Control of building vibration against earthquakes

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ABSTRACT

An aseismic hybrid control system was employed to protect a five-storey benchmark-building model against strong earthquakes. The hybrid control system consists of a base isolation system (laminated rubber bearings) connected to an active control system (a tuned mass damper and an actuator). A five-storey benchmark model is developed to study the effectiveness of the hybrid control system against different ground motions: El-Centro 1940, Hachinohe 1968, Kobe 1995, and Northridge 1994 earthquakes. It was found from the numerical results, that the rubber bearing system alone can perform well against Hachinohe and Northridge ground motions, but not well enough to protect the lower floors of the model against El-Centro and Kobe ground motions. After an active control system was implemented to the rubber-isolated model, further improvements in earthquake resistance against these four earthquakes were obtained, especially against the El-Centro and Kobe. It is shown that a combined use of active and passive control systems, (referred to as hybrid control system), is more effective in reducing the building response under strong earthquakes.

INTRODUCTION

Base isolation as a passive control technique has been developed rapidly for the past two decades to protect structures from the damage caused by earthquakes. The base isolation system, such as rubber bearings, is employed to decouple the horizontal ground motions from the buildings so that the damaging earthquake motions cannot be transmitted to the buildings. Although passive control technique is effective for protecting seismic-excited buildings, there are some limitations. Base isolation systems are usually limited to low-rise buildings; this is because for tall buildings, uplift forces may be generated in the isolation system leading to an instability failure. More importantly, the low stiffness of rubber bearings could cause the displacement of the structure to become too large [2]. The excessive deformations associated with the base isolation system increases the difficulty of its implementation and the overall cost of the buildings.

The application of active control systems to building structures when subjected to strong earthquakes and other natural hazards has become an area of considerable interest both theoretically and experimentally in recent years. The active protective systems differ from the passive ones (e.g. base isolation) in that they require the supply of external power to counter the motion of the structure to be protected. These active control systems usually perform very well in protecting buildings from the damage of strong earthquakes. However, when an active control system is used alone as the primary protective system, the required active control force and force rate to be provided by the external power source may be very large, especially for tall buildings. For the installation of a large active control system with large stand-by energy source, the issues of cost, reliability and practicality remain to be resolved.

(a) Bare frame

(b) Base isolated frame

Figure 1. Five-storey building frame,
(a) Bare frame (b) base isolated frame

More recently, it has been shown that hybrid control systems, a combined use of active and passive control systems, is more effective, beneficial and practical in some cases [3]. The ideal of hybrid control systems is to utilize the advantages of both the passive and active control systems to extend the range of applicability of both control systems to protect the integrity of the buildings. It is shown that the hybrid control systems are very effective in reducing the response of building structures under strong earthquake excitations and that they may be more effective and advantageous than the application of an active control system alone, especially under extreme loading environments such as strong earthquakes.

In this study, a hybrid control system, initially proposed by Yang [3] and consisting of a base isolation system of laminated rubber bearings and an active control system, including a tuned mass damper and an actuator, was used to study the earthquake response of a five-storey benchmark model. The performance of this hybrid control system is evaluated and compared with that of the base isolation system alone. As identified in a previous work [5], the effectiveness of base isolation system of rubber bearings in reducing storey drifts of the five-storey model under strong ground motions is earthquake type dependent. Therefore, the effectiveness of this hybrid control system under different strong earthquakes is evaluated in some detail.

FIVE-STOREY BUILDING MODEL

A five-storey benchmark model designed by Samali [1] and fabricated at the University of Technology, Sydney was adopted by International Association for Structural Control as one of several experimental benchmark building models for shake table testing. The bare frame model, as shown in Fig. 1(a), has dimensions of 1.5m x 1m x 3m with 5 equal storey heights of 0.6m. Its total mass is 1000kg. It consists of two bays in one direction and a single bay in the other. Fig.1 (b) shows the base isolated model with six multilayered laminated rubber bearings with steel reinforcing layers as the load-carrying component of the system.

FORMULATION

Consider an n degree of freedom linear building structure subjected to one-dimensional earthquake ground acceleration. The governing equation of motion is given by

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = HU(t) + \eta\ddot{X}_0(t) \tag{1}$$

in which X(t)=[X_1,X_2,……,X_n]' is a vector of dimension n with X_i(t) being the drift of ith storey unit; U(t)=a vector of dimension r consisting of *r* control forces; and η is a vector of dimension n denoting the influence of earthquake excitation. *M*, *C*, and *K* are (n × n) mass, damping and stiffness matrices, respectively, and *H* is a (n × r) matrix denoting the location of controllers. $\ddot{X},\dot{X}$ represent acceleration and velocity respectively. In the state space form, Equation (1) becomes

$$\dot{Z}(t) = AZ(t) + BU(t) + E(t) \tag{2}$$

Where Z(t) is a 2n state vector, *A* is a (2n × 2n) system matrix, *B* is a (2n × r) matrix and, E(t) is a 2n excitation vector [4].

SIMULATION AND DISCUSSION

The motion equations of the bare model, rubber-isolated model and the model with hybrid control system were numerically solved using Matlab 7.0.2 software package. Linear-Quadratic Regulator (LQR) control was used for the active control system. The lumped mass model used in the simulation is shown in Fig. 2. All four earthquakes, namely, El-Centro 1940, Hachinohe 1968, Kobe 1995, and Northridge 1994 were scaled down by a factor of three on time axis to increase their frequency in order to meet dynamic similitude requirements. To reduce the structural response, the model was first isolated using low damping rubber bearings, (see Fig. 2(b)). Six rubber bearings were mounted between the model and the base. The total mass of the six rubber bearings is m_b=0.2 tonne. The lateral stiffness and viscous damping coefficient are linear with k_b=1200 kN/m and c_b=0.2 kN.sec/m, respectively. For the base isolated system, the six natural frequencies of the entire system are 3.30, 16.65, 31.18, 44.58, 55.65 and 63.36 Hz respectively. It is clear that the fundamental frequency is substantially reduced by the implementation of a base isolation system from 8.38Hz to 3.30Hz as expected. An active control system (a tuned mass damper and an actuator) was then supplemented to form a hybrid control system, (see Fig.2(c)). The mass of the active damper is equal to floor mass of the model with m_d=0.2 tonne.

Seismic response reductions with respect to the bare frame are presented in Table 1. The floor displacements relative to the base (or top of the rubber bearings) are displayed in Fig. 3 and floor accelerations relative to ground in Fig.4, respectively. It is very clear that the present base isolation system can reduce the floor displacements of the model caused by Hachinohe and Northridge earthquakes, while it is not effective against Kobe and El-Centro ground motions. A similar phenomenon is also observed for the floor accelerations. Dependence of the effectiveness of the base isolation system on the type of ground motion has been a long-standing issue for the application of base isolation systems to light-weight structures since the fundamental frequencies of the isolated structures can still be located within the range of earthquake-dominated frequencies. For a base isolated system, assuming that the structure behaves as a rigid body, the frequency of the isolated structure is proportional to $(K_b/M)^{1/2}$, where K_b is the total stiffness of rubber bearings and M the total mass of the system. For a light structure, it is difficult to shift the fundamental frequency of the isolated structure to less than 0.5 Hz. This is due to limitations on rubber bearing dimensions and material properties. When an actuator is installed to rubber bearings to form a hybrid control system, it can be seen from Figs. 3 and 4 that both floor displacements and accelerations of the model can be reduced dramatically, compared with those of the bare frame.

Time histories of rubber bearing deformation with respect to the ground under the El-Centro excitation are presented in Fig. 5. When base isolation alone was used the transient vibrations led to a maximum deformation of 17 mm, which is clearly large and may result in some difficulties in the practical design of the isolated structure and an increase in cost. With a hybrid control system, the maximum value was reduced to a very low level of 2 mm. This low base deformation has obvious design and construction advantages.

Fig. 6 shows the 5^{th} floor accelerations for the three systems, namely bare frame, base isolated system and hybrid system, under Hachinohe excitation. It is clear that a larger period and a faster attenuation of acceleration amplitude occur for the base isolated model with the maximum value of 0.72g being much lower than 2.13g for the unisolated model. However, the hybrid control system is more effective and results in a further decrease of the maximum acceleration being only 0.3g. And the acceleration amplitude attenuates to a very low level after a time lapse of about 3 seconds.

The time histories of the base shear force over 16 seconds of Kobe earthquake are depicted in Fig.7. It was found that the maximum base shear force of isolated model, being 29 kN, is much smaller than 52kN for the bare frame. As a result, the potential damage to the bottom level of the five-storey steel frame is reduced. A further significant decrease in the base shear force, only being 15kN, is obtained when an active control system was supplemented to the base isolated model. The latter decrease is very important not only to the integrity of the five-storey model but also to safety and service life of the rubber bearings.

CONCLUSIONS

In this study, the seismic responses of a five storey benchmark model with a particular laminated rubber bearing system and a hybrid control system were simulated using four different earthquake inputs. It was found that the performance of the base isolation system is strongly dependent on the type and nature of the earthquake ground motion because of light weight of present benchmark laboratory model. However, a combination of active mass damper and the rubber isolation system is much more effective and reduces all major responses due to ground motions regardless of the earthquake type. Moreover, a hybrid control system is capable of lowering base deformation of rubber bearings and base shear force, hence providing conveniences in design and increasing the safety and service life of rubber bearings. Further work is planned to test the performance of this particular isolation and hybrid control system on UTS shake table in order to verify the simulation results.

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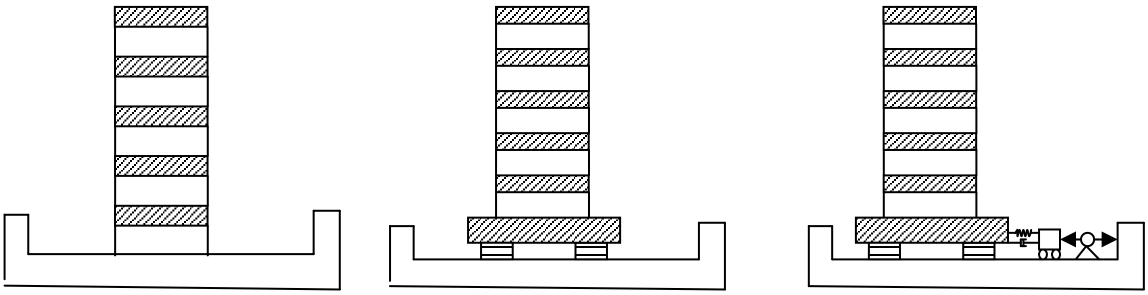
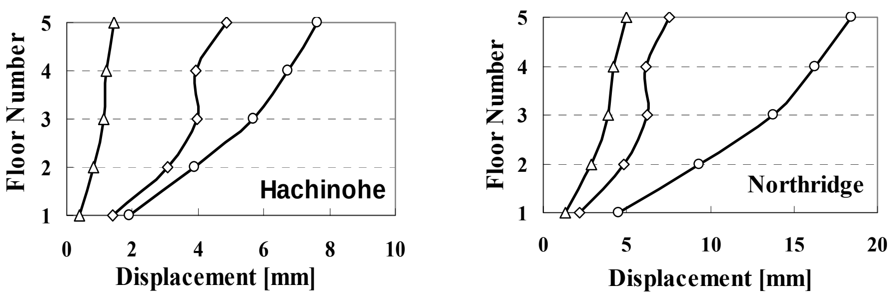


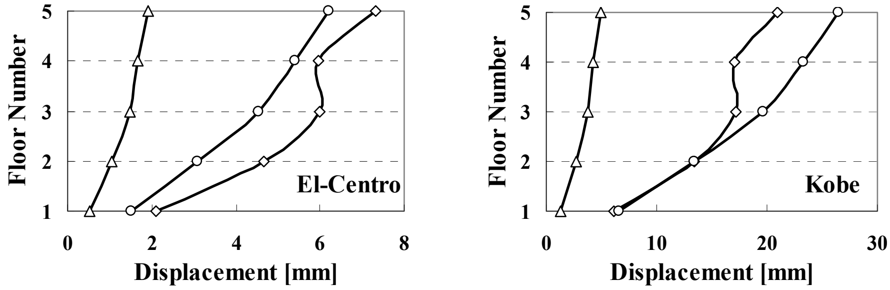
(a) Bare frame (b) Base isolated frame (c) Hybrid controlled frame

Figure 2. Schematic of simplified lumped mass model representing the five-storey building frame

Table 1. Seismic Response Reductions with respect to bare frame

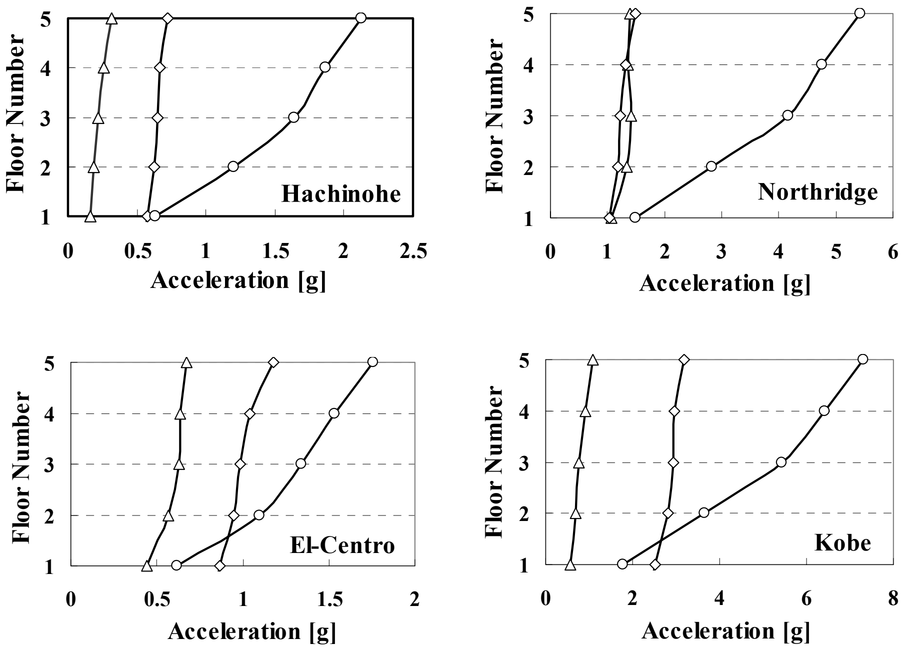
	5^{th} floor peak acceleration relative to ground [g]		5^{th} floor peak displacement relative to base [mm]		Interstorey drift between 3^{rd} and 2^{nd} floor [mm]		Base shear Force [kN]	
	Passive [%]	Hybrid [%]	Passive [%]	Hybrid [%]	Passive [%]	Hybrid [%]	Passive [%]	Hybrid [%]
Hachinohe	65	85	36	88	51	89	56	58
Northridge	73	74	63	80	71	84	75	68
El-Centro	33	62	-18	82	11	81	17	41
Kobe	56	85	21	89	40	83	45	71





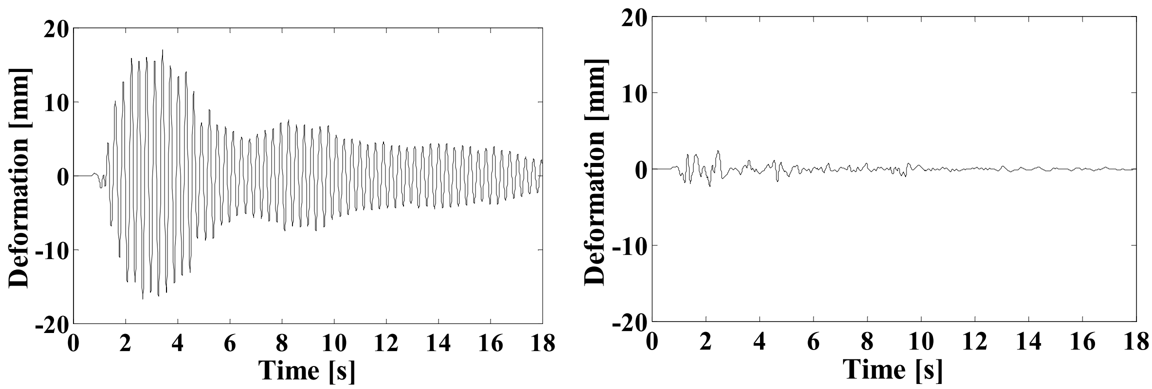
O---- Bare frame; ◊---- Base isolated frame; Δ---- Hybrid controlled frame

Figure 3. Floor displacements with respect to the base of the frame



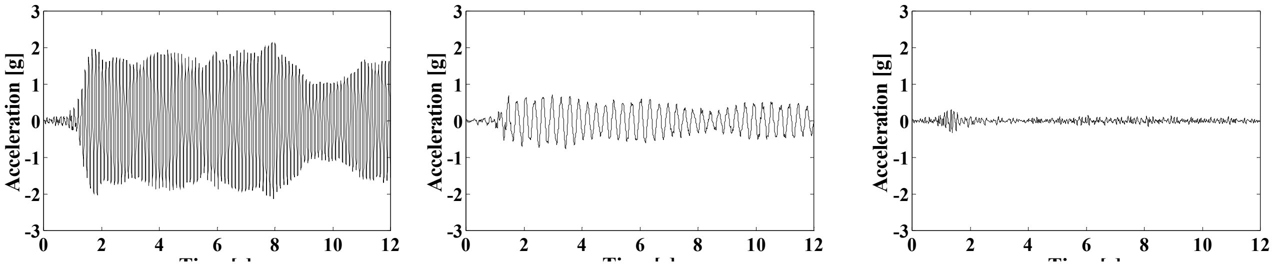
O---- Bare frame; ◊---- Base isolated frame; Δ---- Hybrid controlled frame

Figure 4. Floor accelerations relative to the ground under four different earthquakes



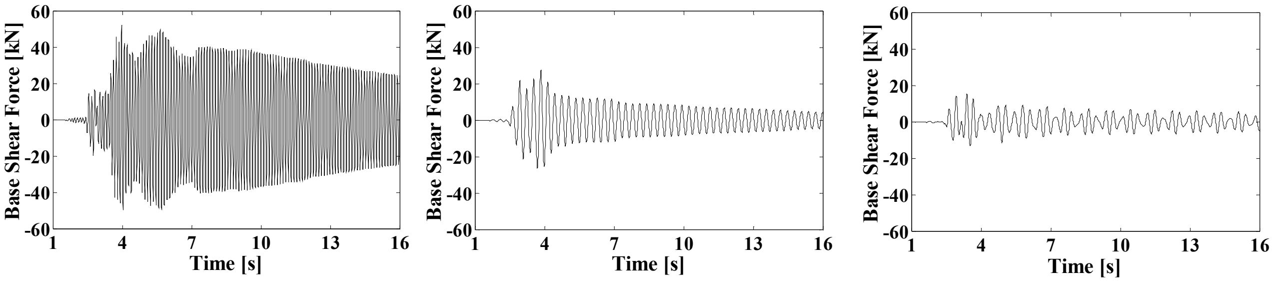
(a) Base isolated frame (b) Hybrid controlled frame

Figure 5. Time histories of rubber bearing deformation with respect to ground subject to El-Centro earthquake



(a) Bare frame (b) Base isolated frame c) Hybrid controlled frame

Figure 6. The 5th floor accelerations relative to ground subject to Hachinohe earthquake



(a) Bare frame (b) Base isolated frame (c) Hybrid controlled frame

Figure 7. Base shear force time histories subject to Kobe earthquake

Note: X axis in horizontal is time in seconds for Figure 5, 6, and 7, respectively.