REVIEW ARTICLE

Overview of Base Isolation, Passive and Active Vibration Control Strategies for Aseismic Design of Structures[1]

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Recent development in passive and active vibration control of structures and their applications to earthquake resisting design is reviewed. Particular attention is given to the base isolation methodology and passive control techniques. The performance of several base isolation devices including the rubber bearing, the sliding-joint, the French system, and the resilient friction isolator for seismic protection of buildings is described. The use of recently developed passive frictional and viscoelastic dampers in structures is discussed. The active control methodologies for protecting the building during earthquakes is presented. The effectiveness of various base isolators, passive dampers and active control strategies under a variety of conditions are described, and their advantages and disadvantages are pointed out. It is shown that the acceleration transmitted to compact stiff structures during an earthquake can be effectively reduced by using properly designed base isolation systems. On the other hand, the passive dampers and active control methodologies may be used for protection of tall buildings against earthquake. In addition, these latter techniques may become useful for seismic rehabilitation of existing structures.

INTRODUCTION

The conventional technique for aseismic design of structures is to strengthen the structural members in order to protect them against strong earthquakes. However, this strengthening strategy inevitably leads to higher masses and hence higher seismic forces. A structure designed in this way may survive a strong earthquake, while it could result intolerable damages to its members, as well as to its sensitive internal equipment. Furthermore, the economical consideration limits the construction of a completely safe structure within the bounds of traditional design methodology.

In the past two decades, significant progress has been made in developing an alternative and attractive design strategy. The new approach is to use passive and active control mechanisms to control the vibration of structure during the earthquake strong motion. Thereby, the structure will become lighter and, eventually can be constructed at lower cost.

In this paper, the recent development on vibration control of civil engineering structures is reviewed. Particular emphasis is placed on

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the recent advances in base isolation technology. Recent studies on passive dampers for dissipating vibration energy of structure and the new development in active and hybrid vibration control methodologies are also described.

BASE ISOLATION

The passive base isolation techniques attempt to decouple the structure from the ground during a seismic event. The approach relays on minimizing the seismic energy that enters the structure, by partly reflecting the energy and partly dissipating it at the foundation level. As a result, the base isolation methodology appears to have considerable potential in preventing earthquake damages to structures and their internal equipment. The base isolation concept has a long history. According to Kelly [1,2], in 1909, a British physician obtained a patent on separating a building from the ground by a layer of talc or sand. However, it is only in the last two decades that this design concept has received serious attention. A number of base isolation systems for various types of structures have been suggested. Several of these have been developed and used to protect buildings, bridges, nuclear power plants and other structures against earthquakes. Extensive reviews on historical and recent developments were provided by Kelly [1,2] and Skinner et al. [3].

LRB System

The most important class of base isolation systems which has been extensively studied and implemented in a number of buildings around the world, is the laminated rubber bearing (LRB) base isolators [1-3]. An LRB isolator is made of alternating layers of rubber and steel with the rubber being vulcanized to the steel plates. The LRB is rather flexible in the horizontal direction but quite stiff in the vertical direction. The horizontal stiffness of the bearing is also designed in such a way that it can resist the wind forces with little or no deformation. The recommended natural period of the LRB base isolation system (for optimal performance) is between 1.5 to 2.5 sec.

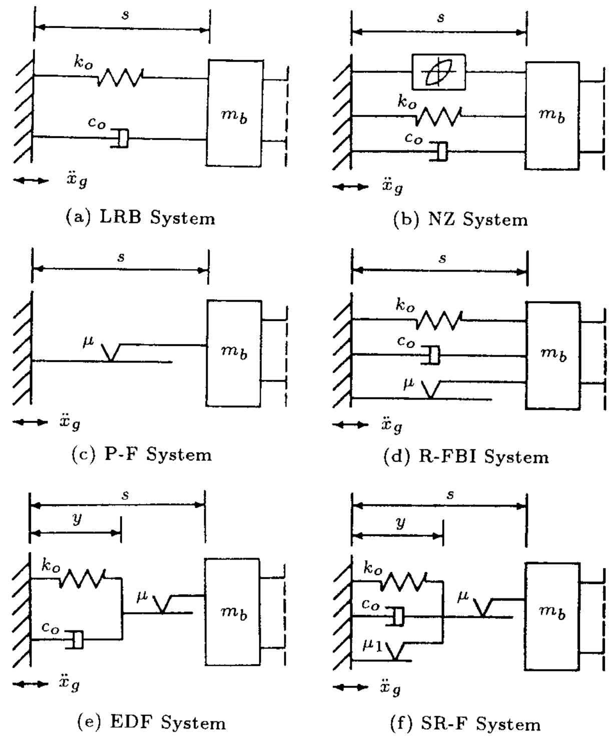

Figure 1. Schematic diagrams of various base isolation systems.

The effective damping ratio of the isolator, ζ_0, varies considerably with the strain of the rubber. According to [4,5], it may be as high as 0.3 for low strain and reduces to about 0.05 for high strain rubber. Figure 1a shows a schematic diagram for an LRB isolator. The GERB system [6], which is composed of helical springs and viscodampers behaves similar to the LRB system in the horizontal direction and its mechanical behavior may also be represented by Figure 1a.

NZ System

The laminated rubber bearing base isolator with a lead core has found wide application in New Zealand, as well as other countries. This system is referred to as the lead core LRB, or the New Zealand (NZ) base isolation system. The lead core is used to reduce the lateral displacement and to offer an additional mechanism for energy dissipation, while the flexibility and restoring force are provided by the rubber bearing. The performance of the NZ isolator (lead core laminated rubber bearing) under a variety of conditions was reported in [2,3,7]. Typically, in a natural period of around 2 sec, an effective damping of about 8% to 10% is assumed. A more detailed hysteretic model for the NZ system was described by Su et al. [8,9] and Fan et al. [10-12]. Figure 1b displays the mechanical behavior of the NZ base isolation system. The mechanical behavior of hysteretic damper [3,13-15] may also be schematically represented by this figure.

P-F System

Base isolation systems, in which the only isolation mechanism is sliding friction, are the pure-friction (P-F) or sliding-joint base isolation systems. In this class of base isolation systems, one or several friction plates, or a layer of sand, are used to isolate the structure from the ground. A schematic diagram for P-F base isolation systems is shown in Figure 1c. There has been a number of theoretical works on the performance of this class of isolators under deterministic or stochastic ground excitations [16-23]. In [24,25], the use of a layer of sand as a simple P-F base isolator for a building in Bejing, China was described. Different P-F systems usually have a friction coefficient in the range of 0.03 to 0.25 [16-23].

R-FBI System

Recently, a base isolation system referred to as the resilient-friction base isolation system (R-FBI) was proposed by Mostaghel [26-28]. This isolator consists of several layers of Teflon coated friction plates with a central core of rubber. The rubber provides the restoring force for the system and, hence, controls the relative displacement, while energy is dissipated by the friction forces. An extensive study of the responses of a five-story building isolated by the R-FBI system was provided by Mostaghel and Khodaverdian [29]. A natural period of 3 to 4.5 sec was suggested for the R-FBI base isolation system in [26-28]. Typically, a friction coefficient of $\mu = 0.05$ and an effective damping coefficient of $\zeta_0 = 0.08$ are used. Figure 1d illustrates the mechanical behavior of the R-FBI system. The Alexisismon base isolation system developed by Ikonomou [30] also makes use of the combined actions of sliding joint and rubber bearings. The rubber element in the Alexisismon system appears to act in bending while in the R-FBI isolator it acts in shear. Although these designs are quite different, the mechanical behavior of the Alexisismon base isolator may also be schematically represented by Figure 1d.

EDF System

Another base isolation system which is used for base isolation of nuclear power plants in regions of high seismicity was developed under the auspices of Electricite de France (EDF) [31]. It has been used in the design of nuclear power plants in France and Iran. Also the Kroeberg nuclear power plant in South Africa relies on the EDF base isolation system for protection against earthquake. An EDF base isolator unit consists of a laminated (steel-reinforced) neoprene pad topped by a lead-bronze plate which is in frictional contact with a steel plate anchored to the base raft of the structure. Whenever there is no sliding in the friction plate, the EDF system behaves as an LRB and the flexibility of the neoprene pad provides isolation for the structure. The presence of the friction plate serves as an additional safety feature for the system. Whenever the ground acceleration becomes very large, sliding occurs which dissipates energy and limits the acceleration transmitted to the superstructure. The behavior of the EDF base isolator is shown schematically in Figure 1e. In practice, the laminated neoprene pad is designed to have a natural period of about 0.8 to 1.2 sec, and the friction coefficient of the friction plate is about 0.2.

SR-F System

A base isolation concept which combines the desirable features of the R-FBI and the EDF systems was proposed in [32]. This system, which is referred to as the sliding resilient-friction (SR-F) base isolation system, is a R-FBI unit with an additional upper friction plate. The behavior of the SR-F isolator is shown schematically in Figure 1f. Whenever the SR-F base isolator behaves as a R-FBI unit. For high ground accelerations, sliding in the upper friction plate occurs which provides an additional mechanism for energy dissipation and increases the overall effectiveness of the isolation system.

Design Requirements

General design requirements for a base isolation system and design criteria for a base-isolated building were described in [1-3,33-35]. In these works, code-type criteria regarding allowable base displacement, peak transmitted acceleration, natural period and seismic coefficient were suggested. Guidelines regarding the design of the rubber bearing base isolation system with or without a lead core were also presented in [1-3,33-35]. In their book, Skinner et al. [3] also provided a listing of existing base-isolated structures around the world. The procedure for design of the NZ (rubber with lead core) system together with certain experimental data on the system performance was presented by Kelly et al. [36]. Recently, Mostaghel et al. [37,38] described the design procedure for the R-FBI system.

Comparative Study

Recently, Su et al. [8,9] carried out several comparative studies of different base isolation devices for rigid and shear beam structures. Fan et al. [10-12] considered the performances of various base isolation systems for a multi-story building under a horizontal sinusoidal, as well as earthquake ground motions. In these works, performances of different base isolation systems subject to various earthquake excitations were studied. The peak absolute acceleration of each floor, the peak base displacement and the peak structural deflection for various base isolation systems were evaluated and the results were compared with each other and with those of the fixed-base structure. The acceleration responses both in time and frequency domains were examined. Earlier, Hadjian and Tseng [39] discussed the requirement of base isolation systems.

Response Spectra

In this section, a three story building is considered and the N00W component of El Centro 1940 earthquake is used as the ground excitation. Parameters of base isolation systems as shown in Table 1 and a structural damping of $\zeta_1 = 0.02$ are considered. For various base isolation systems and for the fixed-base structure, the peak absolute acceleration at different floors of the structure, for a range of structural natural periods, T_1, is evaluated. The resulting response spectra curves are plotted in Figures 2-6.

Figure 2 shows the peak acceleration responses for the fixed-base structure. The constant acceleration of 0.348g for the base floor (which is the peak ground acceleration of the El Centro 1940 earthquake) is also shown in this figure for reference. It is observed that the

Table 1. Values of parameters used for various base isolators.

Base Isolation System	Natural Period T_o(sec)	Damping Coefficient ζ_o	Friction Coefficient $\mu(\mu_1/\mu)$
Pure-Friction (P-F)	-	-	0.1
Laminated Rubber Bearing (LRB)	2	0.08	-
Resilient-Friction(R-FBI)	4	0.08	0.05
Electricite de France (EDF)	1	0.08	0.2
New Zealand (NZ)	2	0.08	-
Sliding Resilient Friction (SR-F)	4	0.08	0.05/0.2

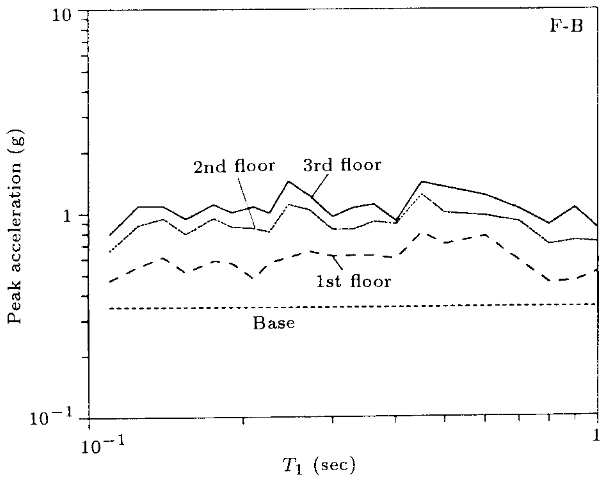

Figure 2. Variations of peak absolute acceleration at various floors of the fixed-base structure.

accelerations is amplified as it is transmitted to the higher floors. The peak acceleration response of the third floor is about 1g which is approximately three times that of the ground excitation.

The peak acceleration responses at various floors for the structure with an LRB system are shown versus the fundamental natural period of the structure in Figure 3. It is observed that the acceleration responses for various floors are almost identical and remain a constant of about 0.15g to 0.2g which is significantly lower than that of the fixed-based structure. This figure clearly shows that the structure with a laminated rubber bearing base isolation system vibrates as a rigid body to seismic excitations.

In figure 4, the peak acceleration responses of a three-story building with a pure friction base isolator are shown. It is noticed that the base floor experiences peak accelerations of about 0.3g to 0.4g throughout the entire range of T_1. However, the acceleration is generally attenuated due to the structural damping as it is transmitted from the base to the first floor. It is also observed that the acceleration is amplified as it propagates from the second floor to the third floor.

Figure 5 illustrates the peak acceleration responses at various floors for the structure which has a R-FBI or SR-F system at its foundation. The general characteristics that were noted for the P-F system are also noticed for these resilient-friction systems. The acceleration is first attenuated and then is amplified as it is transmitted from the lower floor to higher floors. At the third floor, the peak acceleration reaches the same level as the base excitation.

The peak acceleration responses at various floors for the structure with a EDF system are shown in Figure 6. It is observed that the acceleration responses have two distinct features. Similar to the LRB system, the differences of the peak acceleration between

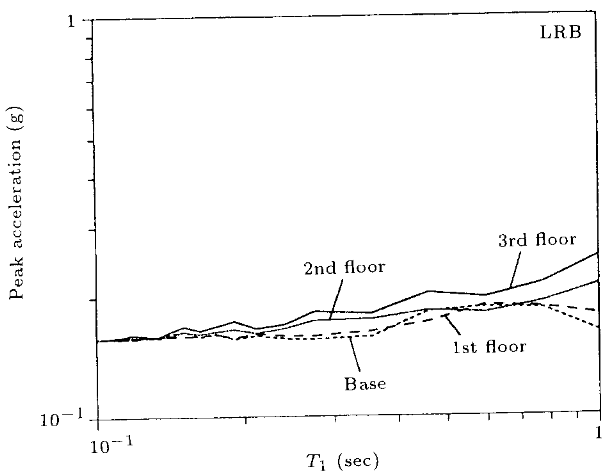

Figure 3. Variations of peak absolute acceleration at various floors of the structure with the LRB isolation system.

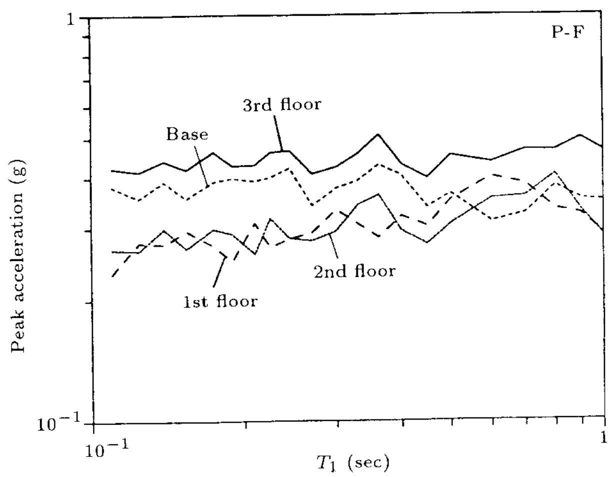

Figure 4. Variations of peak absolute acceleration at various floors of the structure with the P-F isolation system.

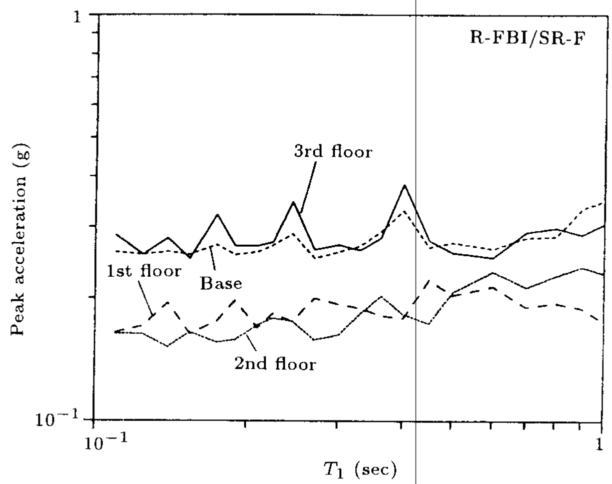

Figure 5. Variations of peak absolute acceleration at various floors of the structure with the R-FBI and SR-F isolation systems.

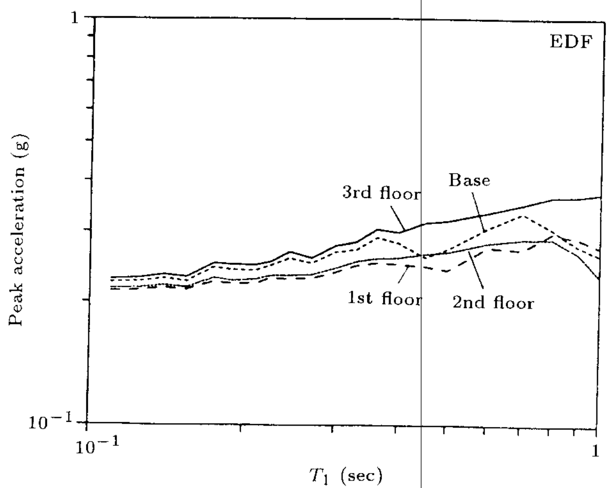

Figure 6. Variations of peak absolute acceleration at various floors of the structure with the EDF isolation system.

different floors increase as the structural stiffness decreases. Furthermore, like the P-F and the R-FBI/SR-F systems, the peak acceleration response decreases as it is transmitted from the base to the first floor, and increases as it is transmitted from the second floor to the third floor. Additional detailed results concerning the performance of various base isolation systems were reported by Su et al. [8,9] and Fan et al. [10-12].

Sensitivity Analysis

The sensitivity of the performance of different base isolation systems to small variations in their properties were studied by a number of authors. Here, certain new results concerning the sensitivity of frictional base isolation systems to variation in the friction coefficient are presented. Figure 7 displays the peak structural deflections for various frictional base isolators subject to the accelerogram of El Centro 1940 earthquake. It is observed that the peak (top floor) deflection response of the structure with a pure friction system is almost identical to that of a structure with a R-FBI system throughout the entire range of friction coefficient. The peak deflections for the EDF system is lower than those of the pure friction and the R-FBI systems for the same value of μ.

As noted before, the SR-F base isolation system has two effective friction coefficients, namely, the friction coefficient of the body plates, μ_1, and that of the upper plate, μ. Figure 8 shows the effect of variations in μ and μ_1 on the peak deflection responses of a structure with a SR-F base isolation system. In this figure, SR-F1 corresponds to the case when the friction coefficient of the upper plate is varied, while μ_1 is kept constant at 0.05. Similarly, SR-F2 denotes the results when μ_1 is changed and μ is fixed at 0.1. It is observed

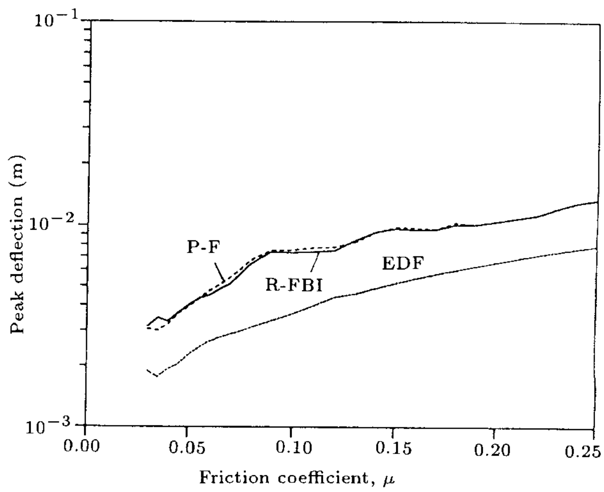

Figure 7. Variations of peak deflections with friction coefficient for different base isolation systems.

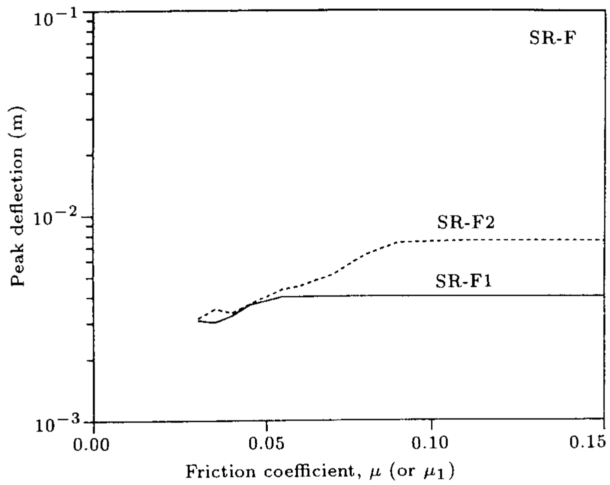

Figure 8. Variations of peak deflections with friction coefficients for the SR-F base isolation system.

that the peak deflection responses for the SR-F1 system increases gradually as μ increases for $\mu < 0.07$. For $\mu > 0.07$, the deflection responses remain a constant of about 4 mm. The peak deflection responses for the SR-F2 system also increase with μ_1, for $\mu_1 < 0.1$, while for $\mu_1 > 0.1$, no noticeable variation is observed.

Figure 9 shows the effect of variation of coefficient of friction on the peak base displacement responses for the P-F, the R-FBI and the EDF systems. It is observed that the peak base displacement responses generally decrease as μ increases. The exception is the EDF system for which the peak base displacement first increases to a peak of about 19 cm at $\mu = 0.05$, and then decreases with further increase in μ. For the R-FBI and the P-F systems, about 50% decrease in their peak base displacement responses is observed when μ varies from 0.03 to 0.1. The effect of variations in friction coefficients of the body and the upper plates on the peak base displacement responses for the SR-F systems are displayed in Figure 10. This figure shows that as μ increases, the peak base displacement of the SR-F1 system first decreases and then remains a constant for $\mu > 0.07$. Similarly, for the SR-F2 system, the peak base displacement decreases with an increase of μ_1 up to $\mu_1 = 0.1$, and then remains a constant for greater value of μ_1. Additional results concerning the sensitivity of base isolation devices to variation in their physical properties were reported by Fan et al. [10-12], among others.

The results presented here and in the earlier works clearly show that the transmitted acceleration and the column stresses of the structure can be significantly reduced by using a properly designed base isolation system. The laminated rubber bearing is highly effective in protecting relatively compact and stiff structures against earthquake. The frictional

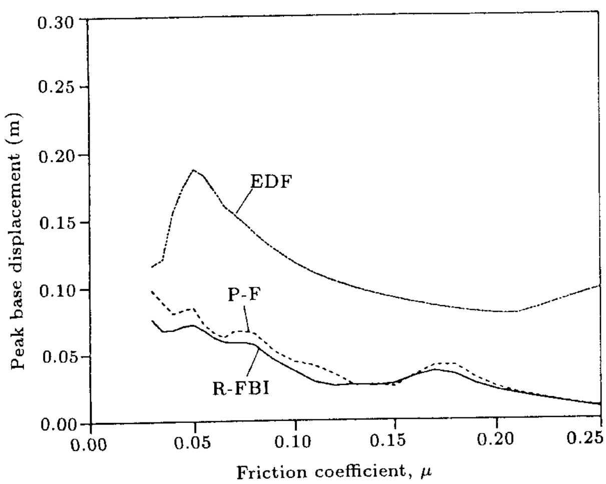

Figure 9. Variations of peak absolute base displacements with friction coefficient for different isolation systems.

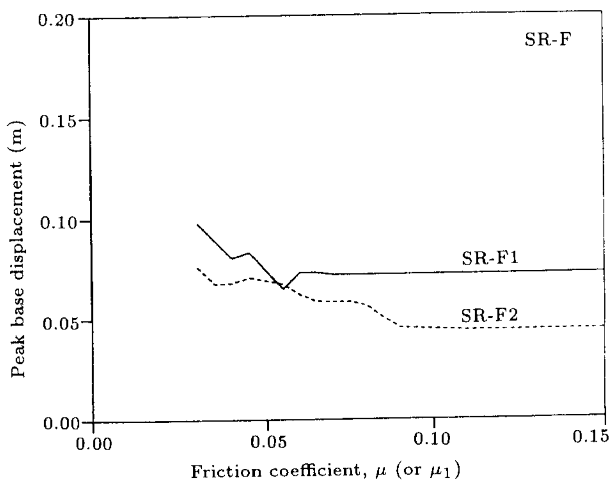

Figure 10. Variations of peak absolute base displacements with friction coefficients for the SR-F isolation system.

systems generate high frequency peaks in the acceleration responses, however, these high frequency peaks do not lead to large structural deformations. The friction-type isolation systems also appear to be less sensitive to the variations in the amplitude and frequency content of the ground excitation in comparison to the rubber bearing type base isolators. The peak structural deflection are not significantly affected by small variations in the friction coefficient of the friction-type isolators.

Secondary Systems

Recent works on responses of secondary systems for fixed-base structures were reported in [40-42] and an extensive state-of-the-art review on the subject was provided by Chen and Soong [43]. Studies on the responses of secondary systems for base-isolated structures are rather scarce. Recently, a series of shaking table studies on the influence of base isolation on light secondary equipment was reported in [44]. Buckle et al. [45] studied floor response spectra for a fast breeder reactor. Kelly and Tsai [46] described the responses of light secondary systems in a five-story building with a laminated rubber bearing base isolation system. Detailed studies of performance of various base isolation systems in protecting the secondary system were performed by Fan and Ahmadi [47,48], Manolis et al. [49,50] and Ahmadi and Su [51].

Figure 11 shows the deflection floor spectra for the top floor of the three story structure with different base isolation systems and the fixed-base one. It is observed that the floor spectra of the fixed-base structure has a sharp peak at the frequency of about 3.33 Hz, because considerable energy is channeled into the fundamental natural frequency of the structure under this broad-band earthquake ground excitation. Beyond this frequency, the spectral amplitude decreases rapidly. Figure 11 also shows that, for $f_s > 2$ Hz, all base isolation systems eliminate the resonance peak and significantly reduce the peak deflection of the secondary system. The LRB system generally leads to the lowest deflection floor spectra among the isolators considered. However, for $f_S < 2$ Hz, the LRB and the EDF systems lead to peak responses higher than those for the fixed-base structure. The LRB system also shows a resonance peak at $f_S = 0.5$ Hz, corresponding to the natural frequency of the isolator. The natural frequencies of the secondary systems are normally higher than that of the structure. Thus, the use of the base isolation systems significantly reduces the peak deflection generated in the secondary systems.

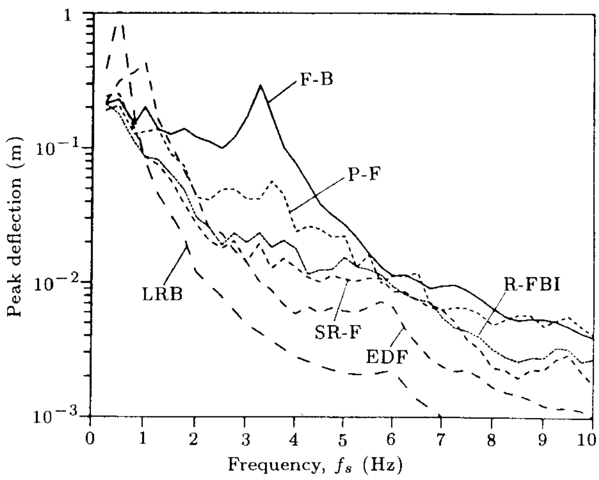

Figure 11. Deflections floor spectra for El Centro 1940 earthquake.

Based on the results presented here and in [3,47,48], it may be concluded that use of base isolation systems provides considerable protection for the secondary systems and the structural contents. Among the isolators considered, the LRB system leads to the lowest peak responses in the secondary systems.

Random Excitations

Sensitivity analysis of buildings with base isolation devices subject to random earthquake excitations was considered by a number of researchers in the past. Extensive literature reviews on the application of equivalent linearization method and other approximation techniques have been provided by Roberts [52,53], Crandall and Zhu [54] and Spanos [55]. Ahmadi, Tadjbakhsh and co-workers [56-62] performed a number of studies on performance of various base isolation systems to random models of earthquake excitations. Stochastic earthquake response of secondary systems in base isolated structures were analyzed in [62]. In these studies, the equivalent linearization method was used for analyzing the responses of structures with nonlinear frictional base isolation systems. It was shown that this method leads to reasonable peak response statistics for the base-isolated structures. More advanced procedures for random response analyses of nonlinear systems were described in the literature. These include the Gaussian and non-Gaussian cumulant-neglect method developed by Noori and Davoodi [63,64], and the Wiener-Hermite functional expansion technique proposed by Jahedi and Ahmadi [65] and Orabi and Ahmadi [66-68]. These techniques, however, have not been used for response analysis of base isolated structures as yet.

PASSIVE DAMPERS

Use of passive dampers for protection of structures against earthquake has attracted considerable attention. Aiken et al. [69], Roik et al. [70] and Scholl [71] performed a series of studies on the effectiveness of frictional dampers for seismic applications. In practice, the frictional dampers are installed at diagonal bracing or at appropriate joints for damping the vibration energy generated by earthquake or wind excitations. Constantinou and Tadjbakhsh [72] described a procedure for optimal design of first story damping of structures. Graesser and Cozzarelli [73] developed a model for hysteretic damping of materials including shape memory energy alloys for seismic applications. Damping of structures was also studied by Liang and Lee [74]. Chang et al. [75] performed a series of experiments on the effectiveness of the viscoelastic dampers. Zhang et al. [76] and Soong and Lai [77], among others, studied the performance of hysteretic and viscoelastic dampers for seismic applications. The viscoelastic and hysteretic dampers are usually made of layers of materials which are made to deform under direct shear in order to dissipate vibrational energy. The earlier studies have shown that properly designed dampers can be highly effective in reducing the peak structural responses. However, their performance is somewhat sensitive to the frequency content of the excitation and the thermal environment that the damper is exposed to.

ACTIVE CONTROL

Active vibration control systems have been successfully utilized for aircraft, spacecraft, mechanical devices and various structures [78-84] in the last two decades. Also, notable success for active vibration control of civil engineering structures have been reported by Abdel-Rahman and Leipholz [85-88], Leipholz [89], Soong and co-workers [90-94], Masri and Caughey [95,96], Yang and co-workers [97-103] and Yao et al. [104-107]. Issues concerning the significance of time delay in vibration control of structures and acceleration control were discussed by Iwan and Hou [108]. Detailed analysis of active control systems were described by Meirovitch [109]. The potential usage of active control for retrofitting existing structures was also discussed by Meirovitch [110]. A procedure for instantaneous active control of distributed parameter buildings was described by Tadjbakhsh and Su [111,112]. Use of hybrid passive and active control of structure was suggested by Pu and Kelly [113] and Kobori et al. [114]. Extensive reviews on active control methodology were provided by Soong [115-117], Meirovitch [109], Kobori [118], and Melcher and Breitbach [119]. Samali et al. [120] studied active control of coupled lateral-torsional motion of wind-excited buildings. Warburton and co-workers [121-123] analyzed the performance of tuned mass damper for vibration control of structures. An extensive review of literature on active vibration control and future research need was provided by Housner et al. [124].

Recently, Lee-Glauser et al. [125] studied the effectiveness of an active vibration absorber (AVA) in conjunction with the use of a model independent active control strategy. Their results for a three story building subjected to the El Centro 1940 earthquake are reproduced in Figure 12. In this figure the structural

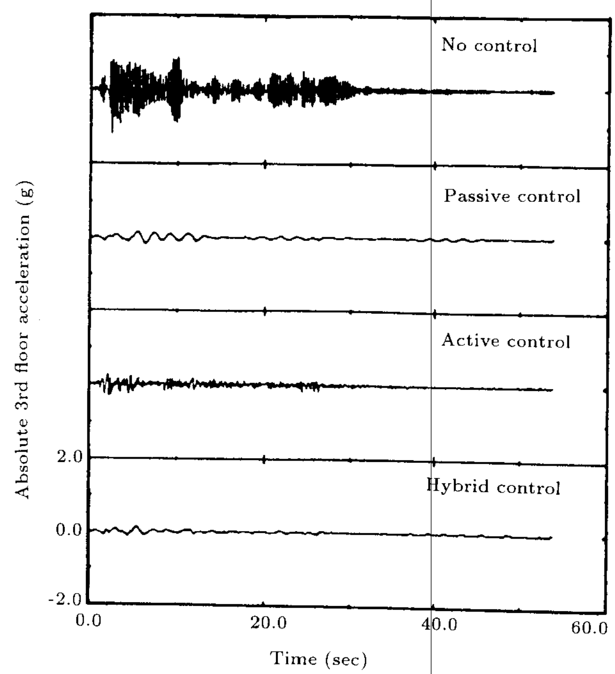

Figure 12. Time histories of absolute accelerations for El Centro 1940 earthquake excitations.

responses for an unprotected structure and the one with a laminated rubber bearing are also shown for comparison. It is observed that the AVA system is highly effective in reducing the peak structural responses.

The presented review indicates that significant progress has been made in active control of structures. In particular, the active control appears to have considerable potential for vibration control of tall buildings and the existing structures.

HYBRID CONTROL

There has been considerable recent interest in developing hybrid (combined passive and active) control systems for structural protection against earthquake. The hybrid system which combines the advantages of passive and active systems could, in principle, be highly effective. Yang and co-workers [126,127] proposed the use of a hybrid system which is composed of an elastomeric bearing and an active or passive tuned mass damper. They showed that the combined system could become highly effective. Reinhorn et al. [128] provided an extensive experimental study of the performance of active tendon and active dampers. Tadjbakhsh and Rofooei [129] and Luco et al. [130] performed computer simulation of the performance of hybrid systems. Active control of frictional isolation system was studied in [131,132]. Application of hybrid vibration control of aerospace structures was reported by Lee-Glauser et al. [133]. These studies clearly showed the feasibility of using a combination of passive and active control systems for optimum performance.

Lee-Glauser et al. [125] also analyzed the performance of a hybrid combination of the AVA system with a passive laminated rubber bearing isolation system for seismic applications. Their resulting acceleration time history for the El Centro 1940 earthquake excitation is shown in Figure 12, and is compared with acceleration levels for the uncontrolled structure, as well as for those with passive and active systems. This figure shows that the hybrid system is highly effective. In [125], it was also shown that the presence of the AVA system will significantly reduce the peak base displacement of the passive isolation system.

CONCLUDING REMARKS

In this review article, the recent developments in passive, active and hybrid vibration control of structures for earthquake protection are presented. Certain results on performance of various base isolation systems and active and hybrid control systems are also described. The presented material indicate that compact and relatively stiff structures during an earthquake can be effectively protected by using a properly designed base isolation system. The passive dampers and active control methodologies are highly effective for protection of tall buildings against earthquake. The hybrid combination of passive and active control strategies may be designed for optimal performance. In addition, these different vibration control techniques may also be used for seismic rehabilitation of existing structures.

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