A Comparative Study on Aseismic Performances of Base Isolation Systems for Multi-Span Continuous Bridge

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Abstract

Various base isolation systems such as the pure-friction, laminated rubber bearing, lead rubber bearing, resilient-friction base isolator and electricité de France systems, which have been used or are considered to have considerable potential for wide applications, are systematically compared and discussed for aseismic performances of multi-span continuous bridge in this study. Sensitivity analyses of the bridge employed the devices are carried out to choose the appropriate design parameters of various devices. The recommended ranges of the design parameters are presented in this study. The design parameters are determined by the reciprocal relationship between the peak deck displacement and the peak overturning moment of the bridge within the recommended ranges, and then the relative effectiveness of the bearings is described for the selected design parameters under different the ground motions. The peak responses of the bridge with the friction-type bearing are less sensitive to substantial variations in the frequency range and the intensity of the ground excitation than those with the rubber-type bearing due to characteristics of the friction element within the range of this study.

1. Introduction

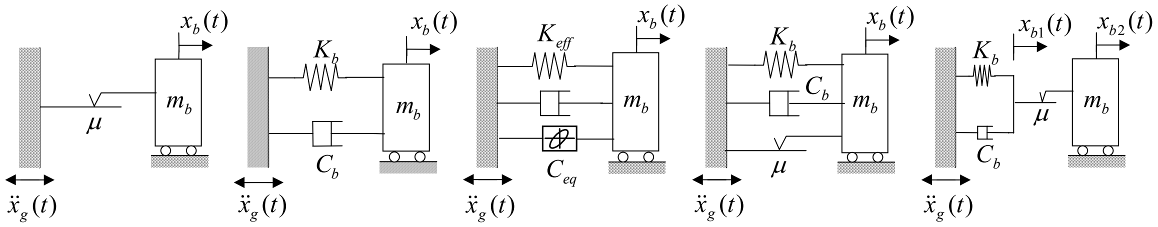
Many aseismic construction designs and technologies have been developed over the years in attempt to mitigate the effects of earthquakes on buildings, bridges and potentially vulnerable contents. The design method using base isolation systems (BISs) is a relatively recent, and evolving technology of this kind. The seismic isolation differs fundamentally from the conventional seismic design approaches in the method by which the period lengthening (detuning) and hysteretic energy-dissipating mechanisms are provided, as well as in the philosophy of how the earthquake attack is withstood.

The seismic isolation consists essentially of the installation of mechanisms, which decouple the structure and/or its contents from potentially damaging earthquake induced ground or support motions. This decoupling is achieved by increasing the flexibility of the system, together with providing appropriate damping. Although it is a relatively recent technology, the seismic isolation has been well evaluated and reviewed and it is widely accepted that the seismic isolation is very effective to mitigate the influence of earthquakes on structures. However, there are few comparative studies on aseismic performances of various BISs for the critical design parameters. Furthermore, most of previous studies are focused on buildings (Lin *et al.*, 1990, Lin *et al.*, 1989, 1990, Mostaghel *et al.*, 1987). On the other hand, there are few studies on bridges in spite that BISs are widely used for them.

To evaluate aseismic performances of BISs and suitable earthquake-resistance design of the bridge, the sensitivity analysis for variations in the design parameters of devices is required. Therefore, a comparative study on aseismic performances of different BISs for multi-span continuous bridge is accomplished in this paper. Sensitivity analyses for variations in the first natural period of the isolated bridge and the friction coefficient of the bearing are also performed under the different ground motions. The recommended ranges of the design parameters are presented in this study. The two design parameters, the first natural period of the isolated bridge and the friction coefficient of the bearing, are determined by the reciprocal relationship between the peak deck displacement (PDD) and the peak overturning moment (POM) of the bridge. The peak responses of the bridge with BISs are obtained, and then the relative effectiveness of different BISs is evaluated for the selected design parameters of devices.

2. Aseismic base isolation systems

A variety of the seismic isolation and energy-dissipation devices has been developed over the years all over the world. The basic features of such devices consist of the horizontal flexibility and the energy dissipative capacity. Here, various leading BISs, which have been used or are considered to have considerable potential for wide applications, are briefly described.



(a) P-F system (b) RB system (c) LRB system (d) R-FBI system (e) EDF system

Figure 1. Schematic diagram of base isolation systems

The pure-friction (P-F) system is classified as the simplest device because it uses only the stick-slip mechanism. A schematic diagram of the P-F system is shown in Figure 1(a). When there is a sliding in the friction plates, the P-F system limits a maximum acceleration transmitted from the substructure to a certain value according to the friction coefficient. However, there may be an excessive deflection or a residual deformation in the friction surface after the seismic event, because the P-F system has no recovering force. Furthermore when the P-F system does not slide, it acts as a fixed one. Because of these reasons, the friction element is used with laminated rubber bearings instead using alone.

Another method of seismically isolating structures is by mounting them on laminated rubber bearings. The laminated rubber bearing (RB) system consists of alternating layers of rubber and steel with the rubber being vulcanized to the steel plates for the horizontal flexibility and the vertical stiffness. The dominant feature of this device is the parallel action of spring and dashpot as shown schematically in Figure 1(b). Because the damping capacity of the RB system is relatively small, it mainly shifts the natural period of the isolated structure to avoid the detrimental earthquake energy.

A lead-plug insert provides hysteretic energy dissipation, therefore, the damping required for a successful seismic isolation system can be incorporated in a single compact component with the RB system. To determine properties of the lead rubber bearing (LRB) system, the bilinear model of characteristic curve is used. The effective stiffness coefficient is obtained with reference to *shear force* versus *displacement* hysteresis loop. In general, the concept of this effective value is a gross approximation, but it works surprisingly well (Skinner *et al.*, 1993).

The resilient-friction base isolator (R-FBI) system makes use of the parallel action of resiliency of rubber and the friction of Teflon coated plates. Similar to the P-F system, it does not slide below the frictional resistance. Unlike the P-F system, however, it has an additional resistance to an increase of deflection and a recovering force by rubber after sliding.

The electricité de France (EDF) system consists of the elastomeric bearing and the friction plates in series. During a low-intensity earthquake, therefore, it behaves as a RB unit and returns to its original position after the seismic event. However when the frictional resistance is exceeded, a sliding will occur and the EDF system may have a residual deformation in the friction surface during a high-intensity earthquake. Owing to the slip in the friction plates, the EDF system limits a maximum acceleration like a P-F unit.

3. Sensitivity analysis

For the sensitivity analysis of various aseismic BISs, the Dong-Jin Bridge is used. It is a continuous bridge with 15 spans and has been constructed in the western coast expressway in Korea. The span length of the bridge is 725m and the width of the superstructure is 12.15m. The longitudinal slope is 0.03%. The superstructure and the substructure are modeled by beam elements. Since, general pre-stressed concrete bridge has structural damping ratios of 2~3%, Rayleigh damping with $\xi = 2\%$ is used in the modeling of the Dong-Jin Bridge.

Among several major earthquake excitations, El Centro (N00W component, 1940), San Fernando (S16E component, 1971) and Mexico City (N90W component, 1985) earthquakes are used as the ground acceleration. These earthquake records have a variety of peak ground acceleration (PGA) and cover various forms of the frequency range. The El Centro accelerogram is typical of those to be expected on the ground of moderate flexibility during a major earthquake. Mexico City earthquake has considerable energy at low frequencies of about 0.5 Hz. Therefore, this earthquake is used to evaluate performances of BISs in the severe input excitation condition.

The commercial finite element analysis program ADINA (automatic dynamic incremental nonlinear analysis) developed by K. J. Bathe is used for the numerical analysis. The method of nonlinear time history analysis is used instead of the response spectrum analysis and the relative effectiveness of different BISs according to variations in the design parameters is studied.

The most important parameters that control performances of aseismic devices are the natural period of the isolated structure and the friction coefficient of the device. Furthermore, aseismic performances of bearings are influenced by the frequency range and PGA of the input ground motions. To obtain variations in the natural period of the isolated bridge, the size of bearing is changed and it leads to variations in the spring constants and damping coefficient of the bearing.

The natural period of the isolated structure should be long enough to avoid the frequency range on which earthquake energy concentrates and short enough to resist the ambient vibration such as traffic or wind induced one. The friction coefficient of the bearing should be large enough to resist the ambient vibration and small enough to have an additional aseismic effect by sliding in the friction plates of the device. Considering these reasons and manufacturing conditions of devices, the first natural period of the isolated bridge is changed from 1.0 sec to 6.0 sec with interval 1.0 sec and the friction coefficient of the bearing is changed from 0.02 to

0.30 with interval 0.04 in this sensitivity analysis.

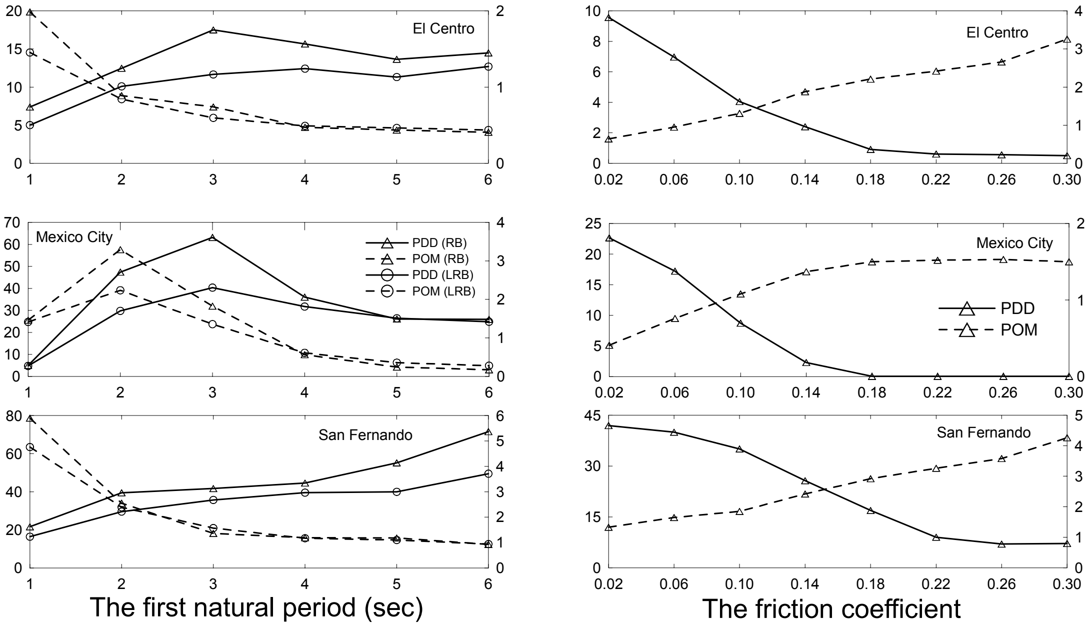
The peak responses of the center pier in the longitudinal direction are calculated and compared. The PDD and the POM are obtained to check the serviceability and the design sectional force.

Variations in the first natural period of the isolated bridge

In this section, the sensitivity of the peak responses to variations in the first natural period of the bridge with aseismic bearings, T_1, is analyzed. Variations of the peak responses of the isolated bridge according to the first natural period are shown in Figures 2(a), 3 and 4.

Figure 2(a) shows that the peak responses of bridge with the rubber-type bearing, such as the RB and LRB systems, have similar trend to the response spectrum of each earthquake because of the linearity of the device.

As a whole, the PDD is increased as the first natural period is increased whereas the POM is decreased because the horizontal flexibility of the bridge is increased. Most of the deck displacement is the deformation of the device, therefore the deformation of pier is negligible as the first natural period is increased. The POM is decreased little when the first natural period is longer than 4.0 sec. The peak responses of the bridge subjected to Mexico City earthquake are amplified in the first natural period of about 2.0 ~ 3.0 sec because earthquake energy is dominant in this range, therefore the resonance is occurred. Due to the additional energy dissipative capacity of a central lead core the peak responses of the bridge with the LRB system are much reduced when compared with a RB unit.



(a) Rubber-type bearing

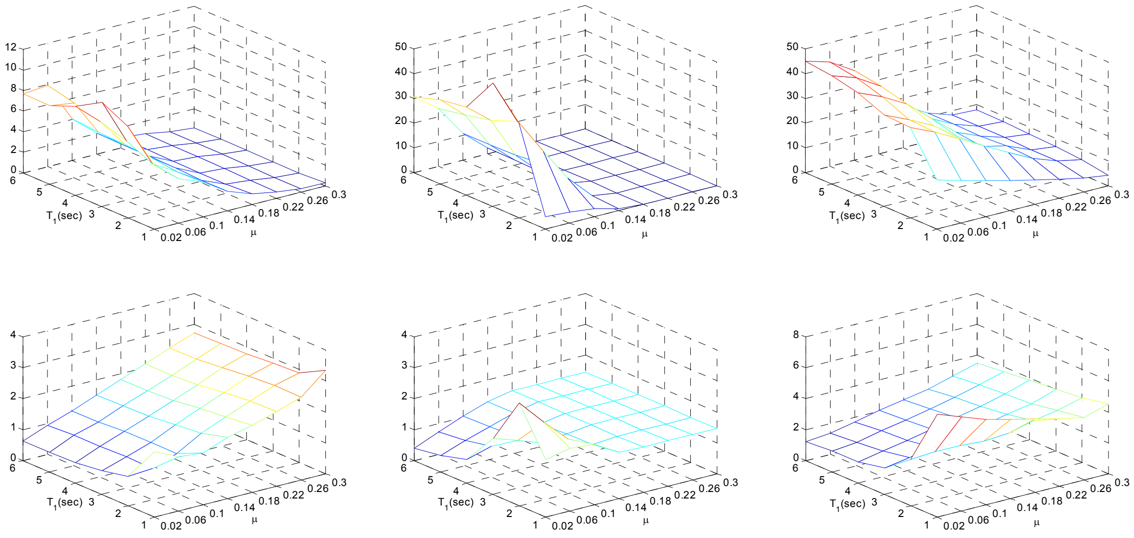
(b) P-F system

Figure 2 Variations of the peak responses with the design parameters

(left axis-PDD: cm, right axis-POM: $\times 10^7$ N·m)

For the R-FBI and EDF systems, the natural period and the friction coefficient are the important design parameters simultaneously. Figure 3 shows the peak responses of the bridge with the R-FBI system versus the design parameters. It is observed that the peak responses of the bridge are similar to the response spectrum of each earthquake for the small value of friction coefficient. As the friction coefficient is increased, however, the peak responses are not sensitive to variations in the first natural period due to characteristics of friction elements. In the friction-type bearing which uses the friction elements in parallel *i.e.,* the R-FBI system, insensitiveness to the natural period may be obvious because the natural period is relatively not an important design parameter. The maximum PDD of three earthquakes is more reduced when compared with the rubber-type bearing due to the frictional resistance of friction elements.

In Figure 4, the peak responses of the bridge with the EDF system show similar trend to those with the rubber-type bearing as the friction coefficient is increased. If there is no sliding in the friction plates, the responses of the bridge are the same as those with a RB unit. However, the PDD is larger when compared with the rubber-type bearing due to the sliding of the friction plates.



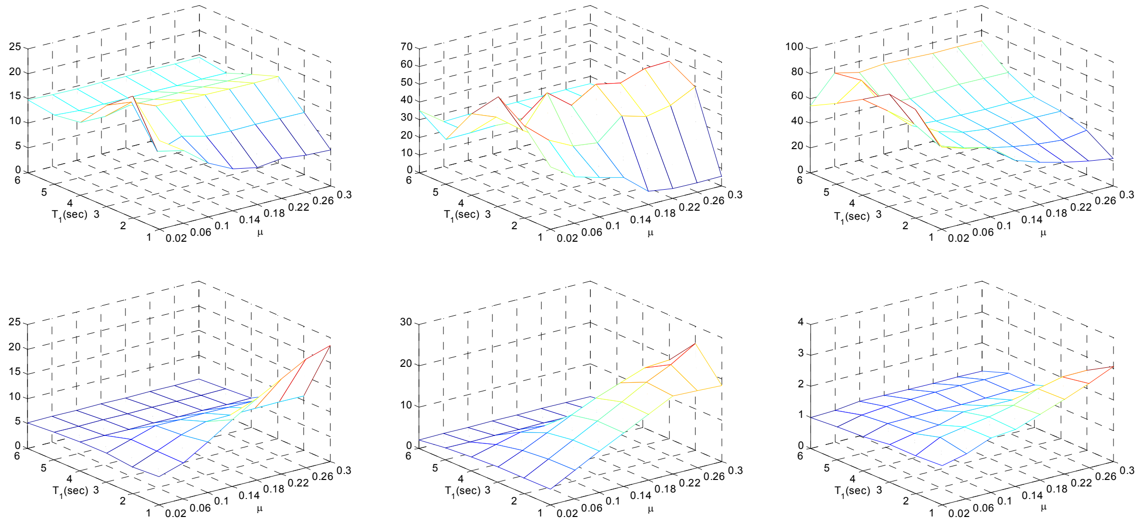
(a) El Centro (b) Mexico City (c) San Fernando

Figure 3. Variations of the peak responses with the design parameters: R-FBI system (upper row- PDD: cm, lower row- POM: $\times 10^7$N·m)

Variations in the friction coefficient of BIS

In this section, the sensitivity of the peak responses to variations in the friction coefficient of the bearing, μ, is discussed. Variations of the peak responses of the isolated bridge according to the friction coefficient of the bearing are shown in Figures 2(b), 3 and 4.

It is observed that an increase of friction coefficient of the P-F system, generally, leads to a decrease of the PDD whereas it leads to an increase of the POM because of influence of the superstructure as shown in Figure 2(b). The most portion of displacement is the sliding deformation of the P-F system and the deformation of pier is negligible. As the friction coefficient is increased, a sliding seldom occurs in the P-F system, therefore the deformation of pier is increased. The P-F system has an excessive deformation when the value of friction coefficient is small and a residual deformation because there is no recovering force.



(a) El Centro (b) Mexico City (c) San Fernando

Figure 4. Variations of the peak responses with the design parameters: EDF system (upper row- PDD: cm, lower row- POM: $\times 10^6$N·m)

The R-FBI system gives an additional resistance to an increase of deflection by the parallel action of stiffness and damping different to the P-F system. Thus, the PDD is smaller than that with a P-F unit whereas the POM is similar. For Mexico City earthquake, the POM is decreased as the friction coefficient is increased for $T_1 = 2.0$ sec opposite to the rubber-type bearing. This is why an increase of friction coefficient for $T_1 = 2.0$ sec reduces the resonance of the isolated bridge and the R-FBI system still provides a certain amount of protection.

When there is no sliding in the upper plate of the EDF system, it behaves like the rubber-type bearing and the peak responses of the bridge remain constant for variations in the friction coefficient as shown in Figure 7. For Mexico City earthquake, when the first natural period is 2.0 sec, the peak responses of the bridge are amplified like those with the rubber-type bearing.

It is impossible to elect the optimal values of the natural period and friction coefficient for the various BISs, because the optimal friction coefficient varies depending on the various design conditions such as soil type, structure type and possible input ground motion. It is possible, however, to recommend the appropriate ranges of the natural period and the friction coefficient. Therefore, within the range of the above sensitivity analyses of the design parameters, it is recommended using the first natural period shorter than 4.0 sec to avoid an excessive deck displacement with suitable overturning moment. Furthermore, the use of adequate friction element is effective in reducing deck displacement. It is recommended using the friction coefficient smaller than 0.18. If the value of friction coefficient is large than 0.18, there is little advantage of reducing deck displacement whereas overturning moment is monotonously increased.

Comparative study for different earthquakes with the selected design parameters

Practical BISs must trade off between the extent of force isolation and acceptable relative displacements across the isolation system during the earthquake motion. The design parameters determined by the reciprocal relationship between the PDD and the POM of the bridge are used for comparisons and analyses of aseismic performances of various BISs with the fixed design parameters instead of the conventionally recommended ones (Lin *et al.*, 1989).

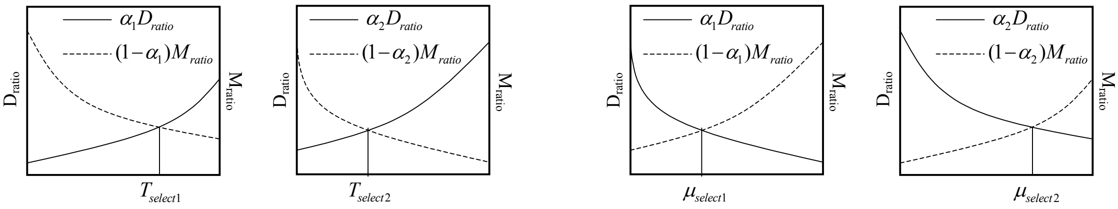
The design parameters of the device are determined by following procedure using San Fernando earthquake in this paper.

First, it is calculated that the ratio of the PDD and the POM to average value according to the first natural period and the friction coefficient, respectively. To consider the influence of small values of results, the average value is used instead of a maximum one.

$$D_{ratio} = \frac{D}{D_{average}}, \quad M_{ratio} = \frac{M}{M_{average}} \qquad \text{(1a, 1b)}$$

The curves of αD_{ratio} and $(1-\alpha)M_{ratio}$ are plotted in Figure 5, for example. The α is a factor that indicates the relative importance of the PDD. The α varies from 0 to 1 and $\alpha = 0.5$, which means same importance of the PDD and the POM, is used in this study. One can consider a different relative importance of the PDD and the POM using the factor α according to various design conditions as shown in Figure 5.

Finally, the crossing point of two curves is selected as the design first natural period of the isolated bridge and/or the friction coefficient of the device. As shown in Figure 5, if α is increased from α_1 to α_2, then the selected first natural period is decreased from $T_{select1}$ to $T_{select2}$, whereas the selected friction coefficient is increased from $\mu_{select1}$ to $\mu_{select2}$. Therefore, the PDD will be decreased with $T_{select2}$ and/or $\mu_{select2}$. Table 1 shows the selected first natural period and the friction coefficient determined by above procedure.



(a) For the first natural period: $T_{select1} > T_{select2}$ for $\alpha_1 < \alpha_2$

(b) For friction coefficient: $\mu_{select1} < \mu_{select2}$ for $\alpha_1 < \alpha_2$

Figure 5. Selection of values of the design parameters

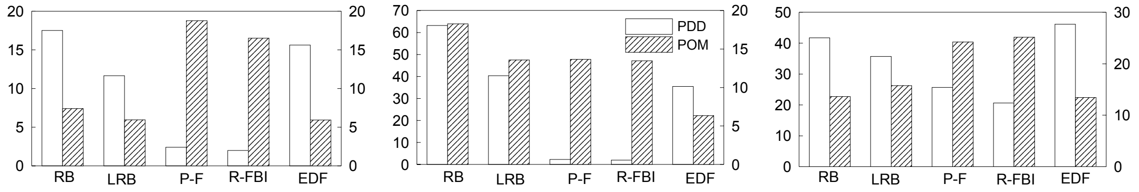
Table 1. The selected values of the design parameters

	T_1 (sec)	μ
RB system	3.0	N/A
LRB system	3.0	N/A
P-F system	N/A	0.14
R-FBI system	3.0	0.14
EDF system	4.0	0.10

The peak responses of the bridge with various BISs, which are designed by the selected parameters of Table 1, are shown in Figure 6.

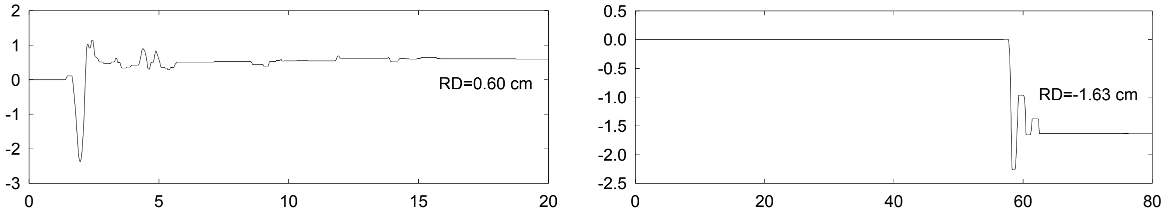
As shown in Figure 6, the performance of BISs varies depending on the input ground motions. While the PDD with the friction-type bearing is generally smaller than that with the rubber-type bearing, the POM is larger due to the friction element. The P-F system has a residual deformation after the seismic event as shown in Figure 7, because it does not have the recovering force. The EDF system has a residual deformation due to the sliding in the friction plates for San Fernando earthquake like a P-F unit as shown in Figure 7.

In Figures 2 ~4 and 6 ~ 7, the peak responses of the bridge with the friction-type bearing are less sensitive to substantial variations in the frequency range and intensity of earthquake excitation due to characteristics of the stick-slip mechanism compared to those with the rubber-type bearing.

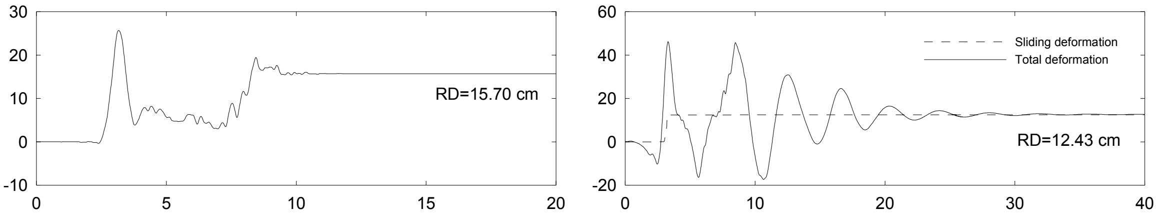


(a) El Centro (b) Mexico City (c) San Fernando

Figure 6. Aseismic performances of various BISs for the selected the values of design parameters (left axis- PDD: cm, right axis- POM: ×10^6N·m)



(a) P-F system: El Centro (b) P-F system: Mexico City



(c) P-F system: San Fernando (d) EDF system: San Fernando

Figure 7. Residual deformation of the P-F and EDF systems

4. Conclusions

Comprehensive sensitivity analyses of several leading BISs such as the P-F, RB, LRB, R-FBI and EDF systems, are presented. The bridge with BISs must trade off between the extent of force isolation and acceptable relative displacements across the isolation system during the earthquake motion. The recommended ranges of the two design parameters *i. e.,* the first natural period of the isolated bridge and the friction coefficient of the bearing are presented in this study. The two design parameters are determined by reciprocal relationship between the PDD and the POM. Comparisons and analyses on aseismic performances of different BISs for the selected design parameters are presented. Based on these results, the following conclusions may be drawn.

The PDD is increased as the first natural period of the isolated bridge is increased and as the friction coefficient of the device is decreased. Contrary to the PDD, the POM is increased as the first natural period is decreased and as the friction coefficient is increased.

Several design parameters of the bearing are influenced by various design conditions such as soil type, structure type and possible input ground motion. Therefore, it is important that adequate design parameters determined by the sensitivity analysis of the bridge with BISs are used in the design of the device instead of the conventionally recommended ones. It is shown within the range of these sensitivity analyses on variations in the design parameters of the bearing and a comparative study on aseismic performances of various BISs with the selected design parameters that the peak responses of the bridge with the friction-type bearing are less sensitive to substantial variations in the frequency range and the intensity of earthquake excitation when compared to those with the rubber-type bearing because of characteristics of friction elements.

Within the range of the parametric study of this paper, it is recommended using the first natural period shorter than 4.0 sec to avoid excessive deck displacement with suitable overturning moment. Furthermore, the use of adequate friction element is effective in reducing deck displacement and it is recommended using the friction coefficient smaller than 0.18. If the value of friction coefficient is larger than 0.18, there is little advantage of reducing deck displacement whereas overturning moment is monotonously increased.

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