Seismic Analysis of Connected Isolated Buildings by VF Dampers

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ABSTRACT :

Seismic response of two adjacent buildings, namely ten and eight storeys inter-connected through semi-active VF damper in which ten storeys building being isolated is investigated under unidirectional excitation due to Imperial Valley earthquake. The two adjacent buildings are modelled as linear shear type building whereas damper and isolators are modelled by modified Bouc-Wen and Wen's model respectively. A friction damper employed is a displacement-dependent energy dissipation device as its force is independent of the velocity and frequency-content of excitation. The performance of seismic response using proposed hybrid control scheme is compared with the semi-active VF control in order to know the effectiveness of the proposed strategy. Further, parametric studies are conducted to study the effects of gain multiplier of damper and isolation damping on the efficacy of proposed hybrid control. It is observed that proposed semi-active hybrid strategies are quite effective in reducing the seismic responses in comparison to semi-active VF control. It is also seen from the parametric study that the performance of the control schemes is influenced by the parameters of the isolator and damper.

KEYWORDS: Adjacent buildings, MR control, Base isolation, Coupled building control, Semi-active hybrid control, Seismic response.

1. INTRODUCTION

Over the past few decades, a great deal of interest has been generated regarding the use of structural control systems to mitigate seismic hazards in civil engineering structures. The traditional approach for seismic protection has been relied on the structures having sufficient strength capacity and ability to deform in a ductile manner. But inadequacy of this approach has been identified during past major earthquake; therefore, relying and developing aseismic design approach also known as structural control approach is the obvious option. This approach has been pursued effectively by the researchers and being implemented to large scale in practices and ensured the structure to be safe from the earthquake impact. One of the approaches is the dissipation of seismic energy using friction mechanism has achieved successful gains in recent decades for the protection of civil structures. Moreover, the VF damper has emerged as one of the most promising as this damper remains in continuous slip state by controlling its clamping force in real time during an earthquake and exhibits efficient energy dissipation (Lu, 2004). One of the new and exciting ideas in the field of structural control is the coupled building control in which impart of forces one upon another due to adjacent dissimilar buildings. Moreover, it avoids impacts between two adjacent buildings (Westermo, 1989; Zhang and Xu, 2000; Xu et al. 1999; Matsagar and Jangid, 2003 etc).Moreover, from the literature review, it is seen that many researchers have taken tremendous efforts for development and its actual implementation for controlling the seismic response. In recent past, The coupled building control has been accepted as a one of the viable and effective solution in reducing the seismic response and avoids damages due to pounding (Bhaskararao and Jangid, 2006). Moreover, this coupled control mechanism becomes more effective when one of the buildings is being isolated (Matsagar and Jangid, 2005). It is also observed that very limited study has been come-up on coupled building control involving base isolation; therefore, it is need for more investigations in this regards. Herein, efforts are made to develop an efficacious hybrid control schemes to mitigate earthquake induced structural damages as well.
Therefore, the present study includes the effectiveness of semiactive hybrid control for the two adjacent RC buildings having different dynamic characteristics, connected by the semi-active VF dampers with taller building is isolated by elastomeric bearing with and without lead core. In addition, parametric studies are

performed to examine the efficacy of semi-active hybrid strategy by varying the important parameters, namely, isolation damping and gain multiplier parameter used in VF damper. The precise objectives of the study are outlined as under

1. Examine the effectiveness of proposed semi-active hybrid control in comparison with semi-active VF control for seismic response reduction.
2. Investigate the influence of isolation damping on the performance of hybrid control system.
3. Study the influence of VF damper gain multiplier parameter on the efficacy of the proposed control strategy.

2 STRUCTURAL MODEL OF COUPLED BUILDING

Two adjacent buildings of different dynamic characteristics, adjoining floors connected through inline VF dampers and taller building is isolated by the elastomeric bearing with and without lead core is shown in Figure 1. The combined building system is idealized as linear shear type building with lateral degrees of freedom at their floor levels. The floors of both buildings are at the same level, but the numbers of stories are different. The system is subjected to unidirectional excitation under the real earthquake, that is, Imperial Valley, 1940 (EQ 1). The spatial variation of ground motion and any effect due to soil structure interaction is neglected.
The governing equations of motion of the combined system is expressed in matrix form as

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=-[M]\{r\}\ddot{u}_g+[D_p]\{f_d\}+[B_p]\{f_b\} \quad (1)$$

where, $[M]$, $[C]$, and $[K]$ are the mass, damping and stiffness matrices of combined system respectively, $\{u\}=\{u_b, u_1, u_2, u_3 \ldots\ldots\ldots u_{m+n+1}\}$, $\{\dot{u}\}$ and $\{\ddot{u}\}$ are the vectors of floor displacement, velocity and acceleration respectively with respect to the ground and consists of response of Building 1 in first $(m+1)$ positions and that of Building 2 in last (n) positions, u_b is the displacement of isolation floor, $\{r\}$ is the vector of influence coefficient having all elements equal to one, $\ddot{u}_g$ is the ground acceleration due to earthquake, $[D_p]$ and $[B_p]$ are the position vector of damper and isolator, $\{f_d\}$ is the damper force vector, and $\{f_b\}$ is the vector of bearing force.
The equations of motion (Eq. 1) may be represented in the form of state-space equation as

$$\{\dot{z}(t)\} = [A]\{z(t)\}+[B_d]\{f_d(t)\}+[B_b]\{f_b(t)\}+[E]\ddot{u}_g(t) \quad (2)$$

where, z is the state variable, A is the system matrix composed of structural mass, stiffness, and damping, B_d and B_b are the distribution matrices for the damper and bearing forces respectively and E is the excitation matrix and are explicitly given as

$$\dot{z}=\begin{bmatrix}\dot{u}\\ \ddot{u}\end{bmatrix};\ z=\begin{bmatrix}u\\ \dot{u}\end{bmatrix};\ A=\begin{bmatrix}O & I\\ -M^{-1}K & -M^{-1}C\end{bmatrix};\ B_d=\begin{bmatrix}O\\ M^{-1}D_p\end{bmatrix},\ B_b=\begin{bmatrix}O\\ M^{-1}B_p\end{bmatrix} \text{and } E=\begin{bmatrix}O\\ -r\end{bmatrix}$$

where, $[I]$ and $[O]$ are the identity and null matrices, respectively; vector $\dot{z}(t)$ represents the state of structural system which contains relative velocity and acceleration responses of structure with respect to ground.

2.1. Computation of VF Damper Force

In order to compute force in the VF damper, a control algorithm, called predictive control law (Lu, 2004) is used, in which, variable slip force of a semi-active VF damper is kept slightly lower than the critical friction force that allows the damper to remain in slip state during an earthquake, which improves the energy dissipation capacity of the damper. The Eq. (2.2) is descritized in time domain (Meirovitch, 1990) and expressed as

$$z(t+\Delta t) = A_d z(t) + B_{dd} f_d(t) + B_{db} f_b(t) + E_d \ddot{u}_g(t) \quad (3)$$

where, (t) and $(t+\Delta t)$ denotes the time step at which a state variable is evaluated, A_d represents the discrete-time system matrix, B_{dd}, B_{db} and E_d are the constant co-efficient matrices which are the discrete-time counterpart of matrices of B_d, B_b and E (Eq. 2.2) respectively and are explicitly given as below
$A_d = e^{A\Delta t}$, $B_{dd} = A^{-1} (A_d - I) B_d$, $B_{db} = A^{-1} (A_d - I) B_b$, and $E_d = A^{-1} (A_d - I) E$, where, I is the identity matrix.
The critical friction force (f_{cr}) of semi-active variable friction damper is given by

$$f_{cr}(t) = \left[G_1 z(t-1) + G_2 f_d(t-1) + G_3 \ddot{u}_g(t-1) \right] \quad (4)$$

where, G_1, G_2 and G_3 are the control gain parameters and are given as $G_1 = k_b D_e (A_d - I)$, $G_2 = k_b D_e B_d + I_e$ and $G_3 = k_b D_e E_d$, where, I_e *is* the another identity matrix with dimension ($N \times N$), k_b is the matrix of bracing stiffness in which diagonal elements and is given as $[k_{br}] = n_b \times k_{br} \times D_e$; where n_b is the number of bracings provided to each story, k_{br} is the bracing stiffness equal to storey stiffness, D_e is a constant matrix composed of damper orientation and is described by the damper displacement and state variable is $u_d(t) = D_e z(t)$
A damper (slip) force from the VF damper is computed by the following equation as

$$f_d(t) = R_f \left[G_1 z(t-1) + G_2 f_d(t-1) + G_3 \ddot{u}_g(t-1) \right] \quad (5)$$

where, R_f is a selectable parameter, called gain multiplier parameter which is the ratio of damper force (slip force) to the critical force of friction.

2.2. Computation of Bearing Force

The restoring force developed in the isolation systems depends upon the type of system considered, and is described for the bearings under consideration as follows

2.2.1 Laminated rubber bearing

Laminated rubber bearing (LRB) consists of alternate layers of natural or synthetic rubber vulcanized between steel shims along with two thick end plates. The bearing deflects the seismic energy by the parallel action of linear spring and viscous damping. The force-deformation behaviour of laminated rubber bearing is assumed as linear. The bearing force generated by this system is given by

$$f_b = c_b \dot{u}_b + k_b u_b \quad (6)$$

where, $\dot{u}_b$ and u_b is the velocity and displacement of base floor, respectively.

2.2.2 Lead rubber bearing

The lead rubber bearing or NZ system is similar to the LRB except the presence of a central lead core. The force deformation behaviour of the bearing is of nonlinear characteristics and its hysteretic behaviour is characterized by the Wen's model (Wen, 1976). The bearing force generated by this system is expressed as

$$f_b = c_b \dot{u}_b + \alpha_b k_b u_b + f_z \quad (7)$$

where, f_z is the restoring force due to presence of lead core and expressed as

$$f_z = (1-\alpha_b) F_y q z_b \quad (8)$$

where, α_b is computed by expression, $\alpha_b = \omega_b^2 M_t q / F_y$, under which F_y is the yield strength of isolator, z_b is the non-dimensional hysteretic displacement component and is solved using hysteretic model, satisfying the nonlinear first order differential equation as below

$$q\dot{z}_b = -\beta \left| v_b \right| zb \left| z_b \right|^{n-1} - \tau v_b \left| z_b \right|^n + A v_b \tag{9}$$

Where, q is the yield displacement of bearing, β and τ is the strengthening coefficient due to lead plug that controls the shape and size of hysteresis loop, n and A are the integer constants which controls the smoothness of transition from elastic to plastic state. These parameters β, τ, n and A are selected so as to provide a rigid-plastic shape.
The parameter of elastomeric isolation system, namely stiffness (k_b), damping (c_b) and yield strength (F_y) are so selected to provide desired value of isolation period (T_b), damping ratio (ξ_b), and yield strength coefficient (F_0) respectively.

3 NUMERICAL STUDY

A study considered the two adjacent RC buildings of ten and eight story with same floor mass and inter-story stiffness, connected by the by MR dampers to the inline floors of adjacent buildings. Further, taller building is isolated by the elastomeric bearing with and without lead core. The mass and stiffness of each story are considered (Ni et al., 2001), as 1600 ton and 1.2×10^7 kN/m, respectively. Besides, mass of isolation floor is taken as 10% in excess of superstructure floor mass, that is, equal to 1760 ton. This gives fundamental time period of Building 1 and Building 2 as 0.48s and 0.39s, respectively. The system is subjected to unidirectional excitation due to real Imperial Valley ground motion (EQ 1). due to earthquake having peak ground acceleration (PGA) is 0.348g. The parameters of MR damper (Yang et al. 2002) have been suitably scaled up, to suit the damper deformation behavior and the values of which are: η= 195s$^{-1,}$ c_{1a}=8106.20 kN-s/m, c_{1b}=7807.90 kN-s/m/V, c_{0a}= 50.30 kN-s/m, c_{0b}=48.70 kN-s/m/V, α_{0a}= 8.70 kN/m, α_{0b}= 6.40 kN/m/V, γ= 496m^{-2}, β= 496 m^{-2}, A_d= 810.50, n= 2, k_0= 0.0054 kN/m, χ_0=0.18 m, k_1=0.0087 kN/m. The maximum command voltage supplied to the MR damper is taken as 6V and parameters considered for the elastomeric base isolation systems are T_b = 2 s, ξ_b = 0.1 and F_0 = 0.05. The VF dampers are used for interconnecting inline adjoining floors with bracing having stiffness (k_{br}) equal to the lateral story stiffness of building (k_s). In order to examine the influence of gain multiplier parameter (R_f) of VF damper on the performance level of the control strategy, three values of R_f, (i.e. 0.03, 0.05, and 0.1) are considered. The semi-active hybrid systems considered in the study are: (1) Hybrid control 1: VF dampers and laminated rubber bearing, (2) Hybrid control 2: VF dampers and lead rubber bearing. The response parameters of interest are: top floor displacement (u_f) and acceleration (a_f), story drift (u_r), bearing displacement (u_b), normalized story shear (S_{sy}/W), and normalized base shear (B_{sy}/W). The study in which, story shear (S_{sy}), base shear (B_{sy}), bearing force (f_b) and isolation strength (F_y) are normalized by weight of respective building. Similarly, damper force (f_d), is normalized by weight of Building 2.
The time varying response of top floor displacement, acceleration, base shear and bearing displacement for Building 1 and 2, for three control strategies, namely, VF control, Hybrid control 1 and 2, are shown in Figures 2 and 3 respectively. It is observed from the figures that significant reduction in response is obtained for Building 1 under hybrid controls as compared to semi-active MR control. Further, it is also observed that only marginal response reduction is seen for Building 2. It is also noted that reduction in response under Hybrid control 1 and 2 is almost matching.
Comparison of peak responses of Building 1 and 2 for different control strategies under considered ground motion is shown in Table 1 with a value of percentage reduction in parenthesis. It is noted that reduction in top floor displacement, acceleration and base shear is to the tune of 80-90 % for Building 1, for hybrid control 1 and 2 as compared to MR control. However, the response reduction in case of Building 2 is in the range of 1-7 %. Further, it is noted that reduction in top floor responses and base shear under Hybrid control 1 and 2 is in close vicinity though, Hybrid control 2 exhibit better reductions in bearing displacement.

3.1. Effects of Isolation Damping

Figures 3 show the variation of peak values of base shear and bearing displacement with respect to the isolation damping. It is observed from Figure 3 that there is slight increase in base shear corresponding to increase in isolation damping. Further, bearing displacement decreases with increase in isolation damping. It is also observed that Hybrid control 2 produces lesser bearing displacement in comparison to Hybrid control 1. It is also observed that physical significance of increasing damping in an isolation system is to counteract the excessive base displacement but it increases the acceleration transmitted to the buildings and hence increases the base shear.
The effects of isolation damping on story drift under Hybrid control 1 and 2 are also shown in Figures 3. It is

observed from Figures that increase in isolation damping leads to decrease in interstory drift. It is also seen from the trends that lower floors are more sensitive to variation in isolation damping as compared to upper floors. Furthermore, similar trends are also observed under Hybrid control 2.

3.2. Influence of Gain Multiplier parameter of VF damper

To study the effect of gain multiplier parameter on seismic performance of the control schemes, three sizes of the parameter (R_f = 0.03, 0.05, 0.1) are considered and the results are shown in Table 2 and 3 for Building 1 and 2, respectively. The percentage reduction in peak top floor displacement, for Imperial Valley earthquake, of Building 1 and 2 for the three considered values of gain multiplier under Hybrid control 3 are 89.38, 88.26, 82.13 and 17.69, 4.45, -15.20, respectively. Similarly, for the Hybrid control 4, percentage reductions are 86.83, 84.34, 77.99 and 14.45, 1.11, -18.29. Further, percentage reduction in peak top floor acceleration of Building 1 and 2 for three considered sizes of gain multiplier under Hybrid control 3 are 49.39, 42.05, 30.79 and 9.29, 2.79, -8.05 respectively. Similarly, for the Hybrid control 4, percentage reductions are 48.36, 39.92, 27.84 and -8.60, -25.61, -50.63, respectively. Peak values of damper force (kN) for VF control, Hybrid control 3 and 4 corresponding to three considered sizes of gain parameter are: 1434.8, 1359.1, 1287.1; 530.0, 545.1, 563.8 and 594.9, 590.9, 590.1, respectively. Further, peak bearing displacement (cm) for Hybrid control 3 and 4 for the three considered values of R_f are 4.71, 3.76, 3.64 and 3.79, 3.36, 3.60 respectively. The trends of results reflected that increase in the gain multiplier results to deterioration in displacement and acceleration control for both the buildings and it is more pronounced in case of Building 2 under Hybrid control 2.

4 CONCLUSIONS

The specific conclusions drawn from the study are as follows.

1. The proposed hybrid control strategies are quite effective in seismic response mitigation as compared to VF control.
2. The response reduction is effective in Building 1 whereas it is marginal for Building 2.
3. Increase in gain multiplier parameter leads to higher damper force and better control over the displacement response.
4. Increase in isolation damping leads to increase in base shear and decrease in bearing displacement, therefore, suitable values of damping have to be chosen so as to keep within limits.
5. Lesser bearing displacement under Hybrid control 2 as compared to Hybrid control 1. This implies that Hybrid control 2 is more effective in preventing impact from the adjacent structures.
6. Large damper force generated in Semi-active VF damper causes better control over displacement response but there is increase in acceleration response and base shear; therefore, gain multiplier used in VF damper has to be suitably chosen to strike the desired balance.

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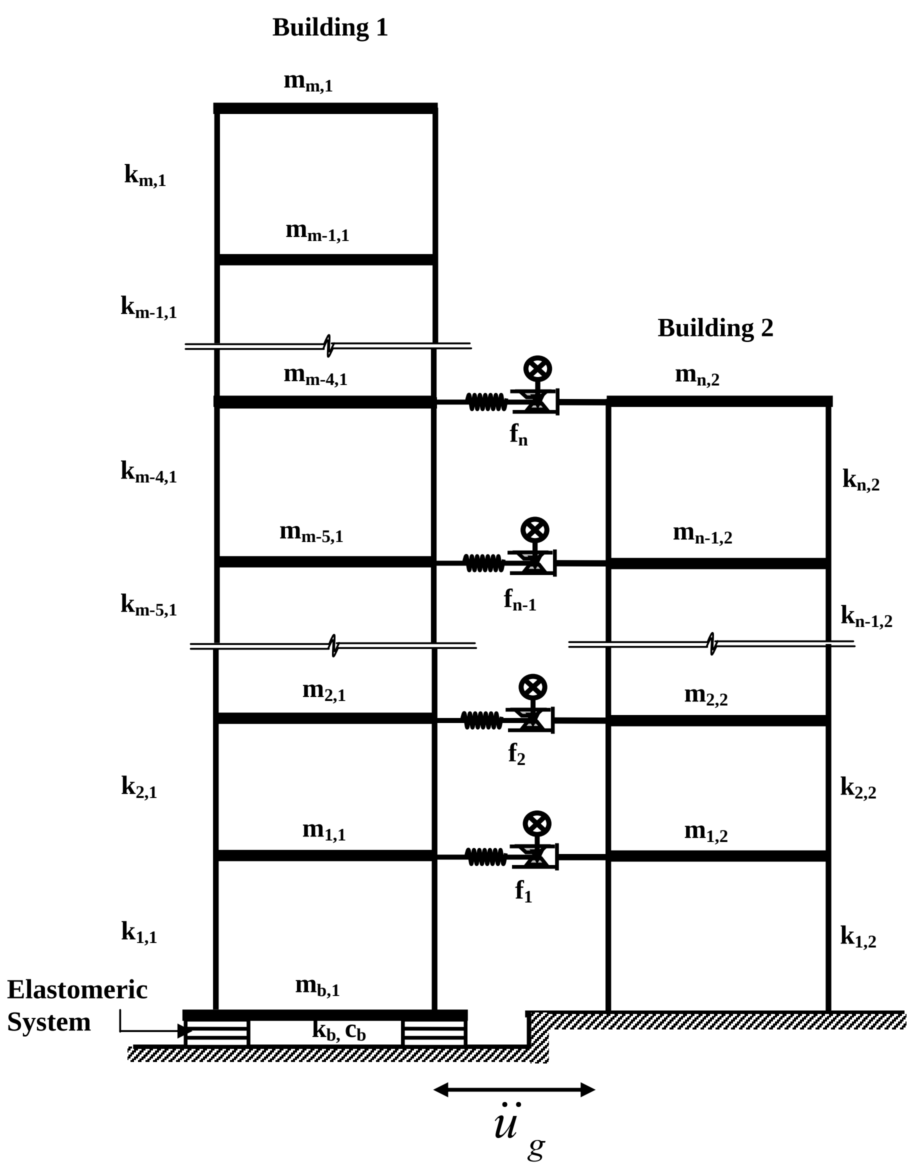

Figure 1 Structural model of isolated coupled building with VF damper

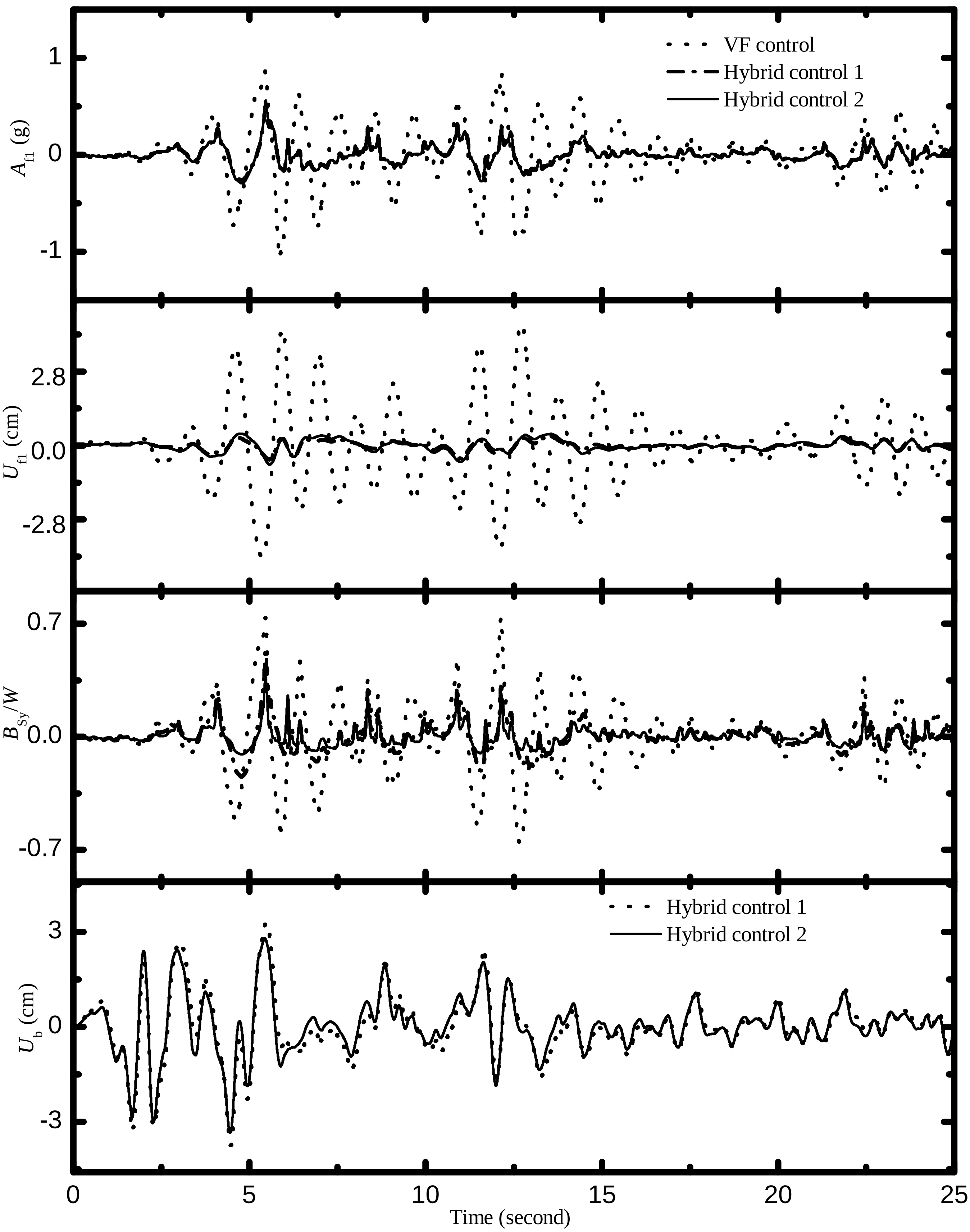

Figure 2 Time variation of top floor displacement, acceleration, base shear and bearing displacement of Building 1 under Imperial Valley, 1940 (R_f= 0.05; T_b= 2s, ξ_b= 0.1, F_0= 0.05)

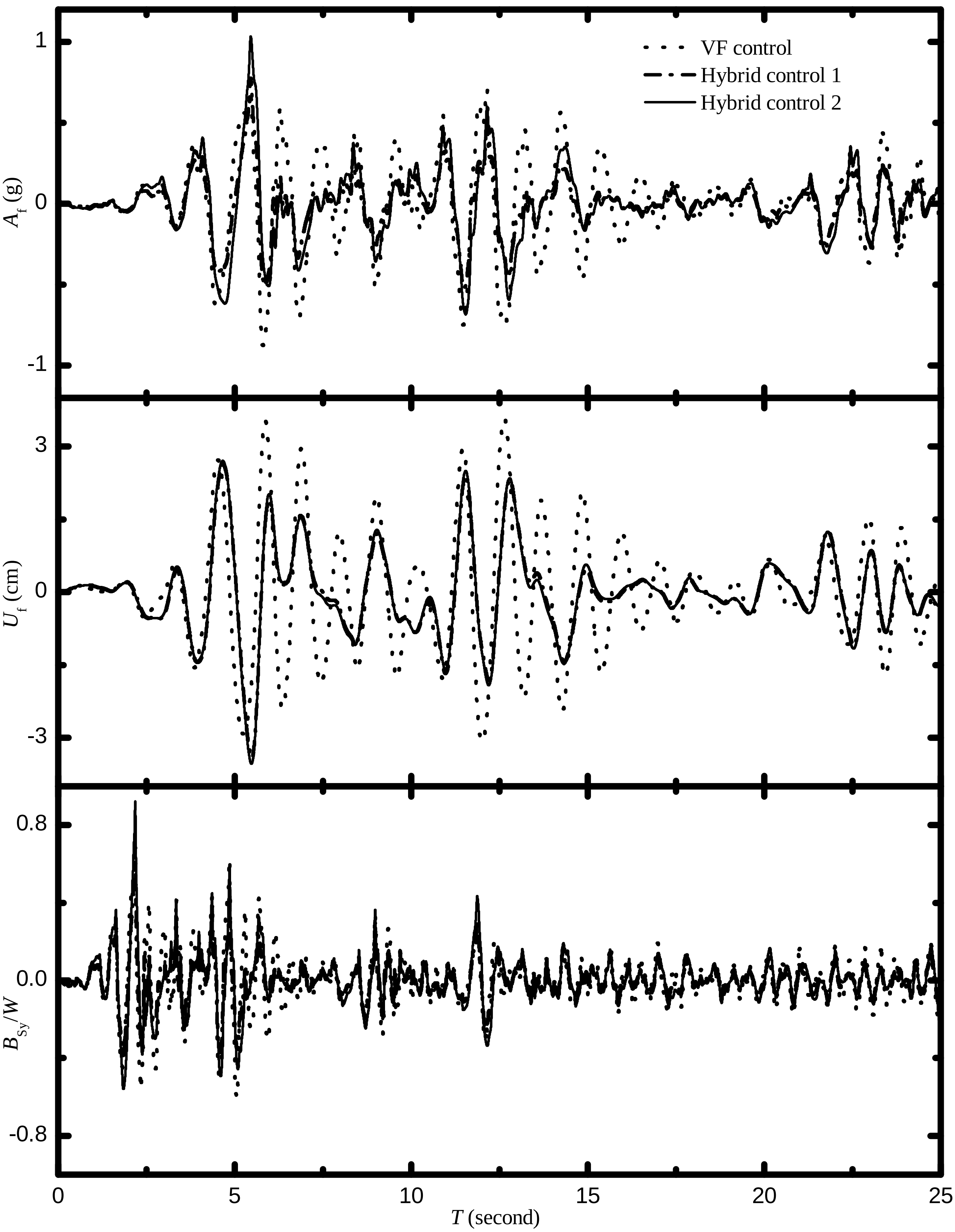

Figure 3 Time variation of top floor displacement, acceleration and base shear of Building 2 under Imperial Valley, 1940 (R_f= 0.05)

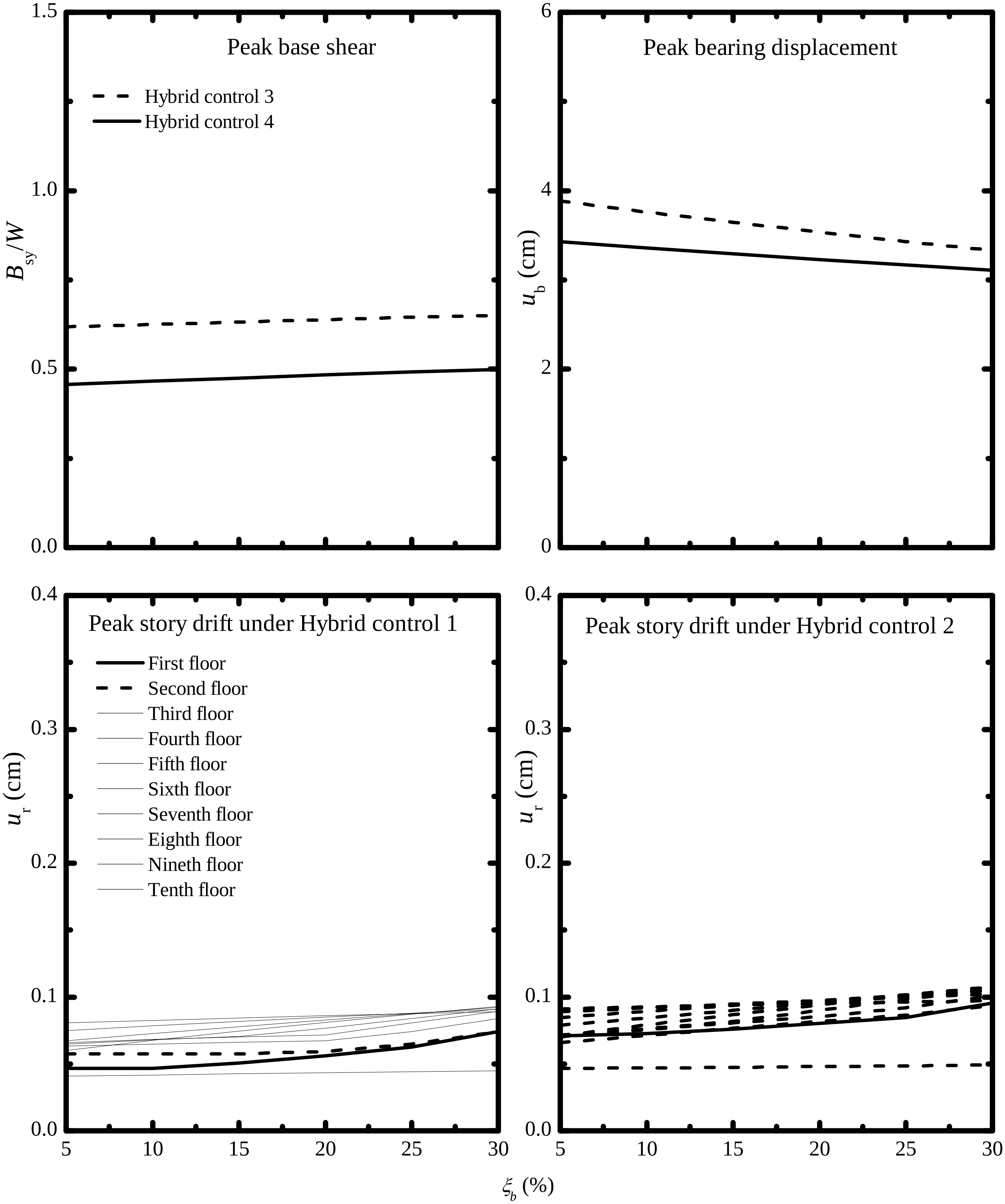

Figure 4 Effect of isolation damping on base shear, bearing displacement and story drift of Building 1 under Imperial Valley, 1940 (R_f= 0.05; T_b= 2s, F_0= 0.05)