Hybrid Coupled Building Control (HCBC), the Effects of Actuator Position

Farshid Fathi[1*] and Omid Bahar[2]

1. Ph.D. Candidate, Earthquake Engineering Dept., Science and Research Branch, Islamic Azad University (IAU), Tehran, Iran, * Corresponding Author; e-mail: f-fathi@iaun.ac.ir
2. Assistant Professor, Structural Engineering Department, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran

Received: 26/10/2011
Accepted: 06/09/2012

ABSTRACT

Coupled Building Control (CBC) has been effectively used to help mitigate the extended responses of the adjacent tall buildings due to strong ground excitations. Extensive analytical studies and experimental tests have shown this control strategy works well for "dissimilar" coupled buildings, but it's completely inefficient for the "similar" buildings. Recently, an innovative scheme for structural control, named the Hybrid Coupled Building Control (HCBC), has been presented by the authors, which improves and develops the CBC strategy. HCBC is applicable to all adjacent buildings; in order to apply the HCBC strategy, one of the adjacent buildings will be equipped with a base isolation system, and an active actuator link will connect the two buildings at a floor level. The primary buildings may be similar or dissimilar but, as a desired case, the "similar" buildings will be concerned here. In the previous works, it's shown that HCBC strategy efficiently decreases the maximum drifts and accelerations of the buildings. This paper investigates the effects of connector location on the performance of HCBC strategy. Analytical results for different configurations are presented in details, and the best choice is introduced.

Keywords:
Hybrid structural control; Hybrid coupled building control; Coupled building control; Adjacent buildings; Actuator position; CBC; HCBC

1. Introduction

Many researches have shown that the Coupled Building Control (CBC) strategy is a feasible method to protect dissimilar adjacent buildings against seismic excitations. It has been used in past two decades as a successful control strategy for dissimilar tall adjacent buildings. CBC was firstly suggested in the United States by Klein et al [1] in 1972, and four years later in Japan by Kunieda [2]. Then, numbers of researchers have developed coupling low, medium and high-rise structures with passive and active devices. Passive control strategies have been studied for both high and low-rise buildings. Gurley et al [3], Kamagata et al [4], Fukuda et al [5], and Sakai et al [6], have studied coupling tall flexible structures with passive devices, while Luco and Wang [7], Luco and De Barros [8], Xu et al [9], and Ko et al [10], have studied low to medium-rise structures. Active control strategies of flexible structures have been investigated by many researchers [8, 9, 11, 12]. Seto [11], successfully controlled fundamental modes of two adjacent flexible buildings in simulation and experiment. Active and semi-active CBC, have been introduced by Christenson and Spencer [13], Christenson et al [14-15]. They studied various coupled building configurations and experimentally verified active coupled building control by acceleration feedback. Zhu et al [16], suggested the semi-active CBC. In addition to the theoretical and experimental researches, full-scale implementation in the Kajima Intelligent Building complex was constructed in Tokyo, Japan in 1989 that consists of two 5 and 9-story buildings coupled by passive devices at their 5th floors. Recently, the connected buildings strategy has been also implemented in HUBα-Sightseeing Gate in Guangzhou for 86.5 meters towers [17]. The CBC method is still an attractive field of research; e.g. recent works done by Ashtiany et al [18-19].

The major constraint limited almost all the previous researches is that the dominant frequencies of the two coupled buildings should not coincide. Hence, for two dynamically similar structures, where all frequencies are the same, CBC is not a proper potential option. This constraint is a vital limitation in architectural design of two or more adjacent buildings in a row. Some efforts have been carried out by some researchers to overcome the mentioned challenge. Yoshida and Seto [20], proposed connecting two dynamically similar structures by attaching the connector link at different points at the height of the two structures. Christenson et al [21], extended this method and demonstrated its effectiveness both analytically and experimentally. However, some of these solutions are difficult to implementation.

Recently, an innovative scheme for controlling adjacent buildings, the Hybrid Coupled Building Control or HCBC, has been presented by the authors, which improves and develops the CBC strategy; Fathi and Bahar [22]. In this control strategy, unlike the traditional CBC, the primary structures may be similar, so that HCBC can be applied to all adjacent buildings; they may possess similar mass, stiffness, damping and heights. In order to apply the HCBC strategy, one of the buildings will be equipped with a base isolation system, and an active actuator link will connect the two buildings at a floor level. This strategy makes the dominant periods of the buildings away from each other, and lets the coupling strategy be effectively applied. The HCBC method may be applied to the existing buildings as a "retrofit method", or its practical performances may be considered during a "new design" procedure. In this paper, the effect of Actuator position on the HCBC performance is presented. Analytical results for different configurations are presented in details, and the best choice is introduced. Firstly, the analytical model, assumptions and control strategy are presented in the following sections.

2. Analytic Model, Assumptions, and Motion Equations

The general concept and analytical model of the Hybrid Coupled Building system is presented in Figure (1); consisting of two adjacent linear elastic shear buildings with similar/dissimilar height, mass, stiffness, and damping properties. The base of one building is fixed and the other building by installing a base isolation system is separated from the ground. The buildings are connected by a single actuator which produces the required Active control forces. The Electro-Hydraulic Actuators (e.g. Servovalve-Controlled Hydraulic Actuators), which is a very common actuator, is assumed herein.

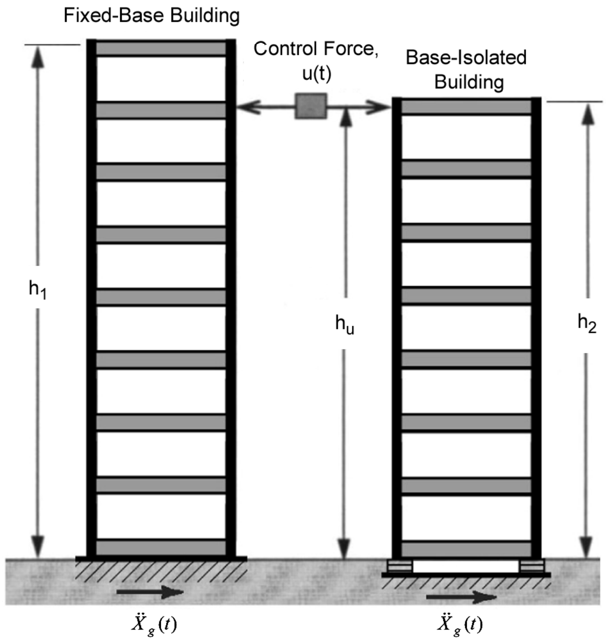

Figure 1. Hybrid coupled building control, analytical model.

The mass is concentrated at the level of each floor, and the stiffness is provided by the mass-less columns of each floor. Similar stories of the both buildings have the same height; out-of-plane effects are neglected; two buildings also experience the same ground excitation. The linear dynamic time-history analysis is used in all cases. The scope of this study has been also limited to the medium rise buildings (about fifteen storeys). Note again that in the traditional CBC method, the two primary buildings should have been dissimilar with fixed bases.

The equations of motion for the Hybrid Coupled Building system can be written in terms of mass, stiffness, and damping matrices of the buildings as follows:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=[\gamma]\{u\}+\{\delta\}\ddot{x}_g \quad (1)$$

where

$[M]=[M_1\ 0;\ 0\ M_2]$

$[C]=[C_1\ 0;\ 0\ C_2]$

$[K]=[K_1\ 0;\ 0\ K_2]$

$[\gamma]=[\gamma_1\ ;\ \gamma_2]$

$\{\delta\}=\{\delta_1\ ;\ \delta_2\}$

M_i, C_i and K_i are mass, damping, and stiffness matrices regarding to the i^th building of the Hybrid system, respectively. γ_i is the location matrix of control force, and δ_i is the influence vector of the earthquake ground acceleration regarding to the i^th building of the Hybrid system. $\{u\}$ is the vector of active control force, and $\ddot{x}_g$ is the ground acceleration time history. It is easier to solve Eq. (1) in the state space form as follows:

$$\{\dot{Z}\}=[A]\{Z\}+[B_u]\{u\}+\{B_r\}\ddot{x}_g \quad (2)$$

where $\{Z\}=\{x;\dot{x}\}^T$, and $[A]=[0\ I;-M^{-1}K-M^{-1}C]$ are the state vector and the system matrix of the Hybrid system, respectively. $[B_u]$, and $\{B_r\}$ are the coefficient matrices in the state space form, where $[B_u]=[0;-M^{-1}\gamma]$ and $\{B_r\}=\{0;-M^{-1}\delta\}$.

3. Equations Solution and Control Algorithm

The state vector $\{Z\}$ can be expressed in terms of modal transformation matrix $[T]$, which is constructed from the eigenvectors of the system matrix $[A]$:

$$\{Z(t)\}=[T]\{\psi(t)\} \quad (3)$$

Substituting Eq. (3) into the state Eq. (2) and pre-multiplying that by $[T]^{-1}$ results in:

$$\{\dot{\psi}(t)\}=[\Phi]\{\psi(t)\}+\{\Gamma(t)\} \quad (4)$$

where

$$[\Phi]=[T]^{-1}[A][T] \quad (5)$$

is the modal plant matrix, and the vector $\{\Gamma(t)\}$ consists of the control force and the excitation terms as follows:

$$\{\Gamma(t)\}=[T]^{-1}[B_u]\{u\}+[T]^{-1}\{B_r\}\ddot{x}_g \quad (6)$$

Solution of Eq. (4) can be obtained by solving the following integral from 0 to a desired time t:

$$\{\psi(t)\}=\int \exp([\Phi](t-\tau))\{\Gamma(t)\}\,d\tau \quad (7)$$

where τ is a dummy variable. This integral may be solved by using a mathematical software package such as MATLAB in continues or discrete time domain. Having $\{\psi(t)\}$ at any time t, the structural response $\{Z(t)\}$ can be determined from Eq. (3). Note that in Eq. (6), earthquake excitation, $\ddot{x}_g$, has been measured up to time instant t, and $\{u(t)\}$ should be obtained by feedback control law.

The classic optimal control algorithm is used to determine the control force from the measured structural responses, i.e. a closed-loop control. Optimal control force $\{u(t)\}$ is regulated by the feedback of the system responses, structural displacements and velocities, presented in the state variable form. Thus, the closed-loop feedback control law is as follows:

$$\{u(t)\}=-[G]\{Z(t)\} \quad (8)$$

where $[G]$ is the control gain matrix of the Hybrid system. Using the classic optimal control algorithm, the control Gain matrix $[G]$ is determined by minimizing the standard quadratic performance index J, given by:

$$J=(1/2)\int(\{Z\}^T[Q]\{Z\}+\{u\}^T[R]\{u\})\,dt \quad (9)$$

where $[Q]$ and $[R]$ are weighting matrices, respectively, for system response and control force. Matrix $[Q]$ can be considered as:

$$[Q]=[\,Q_{di}\times I\ \ 0;\ 0\ \ Q_{vi}\times I\,] \quad (10)$$

In diagonal matrix $[Q]$, Q_{di} and Q_{vi} are weighting coefficients, respectively, related to displacements and velocities. I and 0 are known unit and zero matrices. Because of using only one active actuator link between the two buildings, the weighting matrix $[R]$ reduces to a scalar value R_i

$$[R]=[R_i\times I]=R_i \quad (11)$$

Minimizing the performance index J with respect to the independent variables results in the Riccati Matrix Equation as follows:

$$[P][A]+[A]^T[P]-[P][B_u][R]^{-1}[B_u]^T[P]+[Q]=0 \quad (12)$$

By solving Eq. (12) for $[P]$, the Riccati matrix, the control Gain matrix is determined as follows:

$$[G]=[R]^{-1}[B_u]^T[P] \tag{13}$$

The above mentioned procedure is also known as the Linear Quadratic Regulator (LQR) method, which is here arranged for the Hybrid Coupled Building Control.

4. The Effects of Actuator Position

In order to study the effects of actuator position; various coupled building models with different dynamic property settings, applying different ground excitations have been investigated by a program developed in MATLAB 2009[23] software, capable of analyzing both CBC and HCBC systems with various options. In the following sections, an illustration for the most desired case, applying HCBC for the "similar" buildings, is presented and the outputs are discussed in details. The results show the effect of actuator position on the HCBC performance, and the best choice for the best efficiency is recognized.

4.1. System Performance

The "Performance" of the Hybrid system reflects the system overall ability to reduce structural responses due to seismic excitations. Hence, the story drift and floor absolute acceleration are mature demonstration of the system effectiveness. They should be within a desired level during earthquake ground motions, in order to satisfy both safety and serviceability conditions. They can be used to compare the efficiency of a controlled system under different conditions. The required control force is another important parameter to investigate the controlled system performance.

4.2. The Ground Excitation

The behaviour of various HCBC models has been investigated by changing connector location, during different historical Earthquakes. For the presented illustration, four historical Earthquakes (Tabas 1978, Kobe 1995, El Centro 1940, and Northridge 1994), adopted from PEER strong motions database, have been applied to the HCBC model. In the following sections, the results for Tabas Earthquake are presented in details and a brief review of the results for the other earthquakes is included as well. Tabas longitudinal Acceleration time-history (PGA=0.836g, HP=0.05Hz, NPTS=1642, DT=0.02sec, 09/16/78) is drawn in Figure (2).

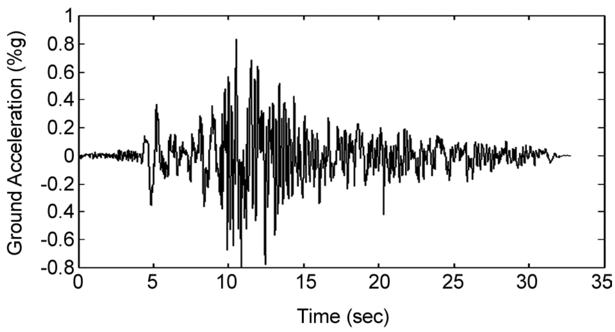

Figure 2. Ground acceleration, Tabas-Ln earthquake, Iran (09/16/78).

4.3. HCBC Model Properties

As mentioned before, HCBC is shown to be an effective strategy to be applied for similar or dissimilar adjacent buildings while the traditional CBC does not work for the similar connected buildings at all Fathi and Bahar [22]. In the following illustration, HCBC strategy is applied for two "similar" shear buildings as a desired case.

Two equal 8-story fixed-base shear buildings are supposed. The structural properties of the buildings are as follows: mass of the floors, m_1 to m_8, are 350 tons; stiffness of the storeys, k_1 to k_8, are 34e4 kN/m; and damping ratios of the modes are assumed to be 2%. In order to apply the HCBC strategy, one of the buildings is equipped with a base isolation system and is connected to the other building by an active actuator link at a floor level. The mass and lateral stiffness of the base-isolation system, mb and kb, are 250 tons and 5e3 kN/m, respectively; considering also 15% damping ratio. The actuator position will change from the top floor to the lower storeys to gain the best performance.

4.4. Results at Any Specific Actuator Position

For any specific actuator position, the HCBC model (consists of two aforementioned 8-story buildings) is excited by the four earthquake records. The best performance is obtained by assigning different weighting matrices $[Q]$ and $[R]$ to the model in order to achieve the least drift and accelerations with the optimal control forces. From this point of view, the best performance of the HCBC model is obtained by changing the values of scalar R_i and analyzing the system for each assignment;

considering $[Q]=[I\ 0;0\ I]$. By comparing the obtained responses for different amounts of 'R_i's, the best performance at any specific actuator position will be achieved. For instance, the comparison of the results for one specific case, actuator position at the 8th floor, is presented for Tabas Earthquake in Figures (3) to (7). These figures show and compare the obtained maximum displacements, drifts, accelerations, velocities of the floors and the required control forces, for five cases of R_i (named t_1 to t_5); see legend description in Table (1).

In each figure, the HCBC results are shown for both the fixed-base (left side) and the base-isolated (right side) buildings using different amounts of R_i. The results for the uncontrolled buildings (single fixed-base (S.Fixed) and single base-isolated (S.Isolated) buildings), and the traditional coupled building (T.Coupled) are also included for comparisons.

Referring to these figures, for this actuator position, the best achieved weighting coefficients of the HCBC model are selected as 5e-6, 1 and 1 for R_i,

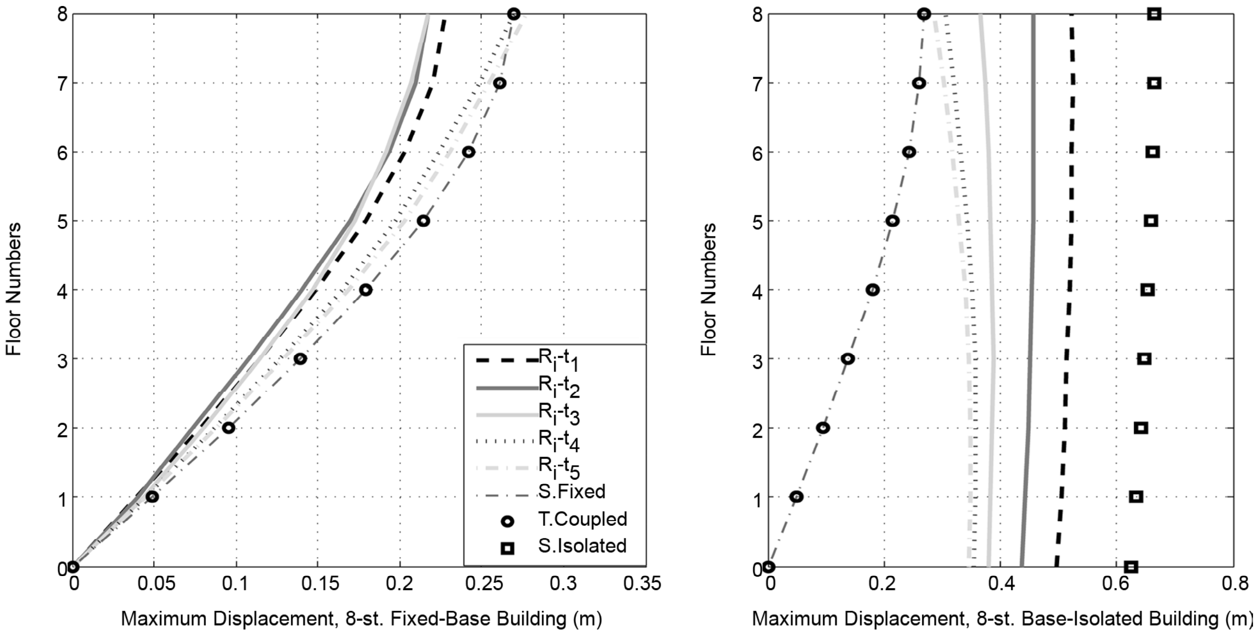

Figure 3. Maximum floor displacements, five Ri settings, meters.

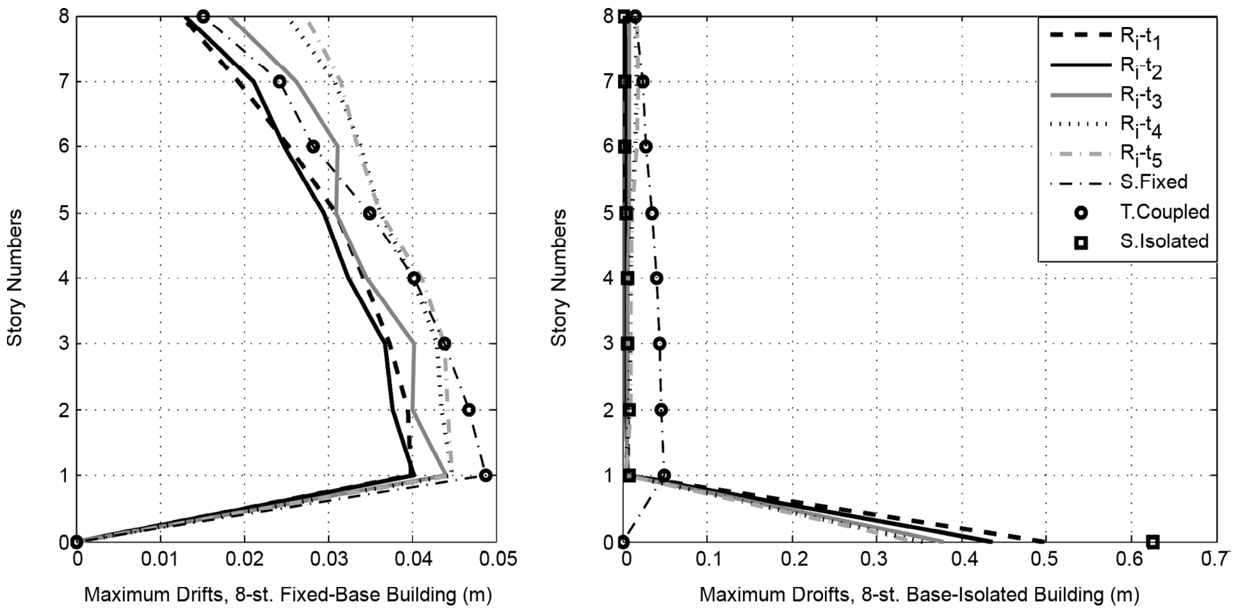

Figure 4. Maximum story drifts, five Ri settings, meters.

Q_{di} and Q_{vi}, respectively; noted as R_i-t_2 in the legends. Then, by those set of assignments, the best performance is achieved, and the following results are obtained:

i) The traditional CBC responses are coincided to that of the single uncontrolled (S.Fixed) buildings for all R_i assignments, and it is seen that it is completely inefficient for two similar buildings.

ii) In the HCBC model, the maximum drifts, accelerations and velocities are significantly decreased for both connected buildings.

iii) In the HCBC fixed-base building, maximum displacements are highly reduced compare to the S.Fixed building. Although, in the HCBC base-isolated building, maximum displacements are increased compared to the uncontrolled S.Fixed building, but reciprocally, the drifts in this building are too much reduced, which is more important

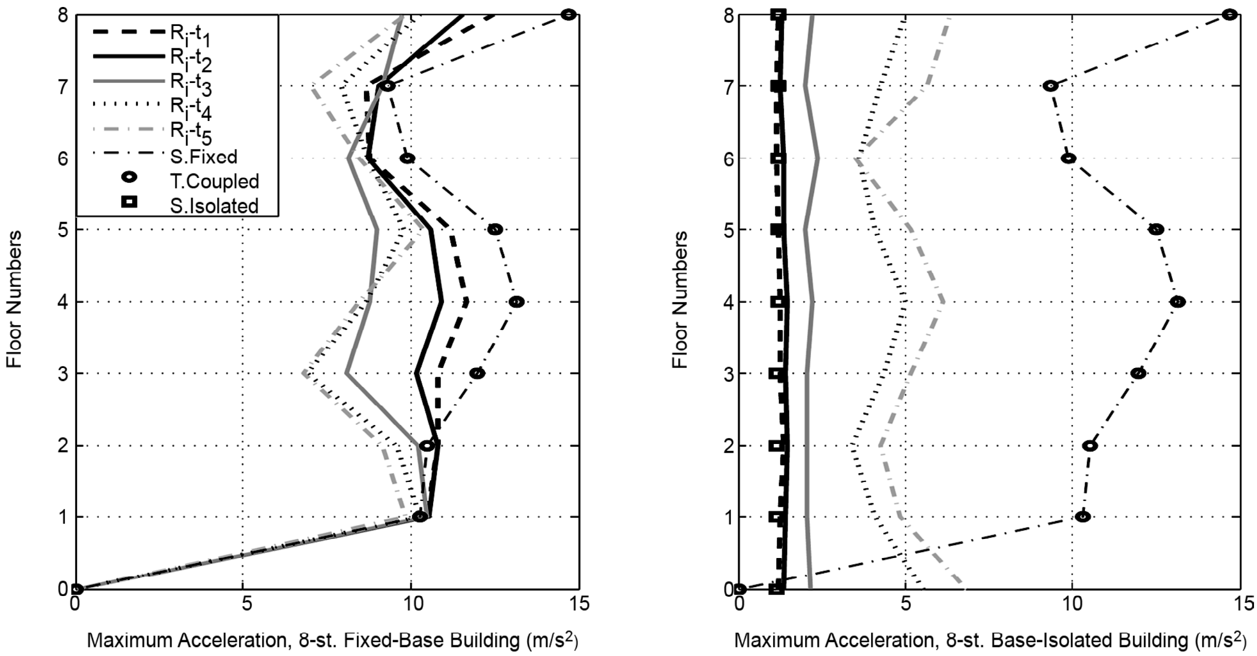

Figure 5. Maximum floor (absolute) accelerations, five R_i settings.

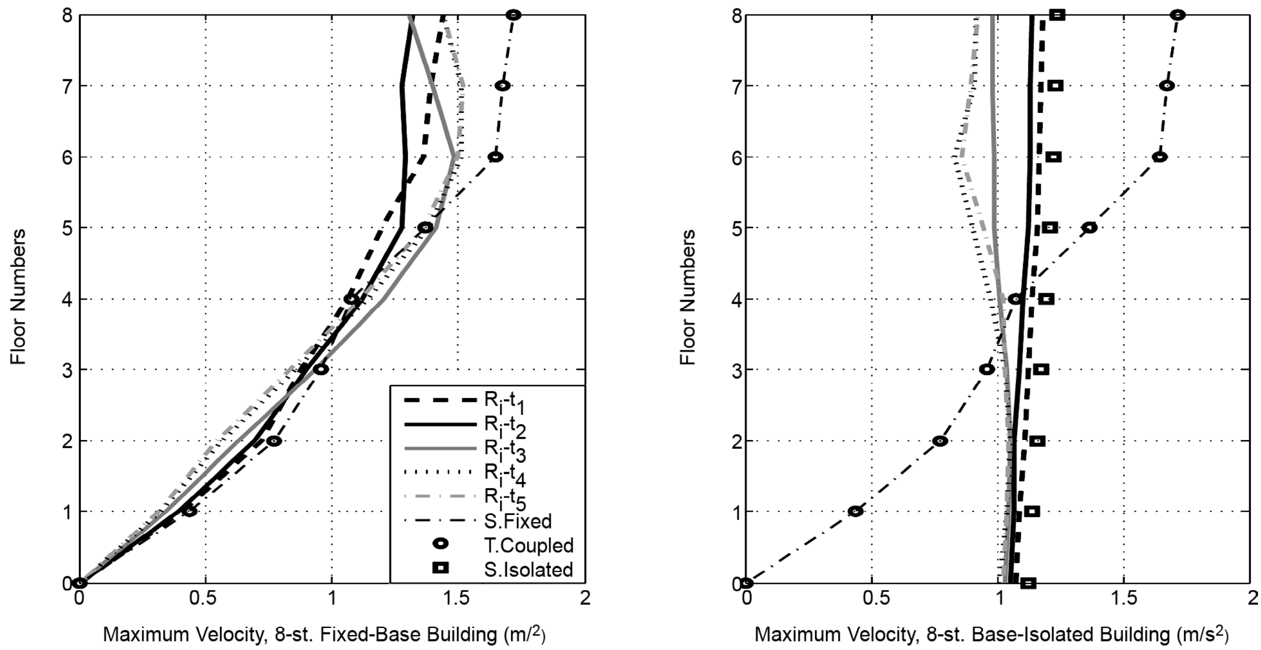

Figure 6. Maximum floor velocities, five R_i settings, meter/seconds.

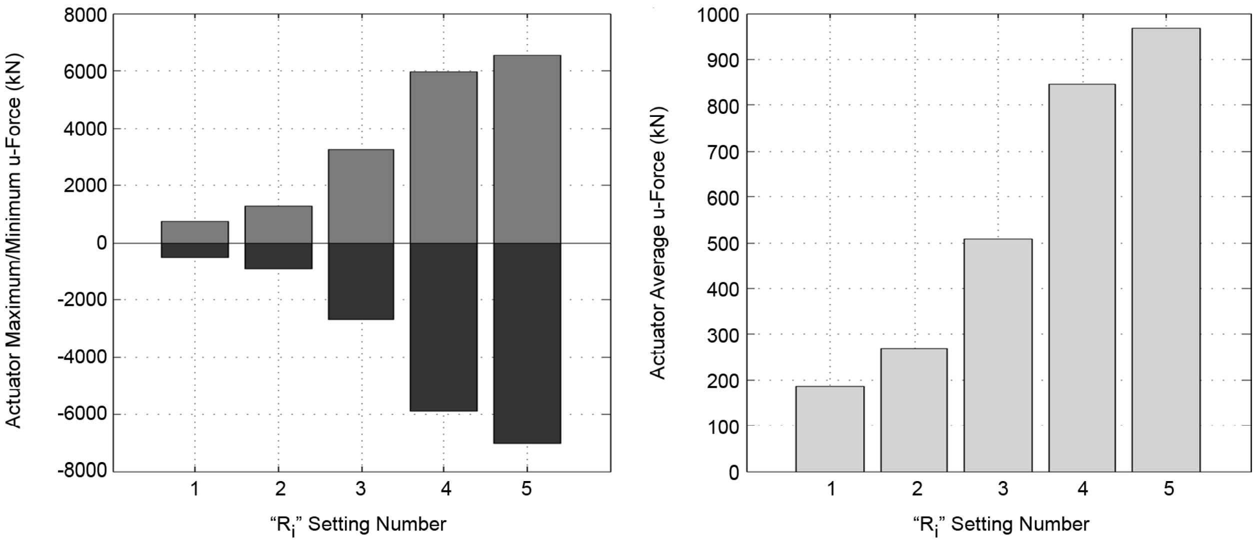

Figure 7. Required control forces, five R_i Settings, kN.

Table 1. Legend descriptions for the Figures (3) to (7).

Legend	R_i - t_1	R_i - t_2	$R_i - t_3$	$R_i - t_4$	$R_i - t_5$	S.Fixed	T.Coupled	S.Isolated
Description	HCBC Model R_i = 1e-5	HCBC Model R_i =5e-6	HCBC Model R_i =1e-6	HCBC Model R_i =1e-7	HCBC Model R_i =1e-8	Single Fixed-Base Building	Traditional CBC Model	Single Isolated Building

for design purposes. Moreover, maximum displacements are highly decreased compared to that of the uncontrolled S.Isolated building.

iv) The undesirable base displacement of the isolated building in the HCBC model is highly reduced compared to that of the uncontrolled S.Isolated building.

v) The selected R_i not only presents better results, but also requires lesser control force in comparison to the most of the other settings.

4.5 Best Choice for Connector Location

It is described in the previous section how to obtain the best Control Gain for any specific actuator position. In this section, those results of different connector locations are compared in order to choose the best performance of the HCBC model. For different actuator positions, named *nr*-t_i, the maximum displacements, drifts, accelerations and velocities of the HCBC model and its required control forces, are presented in Figures (8) to (12); applying Tabas Earthquake. The cases named t1 to t5 in the legends of the figures refer to the actuator position; see legend description in Table (2).

In each figure, the results are available for both the fixed-base building (left side) and the base-isolated building (right side) for different connection locations. The results of the uncontrolled buildings: single fixed-base (S.Fixed) and single base-isolated (S.Isolated), are also included for comparisons.

Based on the results shown in Figure (8), by moving the actuator position from the top floor toward the lower floors, the maximum displacements of the floors are increased. Thus, in order to achieve better performance, the active connecting link should be installed on the higher floors. That was expected

Table 2. Legend descriptions for the Figures (8) to (12).

Legend	*nr* - t_1	*nr* - t_2	*nr* $- t_3$	*nr* $- t_4$	*nr* $- t_5$	S.Fixed	S.Isolated
Description	Actuator at 8th Floor	Actuator at 7th Floor	Actuator at 6th Floor	Actuator at 5th Floor	Actuator at 4th Floor	Single Fixed-Base Building	Single Isolated Building

for the HCBC model: The base-isolated building works as an Active Mass Damper (AMD) for the fixed-base building, higher actuator position means higher tuned-mass location and therefore better performance. The best location choice is the top floor, which significantly reduces the contribution of fundamental modes as in the case of AMD control strategy [24-25]. The maximum displacements are reduced in the HCBC base-isolated building compared to that of single isolated building as well. Referring to Figure (9), it's seen again, by moving the actuator position toward the top floor, the maximum drifts in the fixed-base building will reduce and better performance will be achieved. For the base-isolated building, story drifts are very small and almost not sensitive to actuator positions, and the undesirable displacement at the isolation level is considerably reduced in all cases.

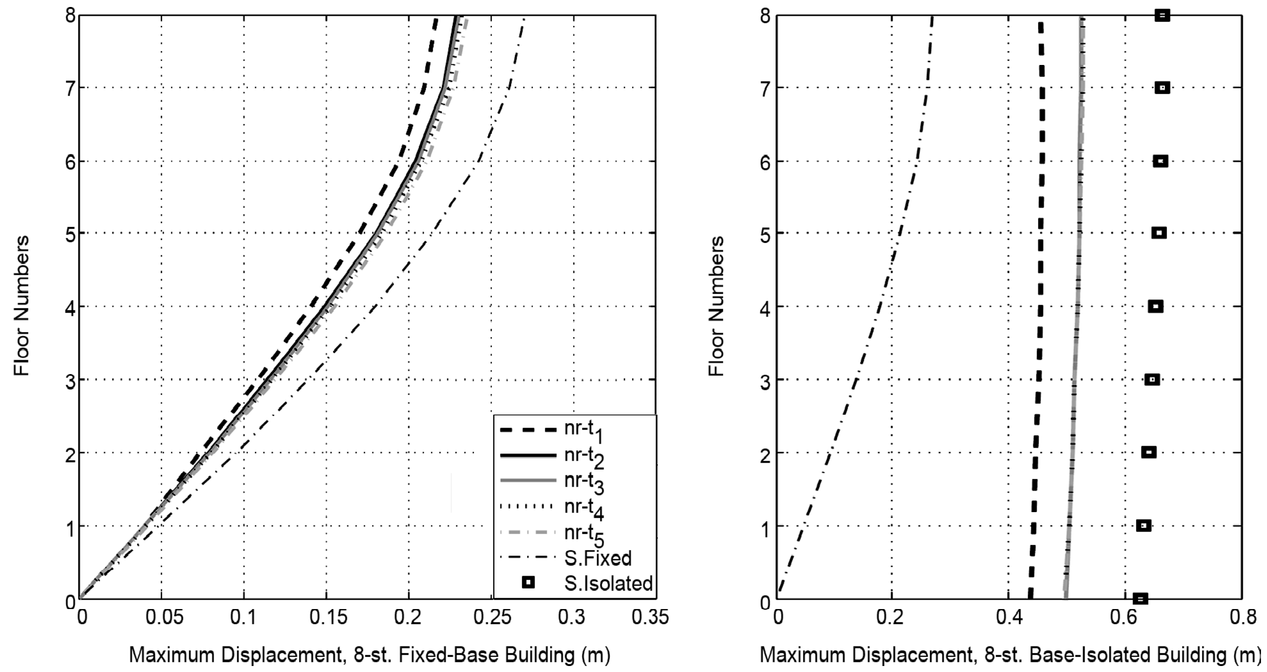

Figure 8. Maximum floor Displacements, five nr Settings, meters.

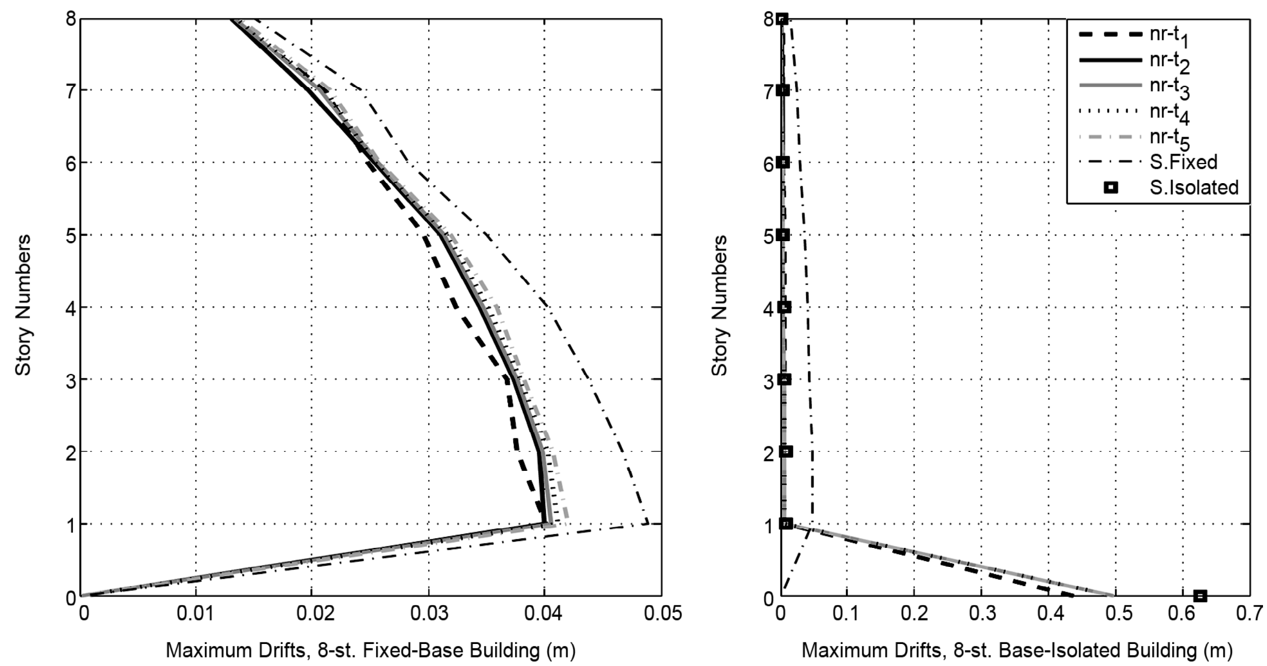

Figure 9. Maximum story Drifts, five nr Settings, meters.

Figure (10) presents the effects of actuator position on maximum amounts of floors accelerations. For the fixed-base building, results show again that, by moving active connecting link toward higher floors, better performance is achieved. All the results for the base-isolated building show excellent performance compared to similar fixed-base (S. Fixed) building. In the base-isolated building, floors accelerations are very small and are very close to single isolated (S.Isolated) results. Based on the results shown in Figure (11), by moving the actuator position toward the higher floors, the maximum velocity of the floors are reduced and the best performance is achieved at top floor. In Figure (12), in view of economical considerations, the required control force is presented for all five cases. As discussed before, the higher the height of connection, the more the efficiency: but it may

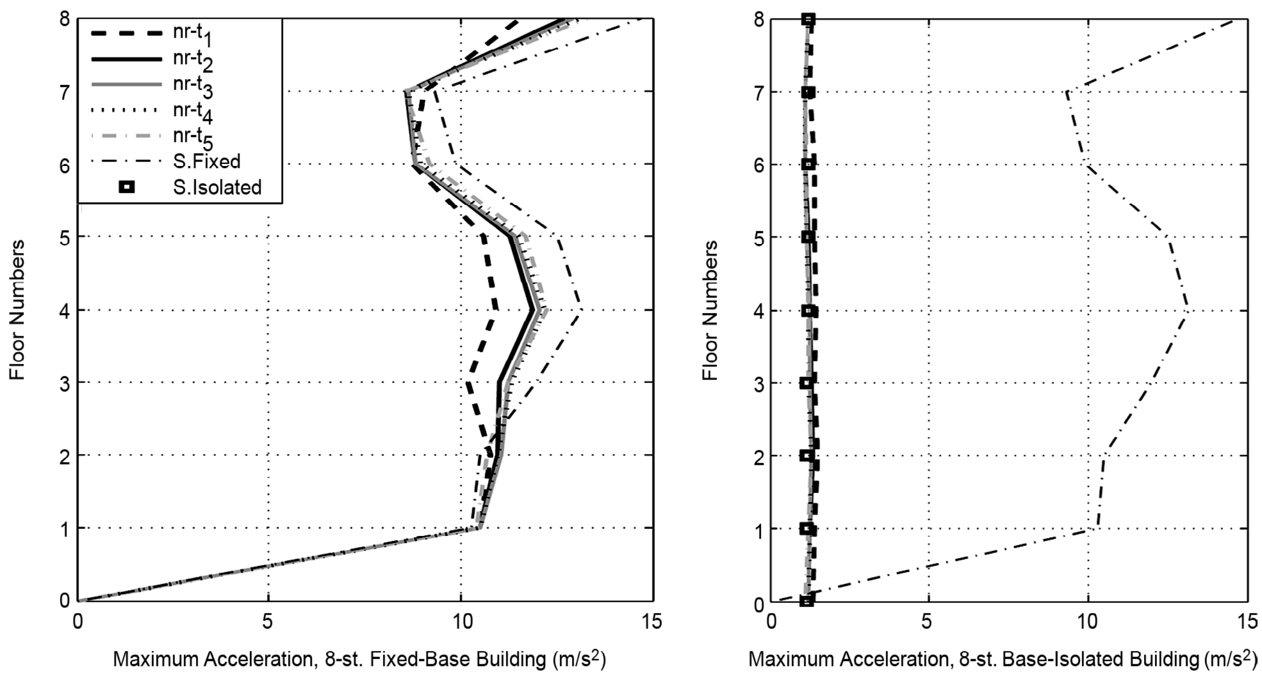

Figure 10. Maximum floor accelerations, five nr Settings (absolute).

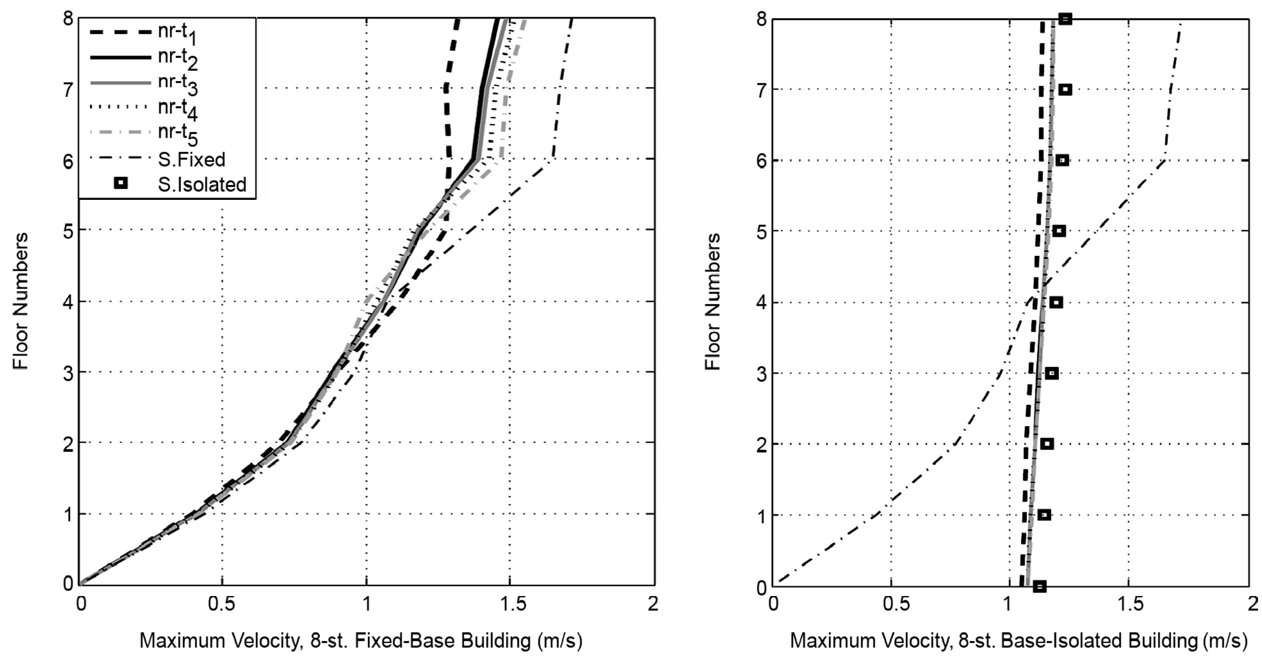

Figure 11. Maximum floor Velocities, five nr Settings, meter/seconds.

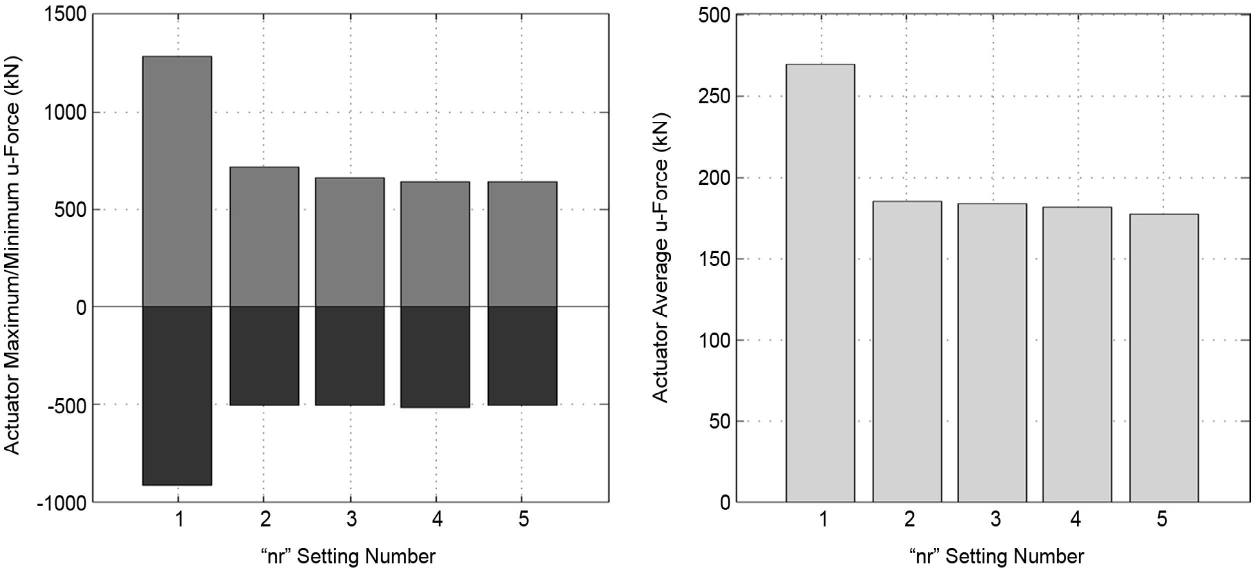

Figure 12. Required Control Forces, five nr Settings, kN.

require more control forces compared to the other choices. Having a better look at this last figure, it's seen that the required control force for the cases t_2 to t_5 are very close and are much less than case t_1 (Top floor position). Thus, for the economical considerations, one may choose the 7th floor for actuator position with relatively good performance.

4.6. Validity for Other Earthquakes

In the previous section, the results of one ground acceleration time-history are employed to distinguish the effects of actuator position on the HCBC performance. In this section, three more ground motion results are introduced. The resulted maximum accelerations, drifts and displacements of previous illustration applying Kobe 1995, El Centro 1940, and Northridge 1994 earthquakes are presented in Tables (3) to (5). The average (of the absolute values) of required control forces which indicates the total energy consumption are also presented for

Table 3. Maximum HCBC responses for Kobe earthquake, in meters or m/s^2.

HCBC Buildings	Position-Response	HCBC nr-t_1	HCBC nr-t_2	HCBC $nr-t_3$	HCBC $nr-t_4$	HCBC $nr-t_5$	Single Fixed	Single Isolated
Fixed Base	Top Floor- Acceleration	12.611	13.574	16.843	16.019	14.636	19.461	--
	1st Story-Drift	0.049	0.051	0.054	0.055	0.059	0.094	--
Isolated Base	Top Floor-Acceleration	3.090	4.246	4.061	4.640	3.533	(19.46)	0.834
	Base-Displacement	0.208	0.207	0.203	0.197	0.192	--	0.215

Table 4. Maximum HCBC responses for El Centro earthquake, in meters or m/s^2.

HCBC Buildings	Position-Response	HCBC nr-t_1	HCBC nr-t_2	HCBC $nr-t_3$	HCBC $nr-t_4$	HCBC $nr-t_5$	Single Fixed	Single Isolated
Fixed Base	Top Floor- Acceleration	3.832	3.981	4.679	5.059	4.986	8.690	--
	1st Story-Drift	0.017	0.018	0.018	0.020	0.021	0.032	--
Isolated Base	Top Floor-Acceleration	1.303	1.554	1.564	1.715	1.433	(8.69)	0.394
	Base-Displacement	0.086	0.085	0.084	0.080	0.077	--	0.111

Table 5. Maximum HCBC responses for Northridge earthquake, in meters or m/s^2.

HCBC Buildings	Position-Response	HCBC $nr-t_1$	HCBC $nr-t_2$	HCBC $nr-t_3$	HCBC $nr-t_4$	HCBC $nr-t_5$	Single Fixed	Single Isolated
Fixed Base	Top Floor- Acceleration	18.190	18.858	19.646	19.309	18.503	20.937	--
	1st Story-Drift	0.073	0.075	0.077	0.078	0.080	0.088	--
Isolated Base	Top Floor-Acceleration	2.055	2.353	2.552	2.982	3.112	(20.94)	1.188
	Base-Displacement	0.366	0.365	0.361	0.356	0.352	--	0.450

Table 6. The average required control forces, kN.

Earthquake	HCBC $nr-t_1$	HCBC $nr-t_2$	HCBC $nr-t_3$	HCBC $nr-t_4$	HCBC $nr-t_5$
Tabas	269.0	184.6	183.4	181.6	177.4
Kobe	386.5	402.9	421.4	448.0	473.7
El Centro	278.3	285.5	294.1	308.7	333.1
Northridge	231.8	233.8	237.7	247.5	258.6

all ground motions in Table (6).

According to the above tables and previous section results, we have:

i) For the fixed-base building of HCBC model, all the results show that, by moving active connecting link toward higher floors, the maximum drifts and accelerations will be reduced, and a better performance will be achieved.

ii) For the HCBC base-isolated building, the maximum top floor accelerations will have the least amount by installing the actuator at the top.

iii) In the HCBC base-isolated building, the undesirable displacement at the isolation level is reduced in all cases compared to that of single base-isolated building. The results for all actuator positions are too close and each one may be slightly smaller depending on the Earthquake.

iv) The selection of actuator position is also related to the required control forces. In Tabas Earthquake, it's seen that top floor position needs the most energy consumption; while the top actuator position in other three earthquakes needs the least amount of control forces in comparison to the other settings.

4.7. Passive-HCBC Strategy

In this section, the introduced HCBC model is compared to its equal Passive-HCBC model. The Passive-HCBC model has the same structure as HCBC, but a Passive Joint Damper (dash pot) is used instead of the active actuator link. Therefore, the active control force $\{u\}$, in Eq. (1), is replaced by a passive control force $P(t) = C_p(\Delta \dot{x})$; in which $\Delta \dot{x}$ is the difference between relative velocities of the connected floors, and C_p is the damping coefficient of damper. The C_p can be selected so that it minimizes the drift and accelerations of the buildings.

Selected results of the above mentioned 8-story HCBC illustration is compared to its Passive-HCBC model in order to compare their performances. The connection link is installed between the top floors, and the Tabas Earthquake is applied to the models. The best performance of the Passive-HCBC model is obtained by 460 (kN.s/m) for C_p, and R_i is equal to 5e-6 for HCBC. Maximum floor displacements and accelerations of HCBC, the Passive-HCBC (P-HCBC), the single fixed-base (S. Fixed) and the single base-isolated (S. Isolated) buildings are shown in Figures (13) and (14). Although, performance of the P-HCBC model is satisfactory in comparison with the single uncontrolled buildings (or conventional CBC strategy), but it is not as a smart strategy as the proposed HCBC method. Better performance of HCBC is recognizable as the less displacement of the isolated building in the HCBC model. In other words, the active link may better control the isolated part of the HCBC model.

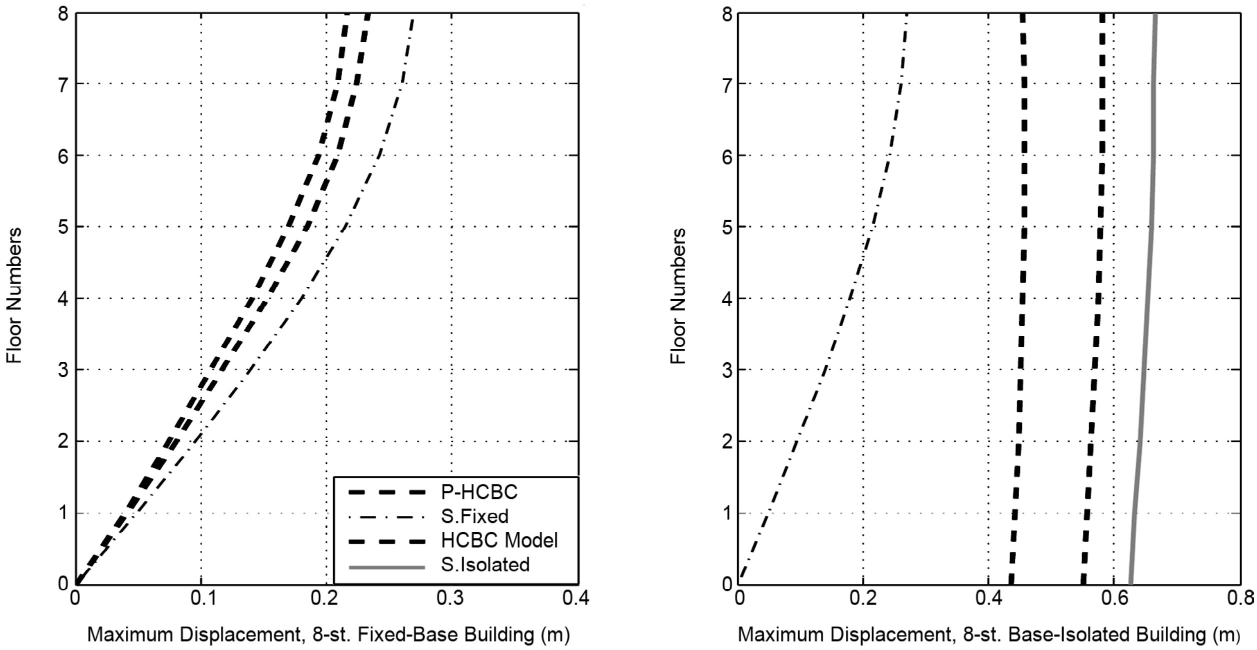

Figure 13. Maximum floor displacements, active and passive HCBC models, meter (C_p = 460 R_i = 5e-6).

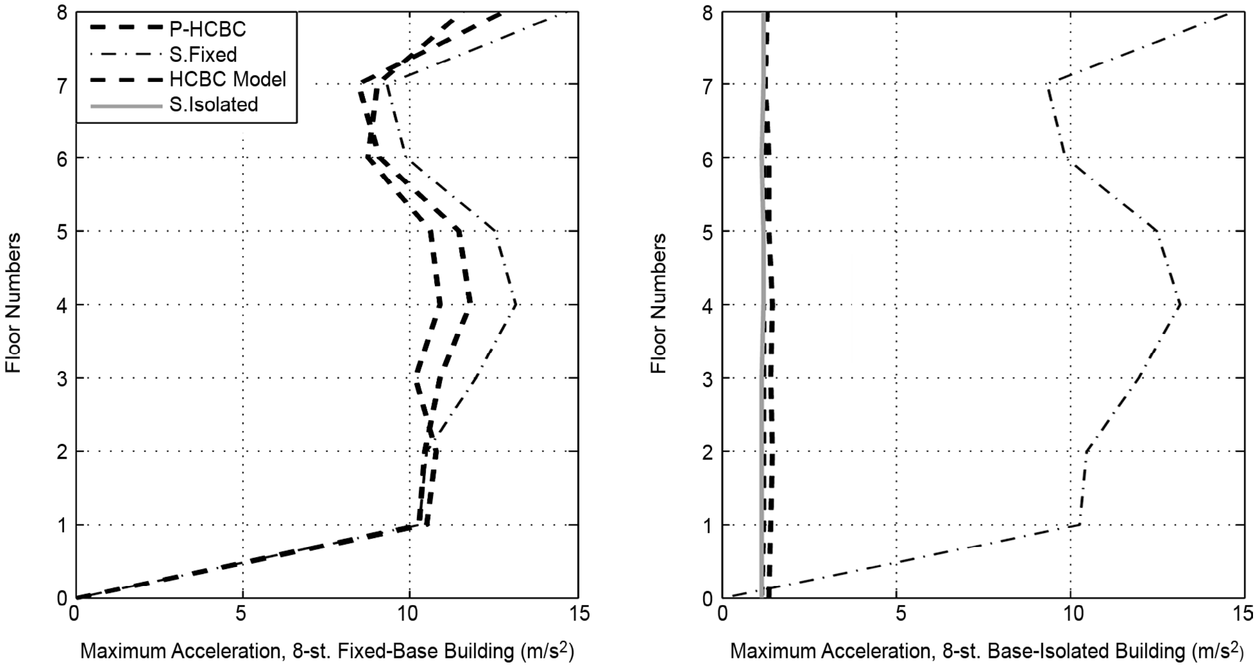

Figure 14. Maximum floor accelerations, active and passive HCBC models, m/s^2 (C_p = 460 R_i = 5e-6).

5. Conclusions

In this paper, the effect of actuator position on the performance of the Hybrid Coupled Building Control (HCBC) is investigated. The HCBC strategy, which has been recently introduced by the authors, is an effective way to control the responses of the adjacent buildings. It improves and develops the traditional CBC strategy and makes it applicable to similar or dissimilar adjacent buildings. In the presented illustration the HCBC strategy is applied for two "similar" buildings, while the conventional CBC could not handle that. The actuator position is switched from the top story to the lower storeys to gain the best performance. For any specific Actuator position, the best performance is obtained by assigning different weighting matrices to the model in order to achieve the least Drift and Accelerations with the optimal Control forces. Results for different connector locations have been compared to choose the best performance for the HCBC model. Based on the detailed results, by moving the actuator position toward the top floor, the responses of HCBC buildings will reduce. The base-isolated building works similar to an Active Mass Damper (AMD) for the fixed-base building, and its efficiency will improve by moving the attached active mass toward the higher levels. Thus, in order to achieve the best performance, the active link should be installed at top floor. For most Earthquakes, the average required control force is lesser in the case of top floor position for actuator, while for some others (e.g. Tabas) it might have greater extents. In such a case, from economical considerations, the floor just beneath the top would be an optimum option for the connector location.

References

1. Klein R.E., Cusano, C., and Stukel, J. (1972). Investigation of a Method to Stabilize Wind Induced Oscillations in Large Structures, *Proc., ASME Winter Annual Meeting*, New York, Paper No. 72-WA/AUT-H.

2. Kunieda, M. (1976). Earthquake-Prevent Design and Earthquake-Proof Design for Structures, *JSME*, **79**(689), 86-91 (in Japanese).

3. Gurley, K., Kareem, A., Bergman, L.A., Johnson, E.A., and Klein, R.E. (1994). Coupling Tall Buildings for Control of Response to Wind, Structural Safety and Reliability, Schueller G.I., Shinozuka, M., and Yao, J.T.P, eds. Balkema, Rotterdam, The Netherlands, 1553-1560.

4. Kamagata, K., Miyajima, K., and Seto, K. (1996). Optimal Design of Damping Devices for Vibration Control of Parallel Structures, *Proc., 3rd Int. Conference on Motion and Vibration Control* (*MOVIC*), (2), Chiba, Japan, 334-339.

5. Fukuda, Y., Matsumoto, Y., and Seto, K. (1996). Bending and Torsional Vibration Control of Flexible Structures Arranged in Parallel, *Proc., 3rd International Conference on Motion and Vibration Control (MOVIC)*, (3), Chiba, Japan.

6. Sakai, D., Sugino, S., Seto, K., Christenson, R.E., Spencer Jr, B.F. (1999). Vibration Control of Parallel Structures Connected with Passive Devices Designed by GA., *Proc., DETC-99, 1999 ASME Design Engineering Technical Conference*, Las Vegas.

7. Luco, J.E. and Wong, H.L. (1994). Control of the Seismic Response of Adjacent Structures, *Proc., 1st World Conference on Structural Control*, Pasadena, California, TA2-21-30.

8. Luco, J.E. and De Barros C.P. (1998). Optimal Damping between Two Adjacent Elastic Structures, *Earthquake Eng. Struct. Dyn.*, **27**, 649-659.

9. Xu, Y.L., He, Q., and Ko, J.M. (1999). Dynamic Response of Damper Connected Adjacent Buildings under Earthquake Excitation, *Eng. Struct.*, **21**, 135-148.

10. Ko, J.M., Ni, Y.Q., and Ying, Z.G. (1999). Dynamic Response of Adjacent Buildings Coupled with Nonlinear Hysteretic Dampers Under Random Seismic Excitation, *Proc., Seminar on New Seismic Design Methodologies for Tall Buildings*, Beijing, 111-122.

11. Seto, K. (1994). Vibration Control Method for Flexible Structures Arranged in Parallel, *Proc., 1st World Conference on Structural Control*, **2**, Pasadena, California, 62-71.

12. Seto, K. (1996). A Structural Control Method of the Vibration of Flexible Buildings in Response to Large Earthquakes and Strong Winds, *Proc., 35th Conference on Decision Control,* Kobe, Japan, 658-663.

13. Christenson, R.E. and Spencer Jr, B.F. (1999). Coupled Building Control Using 'Smart' Dampers, *Proc., 13th Engineering Mechanics Division Conference*, *(CD-R)*, Baltimore ASCE, Reston, Va.

14. Christenson, R.E, Hori, N., Spencer Jr, B.F., and Seto, K. (2003). Coupled Building Control Using Acceleration Feedback, *Computer Aided Civil Infrastructures. Eng.*, **18**(1), 3-17.

15. Christenson R.E. Spencer Jr, B.F., Johnson, E.A., and Seto, K. (2006). Coupled Building Control Considering the Effects of Building/Connector

Configuration, *Journal Struct. Eng.*, **132**(6), 853-863.

16. Zhu, H., Wen, Y., and Iemura, H. (2001). A Study on Interaction Control for Seismic Response of Parallel Structures, *Comput. Struct.*, **79**(2), 231-242.

17. Chen, X.W., Han, X.L., Mao, G.N., and Li, J. (2009). Wind-Induce Response Analysis on a Connected Tall Building Structure with Viscous Dampers, *Journal of Civil, Architectural and Environmental Engineering*, **31**(5), 75-80.

18. Ghafory-Ashtiany, M. and Sarmady, H. (2011). An Investigation on Input Energy of Asym Adjacent Buildings Connected by Viscous Dampers, *Proc., 6th International Conference on Seismology and Earthquake Engineering (SEE6)*, Tehran, Iran.

19. Ghafory-Ashtiany, M., Moghadam, A.S., Sarmady, H. (2011). An Investigation on Base Shear of Asym Adjacent Buildings Connected by Viscous Dampers, *Proc., 6th International Conference on Seismology and Earthquake Engineering (SEE6)*, Tehran, Iran.

20. Yoshida, K. and Seto, K. (2002). Vibration Control of Parallel Flexible Structures with Identical Vibration Property Using Interactive Forces, MOVIC Proc., Int. Symp. on Motion and Vibration Control, 967-972.

21. Christenson, R.E., Makita, K., Seto, K., and Watanabe, T. (2007). Optimal Design Strategy of Connected Control Method for Two Dynamically Similar Structures, *J. Struct. Eng. Mech. ASCE*, 1247-1257.

22. Fathi, F. and Bahar, O. (2011). Hybrid Coupled Building Control, *Proc., 6th International Conf. on Seismology and Earthquake Engineering (SEE6)*, Tehran, Iran.

23. MATLAB (2009). The Math Works, The Language of Technical Computing, MATLAB Release R2009a.

24. Bahar, O. (2001). Introducing, Two New Instantaneous Optimal Control Algorithms, Ph.D. Dissertation, Depart of Civil Eng. University of Shiraz, Iran (in English).

25. Bahar, O., Banan, M.R., and Mahzoon, M. (2005). Studying the Behaviour of Active Mass Drivers during an Earthquake using Discrete Instantaneous Optimal Control Method, *Journal of Seismology and Earthquake Engineering (JSEE)*, **7**(1).