다경간 연속교에 대한 면진용 교좌장치의 내진성능 비교연구

A comparative study on aseismic performances of base isolation systems for multi-span continuous bridge

박규식[1] 이종헌[2] 고만기[3] 이인원[4]

Park, Kyu-Sik Lee, Chong-Heon Ko, Man-Gi Lee, In-Won

요약: 다경간 연속교에 대한 여러가지 면진용 교좌장치들의 내진성능을 비교하였다. 본 연구에서 사용한 면진용 교좌장치들은 P-F, RB, LRB, R-FBI, EDF system 이다. 각 장치의 설계변수를 결정하기 위해 민감도 분석을 수행하였다. 면진장치가 설치된 교량의 고유주기와 장치의 마찰계수는 교량의 상판변위와 교각 밑면 모멘트 사이의 상반된 관계를 이용하여 결정하였다. 민감도 분석을 통해 결정된 설계변수에 대한 각 장치의 각 장치의 내진성능을 비교한 결과 상판변위는 R-FBI system을 설치한 교량이 가장 작았으며, 교각 밑면 모멘트는 EDF system을 설치한 교량이 가장 작았다. 마찰형 장치를 설치한 교량의 응답이 고무형 장치를 설치한 경우보다 외부하중의 강도나 주파수 변화에 덜 민감하였다.

ABSTRACT: Various base isolation systems, which are widely used, are compared for aseismic performances of multi-span continuous bridge. They are the P-F, RB, LRB, R-FBI and EDF systems. Sensitivity analyses are carried out to determine the design parameters of various devices. The design parameters, natural period of the isolated bridge and friction coefficient of the bearing, are determined by the reciprocal relationship between displacement and bending moment of the structure. Then the relative effectiveness of the bearings is described. Bridge with the R-FBI system shows the smallest peak displacement of deck whereas bridge with the EDF system shows the smallest peak bending moment of the lower end of pier in numerical examples. Furthermore, the peak responses of bridge with the friction type bearing are less sensitive to substantial variations in the frequency range and intensity of the ground excitation than those with the rubber type bearing.

핵심용어: 면진용 교좌장치, 교량 구조물, 내진성능, 민감도 분석, 설계변수, 비교연구

KEYWORDS: Base isolation system, Bridge structure, Aseismic performance, Sensitivity analysis, Design parameter, Comparative study

1) 한국과학기술원 토목공학과 박사과정
2) 경일대학교 토목공학과 교수
3) 정회원, 공주대학교 토목공학과 교수
4) 정회원, 한국과학기술원 토목공학과 교수

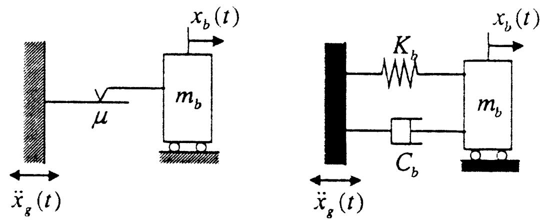
1. Introduction

To reduce the damage and destruction of structures during detrimental earthquake, earthquake-resistance design methods have been studied. The design method that isolates the structure from the severe seismic ground motions reduces the effect of earthquake loading on the structure and its components and equipment through the use of mechanical devices. On account of various advantages offered by this approach, researches on base isolation systems (BISs) have appealed to structural engineers for the last few decades. It is widely known that performances of aseismic bearings are very excellent. But a comparative study on aseismic performances of various BISs for the critical design parameters has been rarely done. Furthermore, most of previous studies are focused on the building structures [1,2,4]. And there are few studies on the bridge structures in spite that BISs are widely used for them.

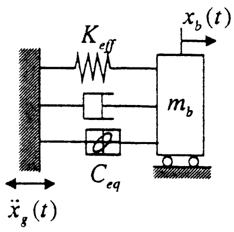
To evaluate aseismic performances of BISs and suitable earthquake-resistance design of structures, the sensitivity analysis for variations in the design parameters of devices is required. Therefore, a comparative study on aseismic performances of different BISs for multi-span continuous bridge is accomplished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

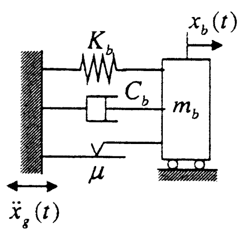
2. Aseismic base isolation systems

BISs have been used in earthquake-resistance design methods for the bridge structures in recent years. Various aseismic BISs have been suggested. The basic features of such devices consist of the horizontal flexibility and the energy dissipative capacity. The horizontal flexibility of the bearing can increase natural period of the isolated structure in order to avoid the frequency range which earthquake energy is dominant. But due to the horizontal flexibility, the displacement of the isolated structure increases. The energy dissipative capacity of the bearing can reduce this increased deflection. Owing to these characteristics of BISs, they can attenuate the harmful horizontal acceleration transmitted to the superstructure and reduce the sectional force of the substructure. Here, various leading BISs, which have been used or are considered to have considerable potential for wide applications, are briefly described.

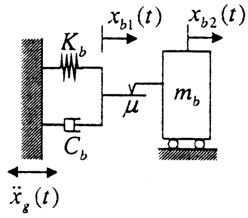


(a) P-F System (b) RB System





(c) LRB System (d) R-FBI System



(e) EDF System

Fig. 1. Schematic diagram of base isolation systems

2.1 The pure-friction (P-F) system

The P-F system is classified as the simplest device because it uses only stick-slip mechanism.

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 friction coefficient. But 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.

2.2 The laminated rubber bearing (RB) system

The RB system is widely studied and used over the world. It 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 parallel action of spring and dashpot as shown schematically in Fig. 1. Because damping capacity of the RB system is relatively small, it mainly shifts natural period of the isolated structure to avoid detrimental earthquake energy.

2.3 The lead rubber bearing (LRB) system

The LRB or New Zealand (NZ) system is also widely studied and used like a RB unit. A central lead core improves performances of the LRB system. It reduces the relative deflection and provides an additional means of energy dissipation.

2.4 The resilient-friction base isolator (R-FBI) system

The R-FBI system makes use of parallel action of resiliency of rubber and friction of Teflon coated plates. Similar to the P-F system, it does not slide below the frictional resistance. But unlike the P-F system, it has an additional resistance to increasing deflection and a recovering force by rubber after sliding.

2.5 The electricité de France (EDF) system

The EDF system consists of the elastomeric bearing and the friction plates in series. So during a low-intensity earthquake, it behaves as a RB unit and returns to its original position after the seismic event. When the frictional resistance is exceeded, slip will occur and the EDF system may have a residual deformation in the friction surface during a high-intensity earthquake. Thanks to 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, Dong-Jin bridge is used. It is a continuous bridge with 15 spans and constructed in the western sea highway. The span length of bridge is 725m and the width of the superstructure is 12.15m. The longitudinal slope is 0.03%. General pre-stressed concrete bridge has structural damping ratio of 2~3%, so Rayleigh damping with $\xi = 2\%$ is used in the modeling of Dong-Jin bridge.

A number of different earthquake excitations are used in the sensitivity analysis. Among several major earthquake excitations, El Centro 1940 (N00W, PGA=0.348g), San Fernando 1971 (S16E, PGA=1.170g) and Mexico City 1985 (N90W, PGA=0.172g) 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. In particular, Mexico City earthquake has considerable energy at low frequencies of about 0.5 Hz. So, 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 [6] is used for numerical analysis.

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 ambient vibration such as traffic or wind induced one. Friction coefficient of the bearing should be large enough to resist 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, natural period of the isolated bridge is changed from 1.0 sec to 6.0 sec with interval 1.0 sec and friction coefficient of the bearing is changed from 0.02 to 0.30 with interval 0.04 in the sensitivity analysis.

The peak responses of the center pier about longitudinal direction are calculated and compared. The peak displacement of deck and the peak bending moment of the lower end of pier are obtained to check the serviceability and the design sectional force.

3.1 Variations in natural period of the isolated bridge

One of the most important features of BISs is to shift natural period of the isolated structure to longer one in order to avoid the dominant frequency range of the earthquake ground excitations. Therefore, parameters such as stiffness of the bearing must be selected very carefully to achieve this goal. The numerical simulation results show that the peak responses of bridge with the rubber type bearing, the RB and LRB systems, have similar trend to the response spectrum of each earthquake because of linearity of the device. As a whole, the peak displacement of deck increases as natural period increases whereas the peak bending moment of the lower end of pier decreases. Most of the displacement of deck with the rubber type bearing is the deformation of the device and it is also observed that the deformation of pier is negligible as natural period increases. Especially, the peak responses of bridge with the rubber type bearing subjected to Mexico City earthquake are amplified in natural period of about 2.0 ~ 3.0 sec because earthquake energy is dominant in this range. Because of the additional energy dissipative capacity of a central lead core, the peak responses of bridge with the LRB system are smaller than those with a RB unit.

For the R-FBI and EDF systems, natural period and friction coefficient are the important design parameters simultaneously. The peak responses of bridge with the R-FBI system are similar to the response spectrum of each earthquake for small value of friction coefficient. But as friction coefficient increases, the peak responses are not sensitive to variations in natural period.

The peak responses of bridge with the EDF system shows similar trend to those with the rubber type bearing as friction coefficient increases. If there is no sliding in the friction plates, the responses of bridge with the EDF system are the same as those with a RB unit.

3.2 Variations in friction coefficient of BIS

For the friction type bearing, friction coefficient is very important design property. It is observed that an increase of friction coefficient of the P-F system, generally, leads to a decrease of the peak displacement of deck while it leads to an increase of the peak bending moment of the lower end of pier because of influence of the superstructure. The most portion of displacement is sliding deformation of the P-F system and the deformation of pier is negligible. As friction coefficient increases, slip seldom occurs in the P-F system, therefore the deformation of pier increases. The P-F system has an excessive deformation and a residual deformation because there is no recovering force.

For the R-FBI and EDF systems, sensitivity of the peak responses to variations in friction coefficient of the bearing according to natural period of the isolated bridge is obtained. The R-FBI system subjected to El Centro earthquake rarely slides for large value of friction coefficient and these results are similar to those of a P-F unit. But the R-FBI system gives additional resistance to an increase of displacement by parallel action of stiffness and damping. Thus the peak displacement of deck is smaller than that with a P-F unit while the peak bending moment of the lower end of pier is larger. For Mexico City earthquake, the peak bending moment of the lower end of pier with the R-FBI system decreases as friction coefficient increases for $T_0 = 2.0$ sec. This is why an increase of friction coefficient for $T_0 = 2.0$ sec reduces 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. The peak responses of bridge with the EDF system remain constant for variations in friction coefficient when there is no sliding. For Mexico City earthquake, the peak responses of bridge with the EDF system are amplified like those with the rubber type bearing.

3.3 Comparative study for different earthquakes with the selected design parameters

For comparisons and analyses of aseismic performances of various BISs with the fixed design parameters, natural period and friction coefficient are determined by the reciprocal relationship between displacement and bending moment of the structure. San Fernando earthquake has a general feature in the response spectrum and it is possible to examine the characteristic of sliding of the friction type bearing owing to relatively large intensity of the ground motion. Natural period of the isolated bridge and friction coefficient of the device are determined by using these features of San Fernando earthquake.

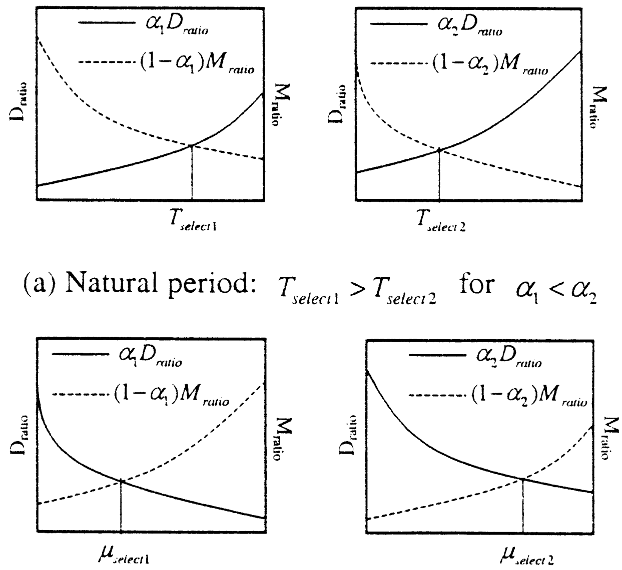
Importance of displacement or bending moment is different according to various design conditions. So, the design parameters of the device are determined by following procedure in this paper.

It is calculated that the ratio of the peak displacement and the peak bending moment to average value according to natural period and friction coefficient, respectively. These values are obtained through the sensitivity analysis using San Fernando earthquake for each bearing. To consider the influence of small values of results, average value is used instead of maximum one.

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

The curves of αD_{ratio} and $(1-\alpha)M_{ratio}$ are plotted in Fig. 2, for example. The α is a factor that indicates the relative importance of displacement. The α varies from 0 to 1 and in this study $\alpha = 0.5$, which means same importance of displacement and bending moment, is used. One can consider a different relative importance of displacement and bending moment using the factor α as shown in Fig. 2.

Finally, the meeting point of two curves is selected as the design natural period of the isolated bridge or friction coefficient of the device. Table 2 shows the selected natural period and friction coefficient determined by above procedure.



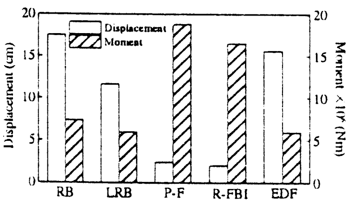
(b) Friction coefficient: $\mu_{select1} < \mu_{select2}$ for $\alpha_1 < \alpha_2$

Fig. 2. Selection of values of the design parameters

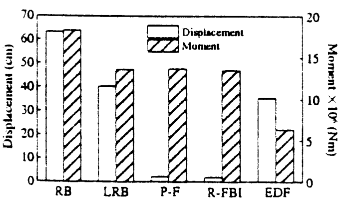
The peak responses of bridge with various BISs, which are designed by the selected parameters of Table 2, are shown in Fig. 3. Generally the peak displacement of deck with the rubber type bearing is larger than that with the friction type bearing while the peak bending moment of the lower end of pier is smaller. The P-F system has a residual deformation after the seismic event as shown in Fig. 4. Bridge with the R-FBI system shows the smallest peak displacement and bridge with the EDF system shows the smallest peak bending moment for all considered earthquakes. The EDF system has a residual deformation for San Fernando earthquake like a P-F unit.

Table 2. Selected values of the design parameters

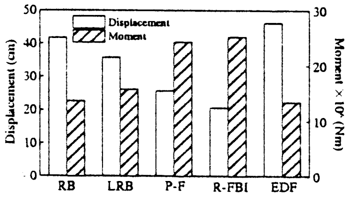
System	Natural period	Friction coefficient
RB	3.0 sec	N/A
LRB	3.0 sec	N/A
P-F	N/A	0.14
R-FBI	3.0 sec	0.14
EDF	4.0 sec	0.10



(a) El Centro

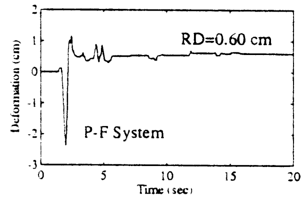


(b) Mexico City

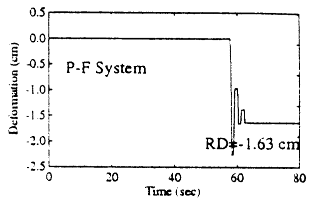


(c) San Fernando

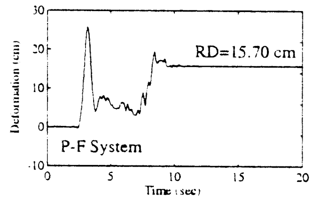
Fig. 3. Aseismic performances of various base isolation systems for the selected values of design parameters



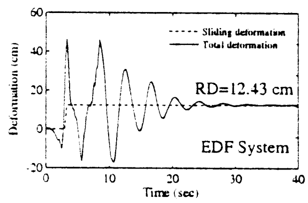
(a) El Centro



(b) Mexico City



(c) San Fernando



(d) El Centro

Fig. 4. Residual deformation (RD) of the P-F and EDF systems

The peak responses of bridge with the friction type bearing are less sensitive to substantial variations in the frequency range and intensity of earthquake excitation due to characteristic of stick-slip mechanism compared to those with the rubber type bearing.

4. Conclusions

Bridge with BISs shows the reciprocal relationship between displacement of deck and bending moment of the lower end of pier. The important design parameters, natural period of the isolated bridge and friction coefficient of the bearing, are determined by this reciprocal relationship. 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 peak displacement of deck increases as natural period of the isolated bridge increases and as friction coefficient of the device decreases. Contrary to the peak displacement, the peak bending moment of the lower end of pier increases as natural period decreases and as friction coefficient increases. Several design parameters of the bearing are influenced by various design conditions such as soil type, structure type and possible input ground motion. So it is important that suitable values determined by the sensitivity analysis, be used in the design of the device instead of fixed ones. 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 show that the peak responses of bridge with the friction type bearing are less sensitive to substantial variations in the frequency range and intensity of earthquake excitation when compared to those with the rubber type bearing. Bridge with the R-FBI system shows the smallest peak displacement of deck due to high-energy dissipative capacity of the frictional element. And bridge with the EDF system shows the smallest peak bending moment of the lower end of pier because of the flexibility of rubber.

Acknowledgements

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References

[1] Lin Su, Goodarz Ahmadi and Iradj G. Tadjbakhsh, (1989), "A comparative study of performances of various base isolation systems, Part I: Shear beam structures," *Earthquake Engineering and Structural Dynamics*, **18**, 11-32.

[2] Lin Su, Goodarz Ahmadi and Iradj G. Tadjbakhsh, (1989), "A comparative study of performances of various base isolation systems, Part II: Sensitivity analysis," *Earthquake Engineering and Structural Dynamics*, **19**, 21-33.

[3] R. Gueraud, J. P. Noel-Leroux, M. Livolant and A. P. Michalopoulos, (1985), "Seismic isolation using sliding-elastomer bearing pads," *Nuclear Engineering and Design*, **84**, 363-377.

[4] N. Mostaghel and M. Khodaverdian, (1987), "Dynamics of resilient-friction base isolator (R-FBI)," *Earthquake Engineering and Structural Dynamics*, **15**, 379-390.

[5] Anil K. Chopra, (1995), Dynamics of structures: Theory and applications to earthquake engineering, *Prentice Hall.*

[6] K. J. Bathe (1999), ADINA: Theory and modeling guide, *ADINA R&D, Inc.*