Seismic Response Control of Asymmetric Plan Building with Semiactive MR Damper

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SUMMARY:
Plan asymmetric buildings are very susceptible to earthquake induced damage due lateral torsional coupling. This creates increased force and higher ductility demand on lateral load-resisting elements leading to excessive edge deformations, and sometimes causes pounding between closely spaced adjacent buildings. In general, excessive deformation in asymmetric-plan buildings may be reduced by redistributing the stiffness and/or mass properties to minimize stiffness eccentricity; however, such redistribution may not be always feasible due to architectural and functional constraints. In last two decades researchers have investigated the application of various control devices for seismic response control of torsionally coupled systems. In this paper, the effectiveness of MR damper based control strategies have been investigated for a plan asymmetric system. A one-story and one-way asymmetric building model with rigidly connected MR dampers on two edges parallel to the axes of asymmetry is subjected to unidirectional ground motion. The results of the study show the effectiveness of the control scheme.

Keywords: torsionally coupled system, semiactive control, and edge displacement.

1. INTRODUCTION

Asymmetric-plan buildings are especially vulnerable to earthquakes due to coupling between lateral and torsional motion compared to buildings with symmetric plans. This creates increased force, hence higher ductility demand on lateral load-resisting elements leading to excessive edge deformations, and sometimes this may also cause pounding between closely spaced adjacent buildings. In general, excessive deformation in asymmetric-plan buildings may be reduced by redistributing the stiffness and/or mass properties to minimize stiffness eccentricity; however, such redistribution may not be always feasible due to architectural or functional constraints.

Researchers have investigated the application of various control devices for seismic response control of torsionally coupled systems; Jangid and Datta (1997) examined the performance of Multiple Tuned Mass Dampers (MTMD) for torsionally coupled system through parametric study. The effect of supplemental damping on the edge deformation of a asymmetric-plan systems was investigated by Goel (1998, 2000), Lin and Chopra (2001) showed that the reduction in earthquake response of the system achieved by supplemental damping is strongly influenced by its planwise distribution. Date and Jangid (2001) investigated the effectiveness of active control system using a structural model of a one story torsionally coupled building.

In this paper, the effectiveness of MR damper based control strategies. That is, passive-off. passive-on and semiactive, have been investigated for seismic response control plan asymmetric buildings. For the study one-story and one-way asymmetric building model with rigidly connected MR dampers on two edges parallel to the axes of asymmetry is considered. The results of the study have showed the effectiveness of the proposed control scheme.

2. STRUCTURAL MODELLING

The building model considered is the idealized one-story one-way plan asymmetric building consisting of rigid deck supporting by structural elements (i.e. wall, columns, moment-frames, braced frames etc.) in each of the two orthogonal directions, in addition the system includes MR dampers installed in the bracing systems in the X-direction. The mass properties of the system are considered to be symmetric about both the axis whereas stiffness properties are considered to be symmetric only about Y-axes. The lack of symmetry in the stiffness properties about X-axes is characterized by the stiffness eccentricity, e_y, defined as the distance between CM and CR. (Figure 4.1).

The three uncoupled natural frequencies of the system can be expressed as-

$$\omega_x = \sqrt{\frac{k_{xx}}{m}} \tag{3.1}$$

$$\omega_y = \sqrt{\frac{k_{yy}}{m}} \tag{3.2}$$

$$\omega_\theta = \sqrt{\frac{k_{\theta\theta}}{m\rho^2}} \tag{3.3}$$

where, m is the mass of the deck, k_{xx} and k_{yy} are the translational stiffness in X and Y direction respectively , $k_{\theta\theta}$ is rotational stiffness and ρ is the mass radius of gyration.

The governing equations of motion of the system in matrix form is expressed as below

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}= [D]\{f_m\}- [M][r]\{\ddot{u}_g\} \tag{3.4}$$

where, M, C, and K are mass, damping, stiffness matrices of the building respectively; f_m is the vector consisting of forces in the MR dampers; D is the damper location matrix; u is the relative displacement vector with respect to the ground, r is the influence coefficient vector, and $\ddot{u}_g$ is the earthquake ground acceleration. The M and K matrices are expressed as

$$M = \begin{bmatrix} m & 0 & 0 \\ 0 & m\rho^2 & 0 \\ 0 & 0 & m \end{bmatrix} \tag{3.5}$$

$$K = \begin{bmatrix} k_{xx} & k_{x\theta} & k_{xy} \\ k_{\theta x} & k_{\theta\theta} & k_{\theta y} \\ k_{yx} & k_{y\theta} & k_{yy} \end{bmatrix} \tag{3.6}$$

For the one-story one way asymmetrical system as shown in Figure 1 the stiffness matrix is explicitly expressed as below.

$$K = \begin{bmatrix} k_{xx} & e_y k_{xx} & 0 \\ e_y k_{xx} & e_y{}^2 k_{xx} + (b/2)^2 k_{yy} & 0 \\ 0 & 0 & k_{yy} \end{bmatrix} \tag{3.7}$$

Other matrices and vectors used in the Eq. (5.4) are explicitly expressed as:

$$u = \begin{Bmatrix} u_x \\ u_\theta \\ u_y \end{Bmatrix} \quad (3.8)$$

$$\mathrm{r} = \begin{Bmatrix} 1 \\ 0 \\ 0 \end{Bmatrix} \quad (3.9)$$

$$\mathrm{D} = \begin{bmatrix} 1 & 1 & 0 \\ -\mathrm{b}_1 & -\mathrm{b}_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (3.10)$$

$$f_m = \begin{Bmatrix} f_f \\ f_s \\ 0 \end{Bmatrix} \quad (3.11)$$

where, b_1 and b_2 are the coordinates of the control force input locations.

The governing Eq. (4) can be expressed in the state-space form as below.

$$\{\dot{Z}\} = [A]\{Z\}+[B]\{f_m\}+[E]\{\ddot{u}_g\} \quad (3.12)$$

where, Z is the state vector, A is the system matrix; B and E are the distribution matrix of the control force and the excitation, respectively. The matrices Z, A, B and E are defined as below:

$$Z = \begin{bmatrix} u \\ \dot{u} \end{bmatrix}; A = \begin{bmatrix} O & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}; \; B = \begin{bmatrix} O \\ M^{-1}D \end{bmatrix}; \; E = -\begin{bmatrix} O \\ r \end{bmatrix} \quad (3.13\text{-}3.16)$$

where, I and O are the identity and null matrices, respectively.

Further, Lyapunov's direct approach to stability analysis in the design of a feedback controller is employed, and the and the Lyapunov function is chosen of the form,

$$L(\{Z\}) = \frac{1}{2}\left\|\{Z\}\right\|_p^{\;2} \quad (3.17)$$

The control voltage is restricted to the range $V \in [0, V_{max}]$ for a fixed set of states. It is underlined that the controller used is on-off controller and is dependent on the sign of the measured control force and the states of the system.

The phenomenological model proposed by Spencer et al. (1997) is used to simulate the dynamic behavior of MR damper. The equation governing the force predicted by this model is

$$f_m = c_1\dot{x} + k_1(u_d - x_0) \quad (3.18)$$

where, the evolutionary variable z is given by

$$\dot{z} = -\gamma\left|v_d - \dot{x}\right|(z)\left|z\right|^{(n-1)} - \beta(v_d - \dot{x})\left|z\right|^n + A_m(v_d - \dot{x}) \quad (3.19)$$

and

$$\dot{x} = \left\{ \frac{1}{(c_0 + c_1)} \right\} \{ \alpha_0 z + c_0 v_d + k_0 (u_d - x) \tag{3.20}$$

where, u_d is the displacement of the damper, for which relative displacements of flexible and stiff edge of the building is taken separately, for damper force on flexible edge (f_f) and stiff edge (f_s), respectively, ; x is the internal pseudo-displacement of the damper; z is the evolutionary variable that describes the hysteretic behavior of the damper; k_1 is the accumulator stiffness; c_0 is the viscous damping at large velocities; c_1 is viscous damping for force roll-off at low velocities**;** k_0 is the stiffness at large velocities; and x_0 is the initial stiffness of spring k_1; α_0 is the evolutionary coefficient; and γ, β, n and A_m are shape parameters of the hysteresis loop. The model parameters dependent on command voltage, c_0, c_1, α_0, are expressed as follows:

$$c_0 = c_{0a} + c_{0b} U \tag{3.21}$$

$$c_1 = c_{1a} + c_{1b} U \tag{3.22}$$

$$\alpha_0 = \alpha_{oa} + \alpha_{ob} U \tag{3.23}$$

where, U is given as output of first order filter.

$$\dot{U} = -\eta (U - V) \tag{3.24}$$

The governing equations of motion are solved using Newmark's step-by step method assuming linear variation of acceleration over a small time interval Δt.

3. NUMERICAL STUDY

A square deck of size 10m, supporting by structural elements and MR dampers rigidly connected on both faces parallel to the X-axes is considered (refer Figure 4.1). The mass and stiffness are so selected to yield uncoupled natural frequency in lateral x-direction equals to 2π rad/second. The system is subjected to unidirectional excitation, and for that four real earthquake ground motions- El-Centro, 1940 (PGA= 0.348g), Loma Prieta, 1989(PGA= 0.570g), Kobe, 1995(PGA= 0.837g) and Northridge, 1994(PGA= 0.843g), have been considered.

The MR damper parameters have been suitably scaled to suit the damper deformation behaviour and the values of which are: η= 195$s^{-1,}$ 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 (Yang et al. 2002)

The effectiveness of MR damper is compared under the three control strategies, namely, passive-off, passive-on and semiactive, under passive-on and passive-off strategies the damper works as a passive device with command voltage set to zero and maximum, respectively, whereas, under semiactive control the damper command voltage is governed by the control law.

Further, the effect of building parameters on the performance of control strategies is examined through a parametric study. The parameters chosen are: ratio of eccentricity to radius of gyration (i.e. $v_1 = e_y / \rho$) hereafter refered as eccentricity ratio; torsional to lateral frequency ratio (i.e. $\nu_2 = \omega_\theta / \omega_x$) hereafter refered as frequency ratio. The response parameters of interest are: peak values of flexible edge displacement (u_f), stiff edge displacement (u_s) and base shear (B_x), the response parameters are normalized with their respective uncontrolled responses and expressed in terms of response ratio R_1 (i.e. u_{fc}/u_{fu}), R_2 (i.e. u_{sc}/u_{su}) and R_3 (B_{xc}/B_{xu}).

Figures 4.2, 4.3 and 4.4 show a comparison of uncontrolled and semiactive controlled time response of flexible edge displacement, stiff edge displacement, and base shear- normalized with weight of deck (B_x/W_d), respectively. It is observed from the figures that the semiactive control scheme reduces edge displacement and base shear significantly.

The influence of frequency ratio on control performance in terms of edge displacement and base shear is depicted through Figure 4.5 - 4.7. The figures also show the comparative performance of three control strategies, namely, passive-off and passive-on and semiactive. The fact that the value of response ratios is always less than one indicates the ability of the MR damper to reduce seismic response.

Figure 4.5 and 5.6 indicates that both passive-on and semiactive control strategies are equally effective in controlling edge displacement; and after initial increase in response as frequency ratio increases the response remains nearly same after frequency ratio beyond 1.5. Further, from the Figure 4.7 it is noted that, except for El-Centro earthquake, the passive-off strategy seems to be performing better for controlling the base shear.

4. FIGURES

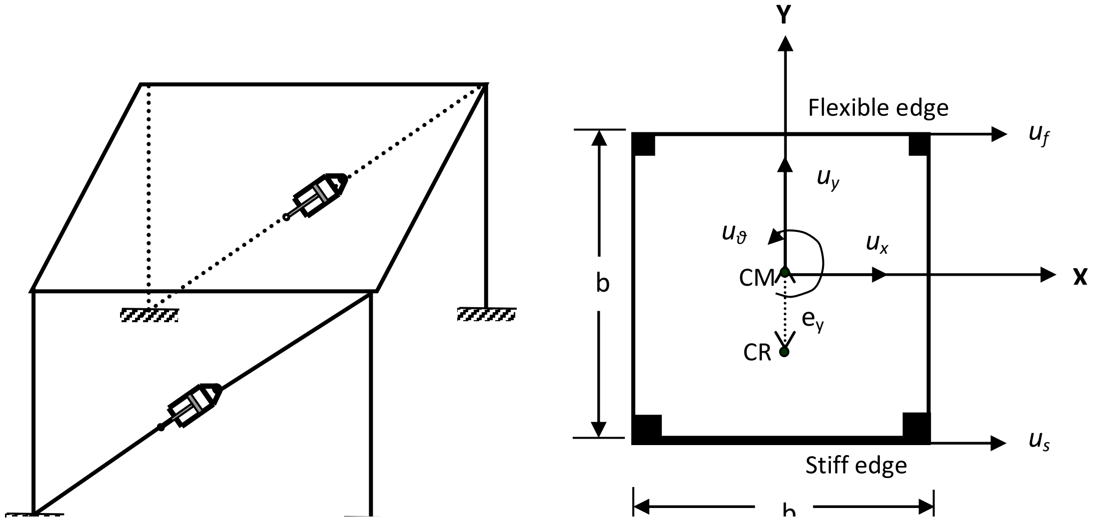

Figure 4.1. Single story plan-asymmetric building with MR dampers.

(a) 3-D view (b) Plan

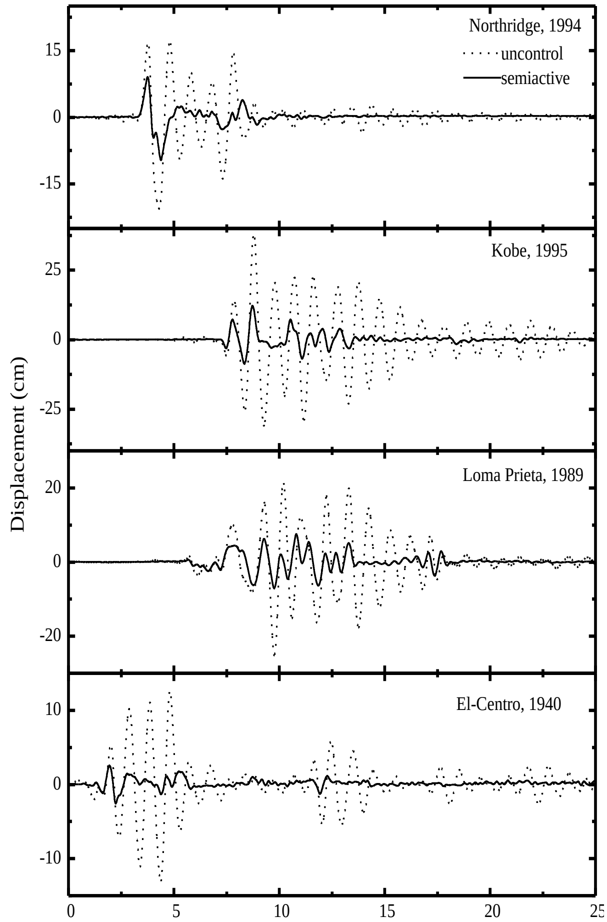

Figure 4.2. Time variation of flexible edge displacement.
(V_{max}=1.5V, n_1=0.1 & n_2=0.1)

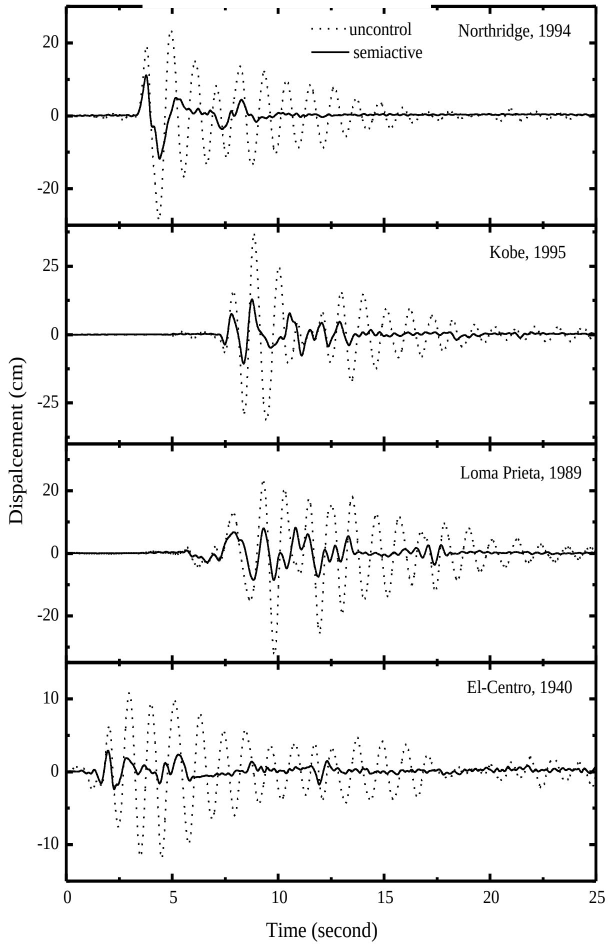

Figure 4.3. Time variation of flexible edge displacement.
(V_{max}=1.5V, n_1=0.1 & n_2=0.1)

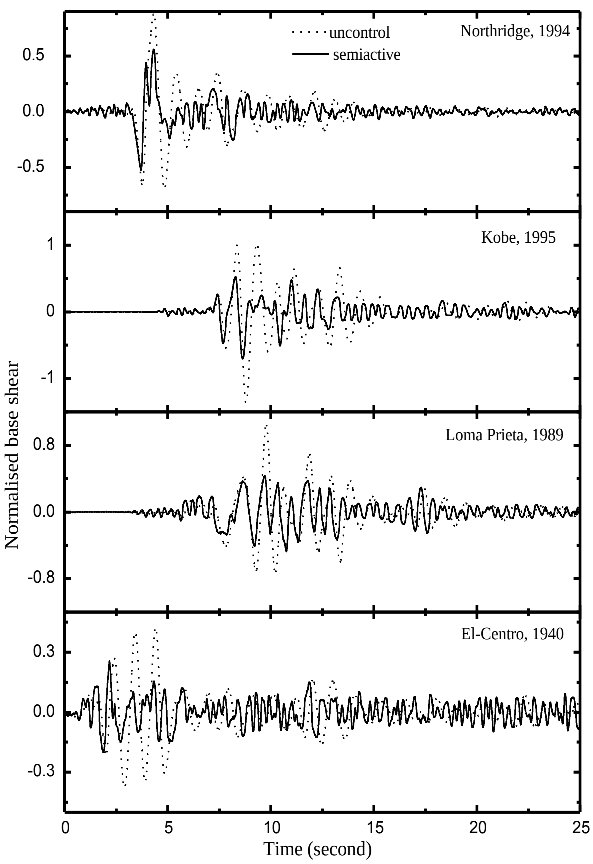

Figure 4.4. Time variation of base shear

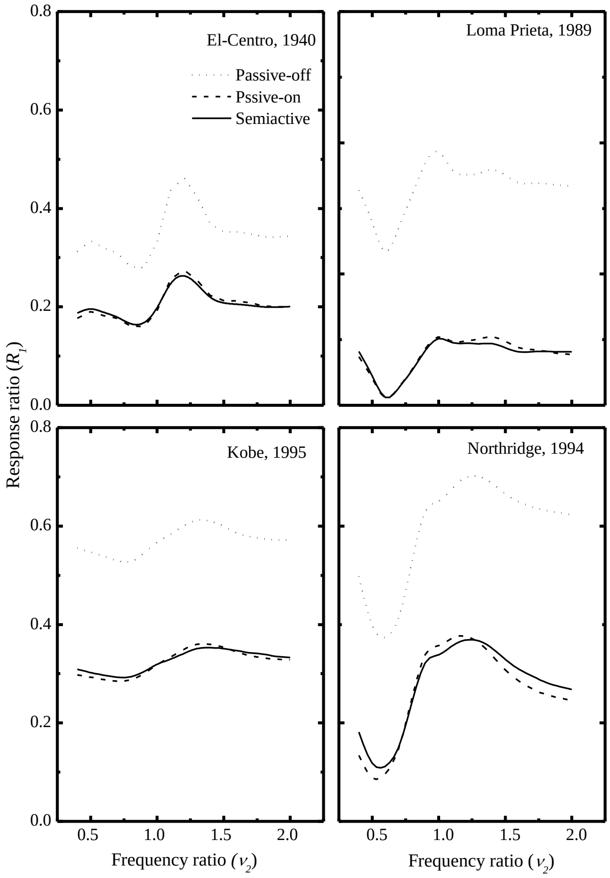

Figure 4.5. Peak displacement of flexible edge

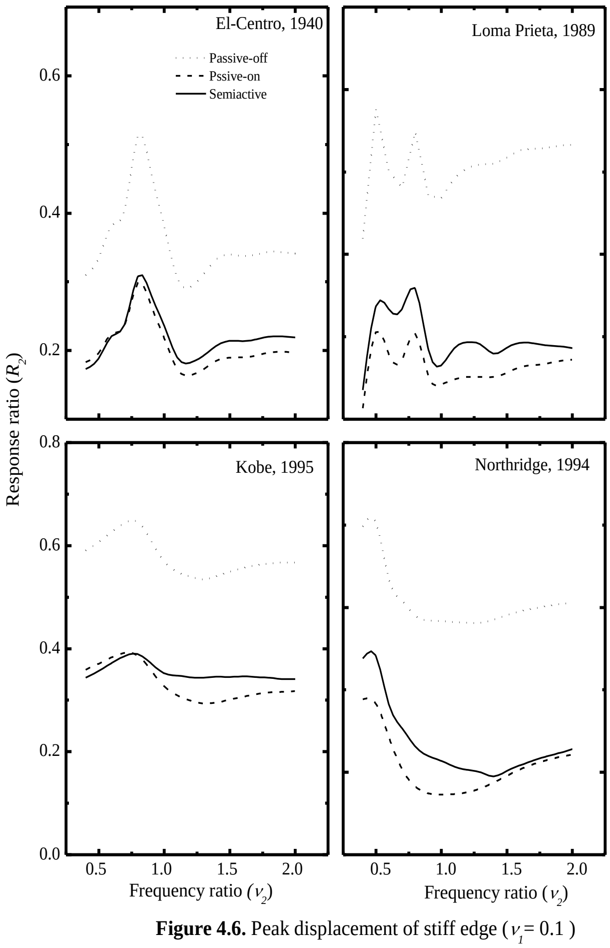

Figure 4.6. Peak displacement of stiff edge (ν_1= 0.1)

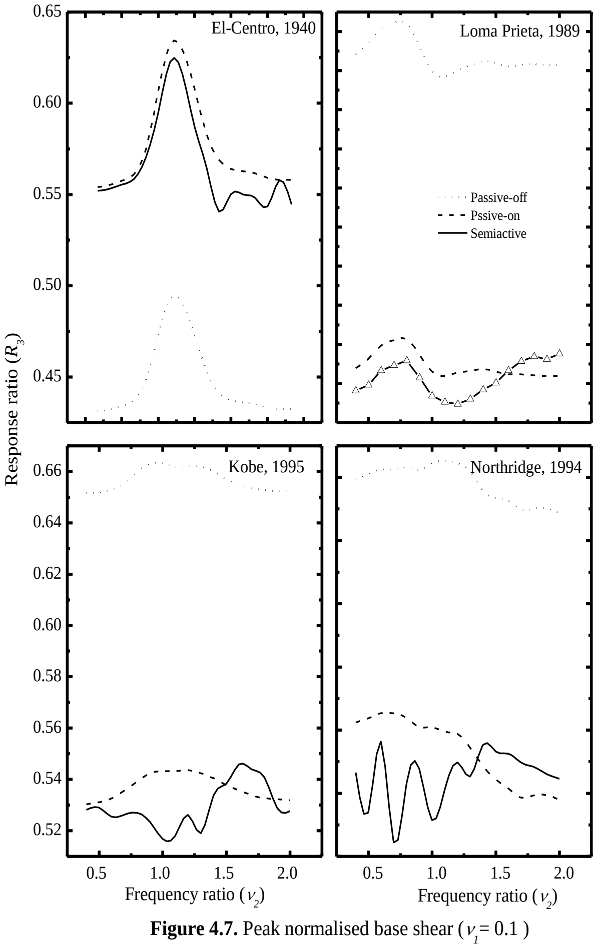

Figure 4.7. Peak normalised base shear (ν_1= 0.1)

5. CONCLUDING REMARKS

It has been observed during past major earthquakes that plan asymmetric building suffer significant damage, especially at corners. The seismic hazard mitigation of such torsionally coupled system has been a challenge for researchers, and they have been investigating various supplemental energy dissipation devices to tackle this problem. In the present study the effectiveness of semi-active MR damper for seismic response control of torsionally coupled building has been investigated, further the influence of system parameter on control performance has been examined through parametric study.
It has been founded that the MR damper based control strategies are effective in controlling the response of torsionally coupled systems, though the relative performance of the three control strategies vary depending on damper and system parameters. The reduction in edge displacement achieved under passive-on and semiactive strategy is quite significant as in both the cases damper stiffness is increased due application of maximum command voltage. It is also noted that relative effectiveness of the control system is higher for a torsionally flexible system.

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