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SEISMIC RESPONSE OF ADJACENT STRUCTURES CONNECTED WITH MAXWELL DAMPERS

C.C. Patel and R.S. Jangid*
Department of Civil Engineering, Indian Institute of Technology Bombay,
Powai, Mumbai-400076, India

ABSTRACT

In this paper, the investigation is carried out to study the structural responses of two adjacent structures connected with Maxwell dampers under various earthquake excitations. The specific objective of this study is to evaluate the optimum damper parameter and its importance in response reduction of adjacent structures coupled by Maxwell dampers. The optimum damper parameter is investigated for the adjacent coupled structures subjected to four different types of earthquake ground motions. A formulation of the equations of motion for the two adjacent multi-degree-of-freedom (MDOF) structures connected with Maxwell dampers is presented. The numerical study is carried out for two adjacent MDOF structures connected with Maxwell dampers having same damper parameter in all dampers as well as, having different damper parameter in the dampers. The investigation is also carried out for effectiveness of the damper in terms of the structural response reduction, namely, displacement, acceleration and shear forces of adjacent connected structures. In addition, to minimize the cost of the dampers, the optimal location of the dampers, rather than providing the dampers at all floor levels is also investigated. Results show that using Maxwell dampers of appropriate parameter to connect the adjacent structures of different fundamental frequencies can effectively reduce earthquake-induced responses of either structure. Further, lesser dampers at appropriate locations can significantly reduce the earthquake response of connected system, there by reducing cost of damper significantly.

Keywords: Adjacent structures; maxwell damper; optimum damper parameters; optimal location; seismic response

1. INTRODUCTION

Recent devastating earthquakes around the world have confirmed the importance of control device in protection of civil engineering structures. Structural control devices have been developed mainly in civil engineering structures, to dissipate energy from earthquake and reduce vibrations in structures, thereby reducing human and material losses. Control systems

* E-mail address of the corresponding author: rsjangid@civil.iitb.ac.in (R.S. Jangid)

can be classified according to their energy consumption as passive, active and semi-active. Passive control refers to system that utilize the response of structure to develop the control forces without requiring Coupling adjacent structures is a developing method of structural control for mitigating structural responses due to wind and seismic excitations. The concept is to allow two dynamically dissimilar structures to exert control forces upon one another to reduce the overall responses of the system. Installation of such devices does not require additional space and the free space available between two adjacent structures can be effectively utilized for placing the control devices. Such types of arrangement are also helpful in reducing the mutual pounding of structures occurred in the past major seismic events such as 1985 Mexico City and 1989 Loma Prieta earthquakes. In the past decade coupled structure control has received increasing attention. Researchers have proposed passive, active and smart damping devices to mitigate the adjoining structure's responses to wind and seismic excitations.

Kobori *et al.* [1] developed bell-shaped hollow connectors to link adjacent buildings in a complex. The bell-shaped hollow connector is made of steel with stabilized hysteretic characteristic when the connector yields so that it can absorb vibration energy of the buildings during a strong earthquake. The yield strength of the connector is difficult to decide because if the yield strength is too high, connector may not function properly but if the yield strength is too low, the energy absorbing capacity may be too small during a strong earthquake. Westermo [2] suggested using hinged links to connect two neighboring floors, if the floors of adjacent buildings are in alignment, to prevent mutual pounding between adjacent buildings during an earthquake. This system can reduce the chance for pounding, but it alters the dynamic characteristics of the unconnected buildings, increases the undesirable torsonal response if the buildings have asymmetric geometry, and increase the base shear of the stiffer building. Investigation carried out by Constantinou and Symans [3] show that the fluid damper exhibits viscoelastic fluid behavior, and that the simplest model to account for this behavior is the Maxwell model. Luco and Barros [4] determined the optimal values for the distribution of viscous dampers inter-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. The largest reduction in the response in first mode is achieved when the taller structure is twice the height of the second structure. Xu *et al.* [5] and Zhang and Xu [6] studied the effectiveness of the fluid damper, connecting the adjacent multi-story buildings under earthquake excitation. The ground acceleration due to earthquake is regarded as a stochastic process and results show that using the fluid dampers to connect the adjacent buildings of different fundamental frequencies can effectively reduce earthquake-induced responses of either building if damper properties are appropriately selected. Zhang and Xu [7] studied the dynamic characteristics and seismic response of adjacent buildings linked by viscoelastic dampers and showed that using the dampers with proper parameters to link the adjacent buildings can increase the modal damping ratios and reduce the seismic response of adjacent buildings significantly. Zhu and Iemura [8] examined the dynamic characteristics of two SDOF buildings coupled with a visco-elastic coupling element subjected 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 parameters of the system on the optimal parameters and control effectiveness. Hatada *et al.* [9] studied the dynamic analysis of structures with Maxwell model. They have formulated the computational method in time domain by introducing a finite element of the Maxwell model into the equation of motion in the discrete-time system. Ni *et al*. [10] developed a method for analyzing the random seismic response of a structural system consisting of two adjacent buildings interconnected by non-linear hysteretic damping devices. The results of the analysis demonstrate that non-linear hysteretic dampers are effective even if they are placed on a few floor levels. Carolina and Lopez [11] studied the affect of the variation of placement and the number of dampers on the seismic response of a frame structure. They showed that the dampers placement influences significantly the structural response and a large number of dampers do not always leads to the best benefit in terms of drift reduction for all stories. Zhu and Xu [12] derived the analytical formulas for determining optimum parameters of Maxwell model-defined fluid dampers used to link two adjacent structures using the principle of minimizing the averaged vibration energy of either the primary structure or the two adjacent structures under a white-noise ground excitation. Although, the above studies confirm the effectiveness of different passive dampers in reducing the earthquake response of connected structures, the performance of structures connected with Maxwell dampers considering different damper properties along the height of structures and their optimal placement are not yet studied. The fluid dampers that operate on the principle of fluid flow through specially shaped orifices and used in Civil Engineering Applications are well modeled using Maxwell model. Bhaskararao and Jangid [13] have investigated the seismic response of the two adjacent structures connected with friction dampers with same slip force as well as different slip force in damper. It has been observed that lesser dampers at appropriate locations can significantly reduce the earthquake response of connected system, and the reduction in the responses when the two MDOF buildings connected with 50% of the total dampers is almost as much as when they are connected at all the floors. The results of previous studies indicated that Maxwell damper is effective in reducing structural responses [6,9,12]. However, the performance of Maxwell damper for response control of adjacent buildings connected had not been investigated.

In this paper, effectiveness of Maxwell dampers in mitigating the seismic response in terms of namely, displacement, acceleration and shear forces of the connected structures under various earthquakes is investigated The specific objectives of the study are: (i) to formulate the equations of motion for two adjacent structures connected with Maxwell dampers; (ii) to identify the optimum damper damping coefficient of Maxwell dampers; (iii) to investigate the optimal location of the dampers instead of providing them at all floors for minimizing cost of the dampers; and (iv) to examine the effect of damper with different damping coefficient along the height of connected system.

2. MATHEMTICAL FORMULATION OF DAMPER CONNECTED STRUCTURES

2.1 Assumptions and Limitations

The two MDOF structures are assumed to be symmetric with their symmetric planes in alignment. The ground motion is assumed to occur in one direction in the symmetric planes of the structures so that the problem can be simplified as a two-dimensional problem as shown in Figure 1. The earthquake excitation is assumed to be not so severe and/ or due to the enhanced energy absorbing capacity of the structures because of the connected dampers, the structures are assumed to be remain in linear elastic and hence, do not yield under the considered earthquake excitations. The floors of each structure are at the same level, but the height of the each structure can be different. Each structure is modeled as a linear MDOF flexible shear type structure with lateral degree-of-freedom at their floor levels. Both structures are assumed to be subjected to the same ground acceleration. Any effects due to spatial variations of the ground motion and 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. Neglecting soil–structure interactions limits the applicability of the results to structures on stiff, firm ground and less restrictively to structures whose foundations are not massive (e.g. footing foundations). The lateral resistance of the structures is assumed to be so large that it does not have any affect on the performance of dampers.

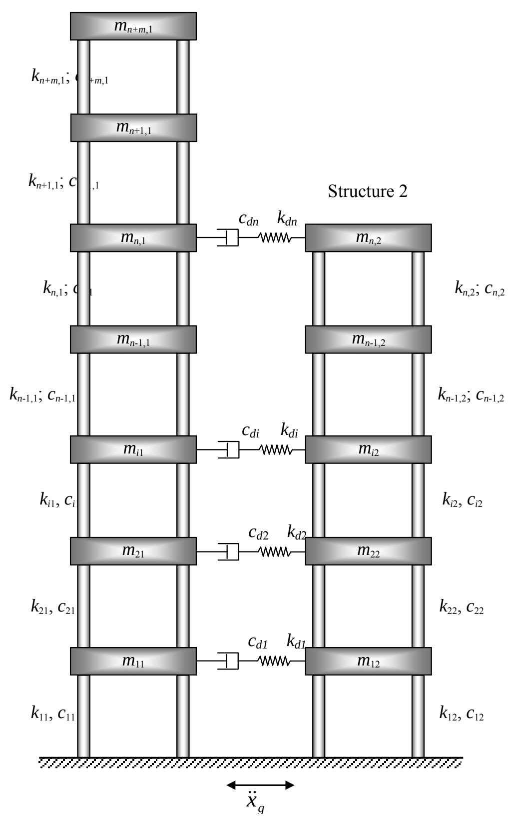

Figure 1. Structural model of two MDOF adjacent structures connected with Maxwell dampers

2.2 Formulation of Equations of Motion of Connected Structures

Let two structures, Structure 1 and Structure 2 have n+m and n stories, respectively as shown in Figure 1 with mass, damping coefficient and shear stiffness values for the i^{th} story are m_{i1}, c_{i1} and k_{i1} for Structure 1 and m_{i2}, c_{i2} and k_{i2} for Structure 2, respectively. The combined system will then be having a total number of degrees of freedom equal to (2n+m).

The fluid dampers that utilize fluid flow through specially shaped orifices for energy dissipation. Each Maxwell damper is modeled as a combination of a linear spring, in which the force is proportional to the relative displacement, and a linear dashpot, in which force is proportional to the relative velocity of its both ends, acting in series as shown in Figure 1. The Maxwell model captures the frequency dependence of the damping and stiffness coefficients observed in the fluid orifice dampers, especially at higher frequencies of deformation. Maxwell dampers need not be provided at all floor levels and can be located at optimal locations, so connected dampers are not shown at all floor levels in Figure 1. Further, the damper parameters in dampers also can be different. The force in damper f_d can be described by the first order Maxwell-model proposed by Bird *et al.* [14]) as given below.

$$f_d + \lambda \frac{df_d}{dt} = c_d\,(\dot{x}_2 - \dot{x}_1) \tag{1}$$

λ is the relaxation time defined by

$$\lambda = c_d / k_d \tag{2}$$

where c_d is the damping coefficient at zero frequency and k_d is the damper stiffness coefficient. The non-dimensional damping ratio at zero frequency (ξ_d) and relaxation time (χ) are defined as

$$\xi_d = \frac{c_d}{2m_1\omega_1} \tag{3}$$

$$\chi = \lambda\omega_1 \tag{4}$$

where, m_1 is the mass of first storey of soft structure and ω_1 is the first natural frequency of soft structure.

The governing equations of motion for the damper-connected system are expressed as

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = -\mathbf{M}\,\mathbf{I}\,\ddot{x}_g + \mathbf{F_D} \tag{5}$$

where **M**, **C** and **K** are the mass, damping and stiffness matrices of the combined system, respectively; $\mathbf{F_D}$ is a vector consisting of the forces in Maxwell dampers; **X** is the relative displacement vector with respect to the ground and consists of Structure 1's displacements in the first $n+m$ positions and the displacements of Structure 2 in the last n positions; **I** is a vector with all its elements equal to unity; and $\ddot{x}_g$ is the earthquake acceleration at the foundations of the structures. The details of each matrix are given in the following:

$$\mathbf{M} = \begin{bmatrix} \mathbf{m}_{n+m,n+m} & \mathbf{o}_{n+m,n} \\ \mathbf{o}_{n,n+m} & \mathbf{m}_{n,n} \end{bmatrix} \; ; \quad \mathbf{K} = \begin{bmatrix} \mathbf{k}_{n+m,n+m} & \mathbf{o}_{n+m,n} \\ \mathbf{o}_{n,n+m} & \mathbf{k}_{n,n} \end{bmatrix} \; ; \quad \mathbf{C} = \begin{bmatrix} \mathbf{c}_{n+m,n+m} & \mathbf{o}_{n+m,n} \\ \mathbf{o}_{n,n+m} & \mathbf{c}_{n,n} \end{bmatrix} \tag{6}$$

$$\mathbf{m}_{n+m,n+m} = \begin{bmatrix} m_{11} & & & & & \\ & m_{21} & & & & \\ & & \cdots & & & \\ & & & \cdots & & \\ & & & & m_{n+m-1,1} & \\ & & & & & m_{n+m,1} \end{bmatrix} \; ; \quad \mathbf{m}_{n,n} = \begin{bmatrix} m_{12} & & & & & \\ & m_{22} & & & & \\ & & \cdots & & & \\ & & & \cdots & & \\ & & & & m_{n-1,2} & \\ & & & & & m_{n2} \end{bmatrix} \tag{7}$$

$$\mathbf{k}_{n+m,n+m} = \begin{bmatrix} k_{11}+k_{21} & -k_{21} & & & & \\ -k_{21} & k_{21}+k_{31} & -k_{31} & & & \\ & & \cdots\cdots & & & \\ & & & \cdots\cdots & & \\ & & & -k_{n+m-1,1} & k_{n+m-1,1}+k_{n+m,1} & -k_{n+m,1} \\ & & & & -k_{n+m,1} & k_{n+m,1} \end{bmatrix} \tag{8}$$

$$\mathbf{k}_{n,n} = \begin{bmatrix} k_{12}+k_{22} & -k_{22} & & & & \\ -k_{22} & k_{22}+k_{32} & -k_{32} & & & \\ & & \cdots\cdots & & & \\ & & & \cdots\cdots & & \\ & & & -k_{n-1,2} & k_{n-1,2}+k_{n2} & -k_{n2} \\ & & & & -k_{n2} & k_{n2} \end{bmatrix} \tag{9}$$

$$\mathbf{c}_{n+m,n+m} = \begin{bmatrix} c_{11}+c_{21} & -c_{21} & & & & \\ -c_{21} & c_{21}+c_{31} & -c_{31} & & & \\ & & \cdots\cdots & & & \\ & & & \cdots\cdots & & \\ & & & -c_{n+m-1,1} & c_{n+m-1,1}+c_{n+m,1} & -c_{n+m,1} \\ & & & & -c_{n+m,1} & c_{n+m,1} \end{bmatrix} \tag{10}$$

$$\mathbf{c}_{n,n} = \begin{bmatrix} c_{12}+c_{22} & -c_{22} & & & & \\ -c_{22} & c_{22}+c_{32} & -c_{32} & & & \\ & \cdots\cdots & & & & \\ & & \cdots\cdots & & & \\ & & -c_{n-1,2} & c_{n-1,2}+c_{n2} & -c_{n2} \\ & & & -c_{n2} & c_{n2} \end{bmatrix} \tag{11}$$

$$\mathbf{F_D^T} = \left\{ \mathbf{f}_{\mathbf{d}(n,1)} \quad \mathbf{o}_{(m,1)} \quad -\mathbf{f}_{\mathbf{d}(n,1)} \right\} \tag{12}$$

$$\mathbf{f_d^T} = \left\{ f_{d1}, f_{d2}, \ldots\ldots, f_{di}, \ldots\ldots, f_{dn-1}, f_{dn} \right\} \tag{13}$$

$$\mathbf{X^T} = \left\{ x_{11}, x_{21}, x_{31}, \ldots\ldots\ldots\ldots, x_{n+m-1,1}, x_{n+m,1}, x_{12}, x_{22}, x_{32}, \ldots\ldots\ldots\ldots, x_{n-1,2}, x_{n2} \right\} \tag{14}$$

'**o**' is the null matrix.
where f_{di} is the force in any i^{th} damper connecting the floors, x_{i1} and x_{i2} of the Structure 1 and Structure 2, respectively and is arrived at from the first order differential equation given by Equation (1), which is solved using fourth order Runge-Kutta method. The force in damper becomes zero corresponding to the floor with no damper. The force mobilized in a damper is non-linear function of the displacement and velocity of the system, as a result, the governing equations of motion are solved in the incremental form using Newmark's step-by-step method assuming constant average acceleration over small time interval, Δt.

3. NUMERICAL STUDY

A thorough study is conducted to arrive at the optimum damper parameters in the Maxwell dampers for MDOF adjacent structures under various earthquake excitations. The earthquake time histories selected to examine the seismic behavior of the two structures are: N00S component of Imperial Valley, 1940, N90E component of Kobe, 1995, N00E component of Northridge, 1994 and N00E component of Loma Prieta, 1989. The peak ground acceleration (PGA) of Imperial Valley, Kobe, Northridge and Loma Prieta earthquake motions are 0.32g, 0.63g, 0.84g and 0.57g, respectively (g is the acceleration due to gravity). The response spectrum for the earthquake time history considered for 2% damping is shown in Figure 2. In this numerical study, the response quantities of interest are peak top floor relative displacements, peak top floor accelerations and peak base shears. The shear force is normalized with the weight of the structure. The study is divided into two parts: (i) two adjacent MDOF structures connected with Maxwell dampers having same damper parameters in all the dampers and (ii) two adjacent MDOF structures connected with Maxwell dampers having different damper parameters in the dampers.

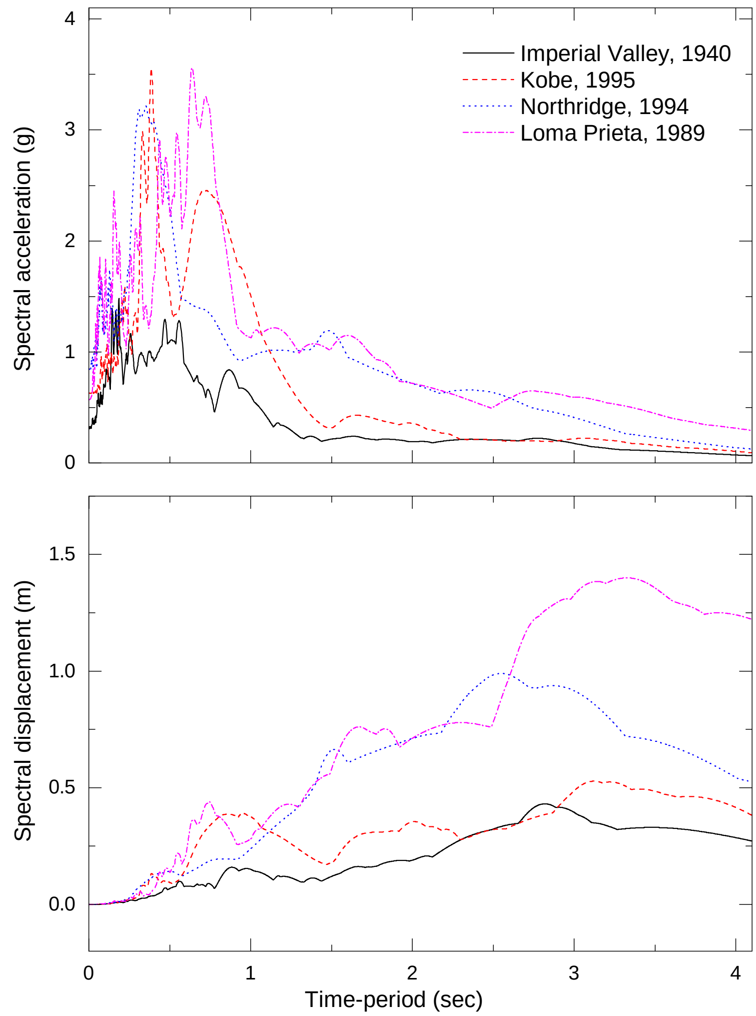

Figure 2. Response spectra of Imperial Valley, 1940; Kobe, 1995; Northridge, 1994; and Loma Prieta, 1989 earthquakes

3.1 Two MDOF structures connected with Maxwell dampers having same damping

For the present study, two adjacent structures with 16 and 8 stories with uniform floor mass and inter-storey stiffness are considered. The masses of the two structures are assumed to be same and the damping ratio in each structure is taken as 2%. The stiffness of each floor of the structures is chosen such that to yield a fundamental time periods of 1.6 sec and 0.8 sec for Structure 1 and Structure 2, respectively and uncontrolled first three natural frequencies corresponding to first three modes are 3.9266, 11.7442, 19.4555 rad/sec and 7.8539, 23.2942, 37.9412 rad/sec for Structure 1 and Structure 2 respectively.. Thus, Structure 1 may be considered as softer structure and Structure 2 as stiffer structure. These frequencies clearly show that the modes of the structures are well separated.

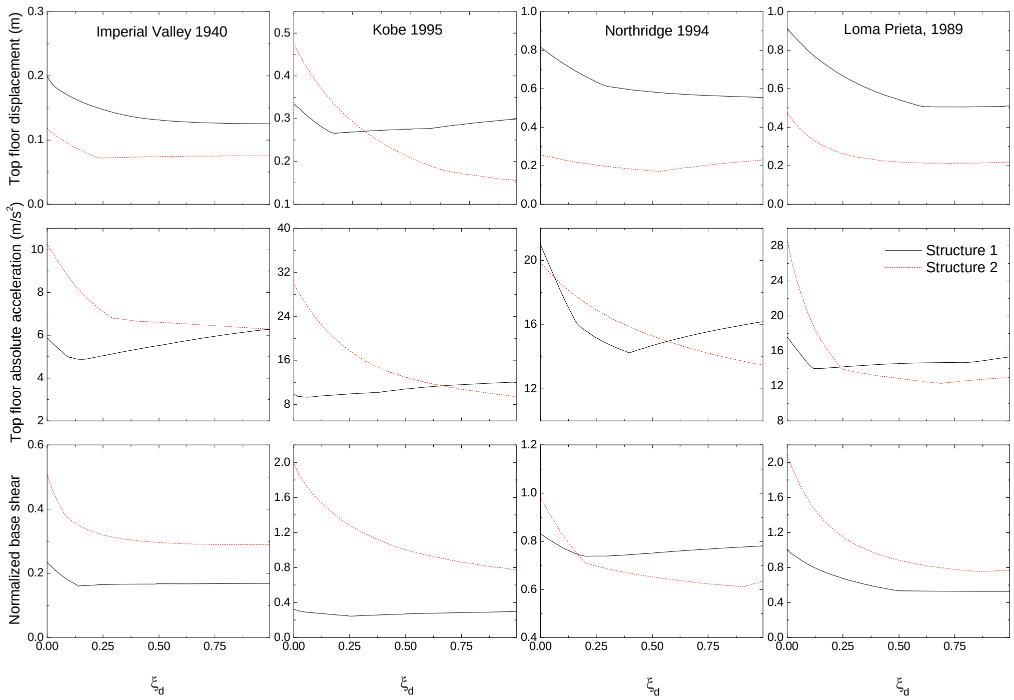

Figure 3. Variation of peak responses of two MDOF structures against normalized damper damping when connected with Maxwell dampers having same damping

Figure 3 shows the variation of the top floor relative displacements, top floor absolute accelerations and base shears of the two structures for all four earthquakes considered. It is observed that the responses of both structures are reduced up to a certain value of the damping and later on, they are again increased. Thus, it is concluded that the optimum damper damping ratio exists to yield the lowest responses of both structures. As the optimum damper damping ratio is not the same for both structures, the optimum value is taken as the one, which gives the lowest sum of the responses of the two structures. In arriving at the optimum value, the emphasis is given on the displacements and base shears of the two structures and at the same time care is taken that acceleration of the structures, as far as possible, are not increased. It is observed that the responses are reduced significantly for the damping ratio is 0.72. For damping ratios higher than this, the performance of the dampers is reduced. At very high damping ratios, the two structures behave as though they are almost rigidly connected. As a result, the displacements and the velocities of the two structures become the same. On the other hand, if the damping value is reduced to zero, the two structures return to the unconnected condition. Hence, the optimum damper damping ratio is taken as 0.72. Further, the results show that a slight variation in the optimum damper parameters does not make much difference in the resulting optimum responses. Thus, small variations in damper parameters over life of the structure do not warrant any adjustments or replacement of Maxwell damper.

The variations of the top floor relative displacements and normalized base shears against non-dimensional relaxation time are shown in Figure 4. There is much reduction in the responses of the structures for a relaxation time of less than 0.1 compared with that of unlinked structures. If the relaxation time is less than 0.01, the relaxation time of damper has no effect on the responses of structures and it is observed that the frequencies of both structures remain same. This property of retaining their structural characteristics after the addition of connected dampers is very useful in practical implementation of the connected dampers for already existing structures. Therefore, the relaxation time of 0.01 may be taken as the optimum for the dampers. If the relaxation time is increased beyond 0.1, it is seen that the structural responses are increased. Moreover, the top floor displacement and the base shear of the stiff structure may increase compared to that of unlinked condition. Thus, it may be considered that the optimum relaxation time is 0.01.

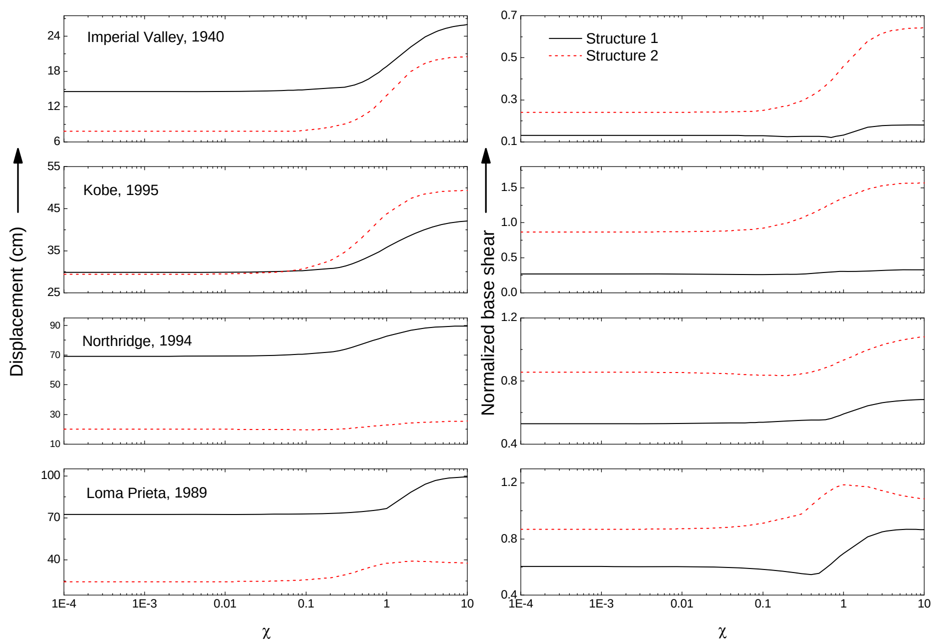

Figure 4. Variation of peak responses of two MDOF structures against normalized relaxation time

The time history of the top floor displacement and base shear responses of the two structures connected by Maxwell dampers, with optimum parameters obtained above, at all the floors are shown in Figures 5 and 6. These figures clearly indicate the effectiveness of dampers in mitigating the earthquake responses of both structures.

The responses of the structures are investigated by considering only four dampers (i.e., 50% of the total) with optimum damper parameters at selected floor locations. The floors whichever has the maximum relative displacement and/or velocity are selected to place the dampers. Many trials are carried out to arrive at the optimal placement of the dampers, among which Figures 7 and 8 show the variation of the displacements and shear forces, respectively in all the floors for four different cases, when case (i) unconnected, case (ii) connected at all the floors, case (iii) connected at 5, 6, 7 and 8 floors and case (iv) connected at 2, 4, 6 and 8 floors. It is found from the figures that the dampers are more effective when they are placed at 5, 6, 7 and 8 floors similar to that obtained in case of viscous damper connected and friction damper connected structures. When the dampers are attached to theses floors, the displacements and shear forces in all stories are reduced almost as much as when they are connected at all floors. Thus, 5, 6, 7 and 8 floors are considered for optimal placement of the dampers. However, from Figure 8, it is observed that in some cases the introduction of dampers may worsen the seismic performance as is seen for Kobe earthquake wherein for Structure 1 the shear force is increased above the 8th floor. This is because, the sway of the taller structure, in this case, is abruptly restricted by the shorter structure and hence, the story shear increases above the height of the shorter structure. This phenomenon is not observed in other earthquakes. Thus, the characteristics of the ground motion influence the structural behavior and its improvement. Therefore, it is necessary and recommended to carry out a thorough and specific study for the problem under consideration before being implemented in practice. The reductions in the peak top floor displacements, peak top floor accelerations and normalized base shears of the two structures for without dampers, connected with viscous dampers at all floors and connected with only five Maxwell dampers at optimal locations are shown in Table 1. It is observed from the table that there is similar reduction in the responses for two damper arrangements and the difference in the reduction of the responses of the two structures with only 50% dampers is not more than 10% of that obtained for the structures with dampers connected at all the floors. Thus, it can be concluded that providing the dampers at all floors need not be the optimum solution and even few dampers may result in the same performance.

3.2 Two MDOF structures connected with Maxwell dampers having different damping

In the above section, the damping in all dampers is taken to be same irrespective of its location along height of the structure However, the maximum relative velocity between both ends of damper will be high in the top-most damper, requiring highest damping and will be reducing when going towards the bottom-most damper, requiring a lowest damping. Hence, here the investigation is carried out, choosing different damping coefficients in different dampers. Note that, the optimum relaxation time in all dampers is considered to be same, as it does not have much effect on the responses as observed from Figure 4. Thus, as the force in the Maxwell damper is proportional to the maximum relative velocity of the connected floors, to arrive at the variation of damping in the dampers, the maximum relative velocity between all floors, under all four earthquakes considered, is obtained. The variation of these maximum relative velocities along the floors is then calculated, from which an average value for variation is arrived at. Moreover, it is observed from Figure 3 that slight variations in optimum damping do not affect the response significantly. Then the damping in different dampers is considered in this variation. These calculations for arriving at the variation of damping in viscous dampers along the floors are shown in Table 2, from which it is noted that the damping force required by the bottom-most damper is almost less than 20% of that required by the top-most damper.

Table 1. Seismic responses of the two structures connected with Maxwell dampers with same damping

Earthquake	Building	Top floor displacement (m)			Top floor abs. acceleration (m/sec^2)			Normalized base shear		
		Unconnected	Connected at all floors	Connected at 4 floors*	Unconnected	Connected at all floors	Connected at 4 floors*	Unconnected	Connected at all floors	Connected at 4 floors*
Imperial Valley, 1940	1	0.201	0.127 (36.98)#	0.125 (38.01)	6.009	5.914 (1.58)	5.998 (0.18)	0.229	0.168 (26.65)	0.167 (26.97)
	2	0.120	0.075 (37.20)	0.074 (37.79)	9.798	6.473 (33.94)	6.301 (35.68)	0.565	0.291 (48.57)	0.301 (46.68)
Kobe, 1995	1	0.333	0.267 (19.83)	0.268 (19.67)	9.782	9.773 (0.09)	9.752 (0.31)	0.327	0.258 (21.21)	0.263 (19.48)
	2	0.473	0.319 (32.70)	0.348 (26.48)	29.844	19.415 (34.95)	21.428 (28.20)	2.017	1.369 (32.12)	1.463 (27.47)
Northridge, 1994	1	0.816	0.566 (30.63)	0.565 (30.76)	21.390	15.473 (27.66)	15.722 (26.50)	0.824	0.766 (6.99)	0.744 (9.69)
	2	0.257	0.199 (22.43)	0.198 (22.94)	20.028	14.335 (24.42)	14.036 (29.97)	0.984	0.627 (36.34)	0.636 (35.38)
Loma Prieta, 1989	1	0.913	0.505 (44.75)	0.495 (45.86)	17.566	14.663 (16.58)	14.353 (18.34)	1.001	0.530 (47.02)	0.543 (45.72)
	2	0.476	0.213 (55.34)	0.211 (55.62)	28.588	12.386 (56.68)	12.238 (57.19)	2.090	0.788 (62.29)	0.807 (61.39)

* connected at the floors 5,6,7 and 8. # quantity within the parentheses denotes the percentage reduction

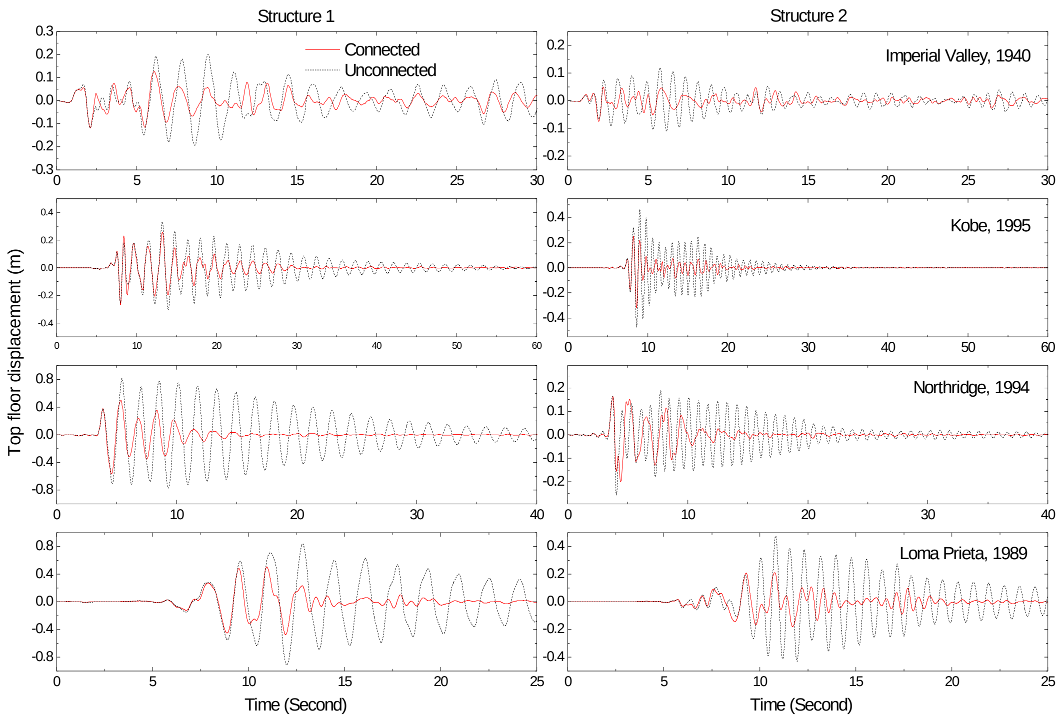

Figure 5. Time histories of the top floor displacements of two MDOF structures

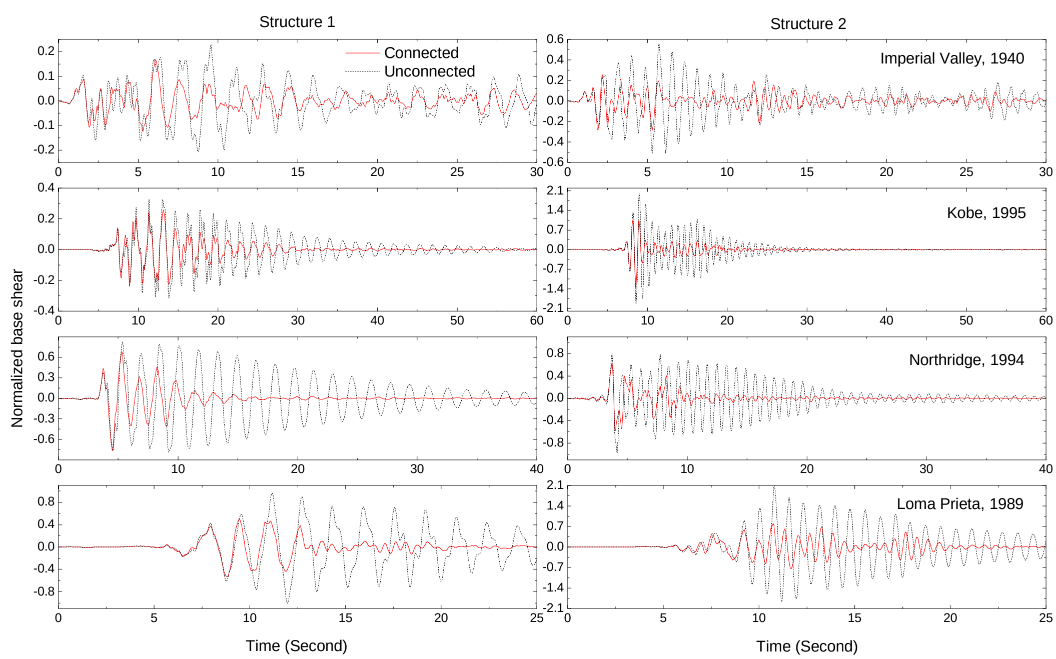

Figure 6. Time histories of the base shears of two MDOF structures

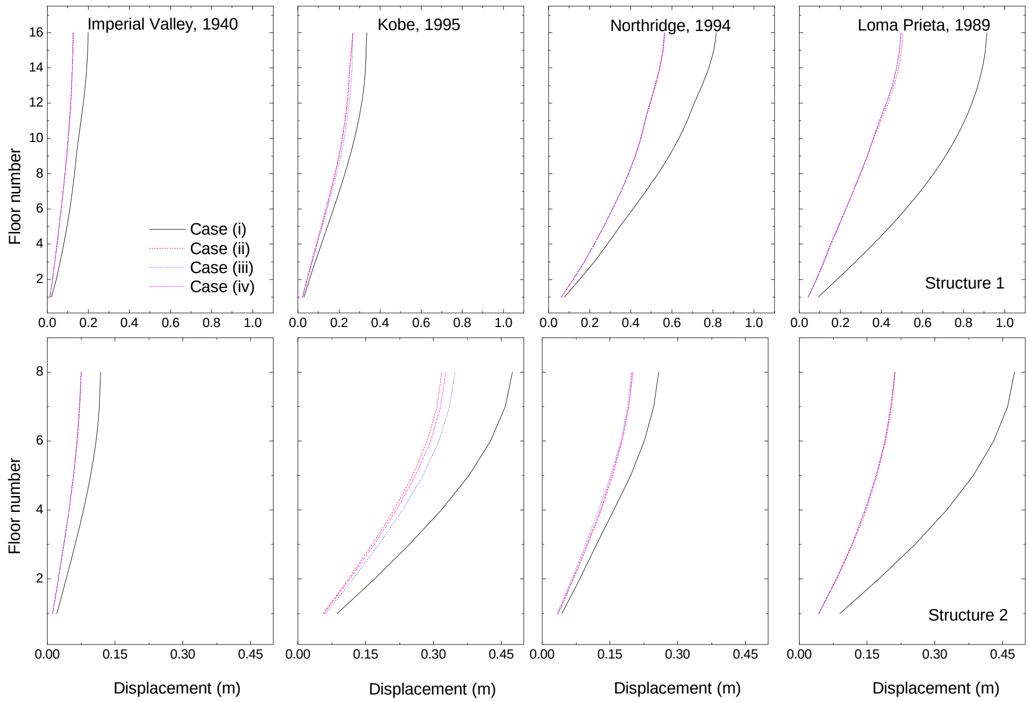

Figure 7. Variation of the floor displacements along the height of structures

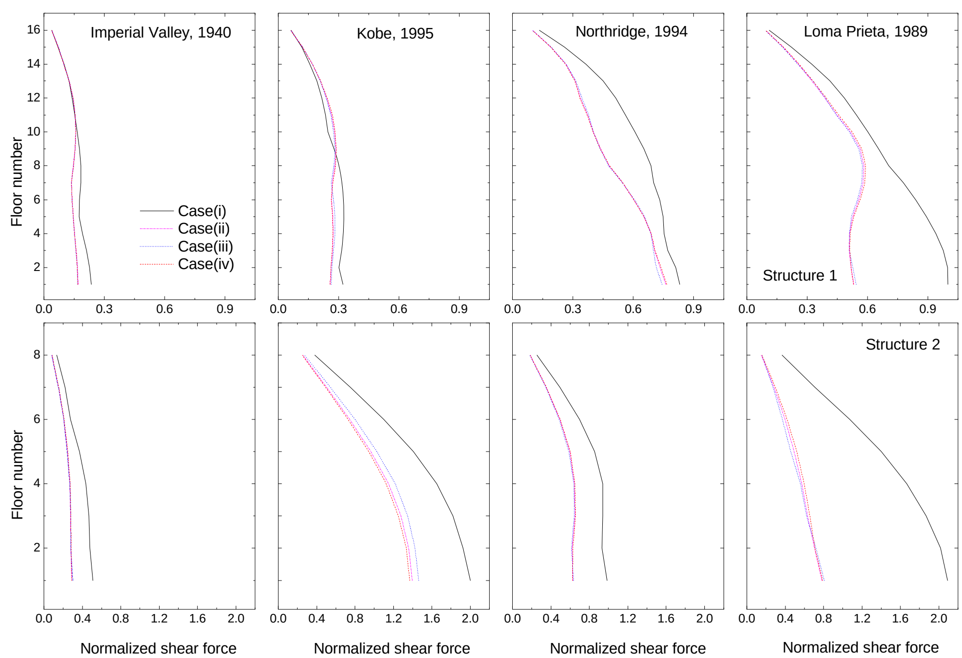

Figure 8. Variation of the floor shears along the height of structures

To arrive at the optimum damping in the viscous dampers with different damping along the floors, the variation of the top floor relative displacements, top floor absolute accelerations and base shears of the two structures against the normalized damping, varying along the floors, is shown in Figure 9 for all the four earthquakes considered. The observations are similar to that observed in the previous section and the normalized optimum damping, in this case, is found to be 0.81 in the top-most damper and the normalized optimum damping in the other dampers being varied in the average variation shown in Table 2. This normalized optimum damping in the top-most damper is slightly more than that obtained in the previous section, as expected.

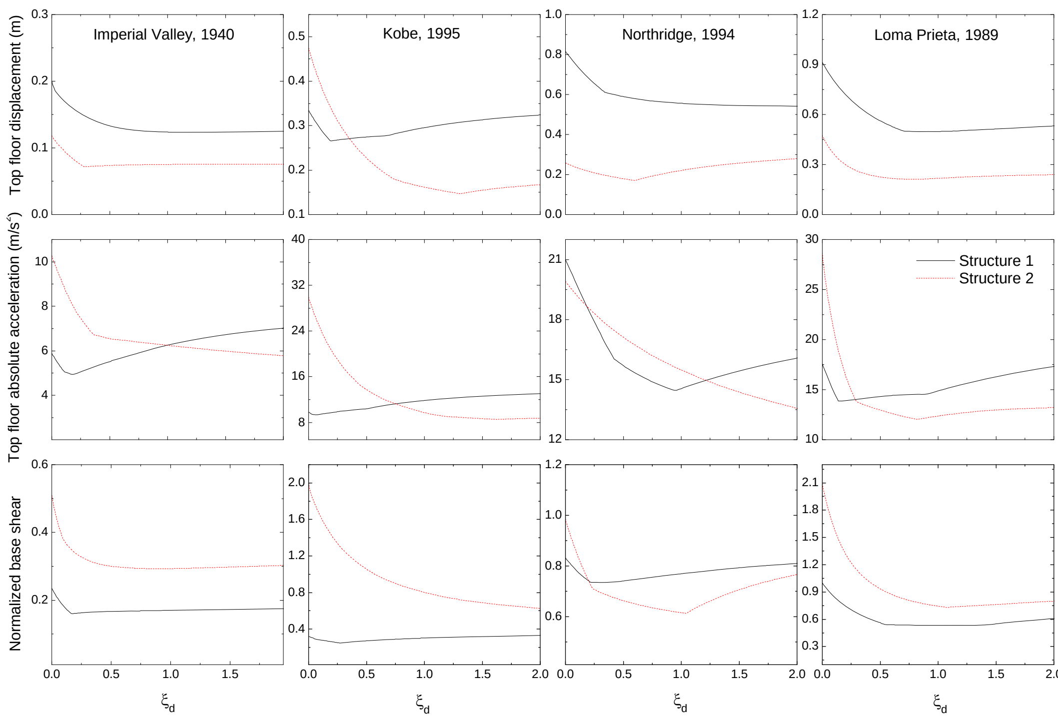

Figure 9. Variation of peak responses of two MDOF structures with normalized damper damping when connected with Maxwell dampers having different damping

The variation of responses along the floors when connected at all floors having (i) same damping in all dampers and (ii) different damping in dampers is compared in Figures 10 and 11 for displacement and shear forces, respectively. It is observed that the reduction in responses obtained when connected with dampers having different damping is as much as that obtained when connected with dampers having same damping in all dampers. This clearly indicates that the damping in all dampers is not required to be same and can be reduced from the top-most damper to the bottom-most damper, in the variation of the maximum relative velocities between adjacent floors, requiring lesser force in other dampers. Thereby the cost of dampers is reduced to a great extent.

Table 2: Percentage variation of maximum relative velocity between adjacent floors with respect to the top one

Floor No.	Imperial Valley, 1940	Kobe, 1995	Northridge, 1994	Loma Prieta, 1989	Average
8	100	100	100	100	100
7	92.19	97.58	94.93	93.82	94.63
6	83.32	92.43	92.16	84.94	88.21
5	73.92	83.55	86.43	74.22	79.53
4	61.38	71.12	76.50	61.99	67.75
3	47.75	55.67	62.12	49.35	53.72
2	34.19	38.05	43.82	34.53	37.64
1	18.58	19.28	22.65	17.81	19.58

To arrive at the optimum placement of viscous dampers, the same procedure that followed in the above section is followed and here also it is observed that when dampers are placed at 5,6,7 and 8 floors, the maximum reductions in the responses are achieved. The reductions in the peak top floor displacements, peak top floor accelerations and normalized base shears of the two structures for, without dampers, connected with viscous dampers at all floors and connected with only four viscous dampers at optimal locations are shown in Table 3. Here also, the results show that there is similar reduction in the responses for the two damper arrangements and the decrease in the reduction of the responses of the two structures with only 50% dampers is not more than 10% of that obtained for the structures with dampers connected at all the floors.

From Tables 1 and 3, it is seen that the responses of the two structures, when they are connected at all floors with the same damping in all dampers and when they are connected with 50% of total dampers with different damping are almost same. Hence, it can be concluded that the reduction in responses, when connected with 50% of total dampers with different damping is as much as when they are connected at all floors with the same damping in all dampers. Thus, the cost of dampers is reduced by almost 50%.

4. CONCLUSIONS

The governing equations of motion are formulated for two adjacent structures connected with Maxwell dampers. The behavior of two adjacent structures connected with Maxwell dampers is investigated under various earthquake excitations. The optimal parameters of the dampers and their optimal placement for the minimum seismic responses of the two structures are studied. The major conclusions drawn from the results of this study for the design of damper to coupled adjacent structures, as summarized below The Maxwell dampers are found to be effective in reducing the earthquake responses of the adjacent connected structures.

Table 3. Seismic responses of the two structures connected with Maxwell dampers having different damping.

Earthquake	Building	Top floor displacement (m)			Top floor acceleration (m/sec^2)			Normalized base shear		
		Unconnected	Connected at all floors	Connected at 4 floors*	Unconnected	Connected at all floors	Connected at 4 floors*	Unconnected	Connected at all floors	Connected at 4 floors*
Imperial Valley, 1940	1	0.201	0.125 (37.81)#	0.125 (37.99)	6.009	6.001 (0.14)	6.008 (0.02)	0.229	0.169 (26.20)	0.167 (26.96)
	2	0.120	0.075 (34.41)	0.074 (37.89)	9.798	6.362 (35.06)	6.2733 (35.97)	0.565	0.294 (48.05)	0.301 (46.71)
Kobe, 1995	1	0.333	0.267 (20.05)	0.269 (19.37)	9.782	9.775 (0.07)	9.750 (0.33)	0.327	0.260 (20.65)	0.265 (18.98)
	2	0.473	0.330 (30.19)	0.351 (25.89)	29.844	20.21 (32.28)	21.607 (27.60)	2.017	1.406 (30.31)	1.473 (26.98)
Northridge, 1994	1	0.816	0.565 (30.80)	0.564 (30.81)	21.390	15.604 (27.05)	15.760 (26.31)	0.824	0.759 (7.83)	0.741 (9.97)
	2	0.257	0.200 (22.29)	0.198 (22.84)	20.028	14.164 (29.28)	13.958 (30.31)	0.984	0.630 (36.01)	0.637 (35.34)
Loma Prieta, 1989	1	0.913	0.498 (45.47)	0.492 (46.09)	17.577	14.524 (17.37)	14.364 (18.28)	1.001	0.534 (46.63)	0.544 (45.61)
	2	0.476	0.211 (55.65)	0.212 (55.54)	28.588	12.042 (57.88)	12.093 (57.70)	2.090	0.789 (62.27)	0.808 (61.33)

* connected at the floors 5,6,7, and 8. # quantity within the parentheses denotes the percentage reduction

1. Optimum damper parameters for Maxwell dampers for minimum earthquake response is different for both the structure, however there exists optimum damper parameters for for the coupled system.
2. The stiffness of the Maxwell dampers also affects its perfor e, which may otherwise increase the responses of structures, if it is not selected properly.
3. Lesser dampers at appropriate locations can reduce the seismic response of the connected system almost as much as when they are connected at all floors.
4. The cost of the damper can be reduced by providing different damping in damper, which is proportion to the relative floor velocity to which damper is connected.
5. The reduction in responses, when connected with 50% of total dampers with different damper parameters is as much as when they are connected at all floors with the same damper parameters in all dampers. Thus, the cost of dampers is reduced by almost 50%.
6. As the damping force is in proportion to the relative velocity of its both ends, the neighboring floors having maximum relative velocity should be chosen for optimal dampers locations.

The study can be further explored considering dynamically two similar structures coupled by dampers, when the two adjacent structures are connected by damper with soil-structure interaction effect, bi-directional ground motion with torsional effects and with different floor heights.

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