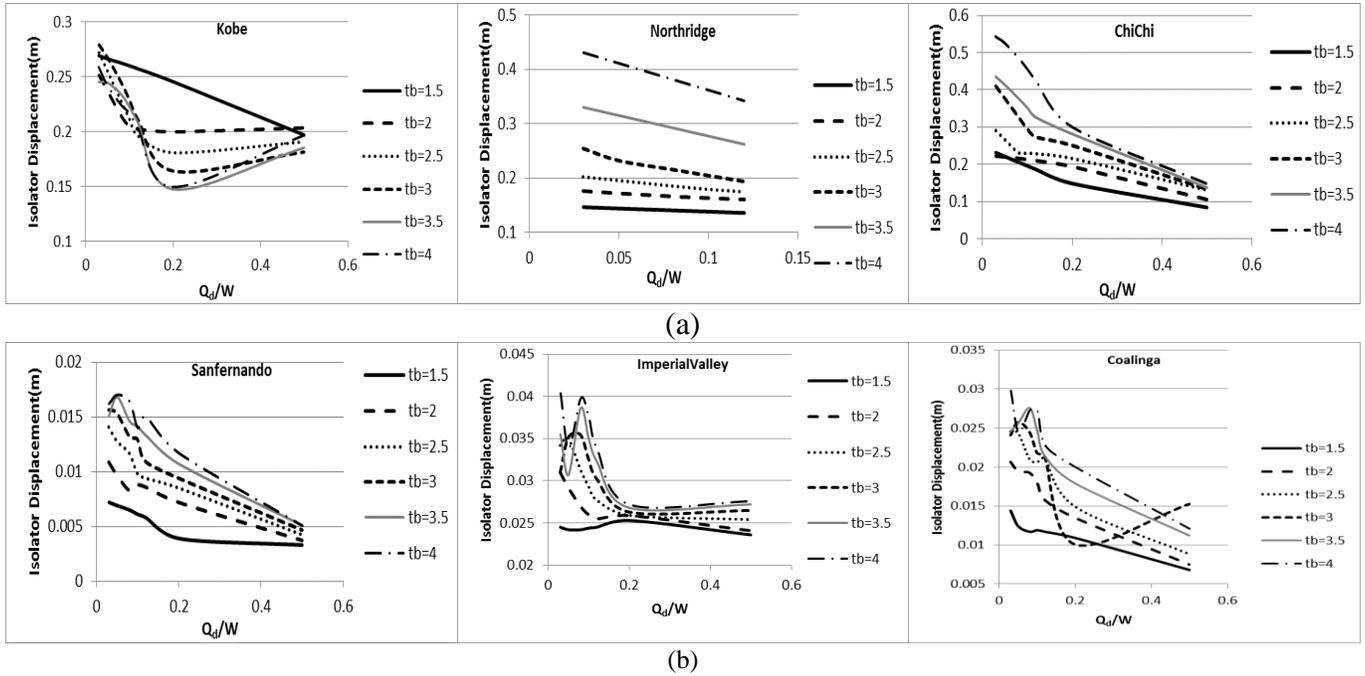


Fig 3. Variation of (a) isolator displacement; against normalized yield strength Q_d/W for various values of time period (T_b) subjected to (a) far-field earthquakes (b) near-field earthquakes.

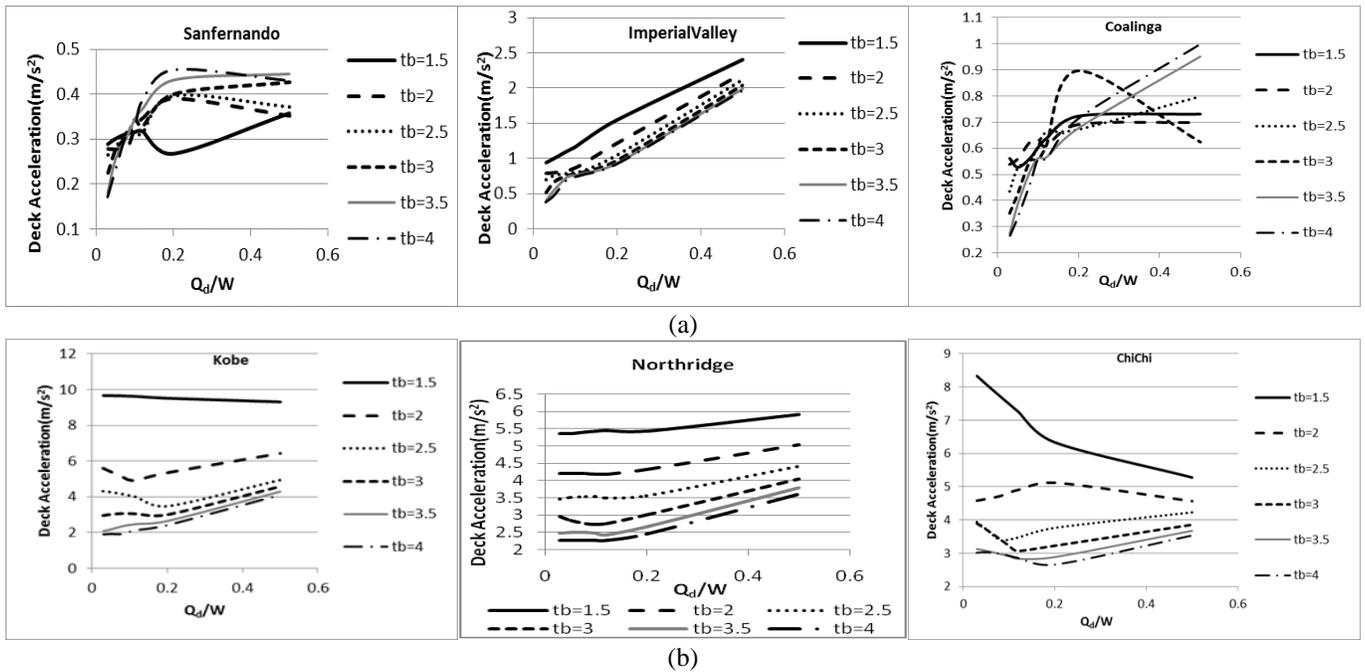
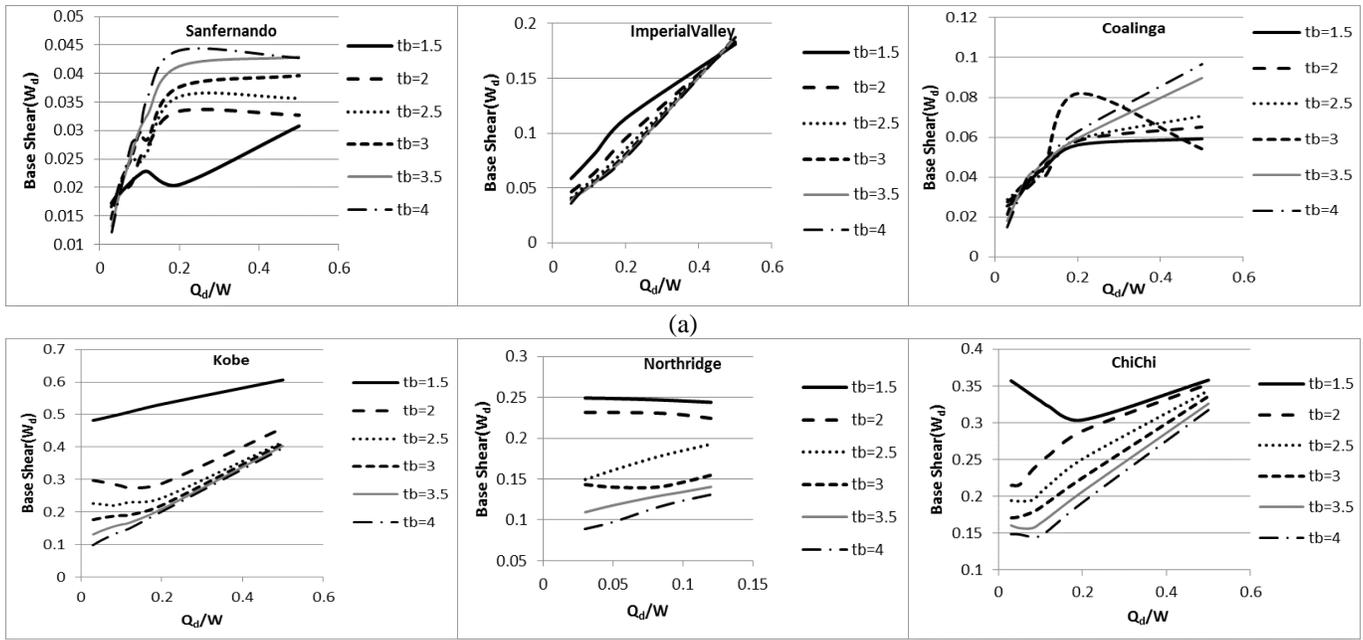
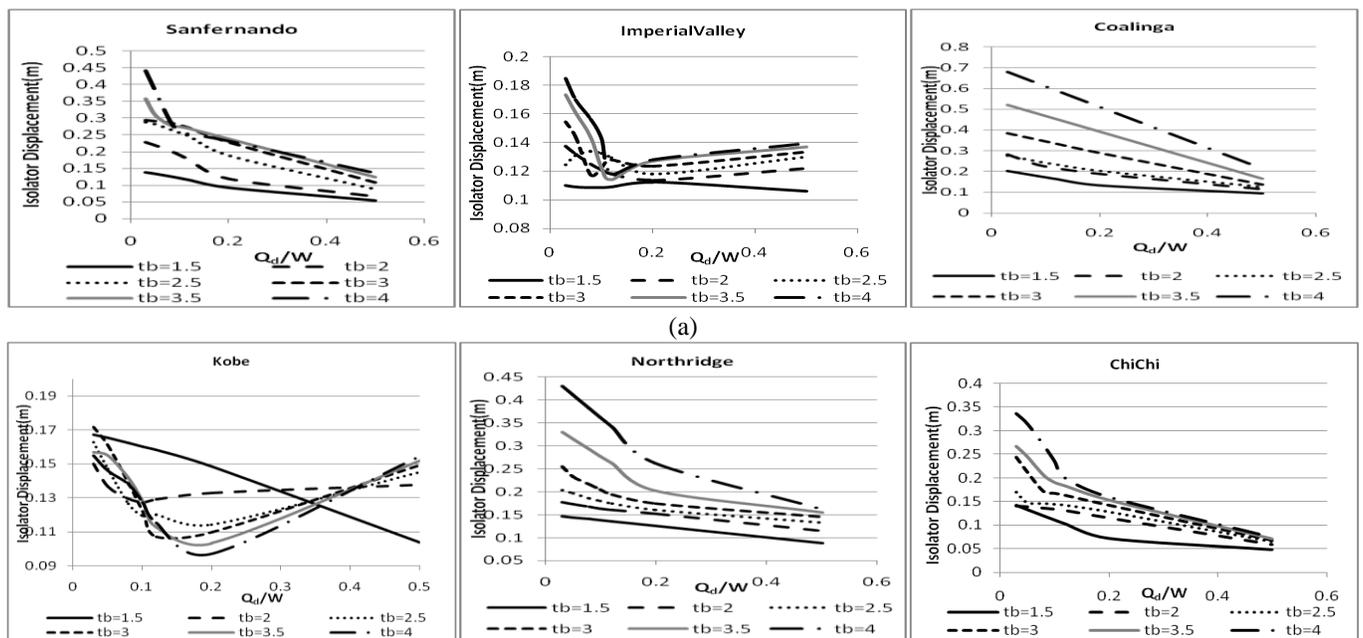


Fig 4. Variation of deck acceleration against normalized yield strength Q_d/W for various values of time period (T_b) subjected to (a) far-field earthquakes (b) near-field earthquakes.



(b)

Fig 5. Variation of Base Shear against normalized yield strength Q_d/W for various values of time period (T_b) subjected to (a) far-field earthquakes (b) near-field earthquakes



(b)

Fig 6. Variation of (a) isolator displacement; against normalized yield strength Q_d/W for various values of time period (T_b) subjected to scaled (a) far-field earthquakes (b).near-field earthquakes.

B. Effect of Elastic Stiffness to Post Yield Stiffness ratio ($\alpha = K_u/K_d$)

α (K_u/K_d) is an index which represent the ratio of post to pre-yielding stiffness of the LRB isolator. The decrease in the value of α makes the system stiffer. To study the effect of α on the performance of bridge structure, the responses of the isolated bridge is plotted in figure 8 and figure 9 by varying the value of α (0.1-0.5) of the isolator (over the range of most favorable values as found in the previous sections i.e., $T_b = 2$ to 3.0 sec, $Q_d/W = 0.05$ to 0.10). Results show that the displacement responses for both near field and far field increases with increase in the ratio and there is decrease in deck acceleration and pier base shear with increase in α . The lowest displacement responses are observed for $T_b = 2$ to 2.5 and $F_0 = 0.10$ (stiffer system) and the lowest deck acceleration and pier base shear are observed for $T_b = 2.5$ to 3 and $F_0 = 0.05$ (flexible system). This explains that a stiffer system with a high F_0 value will give the

maximum response control for displacement and a flexible system with a low F_o will give a maximum response control for acceleration and pier base shear.

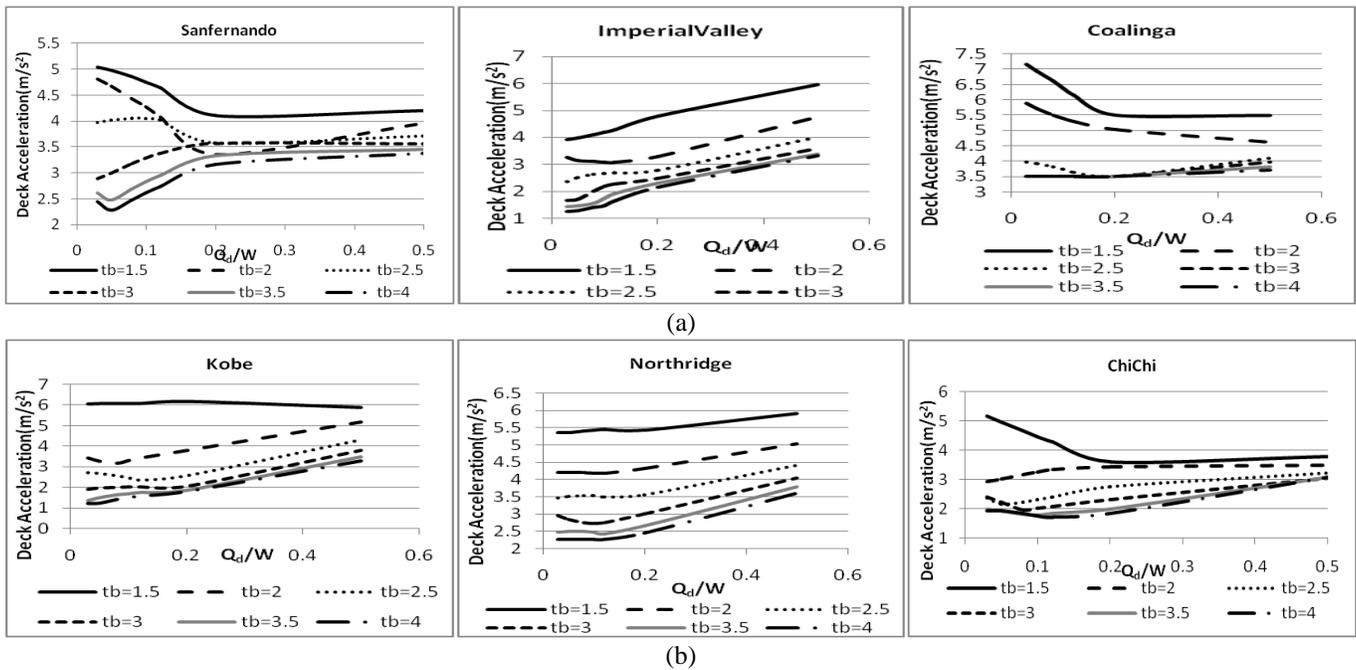


Fig 7. Variation of deck acceleration against normalized yield strength Q_d/W for various values of time period (T_b) subjected to scaled (a) far-field earthquakes (b) near-field earthquakes.

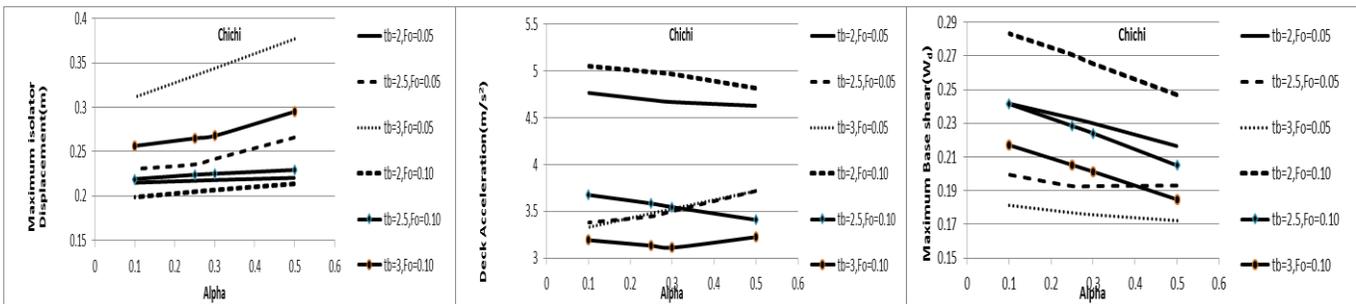


Fig 8. Variation of Isolator displacement, Deck acceleration and Base Shear against α for various values of time period (T_b) and F_o subjected to near-field (Chichi) earthquake.

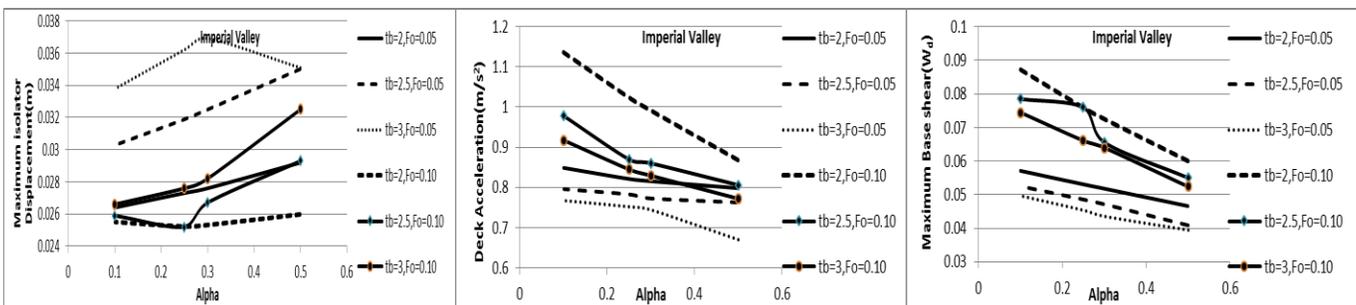


Fig 9. Variation of Isolator displacement, Deck acceleration and Base Shear against α for various values of time period (T_b) and F_o subjected to Imperial Valley (far-field) earthquake

C. Effect of isolation time period (T_b)

The effect of isolation time period is studied for different values of normalized yield strength ($F_o=Q_d/W$). Figure 10 shows the variation of the responses of bridge subjected to near-field and far-field earthquakes with isolation time period (T_b) for different values of F_o . The figure explains that with the increase in time period the isolator displacement increases. It is observed that for lower values

of F_0 , the isolator displacement increases rapidly however, for higher values of F_0 , the rate of increase in displacement is comparatively low since the system becomes stiffer. A stiffer system is preferred for lower isolator displacement. The minimum value of isolator displacement is obtained in the range of 1.5 to 2.5 secs. It is also observed that with increase in time period the deck acceleration and pier base shear decreases for both near-field and far field earthquakes. Considering all the three responses, the isolation time period can be selected in the range of 2-3 secs.

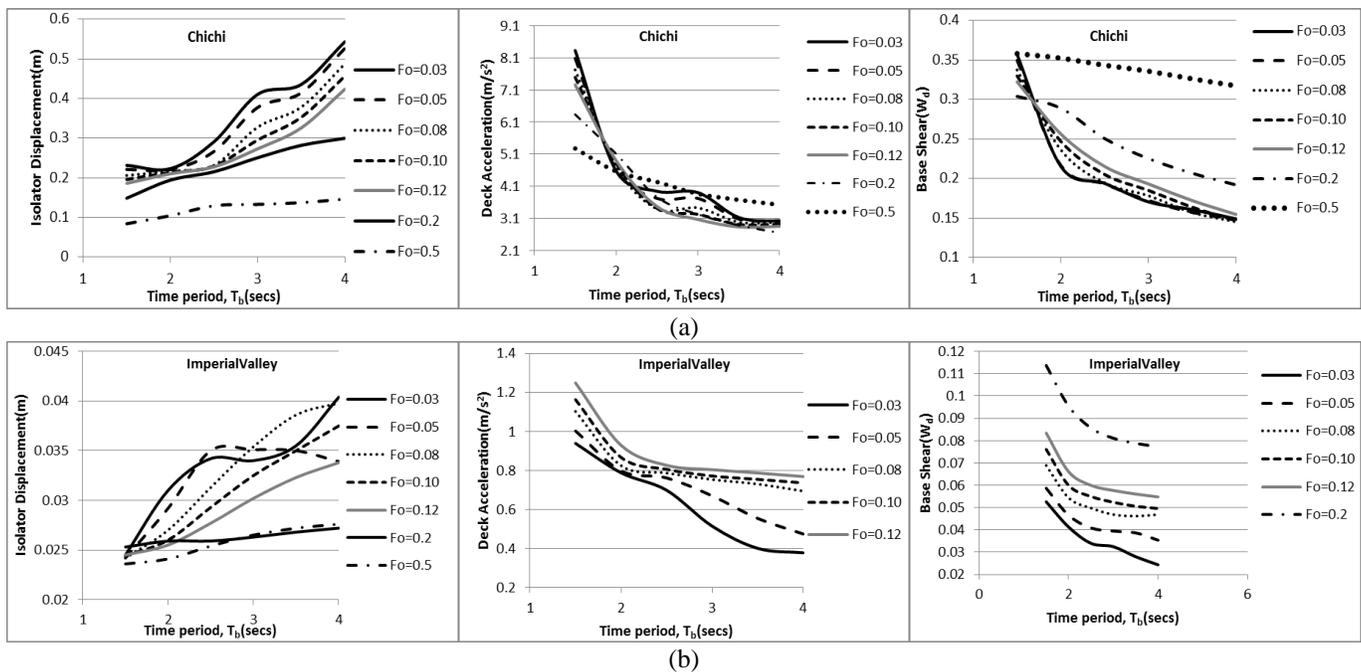


Fig 10. Variation of isolator displacement, deck acceleration and base shear against normalized yield strength Q_d/W for various values of time period (T_b) subjected to (a) near-field earthquakes (b) far-field earthquakes

D. Effect of Damping Ratio (ζ_b)

The effect of damping ratio on the responses of the isolated bridge is studied by varying the responses against the normalized yield strength. The different damping ratios considered are 0.025, 0.05, 0.075, 0.10, 0.12. For all the responses it is observed that, with increase in damping ratio the responses reduce. For higher values of ζ_b the rate of increase is very less when compared to lower values of ζ_b . The ζ_b value ranging from 0.075-0.12 gives the maximum response control.

Based on the study of effect of each of the parameters considered a list of recommended values is presented below in Table 3. The table explains that, for all values of T_b , a low value of Q_d/W and high values of ζ_b and α is recommended to obtain maximum acceleration control and pier base shear control. For displacement control high values of Q_d/w , ζ_b and α are recommended.

For all values of Q_d/W , a low value of T_b is recommended for displacement control and for acceleration control and pier base shear control a high value of T_b is recommended. High values of ζ_b and α are recommended for all values of Q_d/W for the control of all the responses.

In order to achieve maximum displacement control, a high value of Q_d/W and α has to be maintained for all values of damping ratio. For all values of ζ_b , a low T_b value will give maximum displacement control and a high T_b value gives maximum acceleration control and pier base shear control.

For maximum displacement control, a low value of T_b and a high values of Q_d/W , ζ_b and α are recommended. For maximum acceleration control and pier base shear control, high values of T_b , ζ_b and α and a low value of Q_d/W are recommended.

Table 3. Recommended Values for the Parameters of LRB

Isolation time period (T_b)								
T_b			Q_d/W		ξ_b		α	
			Low	High	Low	High	Low	High
Displacement Control	T_b	Low		✓		✓	✓	
		High		✓		✓	✓	
Acceleration Control	T_b	Low	✓			✓		✓
		High	✓			✓		✓
Base Shear	T_b	Low	✓			✓		✓
		High	✓			✓		✓
Normalized yield strength (Q_d/W)								
Q_d/W			T_b		ξ_b		α	
			Low	High	Low	High	Low	High
Displacement Control	Q_d/W	Low	✓			✓	✓	
		High	✓			✓	✓	
Acceleration Control	Q_d/W	Low		✓		✓		✓
		High		✓		✓		✓
Base Shear	Q_d/W	Low		✓		✓		✓
		High		✓		✓		✓
Damping Ratio (ξ_b)								
ξ_b			T_b		Q_d/W		α	
			Low	High	Low	High	Low	High
Displacement Control	ξ_b	Low	✓		✓		✓	
		High	✓		✓		✓	
Acceleration Control	ξ_b	Low		✓	✓			✓
		High		✓	✓			✓
Base Shear	ξ_b	Low		✓	✓			✓
		High		✓	✓			✓
Elastic Stiffness to Post Yield Stiffness ratio (α)								
α			T_b		Q_d/W		ξ_b	
			Low	High	Low	High	Low	High
Displacement Control	α	Low	✓			✓	✓	
		High	✓			✓	✓	
Acceleration Control	α	Low		✓	✓			✓
		High		✓	✓			✓
Base Shear	α	Low		✓	✓			✓
		High		✓	✓			✓

V.CONCLUSION

Seismic responses namely, isolator displacement, deck acceleration, pier base shear of the LRB isolated bridge is studied under different near field and far field ground excitations. The study investigates the performance of the bridge in order to determine the optimum range of different parameters of the isolator for maximum response reduction. From the results of the present study the following conclusions are drawn:

- The LRB isolator is found to be very effective in reducing the responses of the seismically excited isolated bridge. The study explains that the parameters of LRB affect the response of the bridge.
- For the near-field and far field earthquake ground motions the percentage control of different responses, however, are more or less same.
- On investigating the influence of the flexibility of the isolator on the response of the isolated bridge it was found that compared to the isolator displacement the deck acceleration is more sensitive to the variation of isolator flexibility or isolation time period .The results indicate that with the increase in time period the isolator displacement increases however the deck acceleration decreases. For all values of Q_d/W , α , and ξ_b . A stiffer system gives better displacement control and a flexible system gives better acceleration control and pier base shear control. Therefore considering both the controls the T_b in

the range of 2-3 secs is recommended.

- The effect of the normalized yield strength ($F_o=Q_d/W$) is studied for two cases for different post yield stiffness values (k_b) and for different damping ratios (ξ_b). It is studied that for all values of T_b a high Q_d/W value is recommended for displacement control. Increase in F_o stiffens the isolator and this stiffening effect results in reducing the isolator displacement however, the deck acceleration is observed to increase. In case of near-field earthquakes it is also seen that the responses are not much affected by the increase in F_o . But on scaling these earthquakes the deck acceleration increases with increase in F_o . Considering both the cases, the displacement responses are observed to be minimum for the Q_d/W in a range of 0.12 to 0.5 and the acceleration responses are minimum in the range of 0.05-0.10. Hence and values of F_o should neither be too low nor too high. It is also studied that a high value of ξ_b should be maintained to obtain maximum control of the responses.
- With the increase in α (K_u/K_d ratio) of the LRB isolator for all the earthquakes the displacement responses increases and the acceleration and base shear responses reduces. This is because decrease in α value makes the system stiffer. For all values of the parameters considered a high value of α is recommended.
- The percentage control obtained is different for the different earthquakes which shows that the performance of the isolator is dependent on the ground motion characteristics.
- Not much difference is observed in the nature of the variation of responses for both near field and far field earthquakes in spite of having different characteristics. This may be because all the earthquakes have the PGA/PGV ratio almost in the same range.
- The acceleration responses for near field responses are seen to be not much effected by the variation of F_o , however the responses are effected when the earthquake is scaled down. This shows that the PGA also has an effect on the performance of the isolator.

The response of bridge seismically isolated by LRB under earthquake ground motions shows that LRB is effective in controlling the responses for both near-field and far-field earthquakes and there exists a particular range of the parameters for which the responses attain the minimum values.

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