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Seismic response of asymmetric systems with linear and non-linear viscous dampers

Snehal V Mevada* and RS Jangid

Abstract

The seismic response of linearly elastic, single-storey, one-way asymmetric building with linear and non-linear viscous dampers is investigated. The response is obtained by numerically solving the governing equations of motion. The effects of eccentricity ratio, uncoupled lateral time period, ratio of uncoupled torsional to lateral frequency and supplemental damping eccentricity ratio are investigated on peak responses which include lateral, torsional and edge displacements and their acceleration counter parts as well as control forces. To study the effectiveness of dampers, the controlled response of asymmetric system is compared with the corresponding uncontrolled response. Further, to study the effects of torsional coupling, the controlled response of asymmetric system is compared with the corresponding symmetric system. It is shown that the non-linear viscous dampers are quite effective in reducing the responses and the damper force depends on system asymmetry and supplemental damping. Also, the effectiveness of dampers significantly depends on structural and damping eccentricity ratio and torsional to lateral frequency ratio and the effects of torsional coupling are found to be more significant for torsionally flexible and strongly coupled systems. Further, effects of torsional coupling are less for asymmetric systems with non-linear dampers as compared to linear dampers.

Keywords: Seismic response, Asymmetric, Structural eccentricity, Supplemental damping eccentricity, Non-linear viscous damper

Introduction

Post-earthquake damage assessments proved that the asymmetric buildings are much more vulnerable to the severe damage due to earthquake induced vibrations. This attracted attention of many researchers to investigate the seismic response of asymmetric buildings with supplemental energy dissipation devices to mitigate such severe damages. In past, many researchers have investigated the performance of various control techniques such as passive control viz. base isolation and supplemental dampers for lateral-torsional response control of asymmetric structures. Jangid and Datta (1994) investigated the nonlinear response of one-storey torsionally coupled base isolated system and found that if the eccentricity of the building is ignored, the effectiveness of base isolation is overestimated. Jangid and Datta (1995) investigated the stochastic response of one-storey torsionally coupled base isolated building and noticed that the effectiveness of base isolation is reduced for higher eccentricity of superstructure. Jangid (1996) studied the seismic response of one storey, one-way asymmetric base isolated structure. The effects of eccentricity ratio, torsional to lateral frequency ratio, mass ratio and coefficient of friction was studied. Jangid and Datta (1997) investigated the performance of multiple tuned mass dampers (MTMDs) for asymmetric model and found that the effectiveness of MTMDs in controlling translational response is less for an asymmetric system than corresponding symmetric system. Singh et al. (2002) derived the optimum parameters for tuned mass dampers installed in 6-story torsionally coupled building and found damper as effective in reducing the responses. De La Llera et al. (2005) proposed the weak torsional balance condition for system installed with friction dampers such as to minimize the correlation between translation and rotation. It was concluded that the maximum displacements at both edges of the building plan are always similar and less than twice the response of the nominally symmetric counterpart. Matsagar and Jangid (2010)

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evaluated the response of asymmetric base-isolated structure during impact with adjacent structures and without impact. It was concluded that with the increase in torsional coupling, the impact response increases, and it is mandatory to incorporate 3D analysis.

Passive viscous dampers are the efficient and well suited energy dissipation devices, which shall significantly reduce the response of buildings to earthquakes (Symans and Constantinou, 1998; Lee and Taylor, 2001). In recent past, some studies have been done to investigate the effectiveness of linear viscous dampers (LVDs) and non-linear viscous dampers (NLVDs) for symmetric and asymmetric systems. Goel (1998) studied the effects of supplemental viscous damping on seismic response of one-way asymmetric system and found that edge deformations in asymmetric systems can be reduced than those of the same edges in the corresponding symmetric systems by proper selection of supplemental damping parameters. Goel and Booker (2001) investigated the effects of supplemental viscous damping on inelastic seismic response of one-storey asymmetric building and found that the supplemental viscous damping reduces the deformation, ductility, and hysteretic energy dissipation demands in lateral load-resisting elements of asymmetric-plan systems. Lin and Chopra (2001) investigated the linear elastic, one-storey asymmetric building installed with fluid viscous dampers. It was observed that asymmetric distribution of supplemental damping is more effective in reducing the response as compared to symmetric distribution. Lin and Chopra (2002) studied the effectiveness of NLVDs for elastic single storey symmetric system. The study was carried out by assuming symmetric arrangement of dampers. It is shown that NLVDs are advantageous as they achieve the higher reduction in response with reduced damper forces. Lin and Chopra (2003) investigated the effectiveness of NLVDs and viscoelastic dampers for elastic single storey asymmetric system. They studied the effects of dampers for strongly coupled system with structural eccentricity ratio as 0.2 and for two values of exponent for damper as 0.35 and 1. The responses are also studied for different values of damping eccentricities and found that the effectiveness of supplemental damping depends on plan wise distribution of dampers. Goel (2005) studied the seismic response of one-storey, one-way asymmetric system with NLVDs. The parametric study has been done to investigate the effectiveness of NLVDs with equivalent LVDs. The responses are obtained for strongly coupled system for particular value of eccentricity ratio. Further, the response of asymmetric systems with LVDs and NLVDs are compared to evaluate the effects of non linearity and its influence on the effects of plan asymmetry. Petti and De Iuliis (2008) proposed a method to optimally locate the viscous dampers for torsional response control in asymmetric plan systems by using modal analysis techniques. It was found that optimal damping eccentricity moves from the flexible edge to the mass center by reducing the structural eccentricity.

Although, the above studies reflect the effectiveness of NLVDs in controlling the lateral-torsional responses, however, no study has been carried out to investigate effectiveness of LVDs and NLVDs in controlling the lateral, torsional and edge responses including the accelerations quantities. For the buildings, it is equally important and necessary to limit excessive torsional and edge accelerations considering the functional requirements as well as the stability of non-structural components. Hence, it shall be useful to study the effectiveness of dampers in reducing the accelerations. Also, the effectiveness of NLVDs for wide range of eccentricities is not studied so far. Moreover, in earlier findings, responses are studied for strongly coupled systems only and hence it is required to investigate the effectiveness of dampers and effects of asymmetry for torsionally flexible and torsionally stiff systems. Further, it will be interesting to study the effects of change in supplemental damping eccentricities on various displacement and acceleration responses. Moreover, an alternative approach is considered for the present study for deriving the supplemental damping coefficients in comparison to the equivalent energy approach considered by previous researchers. Furthermore, the effects of torsional coupling for various responses and damper forces for asymmetric systems in comparison to corresponding symmetric systems are also not studied in detail in past.

In this paper, the seismic response of linearly elastic, single storey, one-way asymmetric building is investigated under different real earthquake ground motions. The specific objectives of the study are summarized as (i) to study the comparative performance of LVDs and NLVDs in controlling lateral, torsional and edge displacements as well as their acceleration counterparts, (ii) to study the effects of torsional coupling on the effectiveness of LVDs and NLVDs, and (iii) to investigate the influence of important parameters on the effectiveness of LVDs and NLVDs for asymmetric systems. The important parameters considered are eccentricity ratio of superstructure, uncoupled lateral time period, ratio of uncoupled torsional to lateral frequency and supplemental damping eccentricity ratio.

Structural model and solution of equations of motion

The system considered is an idealized one-storey building which consists of a rigid deck supported on columns as shown in Figure 1. Following assumptions are made for the structural system under consideration: (i) floor of the

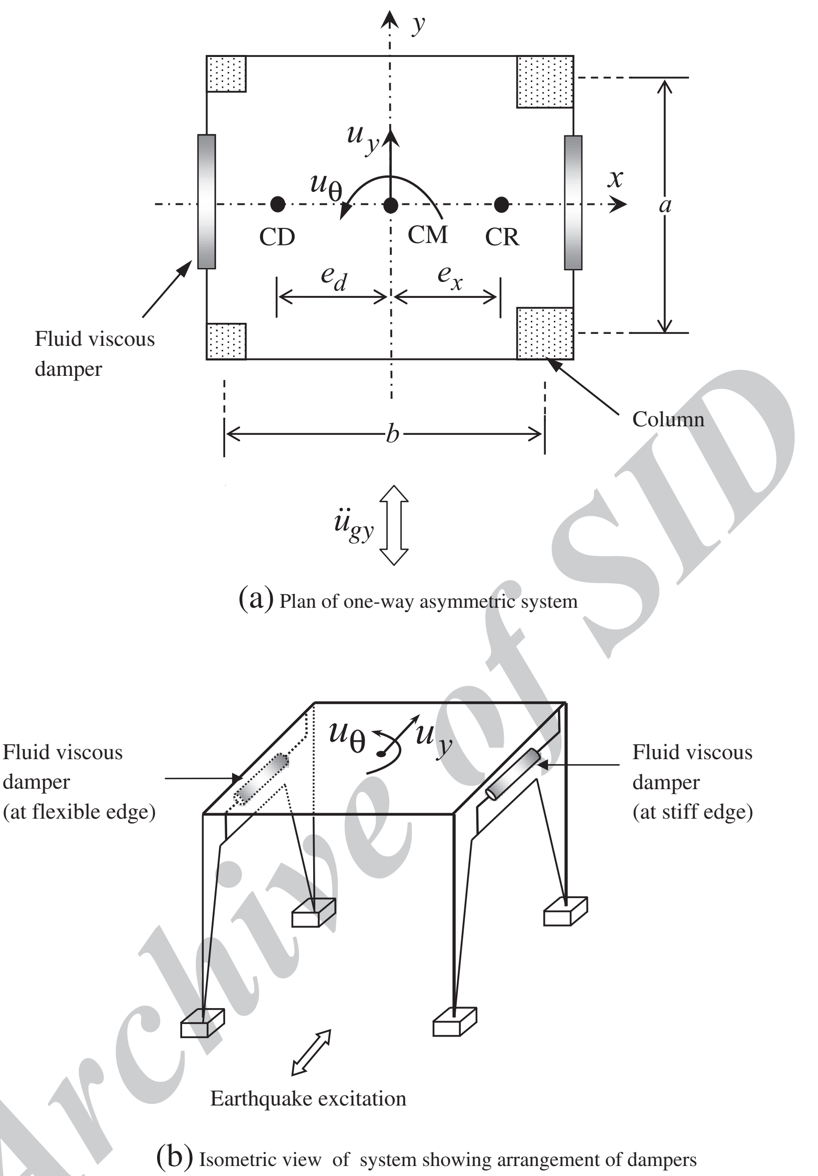

Figure 1 Plan and isometric view of one-way asymmetric system showing arrangement of dampers. (**a**) Plan of one-way asymmetric system. (**b**) Isometric view of system showing arrangement of dampers.

superstructure is assumed as rigid, (ii) force-deformation behaviour of superstructure is considered as linear and within elastic range and (iii) the structure is excited by uni-directional horizontal component of earthquake ground motion. The mass of deck is assumed to be uniformly distributed and hence centre of mass (CM) coincides with the geometrical centre of the deck. The columns are arranged in a way such that it produces the stiffness asymmetry with respect to the CM in one direction and hence, the centre of rigidity (CR) is located at an eccentric distance, e_x from CM in x-direction. The system is symmetric in x-direction and therefore, two degrees-of-freedom are considered for model namely the lateral displacement in y-direction, u_y and torsional displacement, u_θ as represented in Figure 1. The governing equations of motion of the building model with coupled lateral and torsional degrees-of-freedom are obtained by assuming that the control forces provided by the dampers are adequate to keep the response of the structure in the linear range. The equations of motion of the system in the matrix form are expressed as

$$M\ddot{u} + C\dot{u} + Ku = -M\Gamma\ddot{u}_g + \Lambda F \quad (1)$$

where M, $C$and K are mass, damping and stiffness matrices of the system, respectively; $u = \{u_y\, u_\theta\}^{\mathrm{T}}$ is the displacement vector; Γ is the influence coefficient vector; $\ddot{u}_g = \{\ddot{u}_{gy}\ 0\}^T$ is ground acceleration vector; $\ddot{u}_{gy}$ is ground acceleration in y-direction; Λ is the matrix that defines the location of control devices; $F = \{F_{dy}\ F_{d\theta}\}^T$ is the vector of control forces; and F_{dy} and $F_{d\theta}$ are resultant control forces of dampers along y- and θ- direction, respectively.

The mass matrix can be expressed as,

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

where m represents the lumped mass of the deck; and r is the mass radius of gyration about the vertical axis through CM which is given by, $r = \sqrt{(a^2 + b^2)/12}$; where a and b are the plan dimensions of the building.

The stiffness matrix of the system is modified as follows (Goel, 1998)

$$K = K_y \begin{bmatrix} 1 & e_x \\ e_x & {e_x}^2 + r^2 {\Omega_\theta}^2 \end{bmatrix} \tag{3}$$

$$e_x = \frac{1}{K_y} \sum_i K_{yi} x_i \text{ and } \Omega_\theta = \frac{\omega_\theta}{\omega_y} \tag{4}$$

$$\omega_\theta = \sqrt{\frac{K_{\theta r}}{mr^2}} \text{ and } \omega_y = \sqrt{\frac{K_y}{m}} \tag{5}$$

$$K_{\theta r} = K_{\theta\theta} - {e_x}^2 K_y \text{ and } K_{\theta\theta} = \sum_i K_{xi} {y_i}^2 + \sum_i K_{yi} {x_i}^2 \tag{6}$$

where K_y denotes the total lateral stiffness of the system in y-direction; e_x is the structural eccentricity between CM and CR of the system; Ω_θ is the ratio of uncoupled torsional to lateral frequency of the system; K_{yi} indicates the lateral stiffness of i^{th} column in y-direction; x_i is the x-coordinate distance of i^{th} element with respect to CM; ω_y is uncoupled lateral frequency of the system; ω_θ is uncoupled torsional frequency of the system; $K_{\theta r}$ is torsional stiffness of the system about a vertical axis at the CR; $K_{\theta\theta}$ is torsional stiffness of the system about a vertical axis at the CM; K_{xi} indicates the lateral stiffness of i^{th} column in x-direction; and y_i is the y-coordinate distance of i^{th} element with respect to CM.

Let e_d represent the supplemental damping eccentricity defined as the distance between CM and centre of supplemental damping (CD) which reflects the lack of symmetry in the damper properties about the y-axis and expressed as

$$e_d = \frac{1}{C_d} \sum_i C_{di} x_i \tag{7}$$

where C_d is the total damping coefficient of damper system along y-axis; and C_{di} is the damping coefficient of the i^{th} damper along y-axis. The value of C_d is calculated as $C_d = 2\, m\, \omega_y\, \xi_d$, where, ξ_d is the supplemental damping ratio.

The damping matrix of the system is not known explicitly and it is constructed from the Rayleigh's damping considering mass and stiffness proportional as,

$$C = a_0 M + a_1 K \tag{8}$$

in which a_0 and a_1 are the coefficients depends on damping ratio of two vibration modes. For the present study 5% damping is considered for both modes of vibration of system.

The governing equations of motion are solved using the state space method (Hart and Wong, 2000; Lu, 2004) and re-written as

$$\dot{z} = A\, z + B\, F + E\, \ddot{u}_g \tag{9}$$

where $z = \{u \quad \dot{u}\}^{\mathrm{T}}$ is a state vector; A is the system matrix; B is the distribution matrix of control forces; and E is distribution matrix of excitations. These matrices are expressed as,

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}; \quad B = \begin{bmatrix} 0 \\ M^{-1}\Lambda \end{bmatrix} \text{ and } E = -\begin{bmatrix} 0 \\ \Gamma \end{bmatrix} \tag{10}$$

in which I is the identity matrix.

The Eq. (9) is discretized in time domain and the excitation and control forces are assumed to be constant within any time interval, the solution may be written in an incremental form (Hart and Wong, 2000; Lu, 2004),

$$z[k+1] = A_d\, z[k] + B_d\, F[k] + E_d\, \ddot{u}_g[k] \tag{11}$$

where k denotes the time step**;** and $A_d = e^{A\Delta t}$ represents the discrete-time system matrix with Δt as time interval. The constant coefficient matrices B_d and E_d are discrete-time counterparts of matrices B and E and can be written as

$$B_d = A^{-1}(A_d - I)B \text{ and } E_d = A^{-1}(A_d - I)E \tag{12}$$

Modeling of fluid viscous damper

Fluid dampers operate on the principle of fluid flow through orifices and provide forces that always resist structure motion during a seismic event. Figure 2 shows a schematic and mathematical model of typical fluid viscous damper. A typical viscous damper consists of a cylindrical body and central piston which strokes through a fluid filled chamber. The commonly used fluid is silicone based fluid which ensures proper performance and stability. The differential pressure generated across the

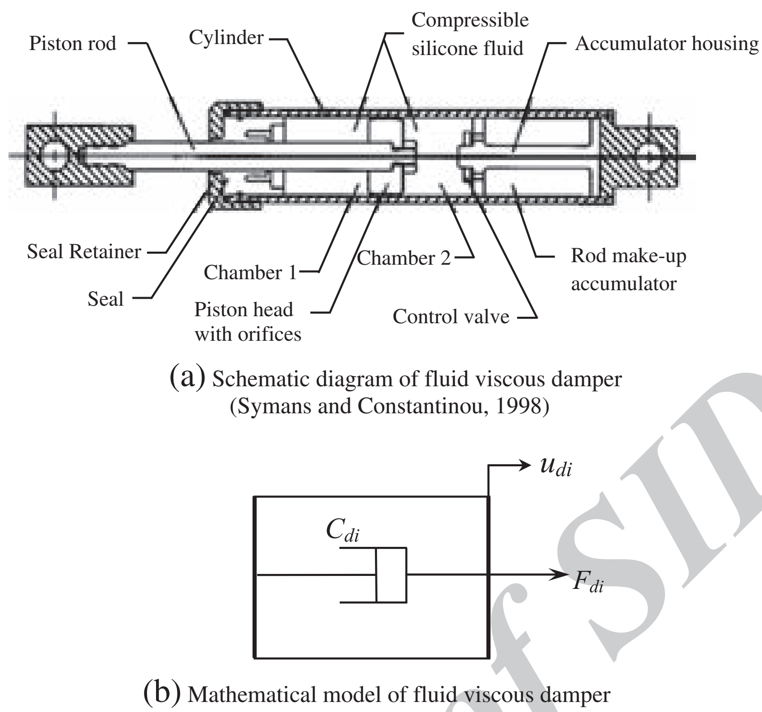

Figure 2 Schematic and mathematical model of the fluid viscous damper. (**a**) Schematic diagram of fluid viscous damper (Symans and Constantinou 1998). (**b**) Mathematical model of fluid viscous damper.

piston head results in the damper force (Symans and Constantinou, 1998; Lee and Taylor, 2001).

The force in a viscous damper, F_{di} (=F_{df} or F_{ds}) is proportional to the relative velocity between the ends of a damper and given by

$$F_{di} = C_{di}|\dot{u}_{di}|^{\alpha} sgn(\dot{u}_{di}) \tag{13}$$

where, C_{di} is damper coefficient of the i^{th} damper, $\dot{u}_{di}$ is relative velocity between the two ends of a damper which is to be considered corresponding to the position of dampers, α is the damper exponent ranging from 0.2 to 1 for seismic applications (Soong and Dargush, 1997) and $sgn(\cdot)$ is signum function. The value of exponent is primarily controlled by the design of piston head orifices. When α = 1, a damper is called as linear viscous damper (LVD) and with the value of α smaller than unity, a damper will behave as nonlinear viscous damper (NLVD). Dampers with α larger than unity have not been seen often in seismic practical applications.

Numerical study

The seismic response of linearly elastic, idealized single-storey, one-way asymmetric building installed with passive fluid viscous dampers is investigated by numerical simulation study. The response quantities of interest are lateral and torsional displacements of floor mass obtained at the CM (u_y and u_θ), displacements at stiff and flexible edges of building (u_{ys} and u_{yf}), lateral and torsional accelerations of floor mass obtained at the CM ($\ddot{u}_y$ and $\ddot{u}_\theta$), accelerations at stiff and flexible edges of building ($\ddot{u}_{ys}$ and $\ddot{u}_{yf}$), control forces of the dampers installed at stiff edge (F_{ds}) and at flexible edge (F_{df}) of building as well as resultant damper force, F_{dy} ($= F_{ds} + F_{df}$). The response of the system is investigated under following parametric variations: structural eccentricity ratio (e_x/r), uncoupled lateral time period of system ($T_y = 2\pi/\omega_y$), ratio of uncoupled torsional to lateral frequency of the system ($\Omega_\theta = \omega_\theta/\omega_y$) and supplemental damping eccentricity ratio (e_d/r). The peak responses are obtained corresponding to the important parameters which are listed above for four considered earthquake ground motions namely, Imperial Valley (1940), Loma Prieta (1989), Northridge (1994) and Kobe (1995) with corresponding peak ground acceleration (PGA) values of 0.31 *g*, 0.96 *g*, 0.89 *g* and 0.82 *g* as per the details summarized in Table 1. The average values of peak responses from four earthquakes are obtained and parametric study is carried out based on these average trends such as to have more definite study under the range of seismic ground motions. For the study carried out herein, the aspect ratio of plan dimension is kept as unity and the mass and stiffness of system are considered such as to have required lateral time period. Further, total two fluid

Table 1 Details of earthquake motions considered for the numerical study

Earthquake	Recording Station	Component	Duration (sec)	PGA (*g*)
Imperial Valley, 19th May, 1940	El Centro (Array # 9)	ELC 180	40	0.31
Loma Prieta, 18th October,1989	Los Gatos Presentation Center	LGP 000	25	0.96
Northridge, 17th January, 1994	Sylmar Converter Station	SCS 142	40	0.89
Kobe, 16th January,1995	Japan Meteorological Agency	KJM 000	48	0.82

viscous dampers (one at each edge) are installed in the building as shown in Figure 1.

In order to study the effectiveness of control system and effects of torsional coupling, the responses are expressed in terms of indices, R_e and R_t defined as follows:

$$R_e = \frac{\text{Peak response of controlled asymmetric system}}{\text{Peak response of corresponding uncontrolled system}} \tag{14}$$

$$R_t = \frac{\text{Peak response of controlled asymmetric system}}{\text{Peak response of corresponding symmetric system}} \tag{15}$$

The value of R_e less than unity indicates that the control system is effective in reducing the responses. On the other hand, the value of R_t reflects the effects of torsional coupling on the effectiveness of control system for asymmetric system as compared to corresponding symmetric system. The value of R_t greater than unity indicates that the response of asymmetric system increases due to torsional coupling and hence the effectiveness of control system is less for asymmetric system as compared to corresponding symmetric system.

In order to investigate the effectiveness of LVDs and NLVDs, the velocity exponent, α as expressed in Eq. (13) is varied from 0.2 (highly non-linear) to 1 (linear) for the systems with Ω_θ = 0.5 (torsionally flexible), Ω_θ = 1 (strongly coupled) and Ω_θ = 2 (torsionally stiff). The responses are obtained for system with T_y = 1 s and intermediate value of eccentricity ratio, e_x/r = 0.3 under four considered earthquakes and variations are shown for the average responses in Figure 3. The supplemental damping ratio, ξ_d is considered as 20%. In the present study, the effects of supplemental damping eccentricity ratio, e_d/r is investigated separately in later sections, hence unless it is specified for the other parametric study, the value of e_d/r is taken as zero implying the symmetric arrangement of dampers on both sides. The response ratios, R_e are obtained for torsional displacement (u_θ), stiff edge displacement (u_{ys}), flexible edge displacement (u_{yf}) as well as their accelerations counterparts (i.e. $\ddot{u}_\theta$, $\ddot{u}_{ys}$ and $\ddot{u}_{yf}$) and its variations against α are plotted. It can be observed from the figure that with the increase in values of α, the ratio, R_e increases for responses u_θ, u_{ys} and u_{yf} corresponding to all values of Ω_θ. On the other hand, for torsional and edge acceleration responses, the variations of R_e remains less sensitive to α. Thus, the effectiveness of fluid viscous dampers decreases in reducing various displacement responses with increase in α. Further, figure also shows the variation of peak control forces of dampers located at stiff edge (F_{ds}), at flexible edge (F_{df}) as well as resultant damper force (F_{dy}). The damper forces are normalized with the weight of deck, W. It is observed that with the increase in values of α, F_{ds} and F_{df} increases except for torsionally flexible system, in which F_{df} decreases. Moreover, F_{dy} slightly decreases initially and then increases with further increase in α and this trend is more significant for torsionally stiff systems. Also, the optimum range for the value of α is found to be 0.3 to 0.6 considering the damper forces. Further, the damper force in NLVDs (α < 1) is smaller than corresponding force in LVDs (α = 1) with higher reduction in responses achieved with NLVDs for system with T_y= 1 s. Thus, the difference between the resultant damper force of NLVDs and LVDs is more for torsionally stiff system as compared to torsionally flexible and strongly coupled systems.

In order to study the effects of supplemental damping ratio, ξ_d for LVDs and NLVDs, the variations of R_e against ξ_d (which is varied from 0 to 80%) are shown in Figures 4 and 5. The value of R_e = 1 corresponding to ξ_d= 0 is representing the uncontrolled response. The responses are obtained for the system with T_y= 1 s and e_x/r = 0.3 for three values of Ω_θ = 0.5, 1 and 2 are shown in Figures 4(a), (b) and 5(a), respectively. The responses are plotted for four values of α (i.e. 0.35, 0.5, 0.7 and 1 representing the NLVD to LVD) which have been seen for the seismic practical applications. It can be observed from the first set of rows of Figures 4(a), (b) and 5(a) that with the increase in ξ_d, the ratio, R_e decreases for torsional (u_θ) and edge displacement (u_{ys} and u_{yf}) responses corresponding to all values of α. This implies that the effectiveness of control system increases with the increase in ξ_d. Moreover, as observed in earlier section, values of R_e corresponding to α = 1 (LVD) are highest followed by the corresponding values obtained from α = 0.7, 0.5 and 0.35 (NLVDs). Furthermore, the second set of rows of Figures 4(a), (b) and 5(a) represents the variations of R_e for torsional ($\ddot{u}_\theta$) and edge

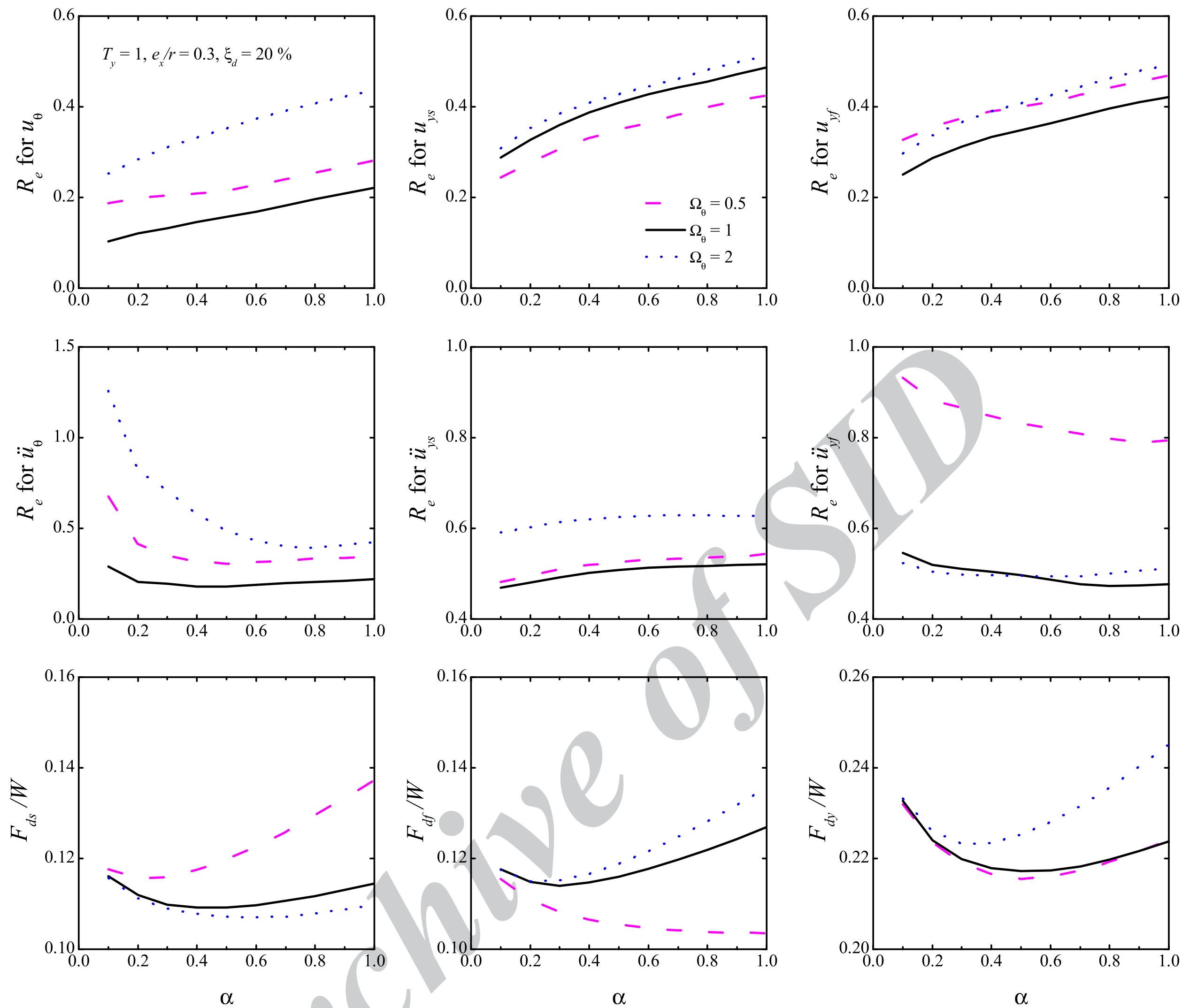

Figure 3 Effect of exponent, α on response ratio, R_e for various displacement and acceleration responses and damper forces.

accelerations ($\ddot{u}_{ys}$ and $\ddot{u}_{yf}$). It is observed that for the systems with Ω_θ = 0.5 and 1, ratio, R_e for $\ddot{u}_{yf}$ first decreases and then increases with further increase in ξ_d. This means, there exist an optimum value of ξ_d for the flexible edge accelerations, which is one of the important response quantities. On the other hand, for $\ddot{u}_\theta$ and $\ddot{u}_{ys}$, ratio, R_e decreases with increase in ξ_d. However, the variations for R_e remains very less sensitive beyond the supplemental damping ratio equal to 30% especially for reducing the edge accelerations. Further, it is noticed that the NLVDs are little more effective than LVDs in reducing the stiff edge accelerations and torsional accelerations for systems with Ω_θ = 0.5 and 1, whereas, for torsionally stiff system, the effectiveness of NLVDs is less as compared to LVDs in reducing torsional accelerations. Further, in general, it is also observed that the reduction in various responses is higher in the range of ξ_d when it is varied from 0 to 30% as compared to the reduction observed beyond 30%. In addition, Figure 5(b) shows the variations of normalized damper force (F_{dy}) against ξ_d. It is observed that with increase in ξ_d, the damper force increases for all values of α, which is as expected. Thus, the increase in supplemental damping ratio increases the effectiveness of dampers in reducing torsional displacement and accelerations, stiff edge displacement and accelerations as well as flexible edge displacements for systems with Ω_θ = 0.5, 1 and 2. On the other hand, the effectiveness decreases for higher supplemental damping ratio in reducing flexible edge accelerations for systems with Ω_θ = 0.5 and 1. Further, resultant damper force of NLVDs is less than the corresponding force of LVDs in the initial range of supplemental damping ratio (up to 30%) and for higher values of damping ratio, the reverse trend is observed.

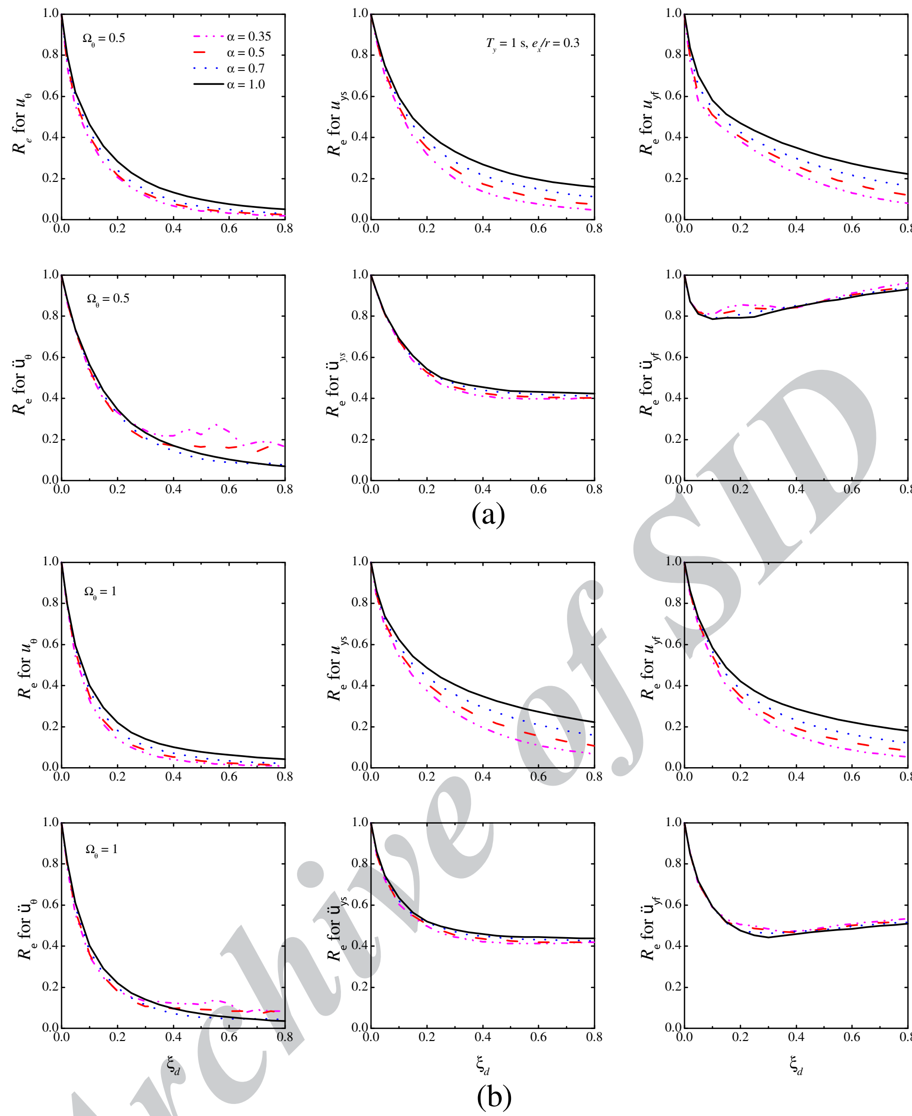

Figure 4 Effect of ξ_d on R_e for various displacement and acceleration responses. (**a**) for Ω_θ = 0.5. (**b**) For Ω_θ =1.

Figure 6 shows the time histories of various displacement and acceleration responses of uncontrolled system compared with corresponding system controlled with LVDs (α = 1) and NLVDs (α = 0.35). The responses are shown for the system with T_y= 1 s, Ω_θ = 1 and e_x/r= 0.3 under Kobe, 1995 earthquake. The significant reduction in displacement and acceleration responses at CM, at flexible and stiff edges as well as torsional responses is observed with dampers and the NLVDs are found to be little more effective than LVDs.

Figure 7 represents the hysteresis loops for the normalized damper force with displacement and velocity for LVDs and NLVDs placed at stiff and flexible edges of the system with T_y = 1 s, Ω_θ = 1 and e_x/r = 0.3 under Kobe, 1995 earthquake. It can be observed from the force-velocity loops that the dampers with α = 1 exhibits a linear behavior whereas, the dampers with α = 0.35 exhibits a non-linear behavior.

In earlier discussions, the effectiveness of control system is studied for the building with intermediate eccentricity. Hence, further it is important and necessary to investigate the effectiveness of dampers in reducing various responses for systems with lower to higher eccentricity range. In order to investigate this, variations of ratio, R_e against eccentricity ratio, e_x/r are shown in Figure 8 for system with T_y = 1 s and Ω_θ = 0.5, 1 and 2. It is clear from the earlier finding that the lesser value of exponent, α gives the higher reduction in responses whereas, higher value of α leads to an increase in damper force. Also, the significant reduction in responses are obtained

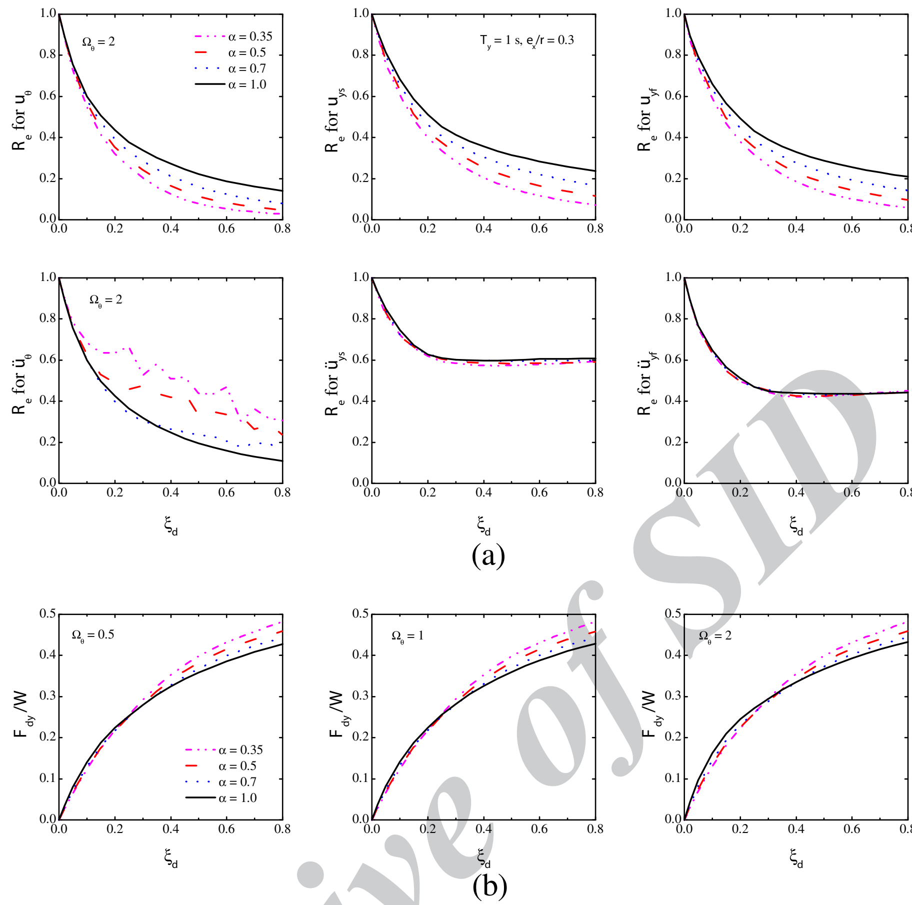

Figure 5 Effect of ξ_d on R_e and normalized resultant damper force. (**a**) For $\Omega_\theta = 2$. (**b**) For normalized resultant damper force (F_{dy}).

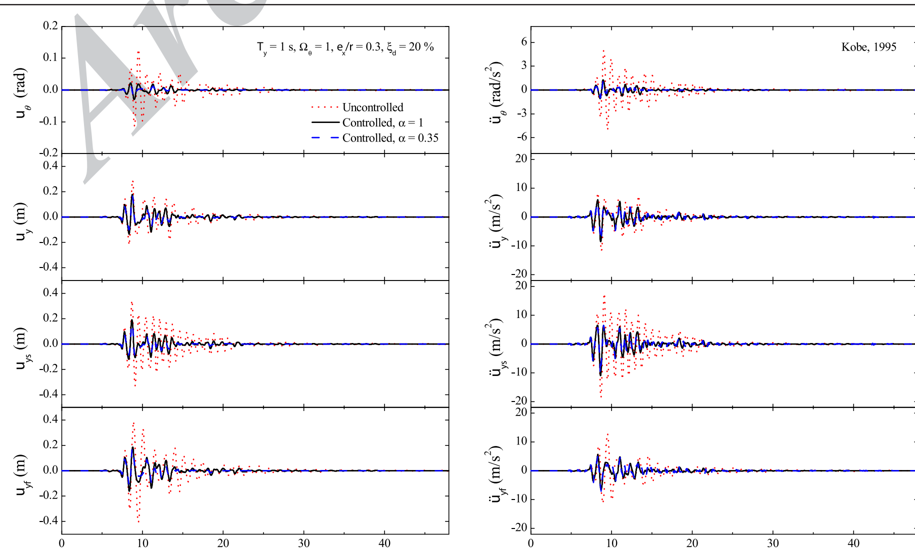

Figure 6 Time histories for various uncontrolled and controlled displacements and accelerations under Kobe, 1995 earthquake.

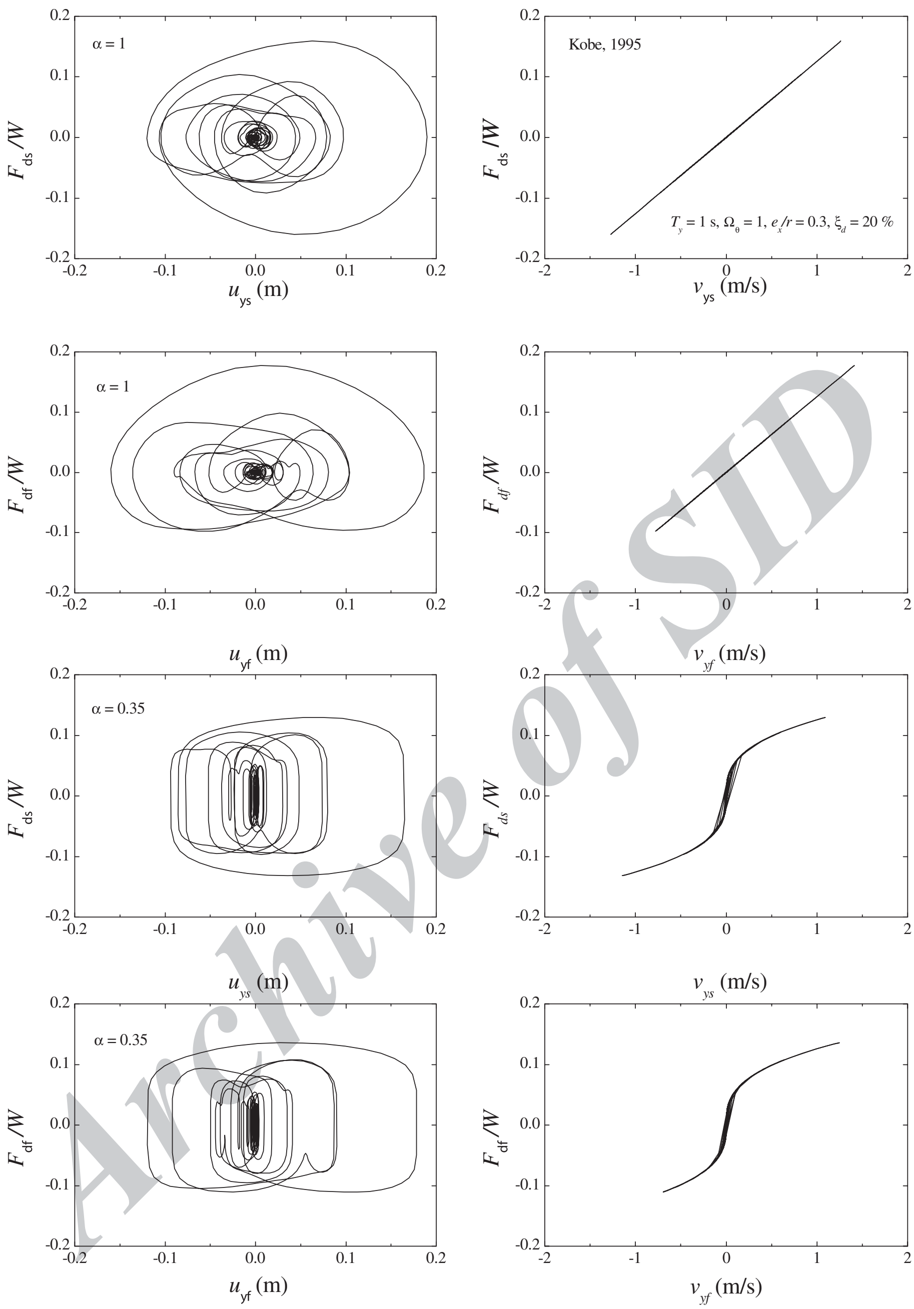

Figure 7 Typical hysteresis loops for LVDs and NLVDs under Kobe, 1995 earthquake.

when ξ_d is near to 20%, whereas, the higher values of that increases the damper force as well as flexible edge accelerations. Hence, for the study carried out from here onwards, ξ_d and α are considered as 20% and 0.35, respectively. It can be observed from the Figure 8 that with increase in e_x/r, the ratio, R_e increases for torsional responses, u_θ and $\ddot{u}_\theta$. This implies that the effectiveness of dampers reduces for the system with higher eccentricities in reducing torsional responses. Moreover, it can be seen that the NLVDs perform better than LVDs for the range of e_x/r values in reducing various displacements and accelerations except for $\ddot{u}_\theta$ for the system with Ω_θ = 2 and $\ddot{u}_{yf}$ for system with Ω_θ = 0.5 in which LVDs perform better than NLVDs. Further, in general, it is observed that the values of R_e for various displacement responses are lesser than the corresponding acceleration responses. This show the dampers are more effective in reducing the displacement responses as

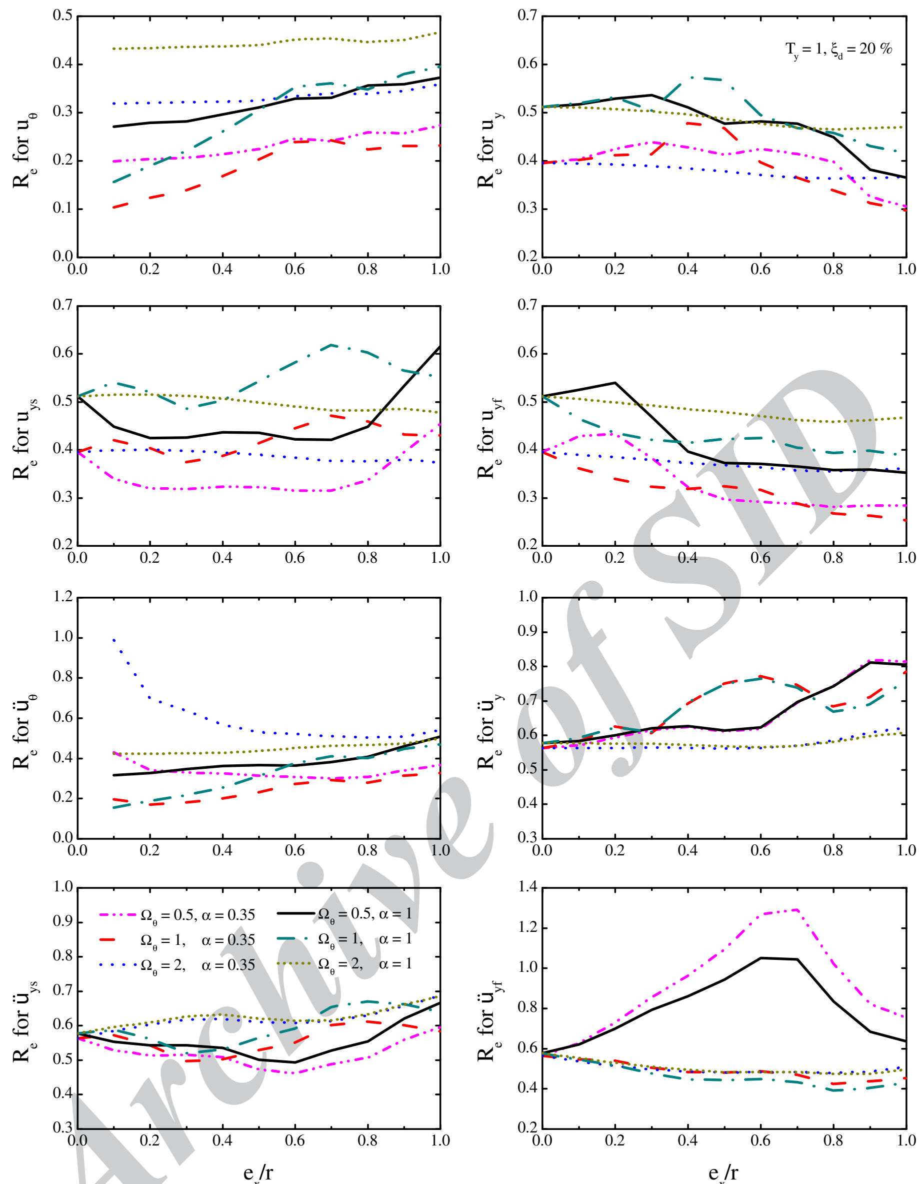

Figure 8 Effect of eccentricity on response ratio, R_e for various displacement and acceleration responses.

compared to acceleration responses. Furthermore, the variation in R_e is more sensitive to the change in e_x/r for acceleration responses as compared to displacement responses for NLVDs. Thus, the effectiveness of NLVDs is more sensitive to the eccentricity ratio for acceleration responses as compared to displacement responses. This phenomenon is more predominant for torsionally flexible and strongly coupled systems.

In order to study the effectiveness of dampers for building (e_x/r = 0.3) with different lateral time periods, the variations of R_e against T_y are shown in Figure 9. It is observed that the values of R_e comes out to be less than unity for all responses for considered range of T_y, in general, which shows the effectiveness of dampers. It is further noticed that R_e for displacement and acceleration responses increases with increase in T_y, in general. However, variations in values of R_e are more sensitive and significant for acceleration responses as compared to displacement responses for NLVDs. It is also observed that NLVDs are more effective in reducing torsional responses (u_θ and $\ddot{u}_\theta$) for strongly coupled system (Ω_θ= 1) followed by systems with Ω_θ = 0.5 and 2. Moreover, for systems with Ω_θ = 1, higher reduction in $\ddot{u}_\theta$ can be achieved with NLVDs as compared to LVDs and for Ω_θ = 2, higher reduction in $\ddot{u}_\theta$ can be achieved with LVDs. For laterally stiff systems with Ω_θ = 0.5, the NLVDs perform

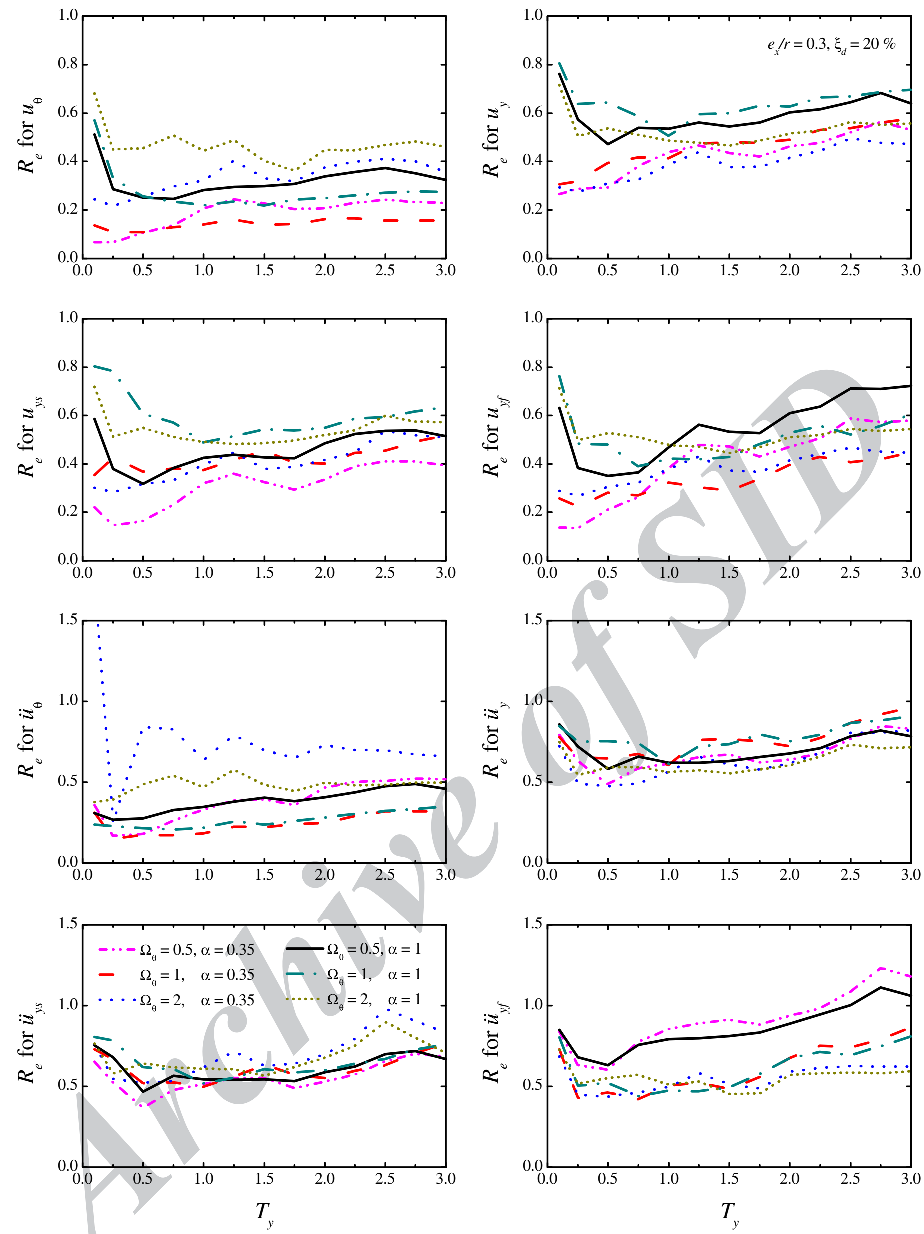

Figure 9 Effect of lateral time period, T_y on response ratio, R_e for various displacement and acceleration responses.

better than LVDs in reducing $\ddot{u}_\theta$ and $\ddot{u}_{yf}$, whereas for laterally flexible systems with Ω_θ = 0.5, LVDs perform better than NLVDs. Thus, effectiveness of dampers decreases with increase in lateral flexibility of building and effectiveness of NLVDs is more in reducing displacement responses as compared to accelerations. Further, NLVDs are more effective than LVDs for laterally flexible to stiff systems with Ω_θ= 0.5, 1 and 2 in reducing various displacements. On the other hand, the comparative performance of LVDs and NLVDs may vary depending on the value of Ω_θ and T_y for reducing acceleration responses.

Figure 10 (a) shows the variation of normalized damper forces against e_x/r for system with T_y = 1 s. It is observed that for the system with Ω_θ= 0.5, the stiff edge damper force, F_{ds} increases initially and then decreases with further increase in e_x/r, whereas an opposite trend is observed for flexible edge damper force, F_{df}. Further, for systems with Ω_θ= 1 and 2, F_{ds} decreases and F_{df} increases with increase in e_x/r for both values of α. It is further observed that for systems with Ω_θ= 0.5, 1 and 2, resultant damper force, F_{dy} decreases with increase in eccentricity ratio. Further, for systems with Ω_θ= 0.5 and

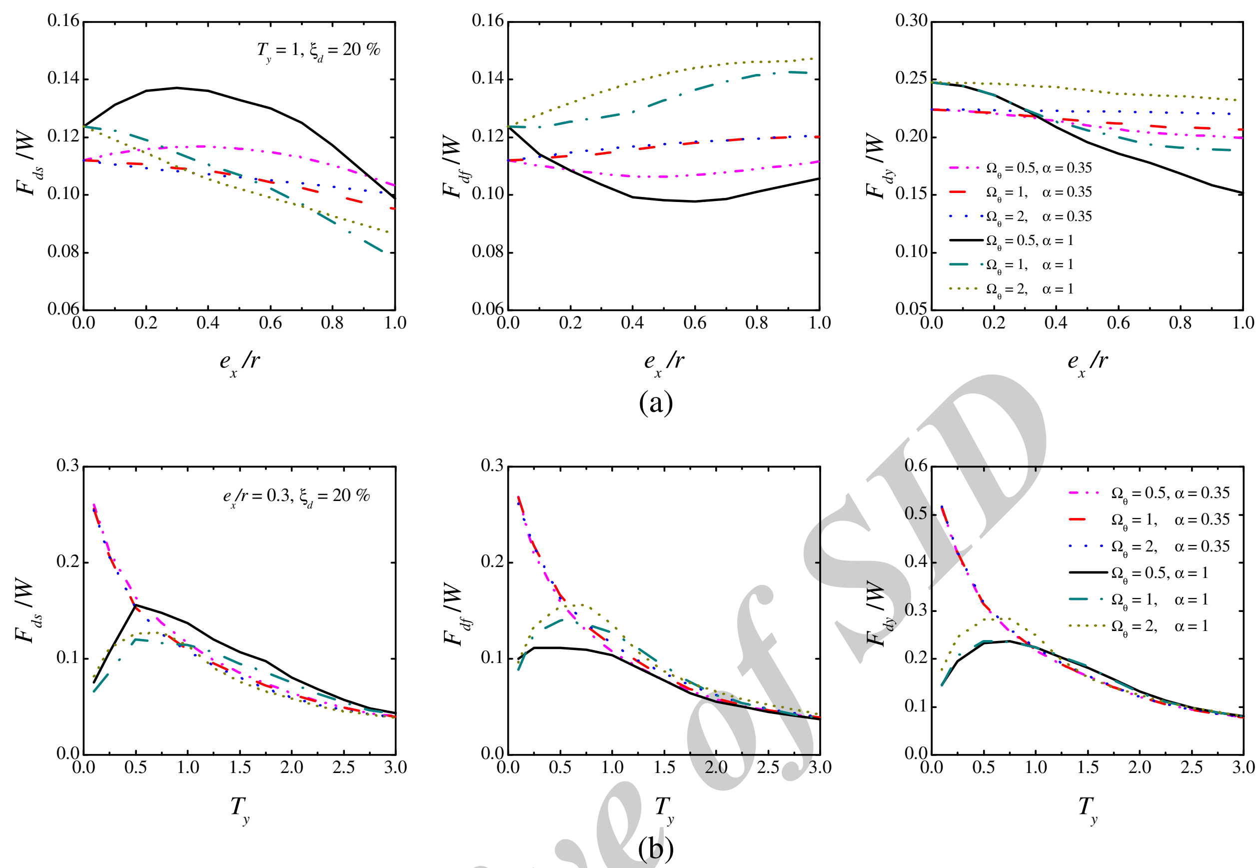

Figure 10 Variation of normalized damper forces for NLVDs and LVDs. (**a**) Variation against e_x/r. (**b**) Variation against T_y.

1, up to an intermediate eccentricity, F_{dy} for NLVDs is less than corresponding force for LVDs, whereas for systems with higher eccentricities, the force in NLVDs increases as compared to LVDs. Moreover, for system with $\Omega_\theta = 2$, F_{dy} is less for NLVDs as compared to LVDs corresponding to all values of e_x/r. In addition, Figure 10 (b) shows the variations of damper forces against lateral time period, T_y. It can be observed that for laterally stiff systems (T_y < 0.75 s), F_{dy} for NLVDs is more than corresponding force of LVDs, whereas for laterally flexible systems (T_y > 0.75 s), F_{dy} for NLVDs is lesser than the corresponding force of LVDs. The similar trends are also observed for individual damper forces i.e. F_{ds} and F_{df}. Thus, the difference between damper force in NLVDs and corresponding force in LVDs strongly depends on structural eccentricity for torsionally flexible and strongly coupled systems as compared to torsionally stiff systems. Also, for laterally stiff systems (T_y < 0.75 s), damper force for NLVDs is more than corresponding force of LVDs. On the other hand, for laterally flexible systems (T_y > 0.75 s), reverse trend is observed and as the lateral flexibility of building increases, the difference between damper force of NLVDs and LVDs decreases.

In the study carried out up to this section, the damping coefficients of both the dampers are kept constant which is implying the zero damping eccentricity. Now, in this section, to investigate the effects of supplemental damping eccentricity, the damping coefficients of both edge dampers are varied such as to have required damping eccentricity, e_d as expressed by Eq. (7). Thus, the variations of R_e against supplemental damping eccentricity ratio, e_d/r for lateral, edge and torsional displacements and accelerations are shown in Figures 11 and 12, respectively. The figures are plotted for four values of T_y (= 0.5, 1, 2 and 3 s). The other parameters considered are e_x/r = 0.3, ξ_d = 20% and α = 0.35. The ratio, e_d/r is varied from negative extreme (i.e. all dampers are located at flexible edge of building) to positive extreme (i.e. all dampers are located at stiff edge of building). It is observed from the first set of rows of Figures 11 and 12, that the ratio, R_e for u_θ and $\ddot{u}_\theta$, initially decreases with the increase in e_d/r, attains some minimum value near to $e_d/r = 0$ and then increases with further increase in e_d/r. For the systems with $\Omega_\theta = 2$, the extreme values of e_d/r leads to very high torsional responses, sometimes higher than the uncontrolled responses. Further, it is

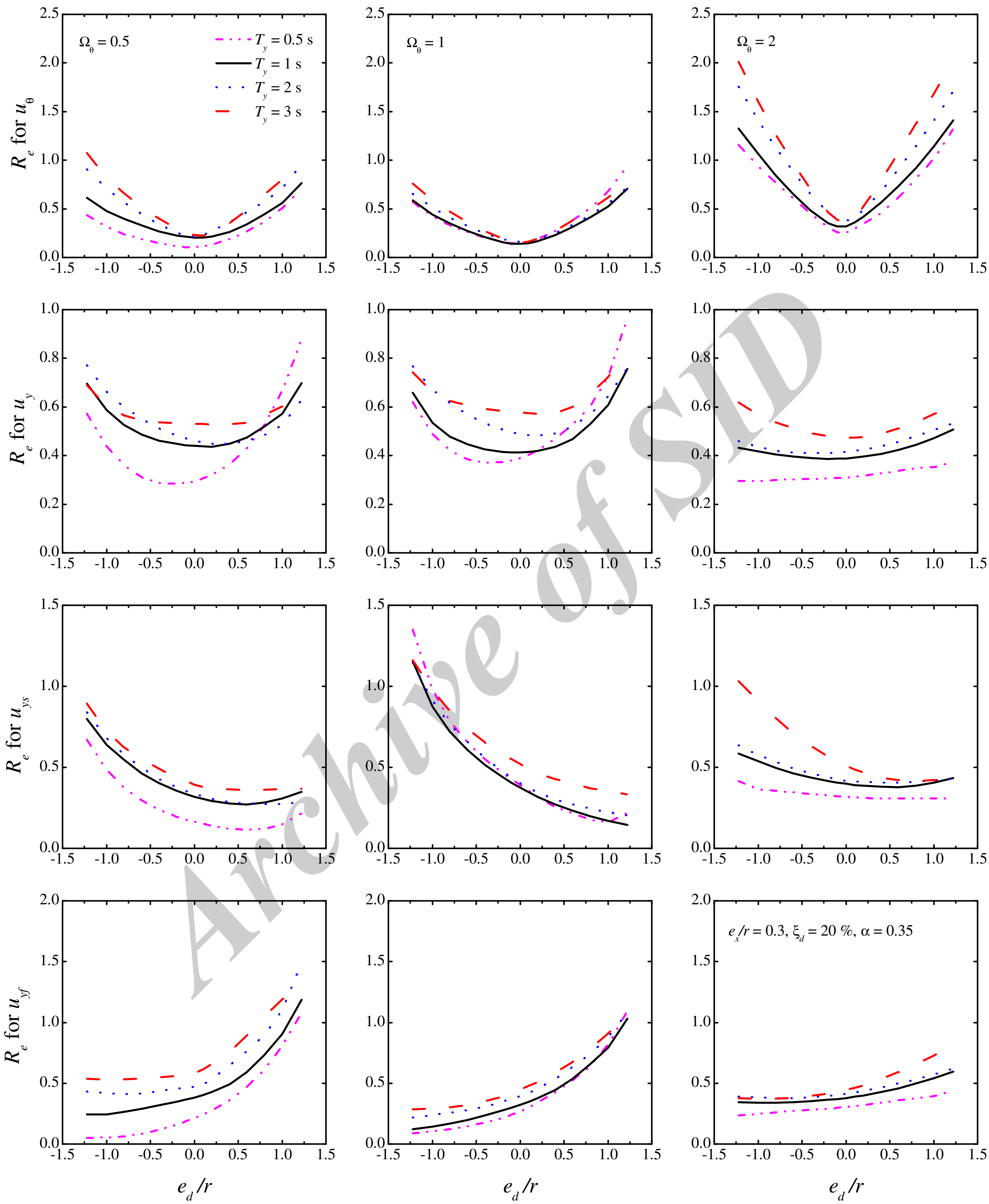

Figure 11 Effect of supplemental damping eccentricity e_d/r on ratio R_e for various displacement responses.

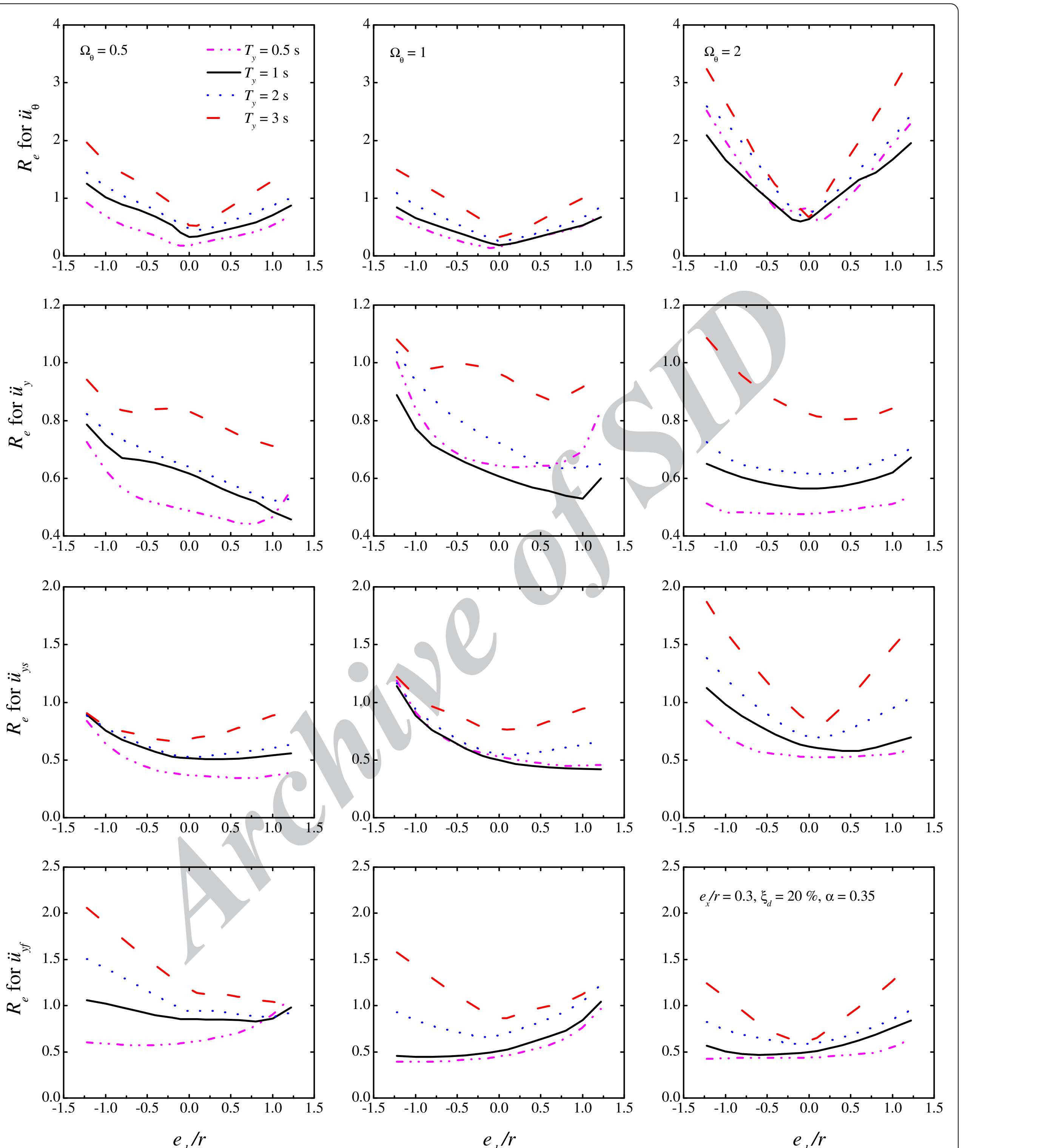

Figure 12 Effect of supplemental damping eccentricity e_d/r on ratio R_e for various accelerations responses.

observed from second set of rows of Figures 11 and 12 that for laterally stiff systems with Ω_θ = 0.5, 1 and 2, values of e_d/r in the range of 0 to - 0.3 (i.e. opposite to e_x/r =0.3) leads to the higher reduction in lateral displacement at CM, u_y and for laterally flexible systems, e_d/r in the range of 0 to 0.3 leads to the higher reduction in u_y. Also, the variation in R_e for u_y is more sensitive to the change in e_d/r for systems with Ω_θ = 0.5 and 1. Moreover, positive values of e_d/r (i.e. CD is on same side of CR) lead to the higher reduction in lateral acceleration at CM, $\ddot{u}_y$.

Further, from third set of rows of Figures 11 and 12 it is observed that as the e_d/r varies from negative to positive, the ratio, R_e for u_{ys} continuously decreases for all values of T_y as well as Ω_θ. This implies that the control system is more effective in reducing u_{ys}, when CD is on same side of CR and CD should be as far as away from the CM to achieve higher reduction in u_{ys}. The similar trends are also observed for stiff edge acceleration, $\ddot{u}_{ys}$ for the laterally stiff system (T_y = 0.5). On the other hand, for laterally flexible systems, ratio, R_e for $\ddot{u}_{ys}$ initially decreases, attains some minimum value (near to the value of e_d/r equal to zero or positive) and then increases with further increase in e_d/r. As the lateral flexibility of building increases, the value of e_d/r for which R_e for $\ddot{u}_{ys}$ attains the minimum values slightly shift from positive end to zero. Similarly, from the last set of row of Figures 11 and 12 it is observed that as the e_d/r varies from negative to positive, the ratio, R_e for u_{yf} continuously increases for all values of T_y. This implies that the control system is more effective in reducing flexible edge displacement, when CD is on opposite side of CR and CD should be as far as away from the CM to achieve higher reduction in u_{yf}. The similar trends are also observed for flexible edge acceleration, $\ddot{u}_{yf}$ for the laterally stiff system (T_y = 0.5). For laterally flexible system with Ω_θ = 0.5, higher reduction in $\ddot{u}_{yf}$ can be achieved with positive values of e_d/r (i.e. CD is on the same side of CR), whereas for systems with Ω_θ = 1 and 2, higher reduction in $\ddot{u}_{yf}$ can be achieved when e_d/r remains near to the value of zero. Moreover, it is observed that for torsionally stiff (Ω_θ = 2) and laterally flexible systems (T_y = 3), by positioning the CD at the edges or near to either of the edges leads to the significant increase in torsional displacement and torsional as well as edge accelerations as compared to uncontrolled responses. Hence for such systems, it is always preferable to keep the CD near to the CM. Further, in general, corresponding to all values of e_d/r, the reduction in various responses are higher for the system with T_y = 0.5, followed by T_y = 1, 2 and 3. Thus, the symmetric arrangement of dampers leads to higher reduction in torsional responses for building with intermediate eccentricity. For laterally stiff systems, location of CD on the same side of CR leads to higher reduction in stiff edge displacement and acceleration and CD is on the opposite side of CR leads to the higher reduction in flexible edge displacement and acceleration. In order to achieve this, CD should be as far as way from CM. For laterally flexible systems, CD on same side of CR and near to CM, leads to higher reduction in edge accelerations, whereas, locating CD at the extreme distance from CM on the side of CR leads to higher reduction in stiff edge displacement and opposite for flexible edge displacement.

In addition to the parametric study carried out to investigate the effectiveness of control system, it is equally important to study the effects of torsional couplings on the effectiveness of control system for asymmetric buildings as compared to corresponding symmetric buildings. Hence, the variations of response ratio, R_t (the ratio between peak response of controlled asymmetric and corresponding symmetric system) for various displacements and accelerations are plotted against eccentricity ratio, e_x/r in Figure 13 for the system with T_y = 1. It is observed that for systems with Ω_θ = 0.5, 1 and 2, ratio, R_t for u_y and $\ddot{u}_y$ decreases with increase in e_x/r and remains less than unity. This implies that u_y and $\ddot{u}_y$ reduces due to torsional coupling and hence effectiveness of control system is more for asymmetric system as compared to corresponding symmetric system. Thus, by neglecting the eccentricity, the effectiveness of control system will be underestimated for u_y and $\ddot{u}_y$ for asymmetric systems as compared to corresponding symmetric systems. Moreover, for torsionally flexible systems up to an intermediate eccentricity (i.e. e_x/r < 0.4), R_t for u_{ys} first increases and then decreases with further increase in eccentricity ratio. For flexible edge displacement, u_{yf}, ratio, R_t remains less than unity up to an intermediate eccentricity and then increases for higher eccentricity. This implies that for torsionally flexible systems with an intermediate eccentricity, u_{ys} increases and u_{yf} reduces due to torsional coupling and hence effectiveness of control system is less for asymmetric system and by ignoring the eccentricity, effectiveness will be overestimated for u_{ys} and underestimated for u_{yf}. On the other hand,, for the system with higher eccentricity, u_{ys} decreases and u_{yf} increases and u_{yf} increases. This implies that, the effectiveness of control system is more for asymmetric system in reducing u_{ys} and it will be underestimated by ignoring the effects of torsional couplings and the effectiveness is less for reducing u_{yf} as compared to the corresponding symmetric systems and it will be overestimated. It is further observed that for systems with Ω_θ = 1 and 2, with the increase in eccentricity, R_t for u_{ys} decreases and for u_{yf} it increases. Hence, by neglecting

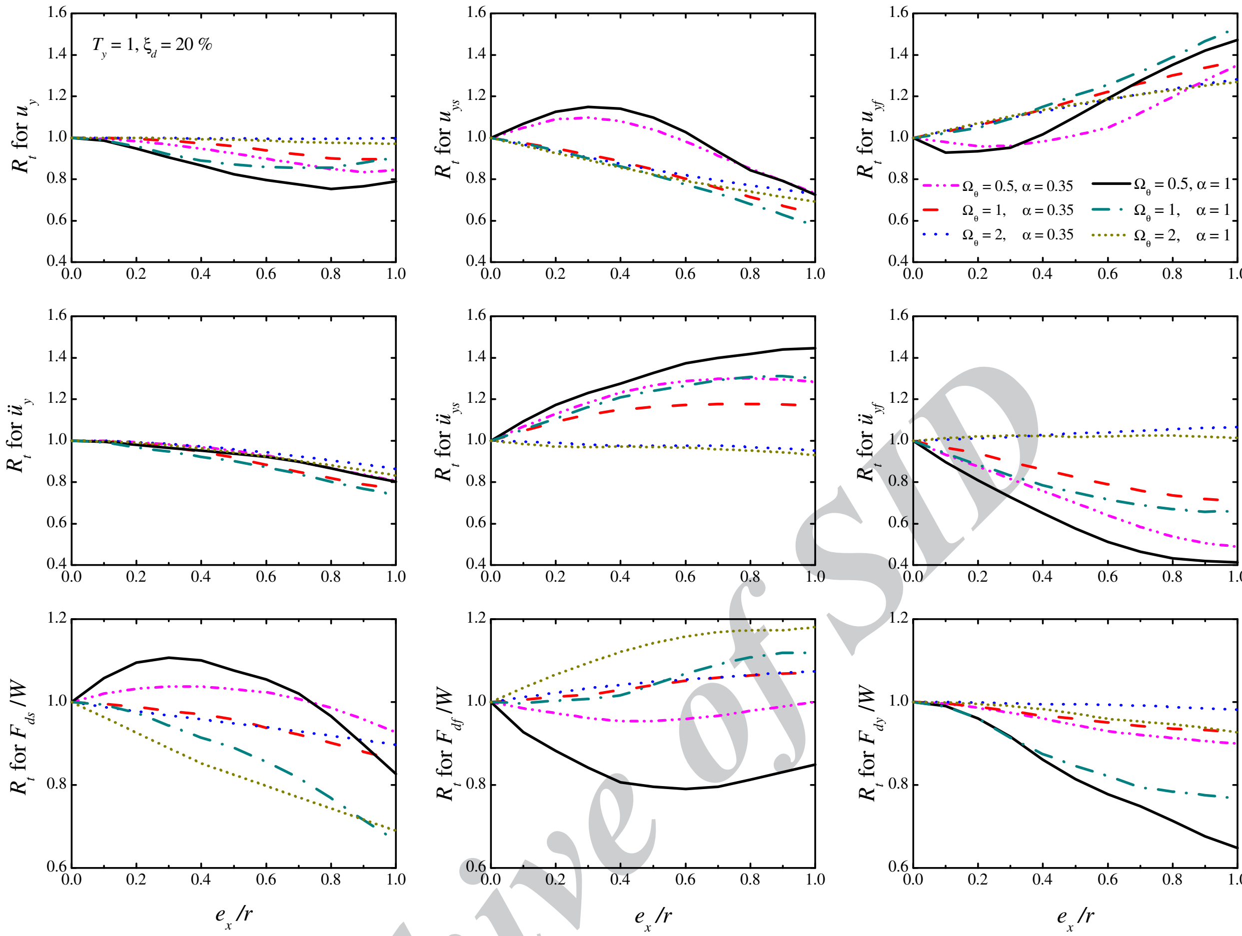

Figure 13 Effect of eccentricity on response ratio, R_t for various displacement and acceleration responses and damper forces.

the effects of eccentricity, the effectiveness of control system will be underestimated for reducing u_{ys} and overestimated for u_{yf} as compared to the corresponding symmetric systems. Furthermore, it is observed that for the system with Ω_θ= 0.5 and 1, with increase in e_x/r, the ratio, R_t for stiff edge acceleration, $\ddot{u}_{ys}$ increases and remains more than unity whereas for flexible edge acceleration, $\ddot{u}_{yf}$, it decreases and remains less than unity. This implies that for asymmetric systems, $\ddot{u}_{ys}$ increases and $\ddot{u}_{yf}$ reduces due to torsional coupling. Hence, the effectiveness of control system is less for asymmetric system in reducing $\ddot{u}_{ys}$ and it will be underestimated by ignoring the asymmetry and the effectiveness is more for reducing $\ddot{u}_{yf}$ and will be underestimated. Further, for system with Ω_θ= 2, the ratio, R_t for $\ddot{u}_{ys}$ and $\ddot{u}_{yf}$ remains near to the unity. Thus, the effects of torsional coupling are more pronounced for torsionally flexible and strongly coupled systems as compared to torsionally stiff systems while estimating the effectiveness of control system for asymmetric systems in reducing edge displacements and edge accelerations as compared to the corresponding symmetric systems.

Moreover, in addition to structural responses, the damper forces also play an important role while studying the effects of torsional coupling. In order to investigate these, variations of ratio, R_t are shown in Figure 13 for peak control forces. It is observed that for torsionally flexible systems, the ratio, R_t for F_{ds} remains more than unity except for system with very high eccentricities and for F_{df}, it remains less than unity whereas, for strongly coupled and torsionally stiff systems, the ratio, R_t for F_{ds} remains less than unity and for F_{df}, it remains more than unity. Thus, by neglecting the eccentricity for torsionally flexible systems, the control forces at flexible edge, will be overestimated and at stiff edge, that will be underestimated as compared to corresponding symmetric systems. Similarly, for strongly coupled and torsionally stiff systems, F_{df} will be underestimated and F_{ds} will be overestimated by ignoring the eccentricity. Moreover, it can be noticed that with increase in e_x/r, ratio, R_t for F_{dy}

decreases and remains less than unity for the systems with Ω_θ= 0.5, 1 and 2. This implies that the total damper forces of asymmetric system remains always less than those of corresponding symmetric system.

In this section, to study the effects of torsional coupling for laterally stiff to laterally flexible systems, the ratio, R_t for various responses are plotted against T_y (varied from 0.1 to 3 s) in Figure 14. The discussion presented herein mainly focuses on observations based on NLVDs. It is observed that for laterally stiff systems (T_y< 0.75 s) with Ω_θ= 0.5, 1 and 2, ratio, R_t for u_{ys} is less than unity and for u_{yf}, it remains more than unity and hence u_{ys} of laterally stiff asymmetric systems is lower u_{yf} is more than those of corresponding symmetric systems. It is further noticed that for laterally flexible systems with Ω_θ= 0.5, R_t for u_{yf} remains less than unity and for u_{ys}, it remains more than unity. Hence, the effectiveness of control system for laterally flexible asymmetric systems is more in reducing u_{yf} as compared to corresponding symmetric systems. Further, for laterally flexible systems with Ω_θ= 1, the ratio, R_t for u_{ys} remains less than unity and for u_{yf}, it is more than unity except for laterally very flexible systems in which, reverse trend is observed. However, the variation in R_t is more significant and sensitive against the change in T_y for torsionally flexible and strongly coupled systems and it is insensitive for torsionally stiff systems. Also, the ratio, R_t for u_y and $\ddot{u}_y$ remains almost near to the unity with the change in T_y. This implies that the difference between these responses of asymmetric and corresponding symmetric systems is very less and hence the effects of torsional coupling and asymmetry are negligible for responses at CM. Furthermore, from the second set of rows of Figure 14, it is observed that for the considered range of T_y for systems with Ω_θ= 0.5 and 1, R_t for $\ddot{u}_{ys}$ remains more than unity and increases continuously with increase in T_y and for $\ddot{u}_{yf}$, the ratio remains less than unity and decreases continuously with increase in T_y. On the other hand, for the system with Ω_θ= 2, for the considered values of T_y, ratio, R_t for $\ddot{u}_{ys}$ and $\ddot{u}_{yf}$ remains almost near to the unity. This shows that for laterally stiff systems, the difference between the edge

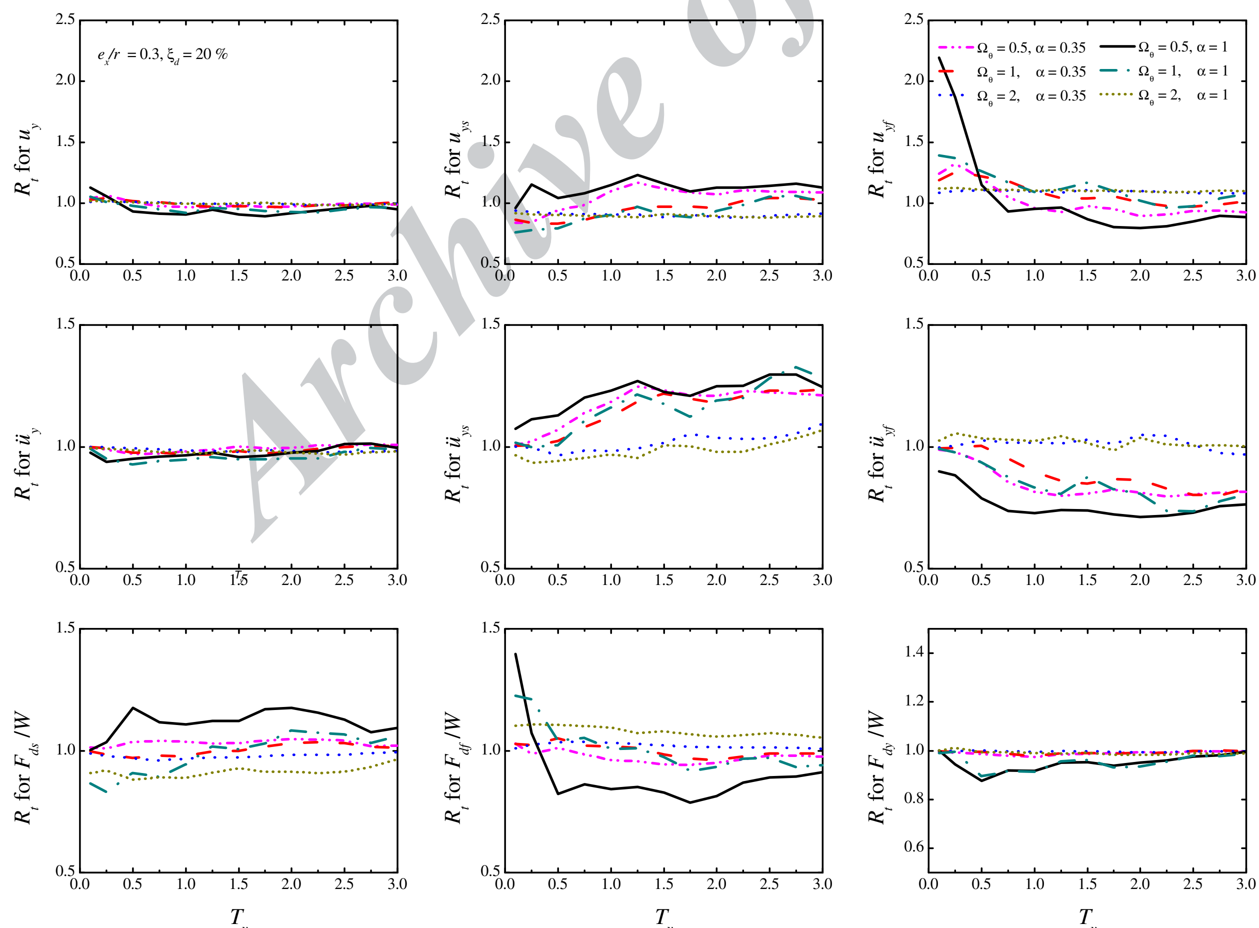

Figure 14 Effect of lateral time period on response ratio, R_t for various displacement and acceleration responses and damper forces.

accelerations of asymmetric and corresponding symmetric system is less and the difference increases with the increase in value of T_y. Thus, the effects of asymmetry are more for laterally flexible asymmetric systems for edge acceleration responses as compared to corresponding symmetric systems.

Furthermore, the variations of R_t for F_{ds}, F_{df} and F_{dy} against T_y are shown in third set of rows of Figure 14. It is observed that for laterally stiff to laterally flexible systems with $\Omega_\theta = 0.5$, ratio, R_t for F_{ds} remains slightly more than unity and for F_{df}, it remains slightly less than unity, whereas, an opposite trend is observed for torsionally stiff systems. Moreover, for laterally stiff systems with $\Omega_\theta = 1$, the ratio, R_t for F_{ds} remains slightly less than unity and for F_{df}, it remains slightly more than unity, whereas, an opposite trend is observed for laterally flexible systems with Ω_θ= 1. However, the ratio, R_t for resultant damper force, F_{dy} remains almost equal to unity corresponding to all values of T_y for Ω_θ = 0.5, 1 and 2 with NLVDs. This implies that the damper force for controlled asymmetric building is almost same as the corresponding symmetric systems with NLVDs.

Further, from Figures 13 and 14, it is observed that the trends for the variation of R_t for various displacement and acceleration responses as well as for damper forces obtained with LVDs are similar to those obtained with NLVDs. However, the variations in values of R_t for various responses as well as for damper forces are much more predominant and sensitive to the change in e_x/r and T_y for the systems installed with LVDs as compared to NLVDs. Further, the values of R_t obtained with NLVDs are much closer to unity as compared to the corresponding values obtained with LVDs. Thus, the difference between the displacement and accelerations responses and control forces of asymmetric and corresponding symmetric system is less for NLVDs as compared to LVDs and hence, the effects of torsional couplings are less for asymmetric system as compared to the corresponding symmetric systems for the systems installed with NLVDs in comparison to systems with LVDs.

Conclusions

The seismic response of linearly elastic, single-storey, one-way asymmetric building with LVDs and NLVDs subjected to different earthquake ground motions is investigated. The response is evaluated with parametric variations to study the comparative performance of LVDs and NLVDs for asymmetric system and the influence of important parameters on the effectiveness of control system for asymmetric systems. The important parameters considered are: eccentricity ratio of superstructure, uncoupled lateral time period, ratio of uncoupled torsional to lateral frequency and supplemental damping eccentricity ratio. From the trend of the results of the present study, the following conclusions can be drawn:

1. The difference between the resultant damper force of NLVDs and LVDs is more for torsionally stiff system as compared to torsionally flexible and strongly coupled systems.
2. The increase in supplemental damping ratio increases the effectiveness of dampers in reducing torsional displacement and accelerations, stiff edge displacement and accelerations as well as flexible edge displacements for systems with Ω_θ = 0.5, 1 and 2. On the other hand, the effectiveness decreases for higher supplemental damping ratio in reducing flexible edge accelerations for systems with Ω_θ = 0.5 and 1. Further, resultant damper force of NLVDs is less than the corresponding force of LVDs in the initial range of supplemental damping ratio (up to 30%) and for higher values of damping ratio, the reverse trend is observed.
3. The effectiveness of NLVDs is more sensitive to the eccentricity ratio for acceleration responses as compared to displacement responses. This phenomenon is more predominant for torsionally flexible and strongly coupled systems.
4. The effectiveness of dampers decreases with increase in lateral flexibility of building and effectiveness of NLVDs is more in reducing displacement responses as compared to accelerations. Further, NLVDs are more effective than LVDs for laterally flexible to stiff systems with Ω_θ= 0.5, 1 and 2 in reducing various displacement responses. On the other hand, the comparative performance of LVDs and NLVDs may vary depending on the value of Ω_θ and T_y for reducing acceleration responses.
5. The difference between resultant damper force in NLVDs and corresponding force in LVDs strongly depends on structural eccentricity for torsionally flexible and strongly coupled systems as compared to torsionally stiff systems. Also, for laterally stiff systems (T_y < 0.75 s), damper force for NLVDs is more than corresponding force of LVDs. On the other hand, for laterally flexible systems (T_y > 0.75 s), reverse trend is observed and as the lateral flexibility of building increases, the difference between damper force of NLVDs and LVDs decreases.
6. The symmetric arrangement of dampers leads to higher reduction in torsional responses for building with intermediate eccentricity. For laterally stiff systems, location of CD on the same side of CR leads to higher reduction in stiff edge displacement and acceleration and CD is on the opposite side of CR leads to the higher reduction

in flexible edge displacement and acceleration. In order to achieve this, CD should be as far as way from CM. For laterally flexible systems, CD on same side of CR and near to CM, leads to higher reduction in edge accelerations, whereas, locating CD at the extreme distance from CM on the side of CR leads to higher reduction in stiff edge displacement and opposite for flexible edge displacement.

7. The effects of torsional coupling are more pronounced for torsionally flexible and strongly coupled systems as compared to torsionally stiff systems while estimating the effectiveness of control system for asymmetric systems in reducing edge displacements and edge accelerations as compared to the corresponding symmetric systems.
8. The effects of asymmetry are more for laterally flexible asymmetric systems for edge acceleration responses as compared to corresponding symmetric systems.
9. The difference between the displacement and accelerations responses and control forces of asymmetric and corresponding symmetric system is less for NLVDs as compared to LVDs and hence, the effects of torsional couplings are less for asymmetric system as compared to the corresponding symmetric systems for the systems installed with NLVDs in comparison to system with LVDs.

Competing interest

The authors declare that they have no competing interests.

Authors' contributions

SVM carried out the numerical simulations for the extensive parametric study, which is presented in the research work, and drafted the manuscript. RSJ gave the guidelines on the important system parameters, which are included for the numerical study, and helped to draft the manuscript. All authors read and approved the final manuscript.

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References

De La Llera JC, Almazan JL, Vial IJ (2005) Torsional balance of plan-asymmetric structures with frictional dampers: analytical results. Earthquake Eng Struct Dyn 34(9):1089–1108
Goel RK (1998) Effects of supplemental viscous damping on seismic response of asymmetric-plan systems. Earthquake Eng Struct Dyn 27(2):25–141
Goel RK, Booker CA (2001) Effects of supplemental viscous damping on inelastic seismic response of asymmetric systems. Earthquake Eng Struct Dyn 30(3):411–430
Goel RK (2005) Seismic response of linear and non-linear asymmetric systems with non-linear fluid viscous dampers. Earthquake Eng Struct Dyn 34(7):825–846
Hart GC, Wong K (2000) Structural Dynamics for Structural Engineers. John Wiley & Sons, Inc, New York
Jangid RS (1996) Seismic response of an asymmetric base isolated structure. Compos Struct 60(2):261–267
Jangid RS, Datta TK (1994) Nonlinear response of torsionally coupled base isolated structure. J Struct Eng 120(1):1–22
Jangid RS, Datta TK (1995) Performance of base isolation systems for asymmetric building subject to random excitation. Eng Struct 17(6):443–454
Jangid RS, Datta TK (1997) Performance of multiple tuned mass dampers for torsionally coupled system. Earthquake Eng Struct Dyn 26(3):307–317
Lee D, Taylor DP (2001) Viscous damper development and future trends. Struct Des Tall Build 10(5):311–320
Lin WH, Chopra AK (2001) Understanding and predicting effects of supplemental viscous damping on seismic response of asymmetric one-storey systems. Earthquake Eng Struct Dyn 30(10):1475–1494
Lin WH, Chopra AK (2002) Earthquake response of elastic SDF systems with non-linear fluid viscous dampers. Earthquake Eng Struct Dyn 31(9):1623–1642
Lin WH, Chopra AK (2003) Asymmetric one-storey elastic systems with non-linear viscous and viscoelastic dampers: earthquake response. Earthquake Eng Struct Dyn 32(4):555–577
Lu LY (2004) Predictive control of seismic structures with semi-active friction dampers. Earthquake Eng Struct Dyn 33(5):647–668
Matsagar VA, Jangid RS (2010) Impact response of torsionally coupled base isolated structure. J Vib Control 16(11):1623–1649
Petti L, De Iuliis M (2008) Torsional seismic response control of asymmetric-plan systems by using viscous dampers. Eng Struct 30(11):3377–3388
Singh MP, Singh S, Moreschi LM (2002) Tuned mass dampers for response control of torsional buildings. Earthquake Eng Struct Dyn 31(4):749–769
Soong TT, Dargush GF (1997) Passive Energy Dissipation Systems in Structural Engineering. John Wiley & Sons, Inc., New York
Symans MD, Constantinou MC (1998) Passive fluid viscous damping systems for seismic energy dissipation. ISET J Earthquake Tech 35(4):185–206

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