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Seismic Response of Adjacent Buildings Connected With Non-linear Viscous and Viscoelastic Dampers

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ABSTRACT
Connecting the adjacent buildings with dampers not only mitigates the structural response, but also avoids pounding. In this paper, the seismic response of two adjacent single storey buildings of different fundamental frequencies connected with various types of dampers under different earthquake excitations is studied. A formulation of the equations of motion for model of buildings connected with dampers is presented. The seismic response of the system is obtained by numerically solving the equations of motion using state-space method. The effectiveness of various types of dampers, viz., non-linear viscos and viscoelastic dampers in terms of the reduction of structural responses (i.e., displacements and accelerations) of connected adjacent buildings is investigated. A parametric study is also conducted to investigate the optimum damping coefficient of the dampers for adjacent single storey connected buildings. Results show that connecting the adjacent single storey buildings of different fundamental frequencies by these dampers can effectively reduce the earthquake induced responses of either building. There exist optimum damper coefficients for minimum earthquake response of the buildings.
Keywords:Adjacent connected buildings, Non-linear viscous dampers, Optimum, Seismic response, Viscoelastic dampers.

I. Introduction

Structures are often built close to each other because of lack of available land in metropolitan cities. To reduce the response of the structure to earthquake excitations, various types of control system devices have been proposed for adjacent buildings. One of the methods to mitigate structure system response is connecting adjacent buildings with dampers. The ground motions during earthquakes cause damage to the structure by generating inertial forces generated by the vibration of the building masses. Tall structures are more vulnerable to the structural damage because the masses at the levels are relatively large, supported by slender columns. The displacement of the upper stories is very large as compared to the lower ones. This includes large shear forces on the base columns. If the separation distances between adjacent buildings are not sufficient, mutual pounding may also occur during an earthquake as observed in the 1985 Mexico City earthquake, the 1989 Loma Prieta earthquake, and many others. To reduce the seismic responses of buildings, adjacent buildings are linked together by connecting dampers, such as the Triple Towers in Downtown Tokyo (Asano et al., 2003, Yang and Lam, 2014). Researchers have proposed different types of connecting devices to connect adjacent buildings. The connecting devices include passive dampers (Bhaskararao and Jangid, 2006; Xu et al., 1999a, b; Zhang and Xu, 2000), active dampers (Christenson et al., 2003; Zhang and Iwan, 2003) and semi-active dampers (Bharti et al., 2010; Christenson et al., 2007; Xu and Ng, 2008).

To prevent mutual pounding between adjacent buildings during an earthquake, Westermo(1989) suggested using hinged links to connect two neighbouring floors if the floors of adjacent buildings are in alignment. It is observed that the system can reduce the chance for pounding, but it alters the dynamic characteristics of the unconnected buildings, enhances undesirable torsional response if the buildings have asymmetric geometry, and increases the base shear of the stiffer building. Luco and Barros(1998) studied the optimum values for the distribution of viscous dampers connecting two adjacent structures of different heights. Under certain conditions, apparent damping ratios as high as 12 and 15 percent can be achieved in the first and second modes of lightly damped structures by the introduction of interconnected dampers. Zhang and Xu (1999)investigated the dynamic characteristics and seismic response of adjacent buildings linked by viscoelastic dampers and it is showed that using the dampers with proper parameters to connect the adjacent buildings can increase the modal damping ratios and reduce the seismic response of adjacent buildings significantly. Hongping and Hirokazu(2000)studied the seismic response of two sdofsystems coupled with a viscoelastic damper subject to stationery white-noise excitation by means of statistical energy analysis techniques. Optimal parameters of the passive coupling element such as damping and stiffness under different circumstances are determined with an emphasis on the influence of the structural parametersof the system on the optimal parameters and control effectiveness (Bhaskararao and Jangid, 2004).Although, the above studies confirm that the dampers are effective in reducing the earthquake response of buildings. However, there is a need to study the comparative performance of different dampers and their optimum parameters.

In this paper, the seismic response of single-storey adjacent connected buildings is investigated under various earthquake ground excitations. The objectives of the study are summarised as (i) to investigate the comparative seismic response of single storey, adjacent buildings connected with non-linear viscous and viscoelastic dampers subjected to earthquake excitations,(ii)to derive the optimum parameters for both dampers, (iii) to obtain the effectiveness of dampers in reducing displacement and acceleration responses.

II. Structural model and Solution of equations of motion

The system considered is an idealized single storey adjacent building having different fundamental time periods. Following assumptions are made for the structural system under consideration: (i) Two buildings are assumed to be symmetric buildings. (ii) The ground motion is assumed to occur in the direction of the symmetric planes of the buildings. (iii) Each building is modelled as a linear single-degree of freedom system where the mass is concentrated at each floor and the stiffness is provided by the columns. (iv) Floors of each building assumed as rigid and at the same levels. (v) The ground acceleration under both the buildings is assumed to be the same and any effects due to spatial variations of the ground motion or due to soil-structure interactions are neglected. Neglecting spatial variations of the ground motion is justified because the total plan dimensions in the direction of excitation are not large.

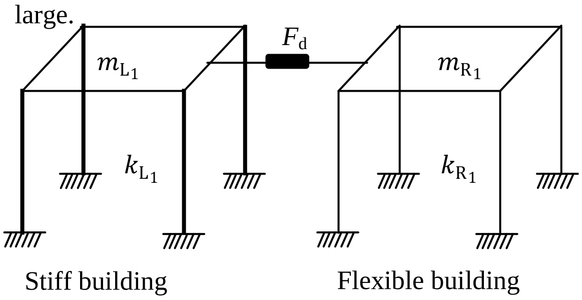

Fig.1 : Adjacent buildings connected with damper

The equations of motion of the connected system are expressed in the matrix form as

$$M\ddot{x} + C\dot{x} + Kx + F_d = -M\,\Gamma\,\ddot{x}_g \qquad \text{….(1)}$$

where, M,C and$K$are the mass matrix, damping matrix and stiffness matrix of the G+m adjacent buildings connected with dampers respectively;$x$is the relative displacement vector with respect to the ground and consists of Building1's displacements in the first $n_1$positions and Building2's displacements in the last $n_2$positions; m is the total degree of freedom of the combined system, $m=n_1+n_2$; $\ddot{x}_g$is the ground acceleration at the foundations of the structures; $F_d$is the connecting damper force and Γ is the influence coefficient matrix.

The formulations of various matrices are as below (Bhaskararao and Jangid, 2006):

Mass matrix of the connected structure,

$$M = \begin{bmatrix} M_L & 0 \\ 0 & M_R \end{bmatrix} \qquad \text{....(2)}$$

Where, $M_L = \begin{bmatrix} m_{L_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & m_{L_{n_1}} \end{bmatrix}$

$$M_R = \begin{bmatrix} m_{R_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & m_{R_{n_2}} \end{bmatrix}$$

Where, m_{L_1},m_{L_2},….,$m_{L_{n1}}$are the mass of the floors of the left building and m_{R_1},m_{R_2},….,$m_{R_{n2}}$are the mass of the floors of the right building.

Stiffness matrix of the connected structure,

$$K = \begin{bmatrix} K_L & 0 \\ 0 & K_R \end{bmatrix} \qquad \text{....(3)}$$

Where,

K_L=

$$\begin{bmatrix} k_{L_1} + k_{L_2} & -k_{L_2} & & & \\ -k_{L_2} & k_{L_2} + k_{L_3} & -k_{L_3} & & \\ & \ldots\ldots & & & \\ & & \ldots\ldots & & \\ & & k_{L_{n_1-1}} + k_{L_{n_1}} & k_{L_{n_1}} & \\ & & -k_{L_{n_1}} & k_{L_{n_1}} & \end{bmatrix}$$

K_R=

$$\begin{bmatrix} k_{R_1} + k_{R_2} & k_{R_2} & & & \\ -k_{R_2} & k_{R_2} + k_{R_3} & -k_{R_3} & & \\ & \ldots\ldots & & & \\ & & \ldots\ldots & & \\ & & k_{R_{n_2-1}} + k_{R_{n_2}} & k_{R_{n_2}} & \\ & & k_{R_{n_2}} & k_{R_{n_2}} & \end{bmatrix}$$

Where, $k_{L_1}, k_{L_2}, \ldots, k_{L_{n_1}}$ are the stiffness of the storeys of the left building and $k_{R_1}, k_{R_2}, \ldots, k_{R_{n_2}}$ are the stiffness of the storeys of the right building.

Damping matrix of the connected structure with damper,

$C = C_s + C_d$ ….(4)

Where, $C_s = \begin{bmatrix} C_L & 0 \\ 0 & C_R \end{bmatrix}$ = Damping matrix of the connected structure,

Considering Rayleigh damping, $C = \alpha M + \beta K$

Where,

$\alpha = (2\xi\omega_i\omega_j) / (\omega_i + \omega_j)$ and $\beta = (2\xi) / (\omega_i + \omega_j)$

$C_L = \alpha_1 M_L + \beta_1 K_L$ and $C_R = \alpha_2 M_R + \beta_2 K$

C_d = Damping matrix of the connected damper

$C_d = \begin{bmatrix} C_{d_i} & -C_{d_i} \\ -C_{d_i} & C_{d_i} \end{bmatrix}$ and $C_{d_i} = \begin{bmatrix} C_{d_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & C_{d_n} \end{bmatrix}$

Where, $C_{d_1}, C_{d_2}, .. C_{d_n}$ are the damping coefficient of the damper.

$F_d = \begin{bmatrix} f_{d_i} \\ 0_{(n_2-n_1),1} \\ -f_{d_i} \end{bmatrix}$ ….(5)

Where, f_{d_i} = vector of forces provided by dampers, and n_1 and n_2 are the total degrees of freedom of the left building and right building respectively, n is the total degrees of freedom of the connected building. α_1, β_1 and α_2, β_2 are the Rayleigh damping coefficients of the left and right buildings.

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

$Z_{(k+1)} = A_d Z_{(k)} + E_d \ddot{x}_{g(k)} + B_d F_d$ ….(6)

$\dot{Z}_{(k)} = A Z_{(k)} + E\, \ddot{x}_{g(k)} + B F_d$ ….(7)

where, k is the time step; $A_d = e^{A\Delta t}$ = Discrete-time system matrix with Δt as time interval; $E_d = (A^{-1} (A_d - I)\, E)$ is the discrete-time counterpart of the matrix of E ; $B_d = (A^{-1} (A_d - I)\, B)$ is discrete-time counterpart of the matrix of B ; $A = \begin{bmatrix} 0 & I \\ M^{-1}K & M^{-1}C \end{bmatrix}$ is the system matrix; $E = \begin{matrix} 0 \\ \Gamma \end{matrix}$ is the distribution matrix of excitations; F_d = vector of the controllable forces provided by the dampers; $Z = \{ x_L x_R \dot{x}_L \dot{x}_R \}$ and $\dot{Z} = \{ \dot{x}_L \dot{x}_R \ddot{x}_L \ddot{x}_R \}$.

III. Modelling and Control laws of dampers

A. *Non-linear viscous damper*

A typical viscous damper consists of viscous material in the form of liquid. One of the types of viscous dampers is fluid viscous damper and there are essentially two categories of it based on the functioning, such as those in which, (a) energy dissipation is achieved through the deformation of viscous fluid (i.e. through fluid viscosity) and (b) energy dissipation is achieved by the principle of flow through orifice. The ideal force out for a viscous damper is given by,

$f_{d_i} = C_{md} \left| \dot{X}_{i_2} - \dot{X}_{i_1} \right|^{\varepsilon} sgn(\dot{X}_{i_2} - \dot{X}_{i_1})$ ….(8)

Where, C_{md} is coefficient of damper, $\dot{X}_{i_2} - \dot{X}_{i_1}$ is relative velocity between the ends of i^{th} damper and ε is exponent having value between 0 and 1, sgn(·) is signum function. The damper with ε =1 is called a LVD (Linear viscous damper). The damper with ε larger than 1 have not been seen often in practical applications. The damper with ε smaller than 1 is called a nonlinear viscous damper which is effective in minimizing high velocity shocks. The value of Ɛ for non-linear viscous damper is ranges from 0 to 1 (Soong, 1997).

B. *Viscoelastic damper*

The force generated in the viscoelastic damper comprises of two components: elastic force and damping force. The elastic force is proportional to the relative displacement between the connected floors, whereas the damping force is essentially proportional to the relative velocity of the piston head with respect to the damper casing. The ideal force out for a viscoelastic damper is given by,

$f_{d_i} = C_d\, (\dot{X}_{i_2} - \dot{X}_{i_1}) + K_d (X_{i_2} - X_{i_1})$ ….(9)

Where, C_d is coefficient of damper, $\dot{X}_{i_2} - \dot{X}_{i_1}$ is relative velocity between the ends of i^{th} damper and K_d is the damper stiffness coefficient, $X_{i_2} - X_{i_1}$ is the relative displacement between the connected floors of the i^{th} damper (Symans et al., 2008).

IV. Numerical Study

For the present study, two adjacent single storey buildings are considered. The floor mass of the both the buildings considered are same. The mass and the stiffness of both the buildings are adjusted such that one building becomes stiff and other as flexible.The fundamental time periodsare 0.513sec and 1.088 sec of Building1 and Building2, respectively. The damping ratio of 5% is considered for both buildings. Thus, the Building1 may be considered as stiff building and Building2 as flexible building (Fig. 1). The earthquake time histories selected to examine the seismic behaviour

of the two buildings are: Imperial Valley 1940(ELC 180),Loma Prieta 1989(LGP 000), Northridge 1994(SCS 142), Kobe 1995(KJM 000). The peak ground acceleration of Imperial Valley, Loma Prieta, North Ridge and Kobe earthquake motions are 0.31g, 0.96g, 0.89g and 0.82g, respectively (g is the acceleration due to gravity).
The seismic response of linearly elastic, idealized single storey adjacent buildings connected with different dampers is investigated by numerical simulation study. Dampers are connected at the same floor level. In order to study the effectiveness of control system the responses are expressed in terms of indexR_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

$$R_e = \frac{\text{Peak response of the control system}}{\text{Peak response of uncontrolled system}} \quad \text{....(10)}$$

Buildings connected with Non-linear viscous damper:

In order to investigate the effectiveness of Non-linear viscous damper (NLVD), adjacent single storey buildings one stiffer and other flexiblehaving time period 0.513 sec and 1.088 sec respectively connected with non-linear viscous dampers at same floor level, subjected to series of four earthquakes and time history analysis is carried out. The velocity exponent$\varepsilon$is taken as 0.5(non-linear). To arrive at the optimum damper damping coefficient $C_{md}$of the dampers, the variation of the response ratio for maximum relative displacements and response ratio for maximum absolute accelerations of the two buildings are plotted with the damper damping coefficient are shown in Fig. 2.The response first decrease with the increase in damping coefficient of damper and then it increases with further increase in the damper coefficient of the damper. The minimum value of the average plot of the responses under four earthquakes is taken as optimum value of the damping coefficient of the connecting damper. From the Fig.2 it is observed that the optimum damper damping coefficient for system connected with non-linear viscous damper is 100,000 N-s/m. The time histories of the floor displacement and acceleration responses of the two buildings connected by non-linear viscous dampers with optimum damping coefficient of 100,000 N-s/m is shown in Fig. 3.

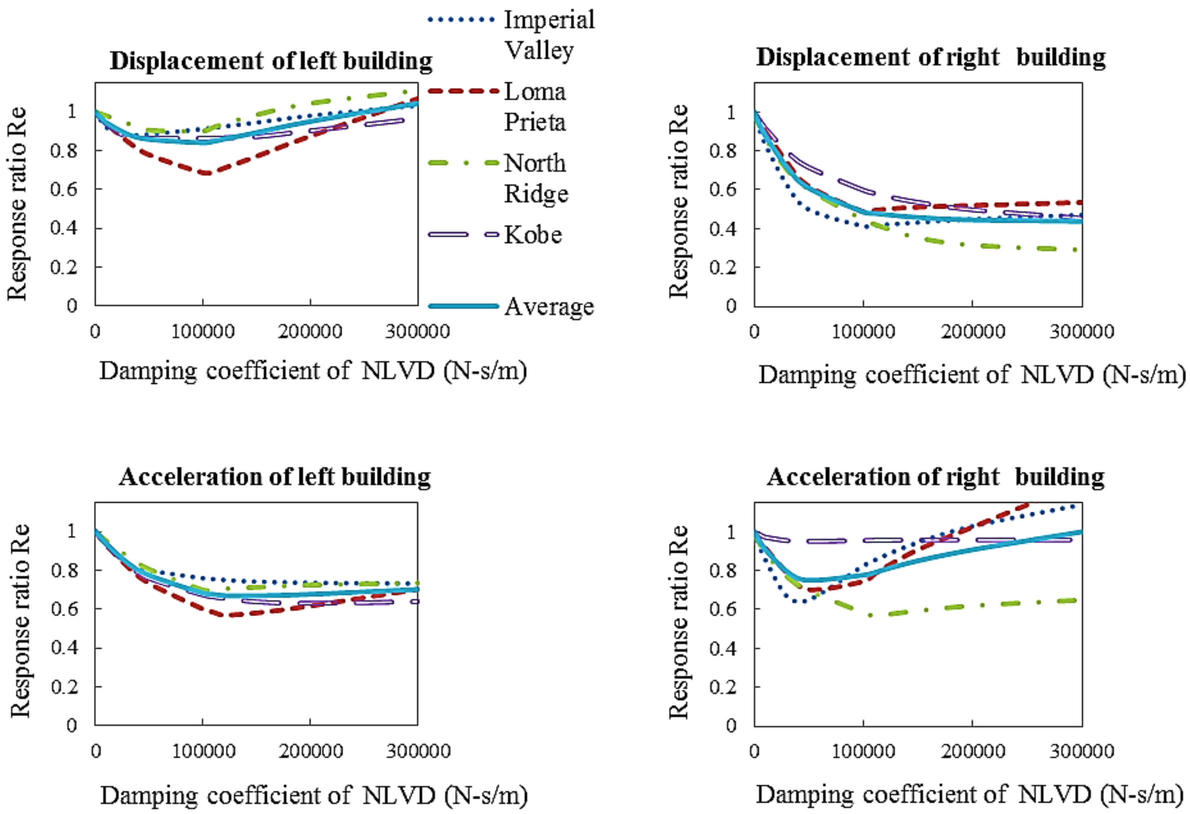

Fig.2 : Response ratio for Maximum displacements and Maximum accelerations with damping coefficient for buildings connected with non-linear viscous damper

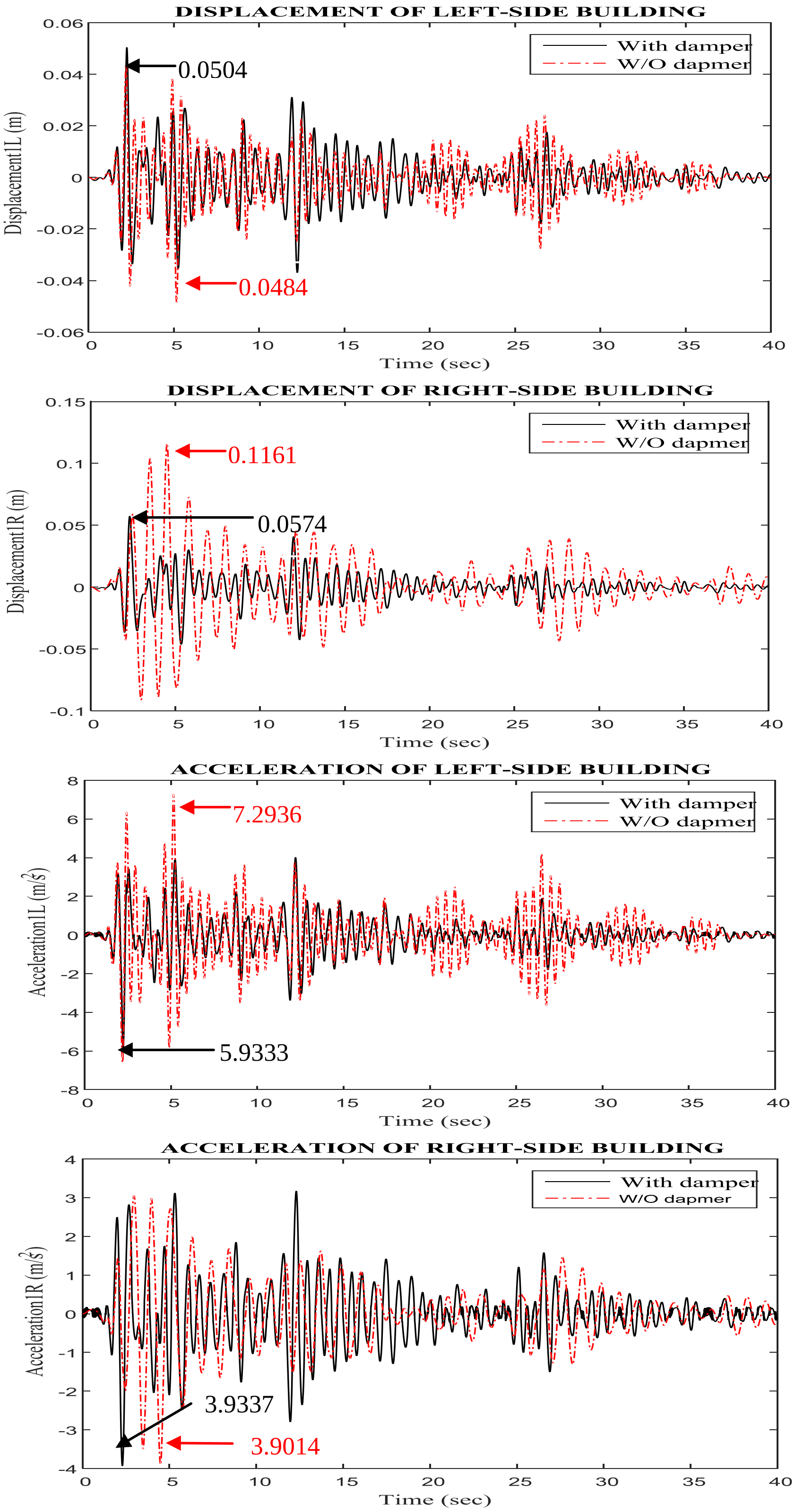

Fig.3 : Time histories of Displacements and Accelerations of buildings connected with non-linear viscous damper under Imperial Valley earthquake

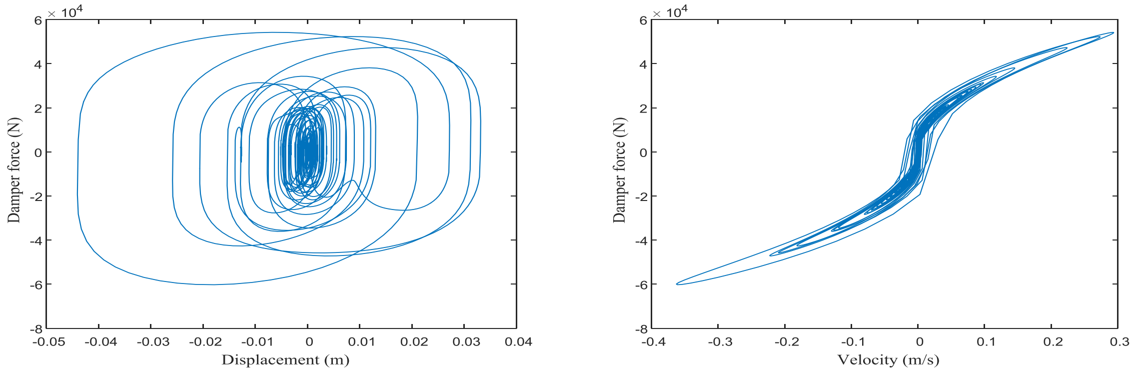

Fig.4 : Hysteresis loops under Imperial Valley earthquake for single storey buildings connected with non-linear viscous damper

Table 1: Maximum values of the response for the adjacent buildings connected with non-linear viscous damper having optimum value of damping coefficient of 100000 N-s/m

Response Disp. (m), Accel. (m/s^2)		**Imperial valley**	**Loma Prieta**	**North Ridge**	**Kobe**
Maximum displacement left building	Uncontrolled	0.0484	0.1219	0.1023	0.1324
	Controlled	0.0504	0.0896	0.1036	0.1169
Maximum displacement right building	Uncontrolled	0.1161	0.2824	0.4950	0.3633
	Controlled	0.0574	0.1463	0.1956	0.2096
Maximum acceleration left building	Uncontrolled	7.2936	18.3671	15.4174	20.0060
	Controlled	5.9333	10.7152	12.4677	14.1311
Maximum acceleration right building	Uncontrolled	3.9014	9.4792	16.5879	12.1986
	Controlled	3.9337	7.7945	9.5453	10.8896

It is observed from the Fig. 3, that damper is quite effective in reducing displacement and acceleration responses. Also, the reduction in displacement response of the flexible building is higher than the stiff building and it is reversed for the acceleration response where the reduction in acceleration is higher in stiff building than the flexible building when buildings connected with non-linear viscous damper.

Fig. 4 shows the hysteresis loops for non-linear viscous damper ($\varepsilon = 0.5$). Damper force-displacement plot defines the energy dissipation capacity of the damper and damper force-velocity plot shows the capacity of the damper and its behaviour. Table 1 shows the response in terms of displacements and accelerations of the adjacent buildings when connected with non-linear viscous damper under Imperial Valley, Loma Prieta, North Ridge and Kobe earthquake excitations. From the Table 1, it is observed that response is considerably reduced.

Buildings connected with viscoelastic damper:

The elastic stiffness coefficient of the connecting damper is taken as 0.5 times the average value of the stiffness of the left and right building.Thus,k_d is taken as 1375000 N/m. The response ratio for maximum relative displacements and response ratio for maximum absolute accelerations of the two buildings are plotted with the damper damping coefficient of the viscoelastic damper are shown in Fig. 5. From the Fig. 5 the optimum value of the dampers damping coefficient $C_d$is found as 200000 N-s/m.The time histories of the floor displacement and acceleration responses of the two buildings connected by viscoelasticdampers with optimum damping coefficient of 200000 N-s/m is shown in Fig. 6.

Fig. 7 shows the hysteresis loops for viscoelastic damper. Damper force-displacement plot defines the energy dissipation capacity of the damper and damper force-velocity plot shows the capacity of the damper and its behaviour.

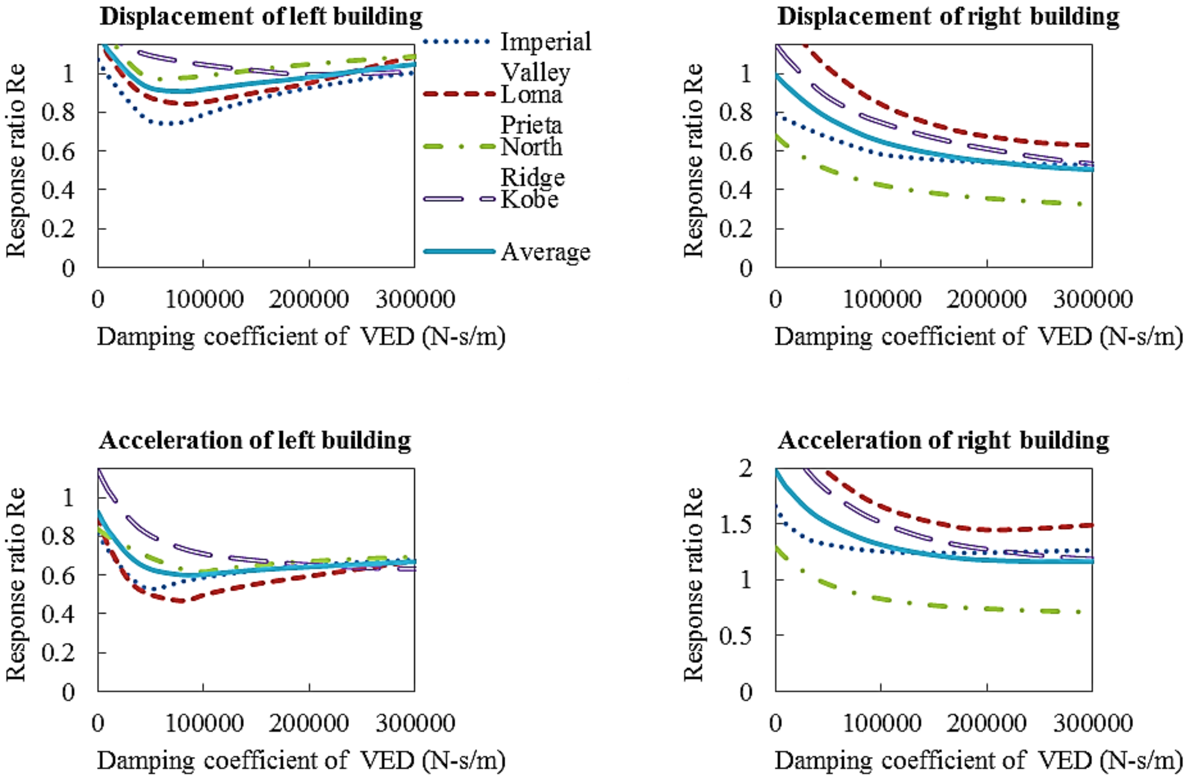

Fig.5: Response ratio for Maximum displacements and Maximum accelerations withdamping coefficient for buildings connected with viscoelastic damper

Table 2: Maximum values of the response for the adjacent buildings connected with viscoelastic damper having optimum value of damping coefficient of 200000 N-s/m

Response Disp.(m) , Accel.(m/s^2)		**Imperial valley**	**Loma Prieta**	**North Ridge**	**Kobe**
Maximum displacement left building	Uncontrolled	0.0484	0.1219	0.1023	0.1324
	Controlled	0.0448	0.1159	0.1072	0.1317
Maximum displacement right building	Uncontrolled	0.1161	0.2824	0.4950	0.3633
	Controlled	0.0631	0.1911	0.1770	0.2223
Maximum acceleration left building	Uncontrolled	7.2936	18.3671	15.4174	20.0060
	Controlled	4.7400	10.9247	10.3464	13.0844
Maximum acceleration right building	Uncontrolled	3.9014	9.4792	16.5879	12.1986
	Controlled	4.8587	13.7364	12.3089	15.5550

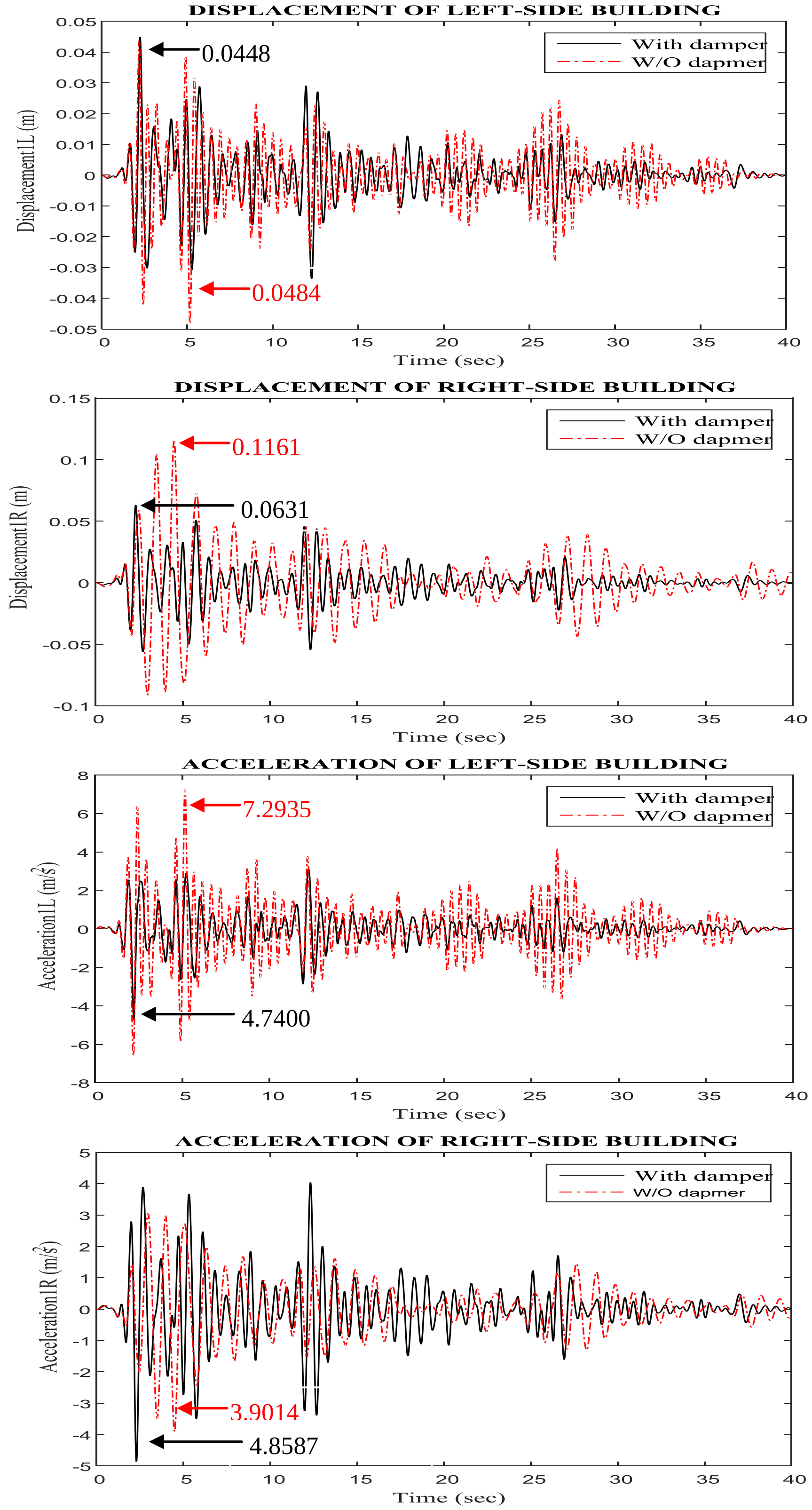

Fig.6 : Time histories of Displacements andAccelerations of buildings connected with viscoelastic damper under Imperial Valley earthquake

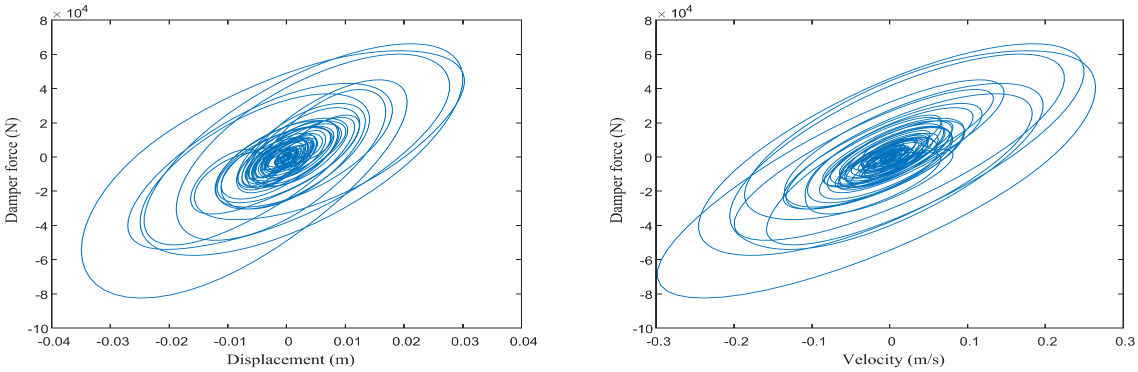

Fig.7: Hysteresis loops under Imperial Valley for earthquake single storey buildings connected with viscoelastic damper

Table 2 shows the response in terms of displacements and accelerations of the adjacent buildings when connected with viscoelastic damper under Imperial Valley, Loma Prieta, North Ridge and Kobe earthquake excitations. From the Table 2, it is clear that response is considerably reduced.

Table 3 shows the average values of responses in terms of maximum relative displacements and maximum absolute accelerations of the adjacent connected buildings with damper for the optimum value of the damping coefficient of the connecting damper.

Table 3: Average values of the response for the adjacent buildings connected with dampers having optimum value

Average values of responses under four earthquakes considered			
Disp.(m) , Accel.(m/s^2)	**Uncontrolled**	**Controlled with NLVD (100000 N-s/m)**	**Controlled with VED (200000 N-s/m)**
Maximum displacement of left building	0.101	0.090	0.100
Maximum displacement of right building	0.314	0.152	0.163
Maximum acceleration of left building	15.271	10.812	9.774
Maximum acceleration of right building	10.542	8.041	11.615

V. Conclusions

The seismic response of single-storey adjacent buildings, one stiffer and other flexible connected with non-linear viscous and viscoelastic dampers and subjected to four earthquake excitations is obtained. The response ratio for maximum relative displacements and maximum absolute accelerations are plotted against damper's damping coefficients and the optimum value of dampers damping coefficient is found out. Fromthe present numerical study, the following conclusionscan be drawn:

1. From the numerical studies carried out for the single storey adjacent buildings connected with non-linear viscous damper and viscoelastic damper, it can be concluded that both dampers are effective in reducing the displacement and acceleration response of the connected buildings.
2. There exists the optimum damping parameters for both dampers for both buildingsconsidered. The optimum value of damping coefficient of non-linear viscous dampers and viscoelastic dampers is 100000 N-s/m and 200000 N-s/m, respectively.
3. Non-linear viscous dampers are more effective than viscoelastic dampers in reducing the displacement response of adjacent connected buildings.
4. It is further observed that the dampers are more effective in reducing the acceleration response of stiff building as compared to the flexible building.

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