IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 08, Issue 5 (May. 2018), ||VIII|| PP 59-67

Seismic Vibration Control of Multi-Storey Asymmetric Building

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Abstract: As recorded in the past, the response of structuresthat are asymmetric when subjected to earthquake have depictedthat they are excessively vulnerable to edge deformations. Theinvestigation presented here examined how the installation ofsupplemental viscous dampers and magneto-rheological dampers controlled the largely prevalent deformations in G+3 storey, one-way asymmetric buildings.Torsional and Lateral displacement for controlled anduncontrolled system were obtained along with the torsional and lateral acceleration response and it was concluded thatlinear viscous dampers are less effective than the non-linear viscous as well asmagneto-rheological dampers.

Keywords: - Asymmetric, eccentricity, viscous dampers, MR dampers

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Date of Submission: 11-05-2018 Date of acceptance: 28-05-2018

Listof symbols

Symbol	**Explanation**
a	Plan dimension in x-direction
a_0, a_1	Rayleigh's damping coefficients depending upon damping ratio for first and second vibration modes
A	System matrix
Ad	Discrete time-system matrix
b	Plan dimension in y-direction
B	Distribution matrix of control forces
Bd	Discrete-time matrix of control matrix
c_{0i}	Viscous damping at large velocities
C_{1i}	Nonlinear roll-off in the force-velocity loops at low velocities
C	Damping matrix
C_d	Total damping coefficient
CR	Centre of resistance
CM	Centre of mass
e_x	Eccentricity (distance between CR and CM)
E	Distribution matrix for excitation forces
E_d	Discrete-time matrix of excitation forces
F_{dy}	Resultant damping force in y-direction
$F_{d\theta}$	Resultant damping force in y-direction
F_{df}	Force in damper in flexible edge
F_{di}	Force in damper in i^{th} damper
F_{ds}	Force in damper in stiff edge
F_{dT}	Resultant damper force
F	Damper force vector
g	Gravitational acceleration
I	Identity matrix
K	Stiffness matrix
K_0	Coefficient present to check the stiffness at large velocities
k_1	Accumulator stiffness
K_{xi}	Lateral stiffness in x-direction
K_{yi}	Lateral stiffness in y-direction
k_y	Total Lateral stiffness in y-direction
$K_{R\theta}$ or $k_{\theta R}$	Torsional stiffness at CM

$k_{\theta\theta}$	Torsional stiffness about vertical axis
m	Limped mass of each slab
M	Mass matrix
r	Mass radius of gyration from CM about vertical axis
T	Time period of building
u_i	Relative displacement at i^{th} stiffness damper
$\ddot{u}_y$ and u_y	Lateral acceleration and displacement at CM
$\ddot{u}_{yf}$ and u_{yf}	Lateral acceleration and displacement at flexible edge
$\ddot{u}_y$ and u_y	Lateral acceleration and displacement at stiff edge
$\ddot{u}_{y\theta}$ and $u_{y\theta}$	Lateral acceleration and displacement in θ-direction
u	Displacement vector
$\dot{u}$	Velocity vector
$\ddot{u}$	Acceleration vector
u_g	Ground acceleration vector
u_{gy}	Ground acceleration in y-direction
x_0	initial displacement of spring k1
x_i	x-coordinate relative to CM
y_i	y-coordinate relative to CM
z	State vector
Γ	Influence coefficient vector
ω_θ	Uncoupled torsional frequency
ω_y	uncoupled lateral frequency
Ωθ	ratio of uncoupled torsional and that of lateral frequency of the system in y-direction
Λ	Location matrix for control forces

I. INTRODUCTION

In recent years, due to advancement in technology, design and increased quality of materials in civil engineering have resulted in lighter and more slender structures. Due to this, the structures in earthquake or wind prone regions are subjected to higher structural vibrations causing serious structural damage and possible structural failure. Structural control itself is a very vast field of study currently and it looks assuring in attainment of lesser structural vibrations when subjected to earthquake loads and strong wind loads. The abstractions of utilizing structural control in order to reduce such vibrations in structures was suggested in the year 1970. A mechanical system is set up in structure to check and minimize these vibrations. For asymmetric buildings the control of the seismic responses are presented here. It is usually observed that symmetric structures are less affected during stronger earthquakes leading to lesser damage than symmetric building. When centre of rigidity and centre of mass are located at different points then structure is called an asymmetric structure.

Chang et al (1998)[1] proposed on how to analyse and design visco-elastic dampers in a 5 storey structure by equivalent strain energy method. Dynamic analysis was carried out where dampers were designed that had different damping ratio at different temperatures. Study was done based on experimental as well as the analytical results and based on that study, the modal strain energy technique has been incorporated into the computer programs ETABS for analysis of structure with supplemental VE Dampers. Goel (2000)[2] identified the system parameters for asymmetric structures with viscous dampers that controlled the seismic responses of the buildings. And also investigated deformations in plan wise asymmetric buildings in which he found that for linearly-elastic, single-story, asymmetric structure having added viscous dampers showed reduced edge deformations. Particularly, it was observed that the symmetric distribution of added damping led to a lesser reduction in values of edge deformations when compared to asymmetric distribution. Kim and Bang (2002)[3] developed a strategy for distribution of viscoelastic dampers for reduction of the torsional displacement as well as acceleration values for an asymmetric structure. Mevada and Jangid (2012) [4] analyzed linearly elastic one-way asymmetric and one-storey structure employed with semi-active variable dampers and investigated it under various actual earthquake motions. The responses were investigated considering the force algorithm of two-step viscous damping to carry out the study the effectivity of the semi-active damper system and the effect resulting due to torsional coupling.

In this paper, the values for seismic response of multi-storey, one-way asymmetric and linearly elastic structure is studied for different actual earthquake ground excitations. The precise objective of this study is summarized as to study the comparative performance of non-linear viscous dampers (NLVDs), linear viscous dampers (LVDs) and passive off magneto-rheological dampers (MR dampers) in curbing the torsional as well as lateral displacements and also their similar acceleration responses.

II. STRUCTURAL MODEL AND GOVERNING EQUATIONS OF MOTION

The system considered is an ideal G+3 structure consisting of columns supporting a rigid slab as stated in the Figure 1. Assumptions that were made for given system are as stated below: (i) slab of the structure is rigid, (ii) force-deformation pattern for the given structure is assumed of being linearly elastic and also (iii) the considered building is excited upon the action of horizontal component of earthquake excitation in single direction. The slab having uniformly distributed mass and so the geometric centre coincides with the structure's centre of mass (CM). The stiffness asymmetry with respect to the CM in only one direction is generated because of the specific arrangement of columns as shown in Figure 1, so in x-direction, there is an eccentric distance, ex between the Centre of stiffness (CR) and CM. The structure has symmetry in x-direction and so, two degrees-of freedom are taken into consideration for model that is the torsional displacement, uθ and the lateral displacement in y-direction, uy as shown in Figure 1. The equation for motion are obtained as

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

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

Where, $r = \sqrt{a^2 + b^2/12}$ is about vertical axis.Based on Goel, 1998, stiffness matrix for the given structure is changed as follows,

$$K = k_y \begin{bmatrix} 1 & e_x \\ e_x & e_x^2 + r^2\Omega_\theta^2 \end{bmatrix} \quad (3)$$

$$\omega_\theta = \sqrt{\frac{K_{\theta r}}{mr^2}} \text{ and } \omega_y = \sqrt{\frac{K_y}{m}} \quad (4)$$

$$e_x = \frac{1}{K_y}\sum_i K_{yi}x_i \text{ and } \Omega_\theta = \frac{\omega_\theta}{\omega_y} \quad (5)$$

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

The damping matrix for the structure is not known in definite manner but is obtained by considering Rayleigh's proportionality as,

$$C_d = a_0 M + a_1 K \quad (7)$$

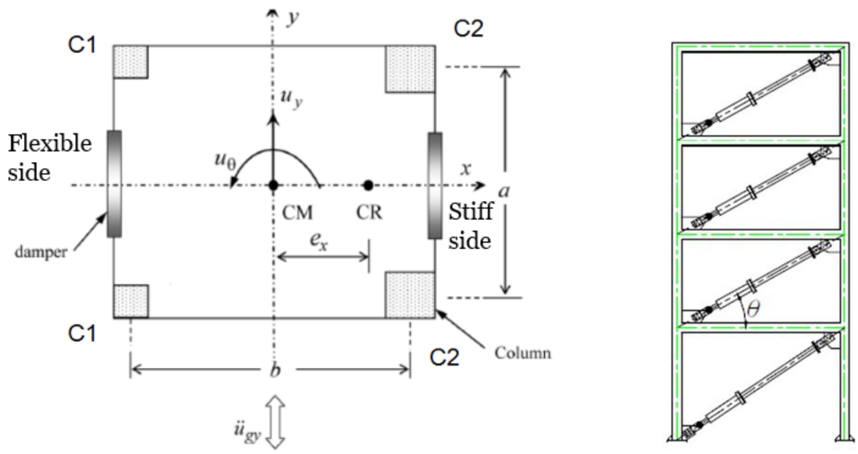

Fig. 1 Plan of one way asymmetric system

For study taken here, both modes of structural vibrations is assumed to be taking 10% damping. The equation for motion are solved by considering the state space method (Hart and Wong, 2000) as,

$$\dot{z} = Az + BF + E\ddot{u}_g \quad (8)$$

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

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix};\ B = \begin{bmatrix} 0 \\ -M^{-1}\Lambda \end{bmatrix} and E = \begin{bmatrix} 0 \\ \Gamma \end{bmatrix} \quad (9)$$

Where, Control forces are taken as constant within any given time intervals, and the solution can be stated in incremental pattern (Hart and Wong, 2000),

$$z[k+1] = A_d z[k] + B_d F[k] + E_d \ddot{u}_g\{k\} \quad (10)$$

Where k is taken as a time step; and Ad = eAΔt depicts the discrete-time system matrix with Δt as time interval. Bd and Ed are matrices of constant coefficient with discrete time similitude of matrices B and E and are written as,

$$B_d = A^{-1}(A_d - I)B\,and\,E_d = A^{-1}(A_d - I)E \quad (11)$$

III. MODEL OF FLUID VISCOUS DAMPER

Viscous dampers operate on the principle of fluid flowing through orifice and provide resisting forces based on the structural motion when subjected to earthquake induced dynamic forces. Figure 2 shows a mathematical and schematical model of viscous damper. An emblematic viscous damper has a cylindrical body which contains central piston within a fluid chamber. The pressure difference generated across the piston assembly which is connected between two ends of building results in damper force. Figure 2 shows the model of viscous damper which is demonstrated by Symans and Constantinou (1998) and Lee-Taylor (2001).

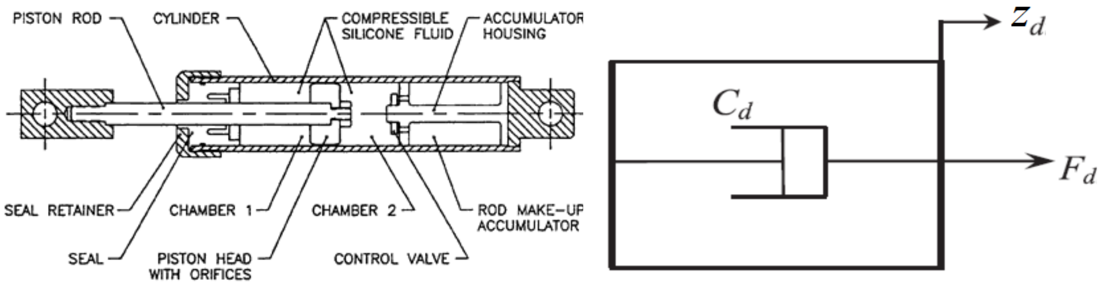

Fig. 2 Mathematical and Schematic model for viscous damper

The force in damper is directly proportional with the relative velocity between the ends of viscous damper as shown in following equation,

$$F_d = C_d |\dot{z}_d|^{\alpha} \operatorname{sgn}(\dot{z}_d) \quad (12)$$

Where, for any i^{th} damper, α is the damper exponent ranging from 0.2 to 1 for seismic application (Soong and Dargush, 1997) and sgn(·) is signum function. The piston head orifices primarily controls the exponent value. When α = 1, it is known as a linear viscous damper (LVD) and for α smaller than 1, given damper is considered as a nonlinear viscous damper (NLVD) which in this case is taken as α = 0.5 for NLVD. Dampers having α greater than 1 have not been used much practically.

IV. MODEL OFMAGNETORHEOLOGICAL DAMPER

Magnetorheological (MR) dampers are semi-active systems using MR fluids to cater control forces that are fairly promising in civil engineering uses. During malfunctioning of hardware they offer highly dependable operation at a bare minimum cost and they behave as a passive damper and hence are considered fail-safe. MR fluids contains micro-sized particles that are polarizable when kept in vicinity of magnetic force. These particles are dispersed withn a special medium like oil of silicon. Whenfluid is acted upon by magnetic field, chains of particlesformrendering the fluid to be semisolid in state, showing plastic behavior. These fluid has large yield strength, lower viscosity and stable hysteretic behaviour over a wide temperature range. It just takes milliseconds for such devices to transit to rheological stability stage furnishing high band-width to devices. As a result of such mechanism higher forces can be generated.

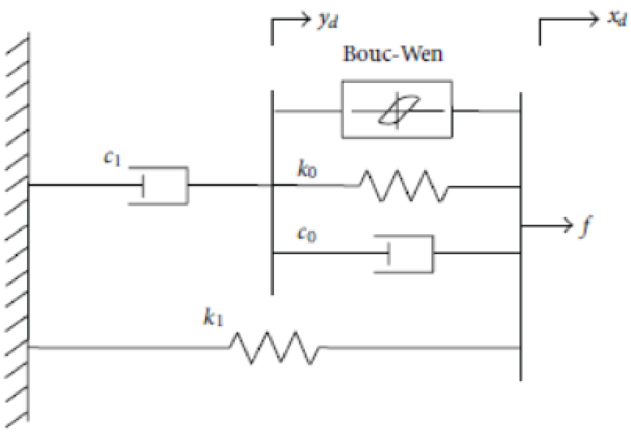

Fig. 3 Mechanical model of the MR damper (Modified Bouc-Wen model)

Presently, the Modified Bouc-Wen model specified by Spencer et al. as shown in Figure 3 is used. Over a wide range of inputs this model accurately predicted the behaviour of prototype MR damper. The equations governing the force predicted by this model is

$$f_i = \alpha_i z_i + c_{0i}(\dot{x}_{di} - \dot{y}_{di}) + k_0(x_{di} - y_{di}) + k_1(x_{di} - x_0)$$
$$= c_{0i}\dot{y}_{di} + k_1(x_{di} - y_{di}) \quad (13)$$

Where, variable $z_i$is given as

$$\dot{z}_i = -\gamma|\dot{x}_{di} - \dot{y}_{di}|z_i|z_i|^{n-1} - \beta_m(\dot{x}_{di} - \dot{y}_{di})|z_i|^n + A_m(\dot{x}_{di} - \dot{y}_{di}) \quad (14)$$
$$\dot{y}_{di} = \frac{1}{(c_{0i} + c_{1i})}\{\alpha_i z_i + c_{0i}\dot{x}_{di} + k_0(x_{di} - y_{di})\}$$

To account for the dependence of the force on the voltage applied to the current driver and the resulting magnetic current, the suggested parameters are

$$\alpha_i = \alpha_a + \alpha_b u_{di}\,,\ c_{0i} = c_{0a} + c_{0b} u_{di}\,,\ c_{1i} = c_{1a} + c_{1b} u_{di} \quad (15)$$

V. NUMERICAL STUDY

Seismic response values of G+3, one-way asymmetric and linearly elastic building is investigated for different actual earthquake ground excitations by studying the numerical simulation. The response values considered are lateral as well as torsional displacements of deck mass at the CM and edges. (u_y, u_θ, u_{ys} and u_{yf} respectively); also lateral and torsional acceleration for deck mass at the CM and edges ($\ddot{u}_y$, $\ddot{u}_\theta$, $\ddot{u}_{ys}$ and $\ddot{u}_{yf}$ respectively) and forces in dampers employed at stiff and flexible edge of structure (F_{ds}, F_{df} respectively) along with the resultant damper force, F_{dy} (= F_{ds} + F_{df}). The response values for the given system is carried under the following parametric variations: lateral time period of the system ($T_y = 2\pi/\omega_y$), $\Omega_\theta = \omega_\theta/\omega_y$ i.e. the ratio of uncoupled torsional to lateral frequency. The dampers employed are LVDs, NLVDs and MR dampers. The peak responses are taken corresponding to parameters listed above for four considering earthquake excitations namely, Loma Prieta (1989), Imperial Valley (1940), Kobe (1995), Northridge (1994) having 0.96 g, 0.31 g, 0.82 g and 0.89 g as peak ground acceleration (PGA) values; details summarized as in Table 1. For the study, the aspect ratio is kept as unity for the given plan dimension. Also, total two dampers placing one at each edge are employed in the structure.

Table 1 Details of earthquake excitations

Earthquake	Recording Station	Component	Duration	PGA (g)
Imperial Valley 19/5/1940	El Centro (Array # 9)	ELC 180	40	0.31
Loma Prieta 18/10/1989	Los Gatos Presentation Center	LGP 000	25	0.96
Northridge 17/1/1994	Sylmar Converter Station	SCS 142	40	0.89
Kobe 16/1/1995	Japan Meteorological Agency	KJM 000	48	0.82

VI. RESULTS AND CONCLUSIONS

For Imperial Valley Earthquake the graphs are shown in Figure 4for uncontrolled structure, structure installed with linear and non-linear viscous dampers and passive off magneto-rheological dampers. Linear and torsional displacement as well as the acceleration values versus time are recorded.

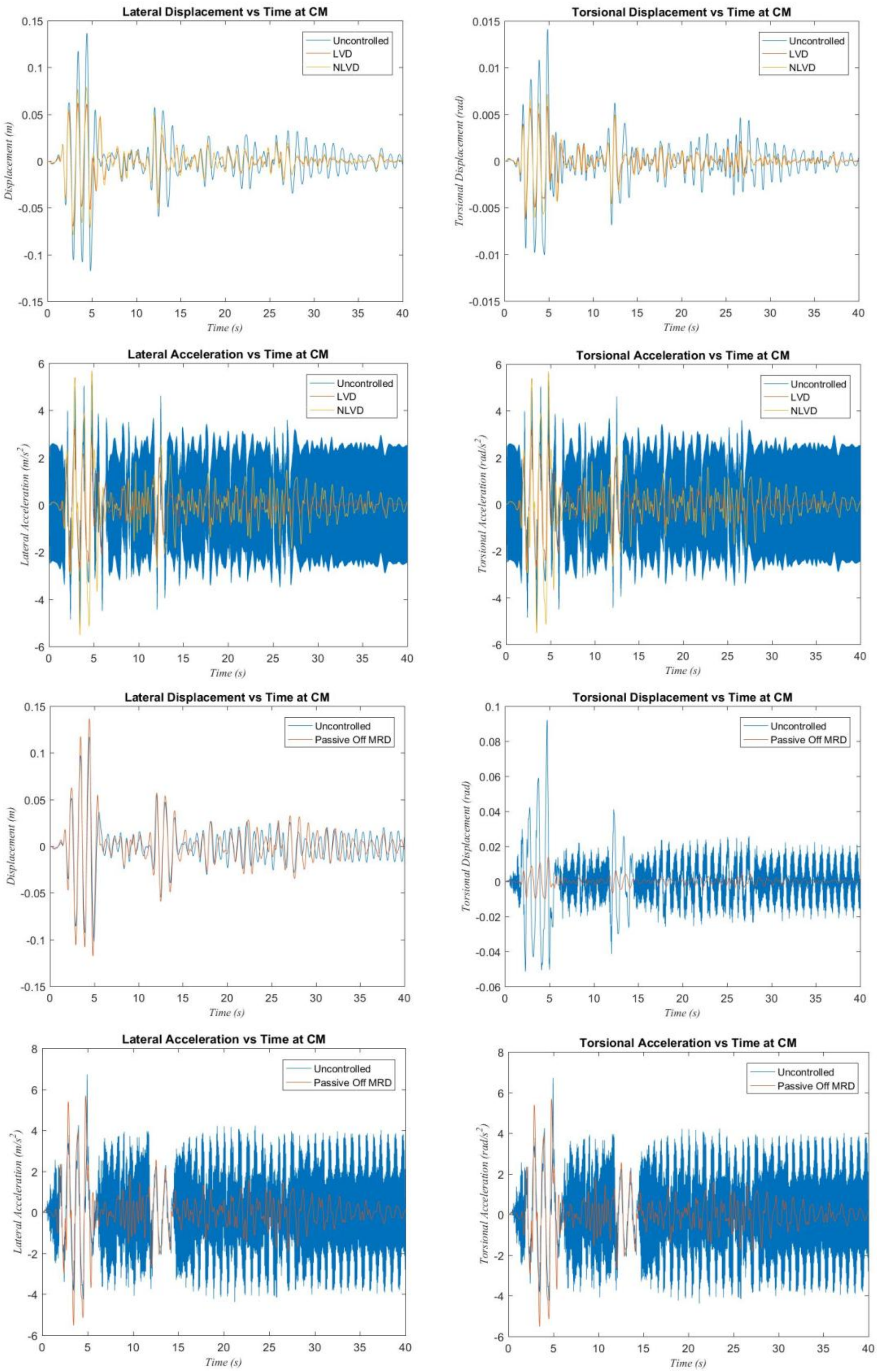

Fig. 4Lateral and torsional responses for Imperial Valley earthquake

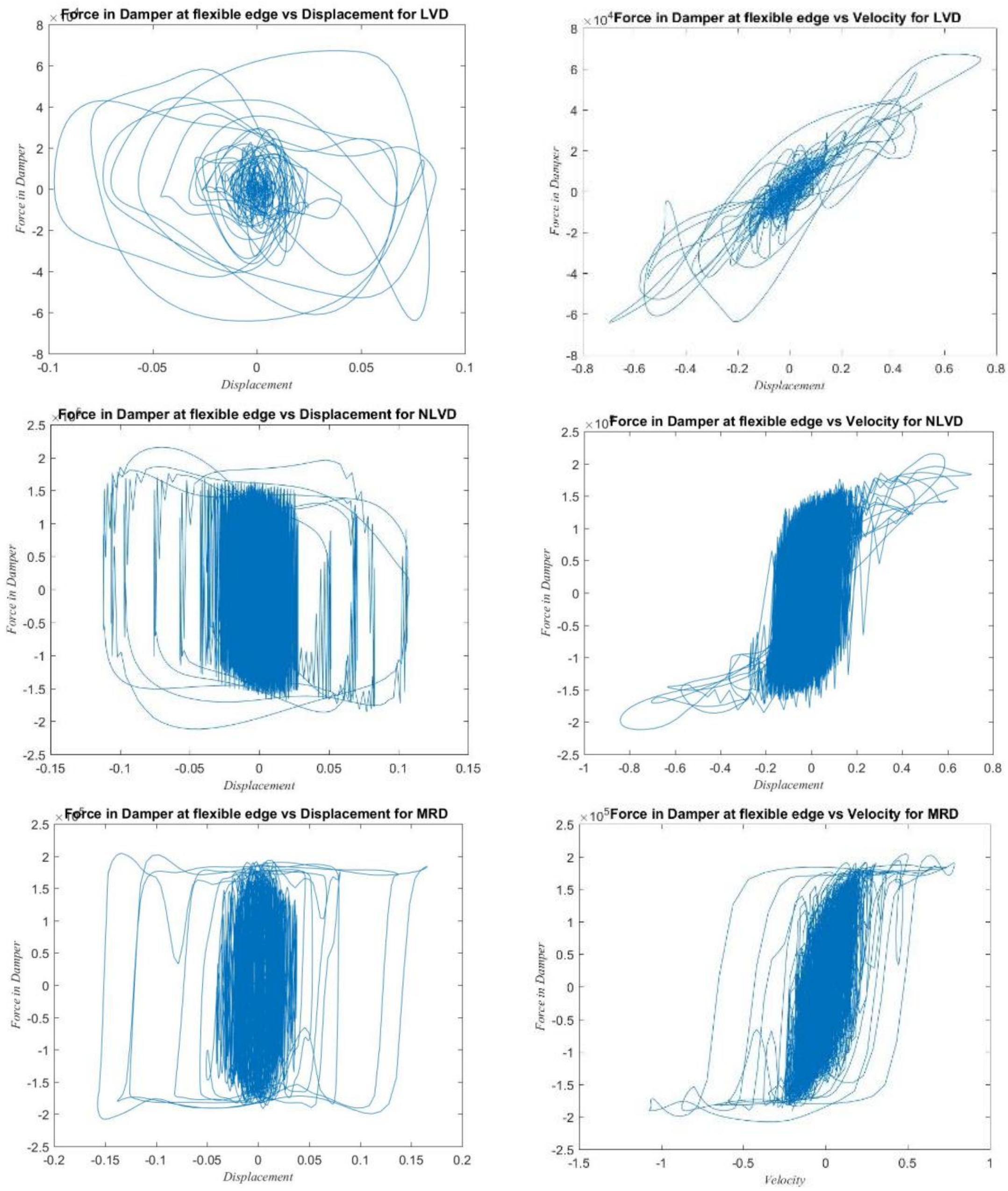

Fig. 5 Hysteresis loop for Imperial Valley earthquake

Figure 5 shows hysteresis loops for Imperial Valley earthquake for flexible edge at top storey. The area under hysteresis loop shows energy dissipated when dampers are placed. The area under damper force vs displacement and that of damper force vs velocity is $6.959x10^5$ and $4.589x10^6$ for MRD, $7.6654x10^4$ and $2.743x10^5$ for LVD and $3.623x10^5$ and $2.743x10^5$ for NLVD. Table 2 shows the maximum values lateral as well as torsional displacement and acceleration for Imperial Valley earthquake. Similarly table 3, 4 and 5 shows the same responses for Kobe, Loma-prieta and North-ridge earthquake.Similarly, the values for energy dissipated forKobe earthquake are $5.9x10^5$and $7.1x10^7$for MRD, $6.7x10^5$and $1.5x10^5$for LVD and $1.5x10^6$and $1.5x10^5$for NLVD; for Loma-prieta are $1.31x10^6$and $3.51x10^6$for MRD, $4.56x10^5$and $8.23x10^5$for LVD and $1.30x10^6$and $8.23x10^5$ for NLVD and for North-ridge are $4.79x10^6$and $5.78x10^6$for MRD, $6.32x10^5$and $1.07x10^6$for LVD and $2.16x10^6$and $1.07x10^6$for NLVD.

Table 2: Responses under Imperial Valley Earthquake

Response parameter	Uncontrolled	Controlled with LVD	% reduction	Controlled with NLVD	% reduction	Controlled with MRD	% reduction
DISPLACEMENT (m)	0.14	0.07	48.81	0.08	42.06	0.12	14.16
ACCELERATION (m/s^2)	0.01	0.01	55.87	0.01	49.21	0.09	-551.3
TORSIONAL DISPLACEMENT (rad)	5.68	3.20	43.60	5.57	2.00	6.72	-18.22
TORSIONAL ACCELERATION (rad/s^2)	1.05	0.63	39.47	1.11	-5.62	1.52	-45.24

Table 3: Responses under Kobe Earthquake

Response parameter	Uncontrolled	Controlled with LVD	% reduction	Controlled with NLVD	% reduction	Controlled with MRD	% reduction
DISPLACEMENT (m)	0.41	0.34	18.21	0.36	11.84	0.75	-83.00
ACCELERATION (m/s^2)	0.05	0.03	27.94	0.04	24.69	0.50	-948.0
TORSIONAL DISPLACEMENT (rad)	18.83	13.74	27.03	16.54	12.19	37.51	-99.18
TORSIONAL ACCELERATION (rad/s^2)	3.51	2.53	28.04	3.08	12.26	6.44	-83.34

Table 4: Responses under Loma-prieta Earthquake

Response parameter	Uncontrolled	Controlled with LVD	% reduction	Controlled with NLVD	% reduction	Controlled with MRD	% reduction
DISPLACEMENT (m)	0.28	0.21	25.78	0.22	19.63	0.27	4.83
ACCELERATION (m/s^2)	0.03	0.02	28.00	0.02	21.49	0.20	-606.15
TORSIONAL DISPLACEMENT (rad)	12.63	8.36	33.82	9.77	22.61	13.57	-7.46
TORSIONAL ACCELERATION (rad/s^2)	2.26	1.43	36.65	1.70	24.67	2.16	4.40

Table 5: Responses under North-ridge Earthquake

Response parameter	Uncontrolled	Controlled with LVD	% reduction	Controlled with NLVD	% reduction	Controlled with MRD	% reduction
DISPLACEMENT (m)	0.41	0.34	17.07	0.36	12.34	0.46	-11.61
ACCELERATION (m/s^2)	0.04	0.03	29.51	0.03	22.25	0.31	-677.42
TORSIONAL DISPLACEMENT (rad)	16.49	14.21	13.79	15.10	8.40	21.79	-32.16
TORSIONAL ACCELERATION (rad/s^2)	2.15	1.56	27.42	1.67	22.31	2.63	-22.13

VII. DISCUSSIONAND CONCLUSION

From figure it is observed that displacement as well as acceleration values both laterally and torsionally, decrease when dampers are installed.It is evident that significant reduction is observed in both displacement and acceleration values. Also it was obtained that NLVDs are more effective than LVDs and MR damper in this case. The MR dampersemployed here have reduced the values to some extent for some cases however the capacity of MR dampers used here in 200kN on increasing which more reductions can be obtained.

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