Response of Two-Way Asymmetric System with Linear & Non Linear Viscous Dampers under Bi-Directional Earthquake

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Abstract-The seismic response of linearly elastic, single-storey, two-way asymmetric building with linear and non-linear viscous dampers under bi-directional earthquake is investigated. The response is obtained by numerically solving the governing equations of motion. The effect of supplementary damping ratio on peak responses which include lateral, torsional and edge displacements and their accelerations are investigated. To study the effectiveness of dampers, the controlled response of asymmetric system is compared with the corresponding uncontrolled response. 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. Furthermore, viscous damping may be used to reduce edge deformations in asymmetric-plan systems.

Keywords: Seismic response, Two-way Asymmetric, Bi-directional earthquake, Non-linear viscous damper.

I. INTRODUCTION

Under the earthquake loads, plane-asymmetric buildings with irregular distributions of mass or stiffness are likely to undergo torsional responses coupled with the translational vibrations. These types of structures are likely to suffer more severe displacement at the corner elements under bi-directional earthquake ground motions. This attracted attention of many researchers to investigate the seismic response of asymmetric buildings with supplemental energy dissipation devices to severe damages. In the past, several studies had been done to investigate the effectiveness of viscous damper in asymmetric structures under uni-directional earthquake.

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. Wen-Hsiung Lin and Anil K. Chopra (2001) investigated understanding of how and why plan-wise distribution of fluid viscous dampers (FVDs) influences the response of linearly elastic, one-story, asymmetric-plan systems. Asymmetric distributions of supplemental damping that are more effective in reducing the response compared to symmetric distribution. Snehal V Mevada and R.S. Jangid (2012) investigated effect of supplementary viscous damping on response of single-storey, one-way asymmetric system and found that response of building is depends on supplemental damping eccentricity ratio and eccentricity ratio.

The synchronized action of two horizontal components of ground motion and structural plans unsymmetrical about both axes remained unsolved and required further investigations. The bi-directional seismic ground motion considered in this paper is more realistic than the single direction excitation.

II. STRUCTURAL MODEL

The system considered is an idealized one-storey building which consists of a rigid floor supported on four columns as shown in Figure 1.1. Following assumptions are made for the structural system under consideration: (i) floor of super structure is considered as axially rigid and flexural rigid, (ii) columns are axially rigid, (iii) force-deformation relationship of superstructure is considered as linear and within elastic range, (iv) thickness of frame is neglected and (v) the structure is excited by bi-directional horizontal component of earthquake ground motion.

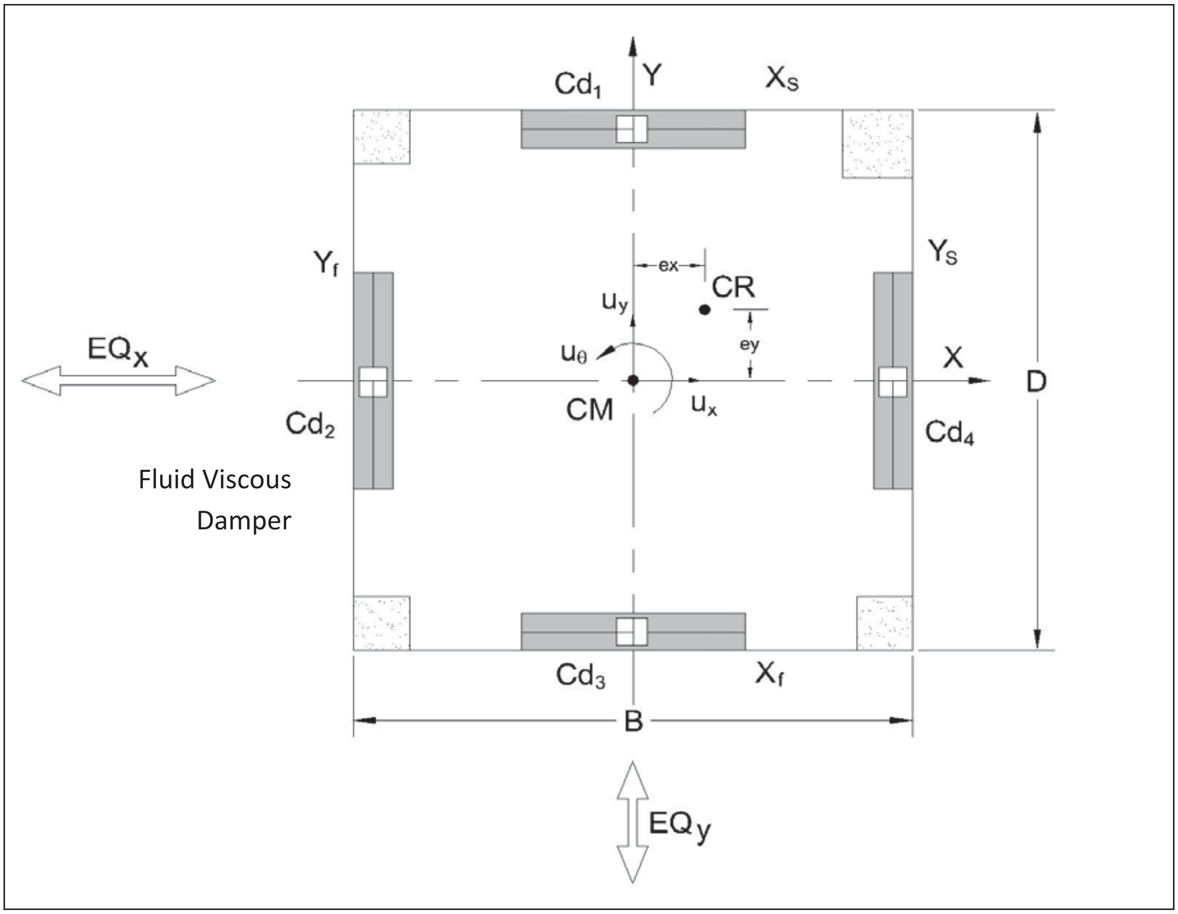

Figure 1.1: Plan and isometric view of two-way asymmetric system.

The mass of floor is assumed to be uniformly distributed and hence centre of mass (CM) coincides with the geometrical centre of the floor. The columns are arranged in a way such that it produces the stiffness asymmetry with respect to the CM in two directions and hence, the centre of rigidity (CR) is located at an eccentric distance, ex from CM in X-direction and ey from CM in Y-direction. The system is un-symmetric about both X-direction and Y-direction; therefore system has three degrees of freedom (3-DOF) are namely lateral displacement in X-direction, u_x Y-direction, u_y and torsional displacement, u_θ as represented in Figure 1.1. Plan wise distribution of additional viscous damping is symmetric about both axes. Arrangement of dampers shown in Figure 1.1, damping constant of all dampers and distance from CM are equal, so that centre of damping (CD) coincides with centre of mass (CM).

Edge of building near the CR is considered as stiff edge and Edge of building far from the CR is considered as flexible edge. In Figure 1.1, stiff and flexible edges in X-direction and Y-direction are shown as X_s, X_f, Y_s and Y_f respectively.

III. SOLUTION OF EQUATIONS OF MOTION

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 elastic range. The equations of motion of the system in the matrix form are expressed as,

$$M\ddot{u} + C\dot{u} + KX = -\left(M\Gamma\ddot{u}_g + \Lambda F_d\right)$$

Where M, C and K are mass, damping and stiffness matrices of the system, respectively; $u = \{u_x\ u_y\ u_\theta\}^T$ is the displacement vector; Γ is influence coefficient vector; $\ddot{u}_g = \{\ddot{u}_{gx}\ \ddot{u}_{gy}\ 0\}^T$ is ground acceleration vector; $\ddot{u}_{gx}$ is ground acceleration in X-direction; $\ddot{u}_{gy}$ is ground acceleration in Y-direction.

$F = \Lambda \times F_d = \{F_{dx}\ F_{dy}\ F_{d\theta}\}^T$ is the vector of resultant control forces. Λ is the matrix that defines the location of control devices; $F_d = \{F_{d1}\ F_{d2}\ F_{d3}\ F_{d4}\}^T$ is the vector of control forces of dampers. F_{dx}, F_{dy} and $F_{d\theta}$ are resultant control forces of dampers along X-, Y- and θ- direction, respectively.

The mass matrix can be expressed as,

$$M = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I_o \end{bmatrix}$$

Where m represents the lumped mass of the floor; and $I_o = m \times \left(\frac{B^2+D^2}{12}\right)$ is mass moment of inertia of floor about vertical axis (Z-axis) at CM; where 'B' and 'D' are the plan dimensions of the building.

The stiffness matrix given by A.K. [4] can be expressed as,

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

Where, K_{xx} & K_{yy} denotes the total lateral stiffness of the system in X-direction & Y-direction respectively; $K_{xy} = K_{yx} = 0$ denotes that u_x and u_y are uncoupled degrees of freedom.

$$K_{x\theta} = K_{\theta x} = \textstyle\sum_i (y_i \times K_{xi}); \qquad K_{y\theta} = K_{\theta y} = \sum_i (x_i \times K_{yi});$$

$$K_{\theta\theta} = \textstyle\sum_i \left(x_i^2 K_{yi} + y_i^2 K_{xi}\right)$$

$K_{\theta\theta}$ is torsional stiffness of system about vertical axis (Z-axis) at CM; K_{xi} and K_{yi} indicates the lateral stiffness of i^{th} column in X-direction and Y-direction respectively; x_i is the x-coordinate distance of i^{th} column with respect to CM and y_i is the y-coordinate distance of ith element with respect to CM.

Cd_x and Cd_y are the total damping coefficient of damper system along x-axis and y-axis respectively. For the system considered Cdx = C1 + C3 and Cdy = C2 + C4; the value of Cd_x and Cd_y are calculated as,

$$Cd_x = 2m \times \omega_x \times \xi_d; \qquad Cd_y = 2m \times \omega_y \times \xi_d$$

Where, ξ_d is the supplemental damping ratio; ω_x and ω_y are natural frequencies of system in uncoupled modes.

$$\omega_x = \sqrt{\frac{K_{xx}}{m}}; \qquad \omega_y = \sqrt{\frac{K_{yy}}{m}}$$

The natural damping matrix of the system [4] constructed from the Rayleigh's damping considering mass and stiffness proportional as,

$$C = a_0 M + a_1 K$$

Where a_0 and a_1 are the coefficients depends on damping ratio of two vibration modes. In system natural damping is 5% of critical damping is considered.

IV. STATE-SPACE REPRESENTATION

To facilitate Time-History analysis by numerical time stepping method above equations of motion of structure representation in state-space form as below [5],

$$\dot{Z}(t) = A\,Z(t) + (-M\Gamma\ddot{u}_g - AF_d)$$

Where,

$$Z(t) = \begin{bmatrix} X(t) \\ \dot{X}(t) \end{bmatrix}_{2n\times 1}; \qquad \dot{Z}(t) = \begin{bmatrix} \dot{X}(t) \\ \ddot{X}(t) \end{bmatrix}_{2n\times 1};$$

$$A = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ D/2 & -B/2 & -D/2 & B/2 \end{bmatrix}; \qquad A = \begin{bmatrix} 0 & 1 \\ -M^{-1}K & -M^{-1}C \end{bmatrix}_{2n\times 2n}$$

In size of matrix and vectors "n" is numbers of degree of freedom(s).

$$Z(t)_{k+1} = e^{A\Delta t}Z(t)_k + e^{At_{k+1}}\int_{t_k}^{t_{k+1}} e^{-As}F(s)\,ds$$

$$\therefore Z(t)_{k+1} = e^{A\Delta t}Z(t)_k + A^{-1}(e^{A\Delta t} - I)F_k$$

Where,

$$F_k = -M\Gamma\ddot{u}_g - AF_d$$

In which, $e^{A\Delta t}$ is state translation matrix of size (2n × 2n) equal to A matrix

V. MODELING OF FLUID VISCOUS DAMPER

Viscous fluid damper operates on the principle of fluid flow through orifices. 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. Force offered by damper always resists the motion of structure. This force is proportional to the relative velocity between the end nodes of damper. In case of purely viscous behavior, material does not return any of the energy stored during loading. All the energy is lost as "pure damping" once the load is removed. Figure 5.1 shows the Mathematical model of fluid viscous damper.

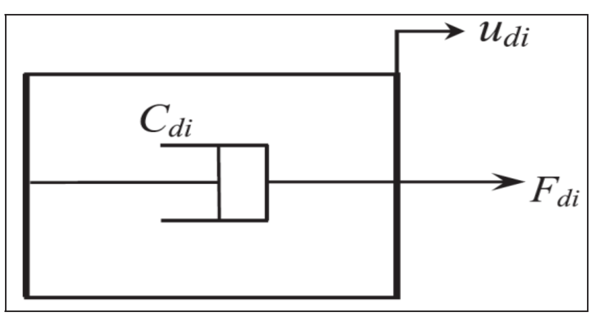

Figure 5.1: Mathematical model of fluid viscous damper.

The force in a viscous damper given by,

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

where, C_{di} is damper coefficient of the ith damper, 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 0.5 to 1 for seismic applications and (sgn) is signum function. When $\alpha = 1$, 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.

VI. NUMERICAL STUDY

The seismic response of linearly elastic, single storey, two-way asymmetric building installed with fluid viscous dampers under two horizontal component of ground motion is investigated. The response quantities are lateral and torsional displacements of floor mass obtained at the CM (u_x, 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, accelerations at stiff and flexible edges of building. The response of the system is investigated under parametric variations of additional damping (ξ_d) and non-linearity exponent of velocity of damper.

The peak responses are obtained by performing time history analysis under four considered earthquake ground motions namely, Imperial Valley (1940), Loma Prieta (1989), Northridge (1994) and Kobe (1995). The details of earthquakes such as peak ground acceleration (PGA), duration and recording station are summarized in Table 6.1. The average values of peak responses from four earthquakes are obtained and study is carried out based on these average responses.

Table 6.1 Details of earthquake motions considered for the numerical study

Earthquake	Recording Station	Duration (sec)	PGA (g)	
			EQx	EQy
Imperial Valley, 19th May, 1940	El Centro	40	0.31	0.22
Loma Prieta, 18th October,1989	Los Gatos Presentation Center	25	0.97	0.59
Northridge, 17th January, 1994	Sylmar Converter Station	40	0.89	0.61
Kobe, 16th January,1995	Japan Meteorological Agency	48	0.82	0.60

In order to study the effectiveness of control system the responses are expressed in terms of indices R_e. The value of R_e less than unity indicates that the control system is effective in reducing the responses. R_e is defined as,

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

Physical quantities of system for analysis are taken as follow; plan dimension of 6m×6m and storey height of 4m. Out of four columns 3-columns are of dimension 0.3m×0.3m and one of dimension 0.37m×0.37m is taken, so two-way asymmetry is achieved. Total effective floor load is 8.25 KN/m^2 taken, so that the lumped mass (m) of system is 30275.25 Kg.

Consecutively to study the effects of supplemental damping ratio, ξd for LVDs and NLVDs, the variations of R_e against ξ_d = 0 to 0.8 (0 to 80%) are shown in Figures 3 and 4. The value of $R_e = 1$ corresponding to $\xi_d = 0$ is representing the uncontrolled response. The responses are plotted for three types of non-linear and linear dampers having velocity exponent (α) is equal to 0.5, 0.75 and 1.

It can be observed from Figure 6.1, R_e for displacements u_x, u_y and u_θ x- direction, y- direction and θ-direction decreases with increasing ξ_d. The value of R_e for displacements u_x, u_y and u_θ with NLVD is lesser than value of R_e for LVD, shows that non linear dampers are more effective than linear dampers. R_e for accelerations A_x, A_y and A_θ in x- direction, y- direction and θ-direction decreases with increasing ξ_d. The value of R_e for accelerations A_x and A_y with LVD and NLVD having velocity exponent (α = 0.75) are decreases as increasing in ξ_d. It is also observed that angular acceleration (A_θ) of system with NLVD having velocity exponent (α = 0.5), value of R_e for A_θ is decreases with increasing ξ_d up to, $\xi_d = 0.3$ (30%) and beyond that it increases extremely, for $\xi_d > 0.3$ NLVD having $\alpha \leq 0.5$ are not effective for reducing angular accelerations.

Displacements of stiff edges and flexible edges in X-direction and Y-direction are u_{xs}, u_{xf}, u_{ys} and u_{yf} respectively. Accelerations of stiff edges and flexible edges in X-direction and Y-direction are A_{xs}, A_{xf}, A_{ys} and A_{yf} respectively. It can be observed from Figure 6.2, R_e for all response quantities (displacement and acceleration) at the stiff edges and flexible edges in x-direction and y-direction decreases with increasing additional damping (ξ_d).

It is observed from Figure 6.1 and Figure 6.2 that all response quantities excluding the peak angular acceleration with an increase in ξ_d. The decrease in these response quantities is rapid in the beginning and it becomes gradual for values of $\xi_d \geq 0.3$ (30%). Hence, $\xi_d = 0.3$ (30%) is considered to be an optimal parameter for the fluid viscous damper for all four earthquakes.

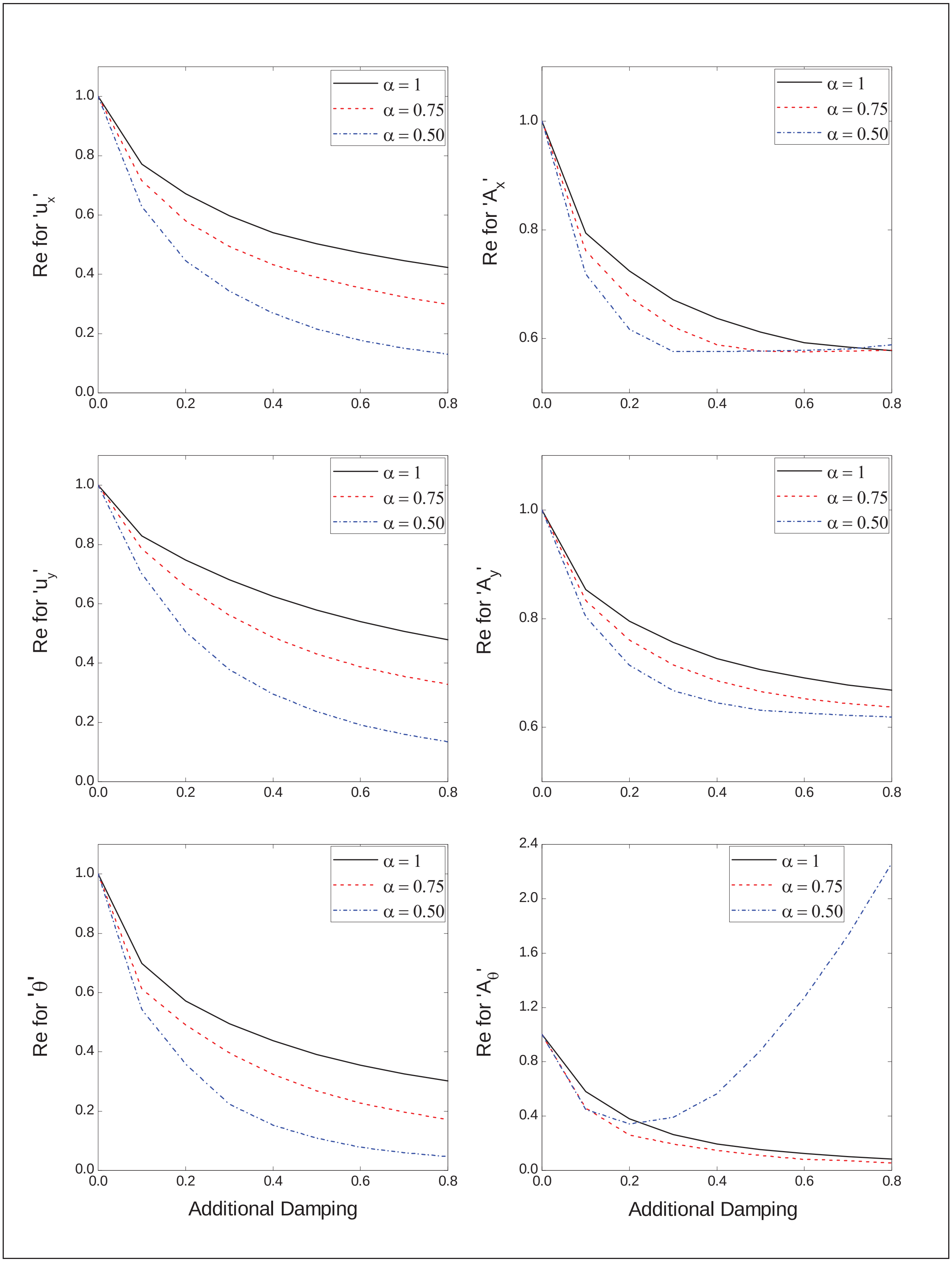

Figure 6.1: Effect of ξ_d and α on R_e for various displacements and accelerations at CM.

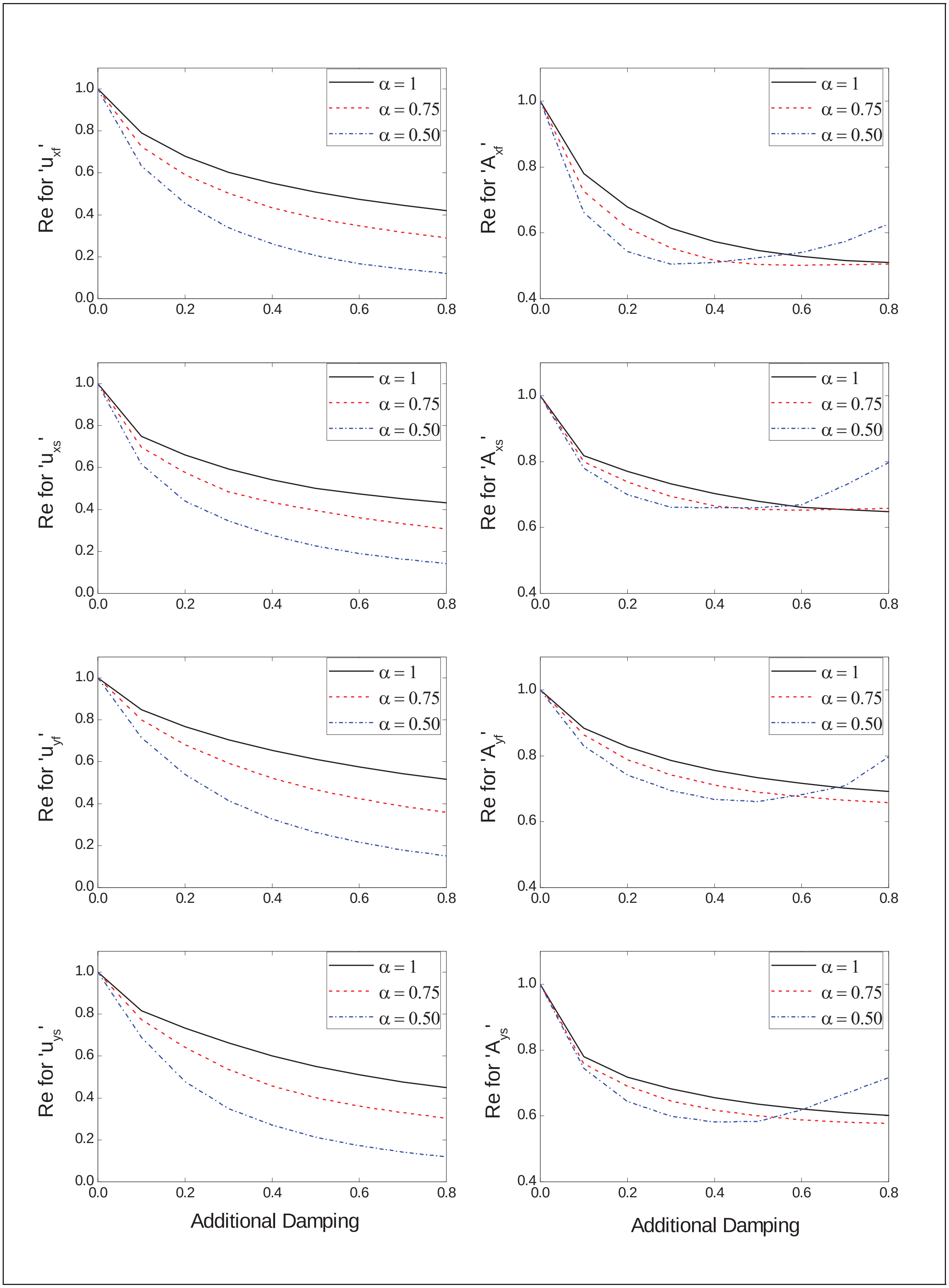

Figure 6.2: Effect of ξd and α on Re for various displacements and accelerations at stiff edges and flexible edges.

Figure 6.3 and Figure 6.4 shows the time histories of various displacements and accelerations responses of uncontrolled system compared with corresponding system controlled with LVDs ($\alpha = 1$) and NLVDs ($\alpha = 0.5$) with additional damping ratio 30% ($\xi_d = 0.3$), which is considered as optimal amount of additional damping.

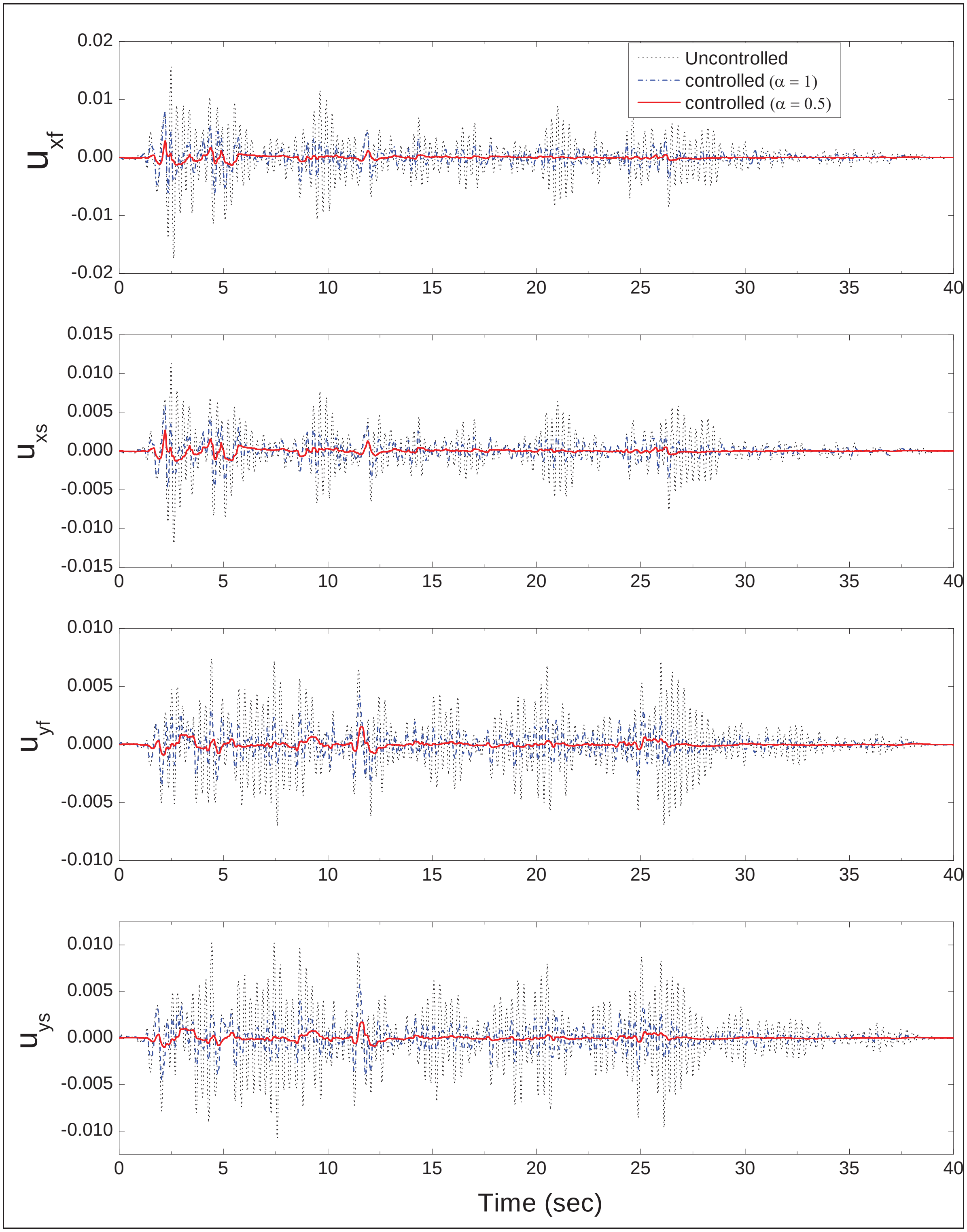

Figure 6.3: Time-History for uncontrolled and controlled stiff edge & flexible edge displacements (m) under Imperial Valley earthquake (considered optimal).

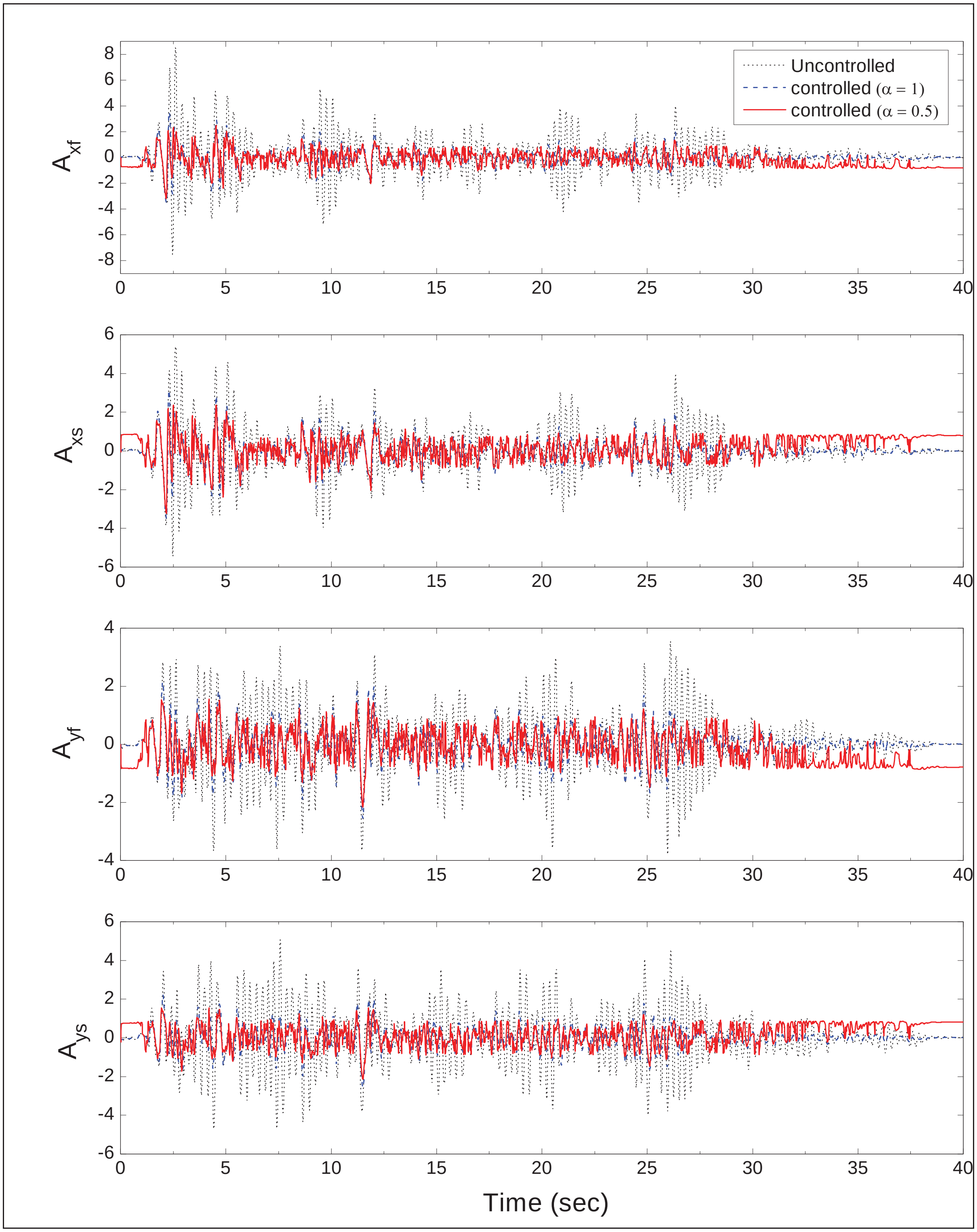

Figure 6.4: Time-History for uncontrolled and controlled stiff edge & flexible edge accelerations (m/sec2) under Imperial Valley earthquake (considered optimal).

It is observed from Figure 6.3 & Figure 6.4, NLVDs are more effective in reducing the edge displacements than LVDs. For edge accelerations, response reduction by NLVDs and LVDs are comparatively less effective than displacements.

VII. CONCLUSION

The seismic response of linearly elastic, single-storey, two-way asymmetric building with linear and non-linear viscous dampers under bi-directional earthquake is investigated. The response is evaluated with parametric variations to study the comparative performance of LVDs and NLVDs for asymmetric system. There are two parameters considered in investigation are additional damping ratio (ξ_d) and velocity exponent of dampers (α). From the patterns of the results of the current study, the following conclusions can be made for the system considered:

1) All response quantities excluding the peak angular acceleration with an increase in ξ_d. The decrease in these response quantities is rapid in the beginning and it becomes gradual for values of $\xi_d \geq 0.3$ (30%). Hence, additional damping 30% of critical damping is considered to be an optimal parameter for the fluid viscous damper for all four earthquakes.
2) Angular acceleration is decreases with increasing additional damping up to 30% and beyond that it increases extremely, for additional damping more than 30% NLVDs having exponent of velocity ($\alpha \leq 0.5$) are not effective for reducing angular accelerations.
3) NLVDs are more effective in reducing the edge displacements than LVDs. For edge accelerations, response reduction by NLVDs and LVDs are comparatively less effective than displacements.

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