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SEISMIC RESPONSE OF TWO-WAY ASYMMETRIC SYSTEM WITH FLUID VISCOUS DAMPER UNDER BI-DIRECTIONAL EARTHQUAKE EXCITATIONS

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Abstract: This study presents, the response of Two-Way Asymmetric System with Fluid Viscous Damper (FVD) under Bi-Directional Earthquake. The response of controlled and uncontrolled Two-way asymmetric system was evaluated by numerically solving the governing equations of motion using state space method. In the study to get effective results the response are obtained under five real earthquake ground motion namely Imperial Valley (1940), Loma Prieta (1989), Northridge (1994), Kobe (1995) and Bhuj (2001). Here to understand the behaviour of system the single-storey, two-way asymmetric system with aspect ratio of 1.0, 1.1, 1.2, 1.3 and 1.4 was adopted. To find out effectiveness of damper, two damper parameters like damping ratio (ζd) and velocity exponent (α) are considered. To compare the controlled system with the uncontrolled system various parameters are considered like displacement, torsional displacement, acceleration, rotational acceleration, base shear, base torque and drift of the structure.

***Index Terms* - asymmetric building; bi-directional excitation; fluid viscous damper; optimum; aspect ratio.**

I. INTRODUCTION

It is well known that under the earthquake loads asymmetric-plan structures are vulnerable. Such structure with irregular distribution of mass and stiffness are likely to undergo torsional responses coupled with translational vibrations. This type of structure are also likely to suffer severe displacement under the bi-directional earthquake excitation. It is therefore not surprising that it attracted attention of many researchers to investigate the seismic behaviour of asymmetric building with supplemental energy dissipation devices under bi-directional excitation. In the past, many studies had been carried out to investigate the effectiveness of viscous damper in asymmetric structures under bi-directional earthquake excitation.

Goel (1998) studied the effects of supplemental viscous damping on seismic response of one-way asymmetric system and found that edge deformations in asymmetric structural systems can be reduced than those of the same edges in the corresponding symmetric structural systems. W. Lin and Anil K. Chopra (2001) investigated understanding of how and why plan wise distribution of fluid viscous dampers (FVDs) influences the behaviour of linearly elastic, single storey, asymmetric-plan system. W. Lin and Anil K. Chopra (2002) also studied the effectiveness of non-linear viscous dampers (NLVDs) for one storey symmetrical system. This study was carried out by assuming symmetric arrangement of dampers in system. It was observed that NLVDs are more effective in reducing response than linear viscous dampers (LVDs) with reduced damper force. Snehal V. Mevada and R.S. Jangid (2012a) studied the effects of supplemental viscous damping on response of single storey, one-way asymmetric system and found that response of structure is depends on supplemental damping eccentricity ratio and eccentricity ratio. Snehal V. Mevada and R.S. Jangid (2012b) studied the seismic response of asymmetric system with variable damper and found that semi-active variable dampers are quite more effective in reducing lateral and torsional displacement. Nirmal S. Mehta and S. V. Mevada (2017) studied seismic response of two-way asymmetric building installed with hybrid arrangement of dampers under bi-directional excitations. The study was carried out on linear elastic, one storey, two-way asymmetric system with are installed with PVDs, semi active friction damper (SAFD) and hybrid arrangements of damper (HYD) subjected to bi-directional excitations. It is observed that effectiveness of HYD is very high as compare to PVD and SAFD. Although above studies reflect the effectiveness of dampers for only one plan dimension aspect ratio for asymmetric building under bi-directional seismic excitation.

In this paper, the seismic response of one storey, two-way asymmetric building installed with fluid viscous damper (FVD) subjected to bi-directional excitation investigated at five different plan aspect ratio with five real earthquake. All the seismic responses was obtained under synchronized action of two horizontal components of ground motion. For the five different plan aspect ratio optimum damping value was investigated simultaneously.

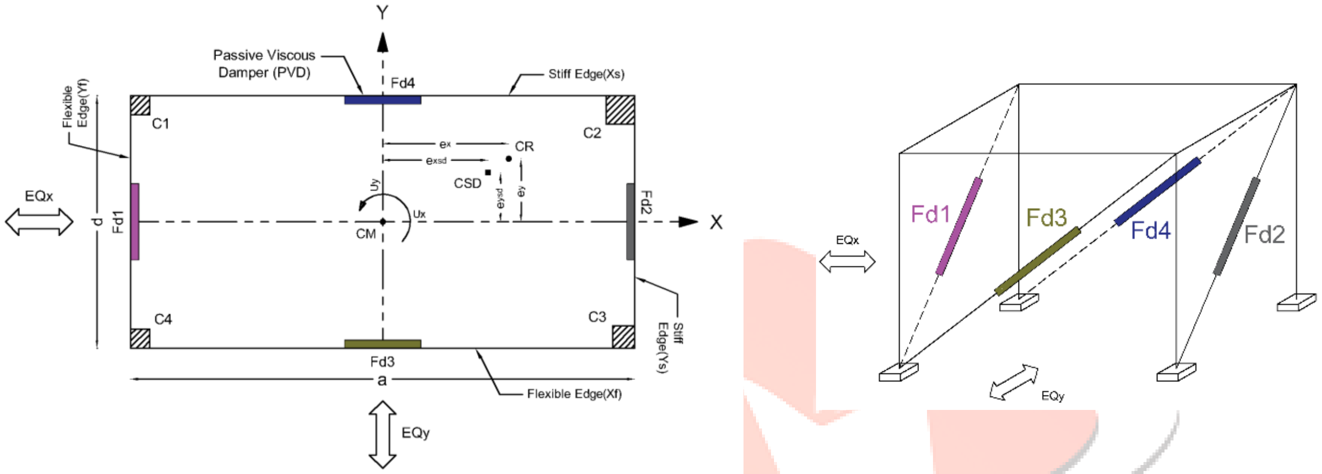
II. STRUCTURAL MODEL

The system considered is an idealized one-storey building which consists of rigid deck supported by structural elements column and beam. Following assumptions are made for the structural system under consideration:

I. Floor of super structure is considered as flexural rigid
II. columns are axially rigid
III. Force-deformation relationship of superstructure is considered as linear and within elastic range.
IV. The system is excited by bi-directional earthquake excitation.

Figure 1 shows the plan and isometric view of one-storey, 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 asymmetric about both the X-direction and Y-direction; therefore system has three degree of freedom (3DOF) namely lateral displacement in X-direction (u_x), Y-direction (u_y) and torsional displacement (u_θ) as represented in Figure 1. PVD are provided equal distance from Cm about both axes as represented in Figure 1. Hence, the centre of supplemental damping (CSD) coincides with the CM. Location of the CSD from the CM is defined by the supplemental damping eccentricity (e_{sd}). Here, CSD coincides with CM therefore supplemental damping eccentricity (e_{sd}) is zero.



(a) (b)

Figure 1 (a) Plan of two-way asymmetric system (b) Isometric view of system showing arrangement of dampers for structure installed with PVD

III. SOLUTION OF EQUATION 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, u

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

Where M is mass, C is damping and K is stiffness of the system. $u = \{ u_x\ u_y\ u_\theta \}^T$ is the displacement vector of system; $\dot{u} = \{ \dot{u}_x\ \dot{u}_y\ \dot{u}_\theta \}^T$ is velocity vector; $\ddot{u} = \{ \ddot{u}_x\ \ddot{u}_y\ \ddot{u}_\theta \}^T$ is the acceleration vector of system; $\ddot{u}_g = \{ \ddot{u}_{gx}\ \ddot{u}_{gy}\ 0 \}^T$ ground acceleration vector of system; ; Γ is the influence coefficient vector of system; $\ddot{u}_{gx}$ is ground acceleration in X-direction and $\ddot{u}_{gy}$ is the ground acceleration in Y-direction; Λ is the damper location matrix which depends on the location of damper; $F = \{ F_{dx} F_{dy} F_{d\theta} \}^T$ is the vector of control forces; F_{dx}, F_{dy} and $F_{d\theta}$ are resultant control forces of damper along X-, Y- and θ-direction, respectively. The mass matrix can be expressed as,

$$M = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & mr^2 \end{bmatrix} \quad (2)$$

Where m is the lumped mass of the deck; and **r** is the mass radius of gyration about the vertical axis through CM which is given by; $r = \sqrt{\frac{a^2+d^2}{12}}$ where a and d is the plan dimension of the building length and width.

The stiffness matrix given by (Chopra A. K., 2007) can be expressed as

$$K = \begin{bmatrix} k_{xx} & k_{yx} & k_{\theta x} \\ k_{xy} & k_{yy} & k_{\theta y} \\ k_{x\theta} & k_{y\theta} & k_{\theta\theta} \end{bmatrix} \quad (3)$$

$$k_{xx} = \sum_i k_{xi}, k_{yy} = \sum_i k_{yi}, \quad (4)$$

Where , k_{xx} and k_{yy} is total lateral stiffness in X and Y –direction respectively.

$k_{x\theta} = k_{\theta x} = \sum_i (y_i \times k_{xi})$, $k_{y\theta} = k_{\theta y} = \sum_i (x_i \times k_{yi})$

$k_{xy} = k_{yx} = 0$, Denotes that u_x and u_y are uncoupled degrees of freedom.

$$k_{\theta\theta} = \sum_i k_{xi} y_i^2 + k_{yi} x_i^2 \quad (5)$$

Here, $k_{\theta\theta}$ is torsional stiffness of system about vertical axis at CM. Where, k_{xi} and k_{yi} are indicates the lateral stiffness of ith column in X-direction and Y-direction, respectively; x_i and y_i are the X-coordinate and Y-coordinate distance of ith column with respect to CM respectively. The damping matrix of the system is not known explicitly and it is constructed from the Rayleigh's damping (HART & WONG, 2000) considering mass and stiffness proportional as,

$$\mathrm{C} = \alpha \mathrm{M} + \beta K \quad (6)$$

In which α and β are the coefficients depends on damping ratio of two vibration modes. For the present study 5% damping is considered as critical damping for both modes of vibration of system.

IV. STATE SPACE REPRESENTATION

The governing equations of motion are solved using the state space method (HART & WONG, 2000) and written as,

$$\dot{z} = Az + HF - E\ddot{u}_g \quad (7)$$

Where, $\dot{z} = \{u \ \ \dot{u}\}^T$ is a state vector;

A = the system matrix;

H = Distribution matrix of control force; and

E = the distribution matrix of excitation.

These matrices are expressed as,

$$\mathrm{A} = \begin{bmatrix} 0 & I \\ -M^{-1}k & -M^{-1}C \end{bmatrix}; \quad (8)$$

$$H = \begin{bmatrix} 0 \\ -M^{-1}\Lambda \end{bmatrix} \quad \text{and} \quad \mathrm{E} = \begin{bmatrix} 0 \\ \Gamma \end{bmatrix} \quad (9)$$

In which I is the identity matrix.

The Equation $\dot{z} = Az + HF - E\ddot{u}_g$ discretized in time domain, excitation and control forces are assumed to be constant within any time interval, the solution may be written in an incremental form

$$z_{k+1} = A_k z_k + H_k F_k - E_k \ddot{u}_{gk} \quad (10)$$

Where, k denote the time step; $A_k = e^{A\Delta t}$ and represent the discrete time step system matrix with Δt is a time interval. The constant coefficient matrices H_k and E_k are discrete time counterparts of matrices H and E and can be written as,

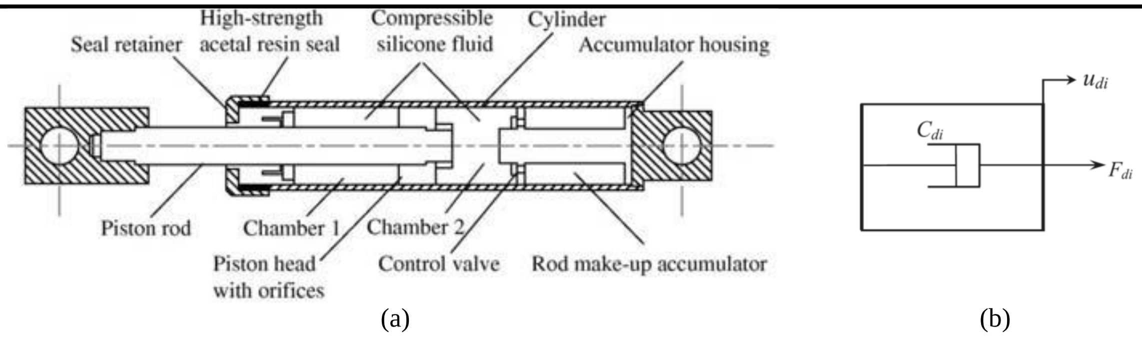
$$H_k = A^{-1}(A_k - I)H \quad \text{and} \quad E_k = A^{-1}(A_k - I)E \quad (11)$$

V. MODELING OF DAMPER

Fluid dampers operate on the principle of fluid flow through orifices and provide forces that always resist structure motion during a seismic event. 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 piston head results in the damper force. The force in a viscous damper, $F_{di}(= F_{ds} \ or \ F_{df})$ is proportional to the relative velocity between the ends of a damper and given by,

$$F_{mdi} = C_{mdi} |\dot{u}_{di}|^{\alpha} \, sgn(\dot{u}_{di}) \quad (12)$$

Where $C_{mdi} = 2m\omega_n\xi$, C_{mdi} is damper coefficient of the i^{th} damper, $\dot{u}_{di}$ is relative velocity between the two end of damper which is to be consider corresponding to the position of the dampers, α is the power law coefficient or damper exponent or velocity exponent ranging from 0.1 to 1 for seismic applications (Soong and Dargush, 1997) and $sgn(.)$ is signup 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).



Source : Symans and Constantious (1998)

Figure 2 (a) Schematic diagram of FVD (b) Mathematical model of FVD

VI. NUMERICAL STUDY

The seismic response of linearly elastic, one storey, two-way asymmetric building installed with fluid viscous dampers under two horizontal component of ground motion is investigated. The response quantities of interest are lateral and torsional displacements of floor mass obtained at the CM (u_x, u_y and u_θ), lateral and torsional accelerations of floor mass obtained at the CM ($\ddot{u}_x$, $\ddot{u}_y$ and $\ddot{u}_\theta$), stiff and flexible edge displacement in X and Y direction (u_{xs}, u_{xf}, u_{ys} and u_{yf}), stiff and flexible edge acceleration in X and Y direction ($\ddot{u}_{xs}$, $\ddot{u}_{xf}$, $\ddot{u}_{ys}$ and $\ddot{u}_{yf}$), base shear in X and Y direction (Vb_x, Vb_y), base torque (Vb_θ) and drift of the structure. The behaviour of the system is investigated under following parametric variations: (i) additional damping ratio (ξ_d), and (ii) power law coefficient of damper or velocity exponent (α). The peak responses are obtained by performing time history analysis under five considered earthquake ground motions namely, Imperial Valley (1940), Loma Prieta (1989), Northridge (1994), Kobe (1995) and Bhuj (2001). The details of earthquakes such as peak ground acceleration (PGA), duration and recording station are summarized in Table 1.

Table 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, 17th January 1995	Japan Meteorological Agency	48	0.82	0.60
Bhuj, 26th January 2001	Ahmadabad	133	0.78	1.04

For the study carried out herein, the aspect ratio of plan dimension is varying from 1.0, 1.1, 1.2, 1.3, 1.4 and the mass and stiffness of system are considered such as to have required lateral time period. Further, total four PVDs dampers are installed in the system as shown in Figure 1. In this study to find out the effectiveness of control system the responses are expressed in terms of indices R_e. it is defined as

$$Re = \frac{peak\ responce\ of\ controlled\ system}{epeak\ responce\ of\ uncontrolled\ system}$$

The value of R_e less than unity indicates that the control system, it means effective in reducing the responses. On the other hand, the value of R_e more than unity indicate that the control system is not effective in reducing the responses. Physical quantities of the system for analysis are taken as follows; plan dimension of 7 m × 7 m and storey height of 6.2 m. Out of four columns two column are of dimension 0.3 m × 0.3 m, one column is of 0.350 m × 0.350 m and another one column is of 0.4 m × 0.4 m is taken, so two-way asymmetry is achieved. The length of width of plan dimension varies with change of aspect ratio from 1 to 1.4. The lumped mass (*m*) and stiffness eccentricity varies with aspect ratio.

In order to investigate the effectiveness of PVDs, the velocity exponent (α) as expressed in Eq.12 is varied from 0.1 (highly non-linear) to 1 (linear) using increment of 0.1 and damping ratio (ξ_d) is varied from 5% to 70% with increment of 5%. Figure 3 represent the typical hysteresis loops at aspect ratio 1.0 for normalized damper force (Fds) with displacement (u_{xs}) and velocity (V_{xs}) for PVD placed at stiff edge of structure. The response ratio, R_e are obtained for u_x,u_y,u_θ,$\ddot{u}_x$, $\ddot{u}_y$ and $\ddot{u}_\theta$ due to bi-directional earthquake excitation. The responses are obtained for system with aspect ratio 1.2 under all five considered earthquake listed in Table 3.

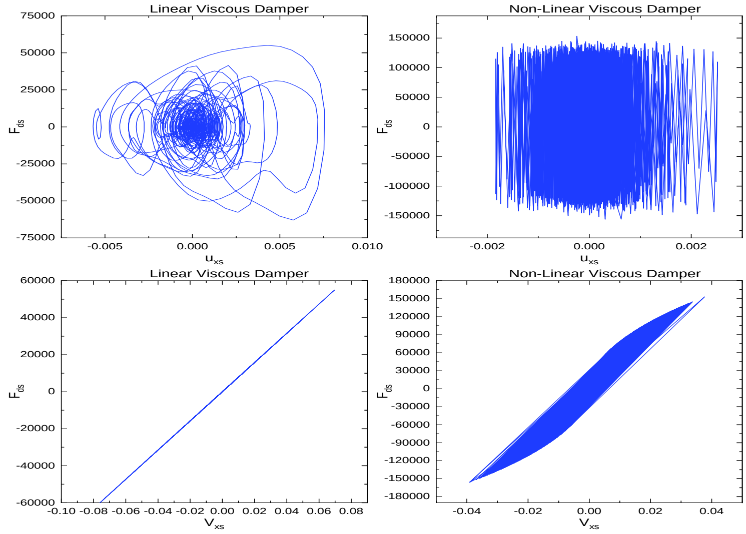


Figure 3 when aspect ratio 1.0, Damper force-displacement and velocity loops for PVD damper located at stiff edge and flexible edge under Imperial Valley, 1940 Earthquake

It can be observed from the figures that with increase in value of α, the ratio, Re increases for response for u_x, u_y. On the other hand, with the increases in value of α, the ratio, Re decreases for response $\ddot{u}_x$, $\ddot{u}_y$. It is also observed that torsional displacement u_θ and torsional acceleration $\ddot{u}_\theta$, Re factor is more than 1 for in between 0.1 to 0.4, so in these range of the damper is not so much effective to mitigate response of the structure. From the results optimum value of α and ξ_d are 0.5 and 54% respectively. For aspect ratio 1.2, variation against α and ξ_d is plotted as shown in Figure 4 to Figure 8.

Table 2 Optimal value of α and ξ_d

Optimum Parameters for the considered system		
Aspect Ratio	*Alpha (α)*	*Damping (ξ_d)*
1.0	0.47	54.12
1.1	0.48	52.67
1.2	0.506	52.67
1.3	0.51	53.33
1.4	0.52	53.67
Optimum Avg.	***0.5***	***54%***

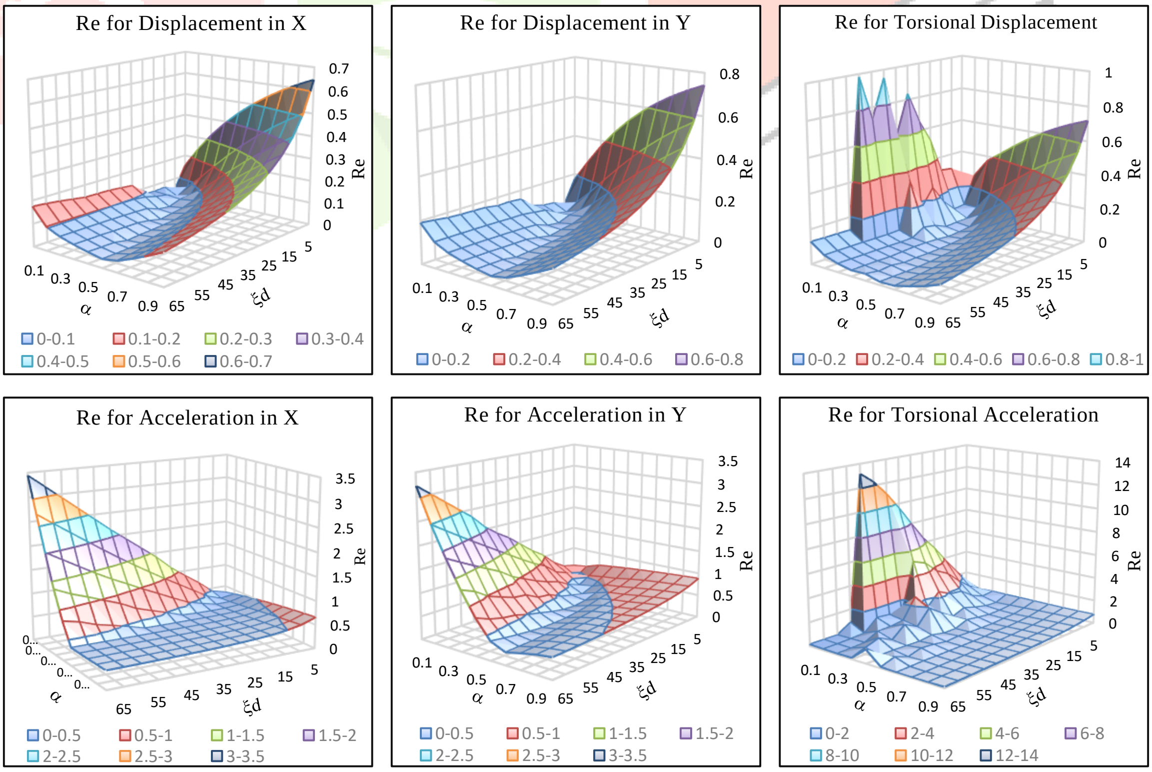


Figure 4 When aspect ratio 1.2, Effect of exponent (α) and damping ratio (ξd) on response ratio. Re for PVD various displacement and acceleration under Imperial Valley, 1940 Earthquake

It can be observed from the Figures 4 to 8 that when the values of velocity exponent (α) in between 0.35 to 0.55, the damper is most effective to mitigate various responses. It is observed that with the increase of damping ratio (ξ_d) the ratio R_e increase for response u_x, u_y. It can be also observed that when the value of α is less than 0.35 and more than 0.55 the ratio of R_e decrease for response u_x, u_y. Here it is noticed that, when the value of α and ξ_d is between 0.1 to 0.45 and 35% to 70% damping, respectively, damper is not effective in reducing acceleration response $\ddot{u}_x, \ddot{u}_y$. It can also observed that when the value of α, between 0.45 and 1 the ratio, R_e decreased for acceleration response $\ddot{u}_x, \ddot{u}_y$. It happens because when the value of α is more than 0.45 PVD behaves like a bracing. Due to this behaviour of viscous damper, it worsen the seismic response for lateral acceleration $\ddot{u}_x, \ddot{u}_y$.

It is noticed that torsional displacement (u_θ) and torsional acceleration ($\ddot{u}_\theta$), Re factor is more than 1 for α and ξ_d is between 0.1 to 0.45 and 55% to 70% damping, respectively. So in this range damper is not effective to reduce response of the structure. From this parametric variation study over five different aspect ratio from 1.0-1.4, the optimum value of α and ξ_d are found to be 0.5 and 54% respectively, Table. 2.

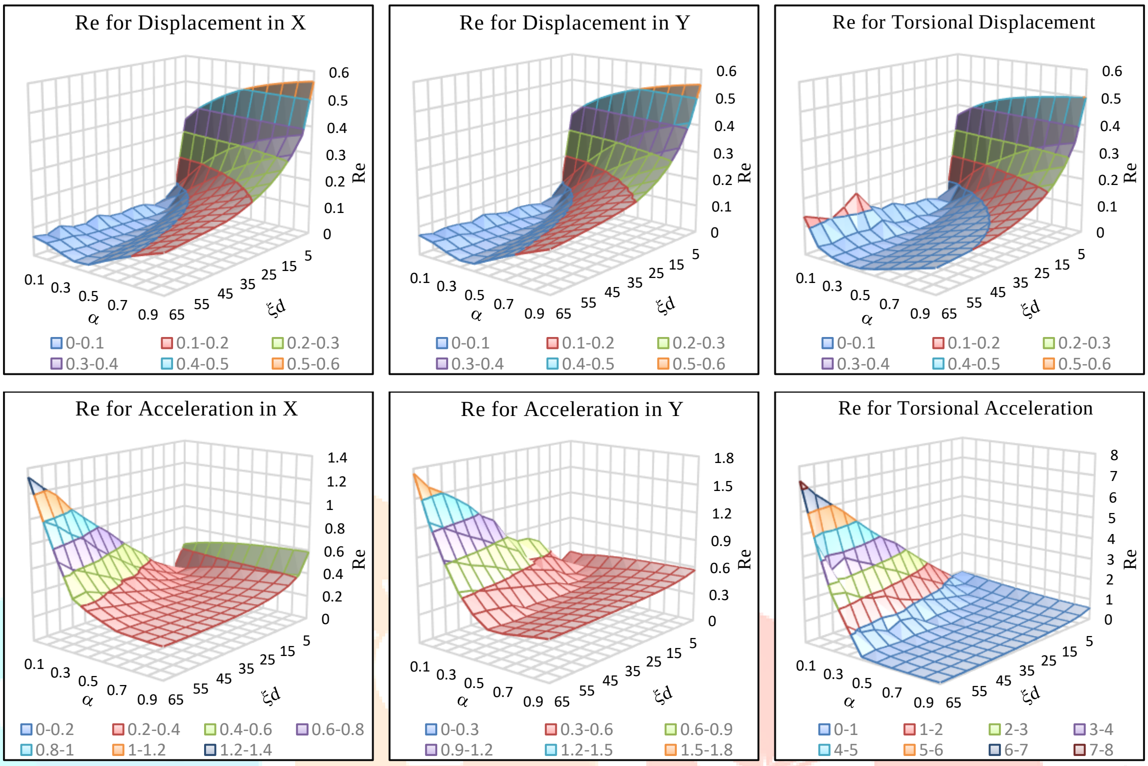


Figure 5 When aspect ratio 1.2, Effect of exponent (α) and damping ratio (ξd) on response ratio. Re for PVD various displacement and acceleration under Loma Prieta, 1989 Earthquake

Table 3 shows the edge response quantities for PVDs control system, when aspect ratio 1.2 under five earthquake excitation. Figure 9 show the graphical representation of average values of displacement and acceleration response of all five aspect ratios. From the figure 9, it can be observed that PVDs are effective in reducing edge displacement and acceleration.

Table 4 shows the storey drift of the structure under uncontrolled and controlled system. As per IS 1893 (Part I) : 2016, clu.7.11.1, storey drift in any storey due to minimum specification design lateral force, with partial load factor of 1.0, shall not exceed 0.004 times the storey height. It can be observed from table that the permissible limit of drift of considered structure is 0.0248 m, when the structure is uncontrolled, the drift of structure is exceeding the permissible limit for all aspect ratios. While the structure is installed with PVDs the drift of the structure is reduced and under permissible limit for all five aspect ratios.

Figure 10 show the time histories for various uncontrolled and controlled displacement as well acceleration response using PVD for Imperial Valley 1940 earthquake. These time histories are plotted using optimum parameter of table 3.2 of PVD for aspect ratio 1.2. Further, the similar tend are also observed for the system under different earthquakes and different aspect ratios. It is observed that there is significant reduction in various response, when the structure is installed with PVD damper.

The Time history for various controlled and uncontrolled system using α=0.5 and ξ_d=10% under all five earthquake is plotted, Figure 10 showa time history of aspect ratio 1.2 sysyem under Imperial Valley 1940 earthquake. It can be observed from figures various response are very much reducing in structure installed with PVD (Controlled System). On the other hand when structure installed with very high additional damping ξ_d = 54% the acceleration response are very high as compared to uncontrolled system.

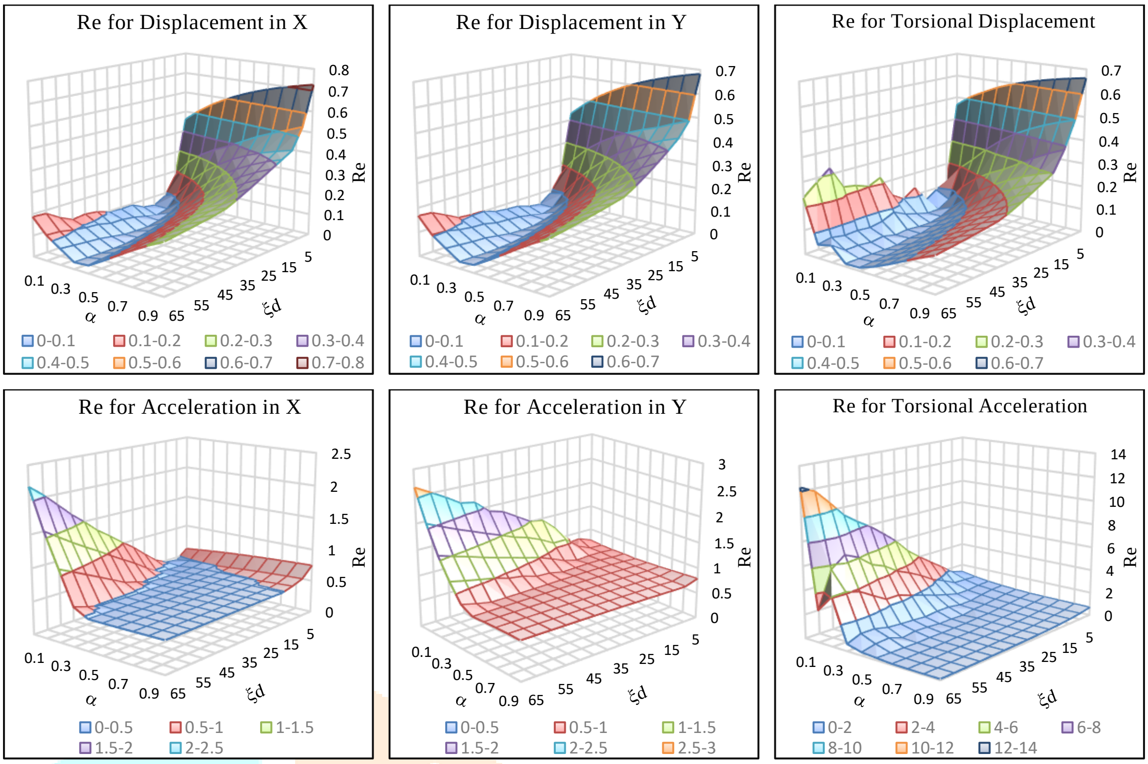


Figure 6 When aspect ratio 1.2, Effect of exponent (α) and damping ratio (ξd) on response ratio. Re for PVD various displacement and acceleration under Northridge, 1994 Earthquake

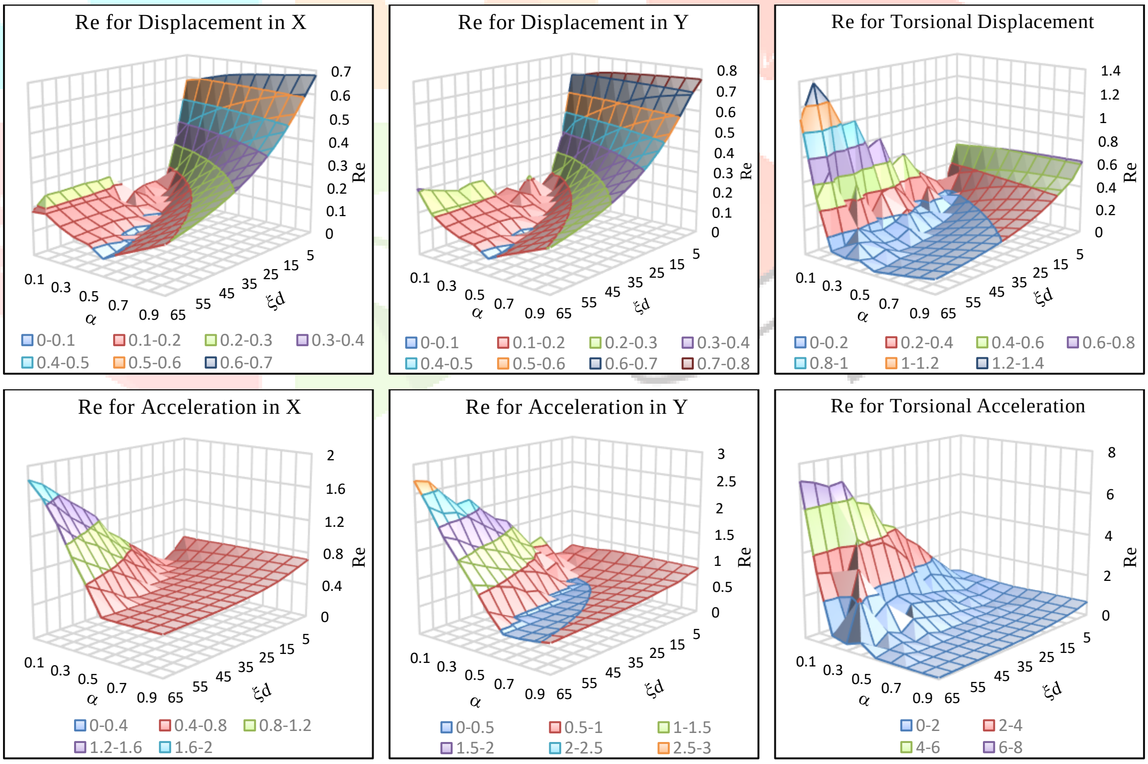


Figure 7 When aspect ratio 1.2, Effect of exponent (α) and damping ratio (ξd) on response ratio. Re for PVD various displacement and acceleration under Kobe, 1995 Earthquake

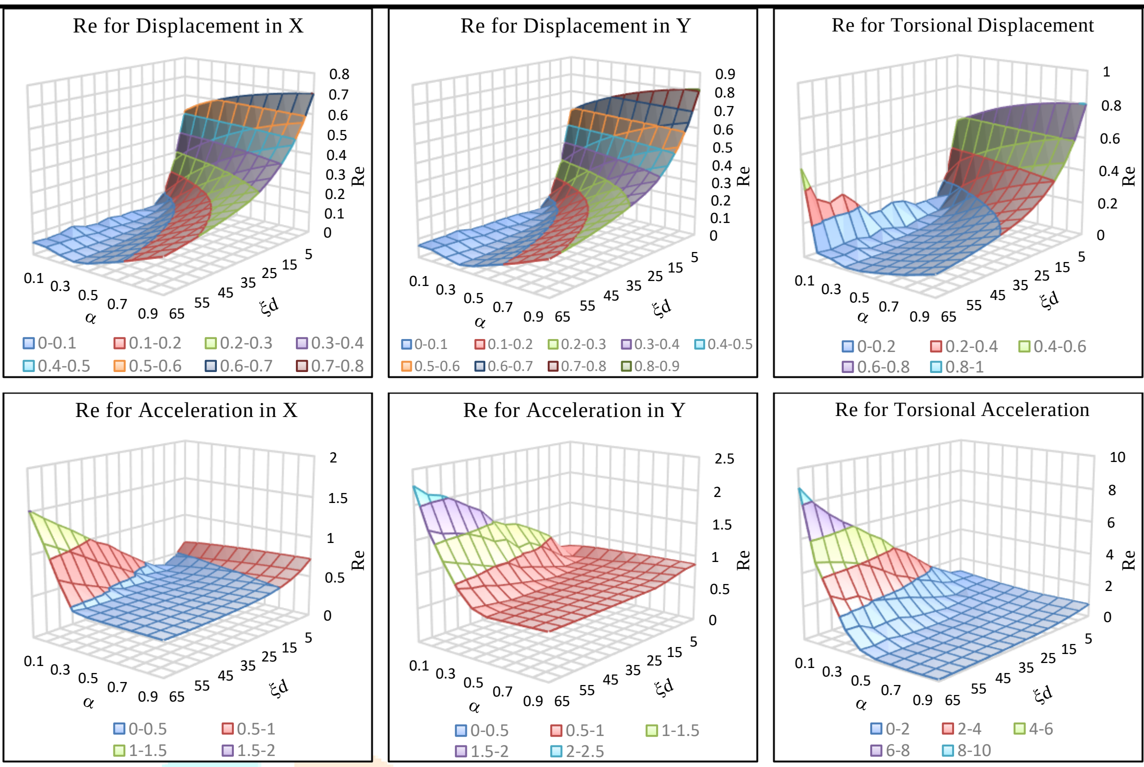


Figure 8 When aspect ratio 1.2, Effect of exponent (α) and damping ratio (ξd) on response ratio. Re for PVD various displacement and acceleration under Bhuj, 2001 Earthquake

Table 3 Response quantities for PVD control system under five earthquake, when aspect ratio 1.2

Response	*Control system*	*Imperial Valley, 1940*	*Loma Prieta, 1989*	*Northridge, 1994*	*Kobe, 1995*	*Bhuj, 2001*	*Average percentage reduction*
u_x (m)	Uncontrolled	0.0533	0.1492	0.0790	0.1313	0.0799	
	PVD	0.0021	0.0070	0.0056	0.0070	0.0074	
	Reduction	*(96.04)*	*(95.31)*	*(92.97)*	*(94.68)*	*(90.75)*	*93.95*
u_y (m)	Uncontrolled	0.0533	0.1439	0.0833	0.1221	0.0884	
	PVD	0.0021	0.0070	0.0056	0.0067	0.0076	
	Reduction	*(96.04)*	*(95.15))*	*(93.30)*	*(94.51)*	*(91.41)*	*94.08*
u_θ (rad)	Uncontrolled	0.0041	0.0135	0.0085	0.0118	0.0098	
	PVD	0.0001	0.0002	0.0002	0.0004	0.0003	
	Reduction	*(98.22)*	*(98.57)*	*(97.37)*	*(96.60)*	*(97.36)*	*97.62*
$\ddot{u}_x$ (m/sec^2)	Uncontrolled	8.2519	19.9401	12.5048	15.644	17.436	
	PVD	0.6542	6.2979	5.8801	1.2753	6.8740	
	Reduction	*(92.07)*	*(68.42)*	*(52.98)*	*(91.85)*	*(60.58)*	*73.18*
$\ddot{u}_y$ (m/sec^2)	Uncontrolled	5.6781	18.3909	12.3894	13.650	15.916	
	PVD	0.7269	7.6579	8.4781	1.8924	8.3979	
	Reduction	*(87.20)*	*(58.36)*	*(31.57)*	*(86.14)*	*(47.24)*	*62.10*
$\ddot{u}_\theta$ (rad/sec^2)	Uncontrolled	0.5908	1.6545	0.8503	1.9892	1.4146	
	PVD	0.1692	0.3136	0.2037	0.9316	0.5419	
	Reduction	*(71.35)*	*(81.05)*	*(76.04)*	*(53.16)*	*(61.69)*	*68.66*

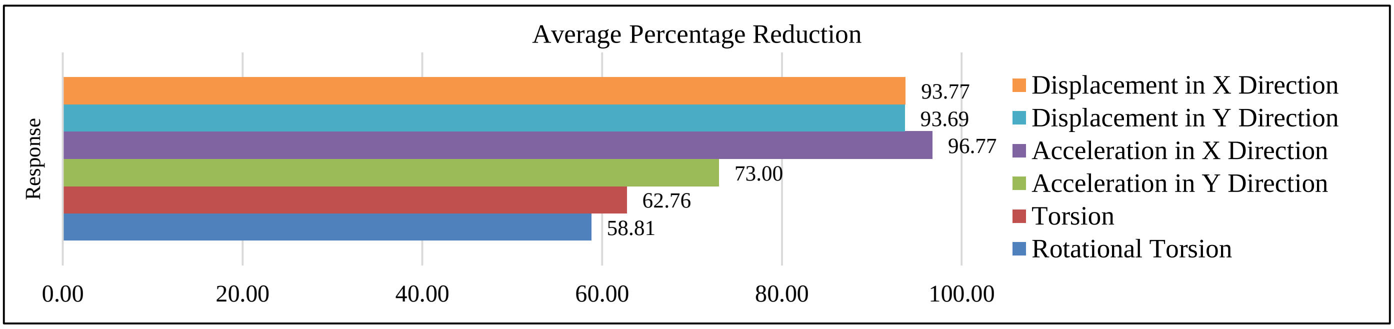


Figure 9 for all aspect ratio, average percentage reduction in all five earthquake

Table 4 Storey Drift

Aspect ratio	*Earthquake*	*Drift as per IS:1893 (Part I):2016*	*Structure without damper (uncontrolled)*		*Controlled PVD*	
1.0	Imperial Valley, 1940	0.0248 m	0.05930 m	Unsafe	0.00237 m	Safe
	Loma Prieta, 1989	0.0248 m	0.17999 m	Unsafe	0.00798 m	Safe
	Northridge, 1994	0.0248 m	0.09916 m	Unsafe	0.00678 m	Safe
	Kobe, 1995	0.0248 m	0.14162 m	Unsafe	0.01008 m	Safe
	Bhuj, 2001	0.0248 m	0.10361 m	Unsafe	0.00865 m	Safe
1.1	Imperial Valley, 1940	0.0248 m	0.05653 m	Unsafe	0.00225 m	Safe
	Loma Prieta, 1989	0.0248 m	0.15035 m	Unsafe	0.00748 m	Safe
	Northridge, 1994	0.0248 m	0.09034 m	Unsafe	0.00604 m	Safe
	Kobe, 1995	0.0248 m	0.13531 m	Unsafe	0.00840 m	Safe
	Bhuj, 2001	0.0248 m	0.09813 m	Unsafe	0.00814 m	Safe
1.2	Imperial Valley, 1940	0.0248 m	0.05332 m	Unsafe	0.00211 m	Safe
	Loma Prieta, 1989	0.0248 m	0.14925 m	Unsafe	0.00700 m	Safe
	Northridge, 1994	0.0248 m	0.08334 m	Unsafe	0.00558 m	Safe
	Kobe, 1995	0.0248 m	0.13125 m	Unsafe	0.00698 m	Safe
	Bhuj, 2001	0.0248 m	0.08840 m	Unsafe	0.00759 m	Safe
1.3	Imperial Valley, 1940	0.0248 m	0.05461 m	Unsafe	0.00234 m	Safe
	Loma Prieta, 1989	0.0248 m	0.14296 m	Unsafe	0.00660 m	Safe
	Northridge, 1994	0.0248 m	0.07760 m	Unsafe	0.00521 m	Safe
	Kobe, 1995	0.0248 m	0.12332 m	Unsafe	0.00725 m	Safe
	Bhuj, 2001	0.0248 m	0.09338 m	Unsafe	0.00713 m	Safe
1.4	Imperial Valley, 1940	0.0248 m	0.04990 m	Unsafe	0.00256 m	Safe
	Loma Prieta, 1989	0.0248 m	0.12845 m	Unsafe	0.00624 m	Safe
	Northridge, 1994	0.0248 m	0.07270 m	Unsafe	0.00490 m	Safe
	Kobe, 1995	0.0248 m	0.13143 m	Unsafe	0.00718 m	Safe
	Bhuj, 2001	0.0248 m	0.10170 m	Unsafe	0.00675 m	Safe

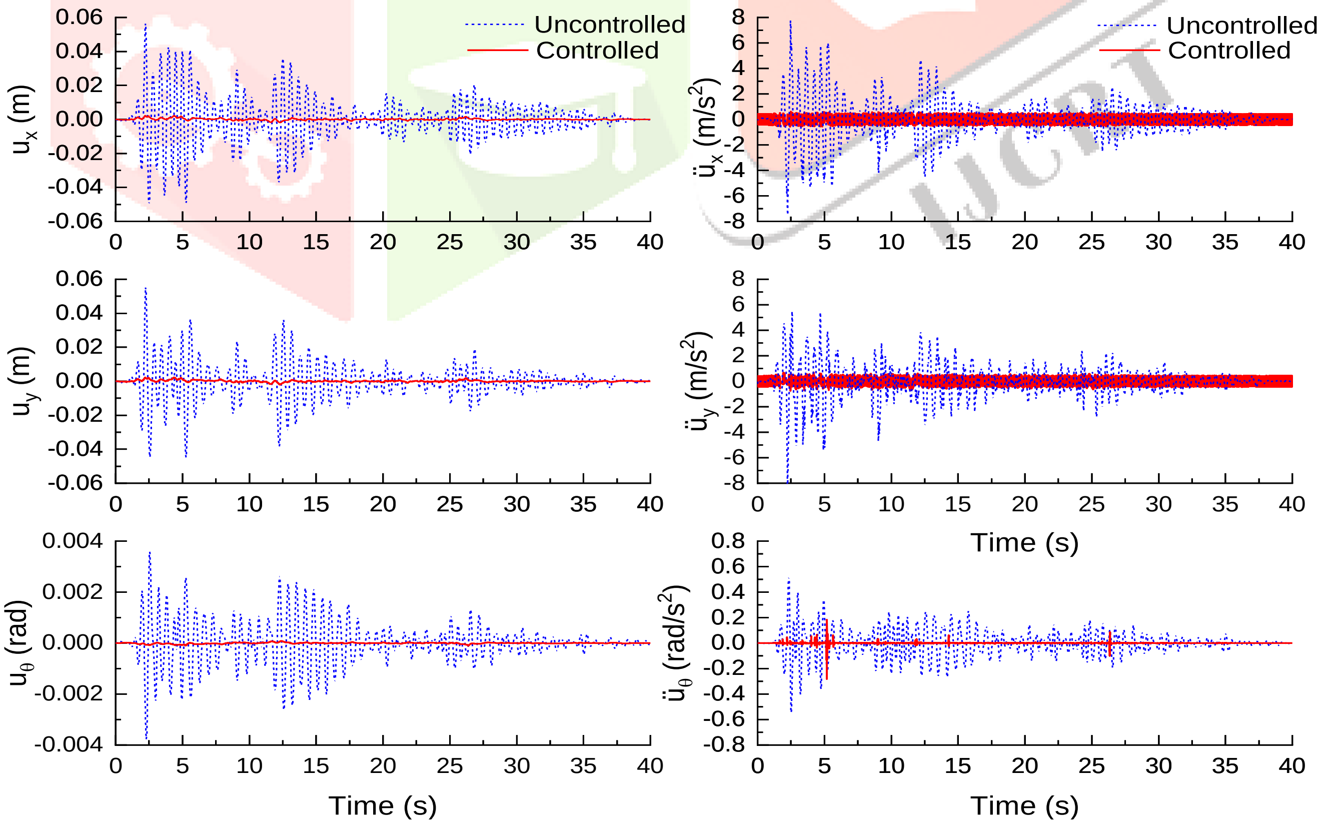


Figure 10 When aspect Ratio 1.2, Time Histories for various uncontrolled and controlled displacement and acceleration using PVD under Imperial Valley, 1940 Earthquake.

VII. CONCLUSION

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

1. Non-linear viscous damper are more effective in reducing the edge displacements than linear viscous damper. For edge accelerations, response reduction by NLVDs and LVDs are relatively less effective than displacements.
2. From the result, at damping ratio (ξ_d) of 54 % and velocity exponent (α) of 0.5 we found the optimum parameters of structure like displacement, torsional displacement, acceleration, base shear, base torque and drift.
3. The significant reduction in drift of the structure found at optimum parameters per IS: 1893 (Part 1):2016 when structure is installed with NLVDs.
4. NLVDs not effective in reducing the response of torsional acceleration and the base shear as compared to the displacement of the structure.
5. There exist optimum value for damping ratio (ξ_d) and velocity exponent (α).
6. Damper force depends on asymmetry of structural system and amount of supplemental damping.

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