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# Seismic Response Control of Similar Adjacent Structures Connected by Maxwell Dampers

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**Abstract**

The seismic response analysis of dynamically similar adjacent structures connected by Maxwell dampers is studied. The structural response for four different types of earthquake ground motions is investigated. The formulation of the equations of motion for two adjacent multi-degrees-of-freedom structures connected with Maxwell dampers is presented. The dampers effectiveness is evaluated in terms of hte reduction of structural responses namely displacement, acceleration and base shear force of the connected adjacent structures. A parametric study is carried out to obtain the optimum damper parameter for minimum response of the connected structures. Results show that Maxwell damper is quite effective for seismic response control of either structure by selecting appropriate parameter of damper. Further, lesser damper at appropriate locations can significantly reduce the earthquake response of the connected system.

*Keywords*: Maxwell Damper, passive control, seismic response, similar structure

## 1. Introduction

To protect the structures against natural loads like strong wind and earthquake which are random in nature, is challenging task for civil engineering community. The use of energy dissipation device and control mechanism into structure is another alternate to conventional design approach of the structure which provides the minimum level of protection. The various passive dampers are some of the preferred energy dissipation devices used to mitigate the excessive structural vibration due to earthquake loads. The control strategies are able to modify dynamically the response of the structure in a desirable manner. It termed as protective systems for the new structures. Dutta[1] presented the state-of-the-art review on active control of structures. The review includes the theoretical backgrounds of different active control schemes, limitations and difficulties of their practical implementation and brief introduction on semi-active control. The passive energy dissipation devices commonly use in practice are viscous damper, viscoelastic dampers, metallic yielding dampers, lead extrusion damper, tuned mass or tuned liquid dampers. Soong and Dargush [2] and Constantinou et. al. [3] give more complete details on the mechanics and working principles of these devices. Linear viscous damper model used to model fluid orifice damper give rise to damping forces that are out-of-phase with deformation and deformation dependent forces. The damper force of majority orifice dampers would be displacement dependent at higher frequencies of deformations and thus provide stiffness to the system. Constantinou and Syman [4] presented the experimental investigation on seismic response of buildings with supplemental fluid dampers. The results show that the fluid damper exhibits viscoelastic fluid behaviour. The simplest model to account the viscoelastic behaviour of fluid damper is the Maxwell model in which the force-deformation relationship is described by a first-order differential equation. The frequency dependent characteristic is introduced by the spring element in series with the viscous dashpot. Lewandowski and Chorazyczewski [5] presented the methods for the identification of hte parameters of the Maxwell fractional model and Kelvin-Viogt fraction model.

Due to different dynamic properties, adjacent structures can vibrate out of phase during earthquake excitation and creates relative displacement problems. Various control strategy not only applied effectively to the individual buildings but also applied effectively to the adjacent buildings. Matsagar and Jangid [6] presented the seismic response analysis of the base-isolated adjacent structures connected with visco-elastic dampers. The analysis results show that for the existing under-designed fixed base structure, the base isolation of both or one of the adjacent building found advantageous in the retrofitting works. Hatada et. Al. [7] studied the dynamic analysis of structures with Maxwell model. The computational method in time domain have formulated by introducing a finite element of the Maxwell model into the equation of motion in the discrete-time series. Patel and Jangid [8] investigated the

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performance of Maxwell dampers connecting two adjacent multi-degree-of-freedom (MDOF) structures under real earthquake excitations. Patel [9] presented the response behaviour of two parallel single-degree-of-freedom (SDOF) structures connected with Maxwell damper subjected to non-stationary as well as stationary white-noise random excitation. The influence of parameters such as relaxation time of damper, frequency and mass ratio of connected structures on the performance of damper have presented. The closed-form expression for optimum damper damping for the minimum value of mean square relative displacement and absolute acceleration of either of coupled structures also presented.

When the adjacent structures have the same properties, the response of the two structures does not have difference in their motion phases. Therefore, the relative displacement and the relative velocity of the connecting damper between the two structures will become zero theoretically or practically nearly zero. The resultant control force becomes zero theoretically or being very small practically and meaningless in control effect. Patel and Jangid [10] presented inter-building damper coupling approach for the dynamically similar adjacent structures with three different configurations of inter-connecting damper distributions. The main purpose is how to differently amplify the relative response of the two ends of the damper. Above studies confirms the effectiveness of passive dampers connecting adjacent dissimilar structure as well as similar connected structures for seismic response mitigation. In this paper, the performance of Maxwell damper for seismic response mitigation of parallel similar MDOF connected structure under various real earthquake excitations is investigated. The specific objective of the study are to: (i) formulate the equation of motion for the two parallel similar structures connected with Maxwell dampers; (ii) investigate the performance of Maxwell damper for seismic response reduction of the parallel structures; (iii) identify the optimum damper parameter of the Maxwell damper and (iv) investigate the optimal placement of the dampers instead of providing at all the floor.

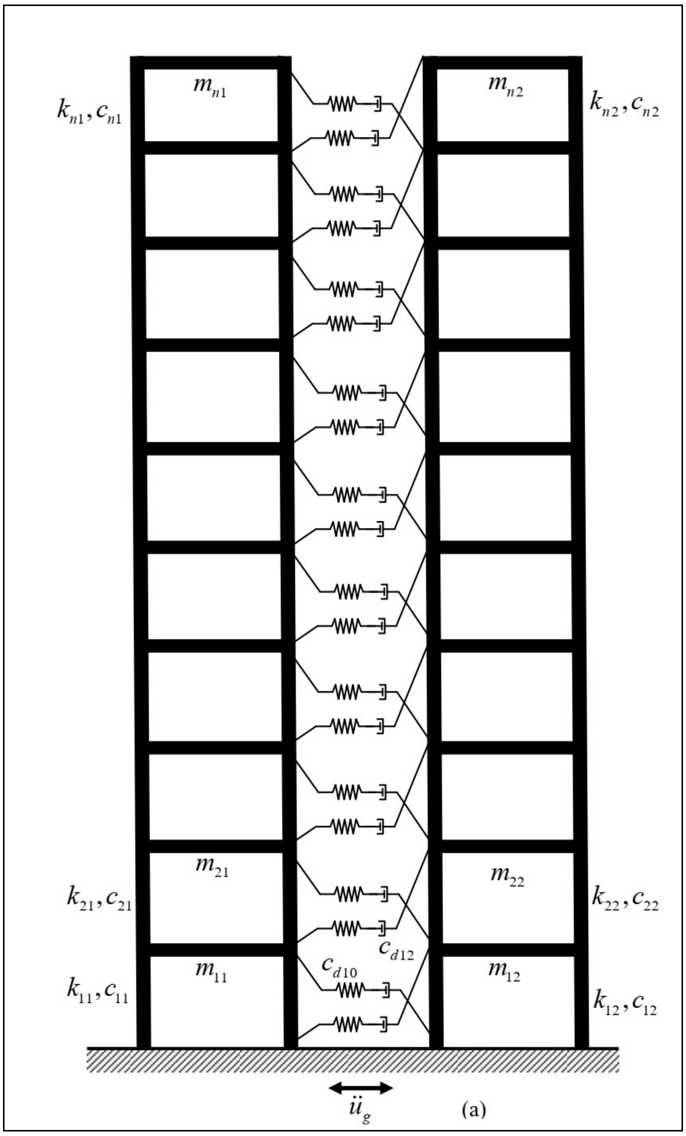
## 2. Structural model of similar connected structures

Let us consider the two MDOF parallel structures having $n$ stories with the mass, damping coefficient and shear stiffness for the $i$ th storey are $m_i, c_i, k_i$ respectively, as shown in Fig.1. The combined system will then be having a total number of degrees of freedom equal to $2n$. The two 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 and both the structures subjected to the same ground excitation. The floor of each structure is at the same level. Each structure is been modeled as a linear MDOF flexible shear-type structure with lateral degree-of-freedom at their floor levels. The dampers connecting the two structures enhanced the energy absorbing capacity of the coupled system and the earthquake excitation is assumed to be not so sever, the structures are assumed to be remaining in linear elastic. The effect of soil-structure interaction is neglected. 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 ends, acting in series as shown in Fig.1. The Maxwell model captures the frequency dependence of the damping and stiffness coefficient observed in the fluid orifice dampers, especially at higher frequencies of deformation. The force in the Maxwell damper $f$ can be described by the first order differential equation proposed by Bird et al. [11] given as

$$f + \lambda \frac{df}{dt} = c_d \left( \dot{u}_r \right) \quad (1)$$

where $c_d$ is the damping coefficient at zero frequency, $\lambda$ is the relaxation time defined by $\lambda = c_d / k_d$, with $k_d$ is the damper stiffness coefficient and $\dot{u}r$ is the relative velocity of damper ends.

The non dimensional damping ratio at zero frequency $\xi_d$ and relaxation time $\chi$ are defined as $\xi_d = c_d / 2m_1\omega_1$ and $\chi = \lambda\omega_1$. where $m_1$ is the mass of first story and $\omega_1$ is the first natural frequency of the structure.



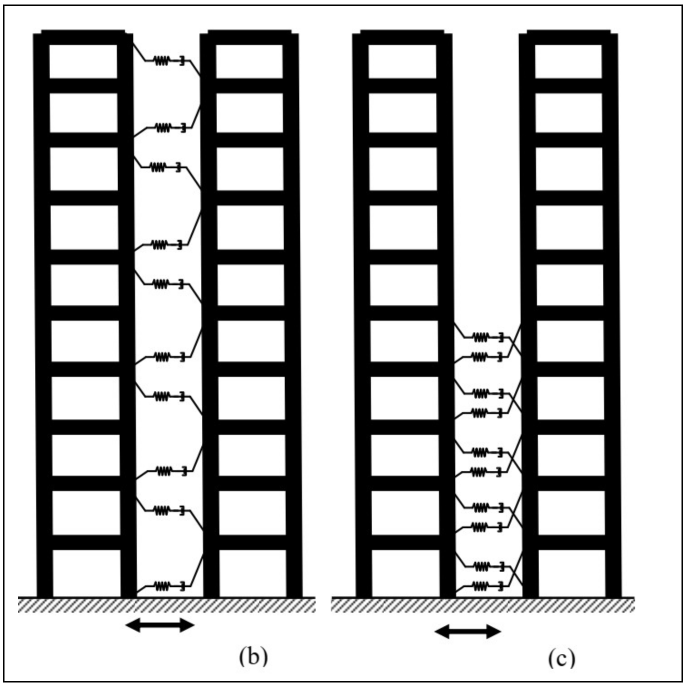



Fig.1 Two parallel similar MDOF structures connected with Maxwell dampers and different damper arrangements

The governing equation of motion of the damper connected system expressed as

$$M\ddot{U} + C\dot{U} + KU + F = -MI\ddot{u}_g \quad (2)$$

where M, K and C are the mass, stiffness and damping matrices of the coupled structural system, respectively; $F$ is the vector consisting the force in Maxwell damper; $U$ is the relative displacement with respect to the ground; $I$ is a vector with all its elements equal to unity; and $\ddot{u}_g$ is the earthquake acceleration at the foundation of the structures. The over dot represent time derivative. The details of each matrix is given as,

$$M = \begin{bmatrix} m_{(n,n)} & 0 \\ 0 & m_{(n,n)} \end{bmatrix}; K = \begin{bmatrix} k_{(n,n)} & 0 \\ 0 & k_{(n,n)} \end{bmatrix}; C = \begin{bmatrix} c_{(n,n)} & 0 \\ 0 & c_{(n,n)} \end{bmatrix}; \quad (3)$$

$$F^T = \{ f_{(n,1)} \quad -f_{(n,1)} \} \; ; \; f^T = \{ f_1, f_2, f_3 \quad \ldots \quad f_n \} \quad (4)$$

$$U^T = \{ u_{11}, u_{21} \quad u_{n1}, u_{21}, u_{22}, \ldots \quad u_{n2} \} \quad (5)$$

The damper force $f$ is obtained by solving first order differential equation given by Eq. (1), which is solved using forth order Runge-Kutta method. The force in damper becomes zero corresponding to the floor with no damper. The governing equation of motion are solved in the incremental form using Newmark's method assuming constant average acceleration over small time interval $\Delta t$. The structural control criteria depend on the nature of dynamic loads and the response quantities of interest. In case of stiff structure, acceleration is of more concern, generating higher inertia force in the structure, should be mitigated. Whereas, in case of flexible structure, displacement is predominant that needs to be controlled.

## 3. Numerical study

The performance of Maxwell damper for response control of two parallel MDOF structures under four real earthquake ground motion excitations is investigated. The ground motion excitation considered are Imperial Valley, 1940, with peak ground acceleration (PGA) 0.32 g; Lome Prieta, 1989 with PGA 0.57 g; Northridge, 1994 with PGA 0.84 g and Kobe, 1995 with PGA 0.63 g (g is acceleration due to gravity). The ground motion considered are comprise of PGA varying from a low value to a high value. In this numerical study, the response quantities of interest are peak value of top floor relative displacement, peak value of top floor acceleration and peak value of base shear. The shear force is normalized with the weight of the structure. The two parallel structure with 10 stories with uniform floor mass and inter-story stiffness are considered. The damping ratio in structure is considered as 5 %. The mass and stiffness of each floor of the structure are chosen such that the fundamental time period of structure yield T=2.25 sec and uncontrolled first three natural frequencies corresponding to first three modes are 2.7937, 8.3188 and 13.6581 red/sec. The variation of the displacement, acceleration and base shear of the structures against the non-dimensional damping ratio for all four considered earthquakes are shown in Fig. 2. It is observed that the displacement response decreases with increase in damper damping , whereas, the acceleration and base shear responses are reduced up to certain increase in damper and after certain value they are again increases. Thus, it is conclude that the optimum damper damping ratio exists to yield the lowest responses. As the optimum damper damping is not the same for all the responses. In arriving at the optimum value, the emphasis is given on the displacement and base shear of the structure and a the same time care is taken that acceleration of the structures, as far as possible, is not increases.

At very high damping ratio, the two structures behave as through they are almost rigidly connected. As a result, the relative displacement and the relative velocity of the

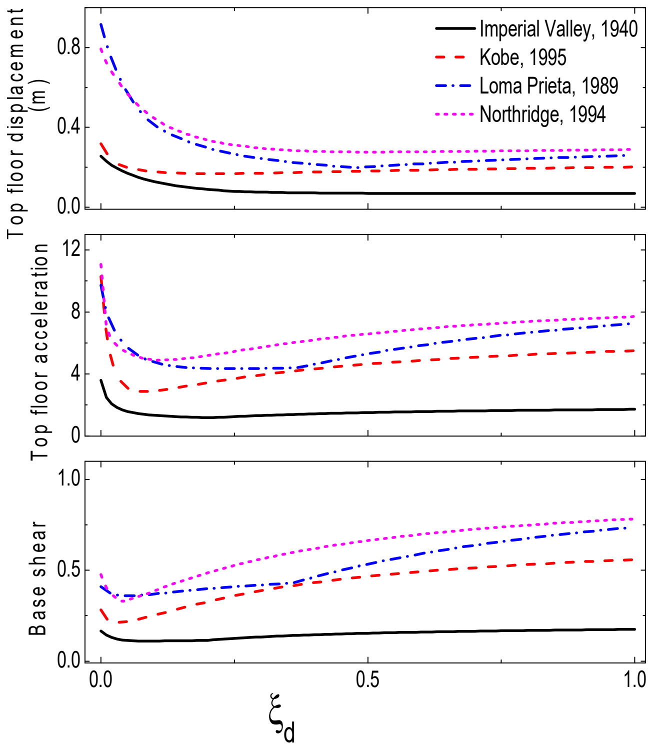



Fig. 2 Variation of peak responses of Maxwell damper connected two parallel similar MDOF structures against normalized damper damping

connected floor become very less and the damper losses its effectiveness. On the other hand, if the damping value is reduce to zero, the two structures return to the unconnected condition. It is also observed that the characteristics of the ground motion like PGA, large magnitude, frequency content, near field etc. Influence the optimal value of the damping coefficient of Maxwell damper. The variation of the top floor relative displacement and normalized base shear against non-dimensional relaxation time are shown in Fig. 3.

There is much reduction in the response of the structure for a relaxation time of less than 0.1 compared with that of unconnected structures. If the relaxation time is less than 0.01, the relaxation time of the damper has no effect on the structures and it is observed that the frequencies of both structures remain same.

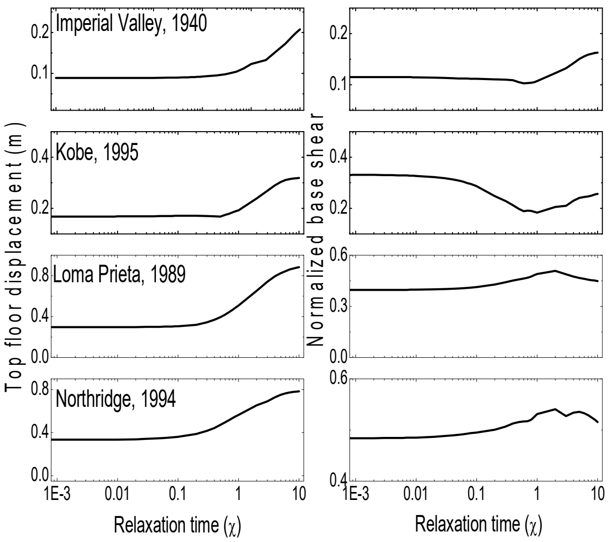



Fig. 3 Variation of peak responses of two MDOF structures against normalized relaxation time

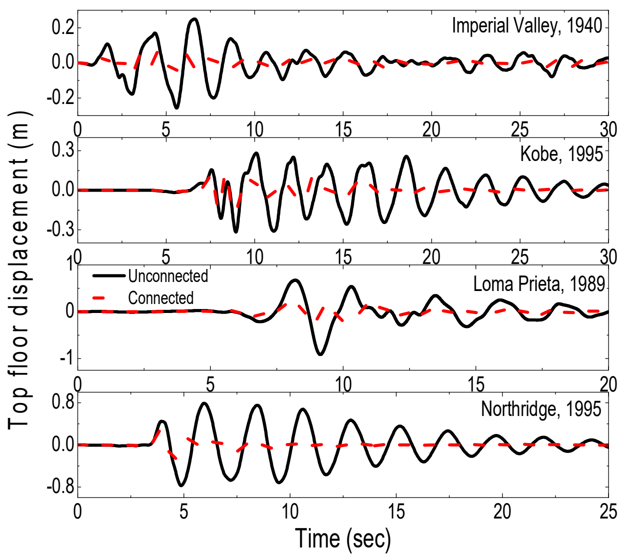



Fig. 4 Time histories of top floor displacement of similar parallel MDOF connected structures

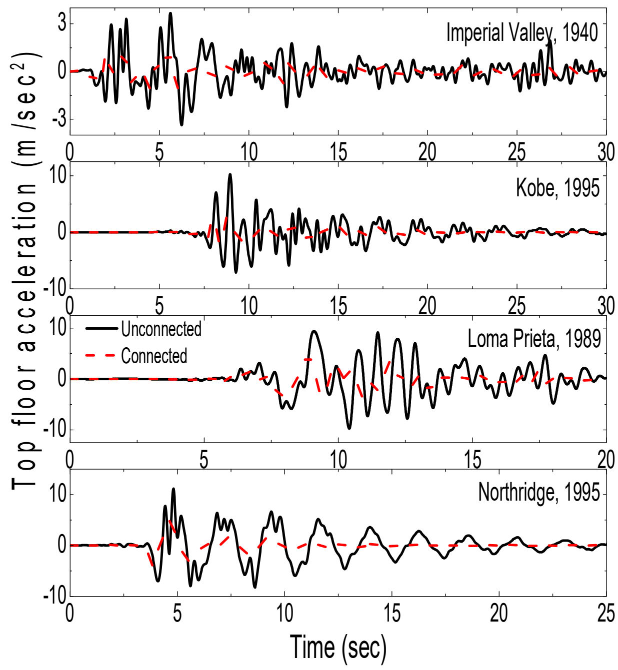



Fig. 5 Time histories of top floor acceleration of similar parallel MDOF connected structures

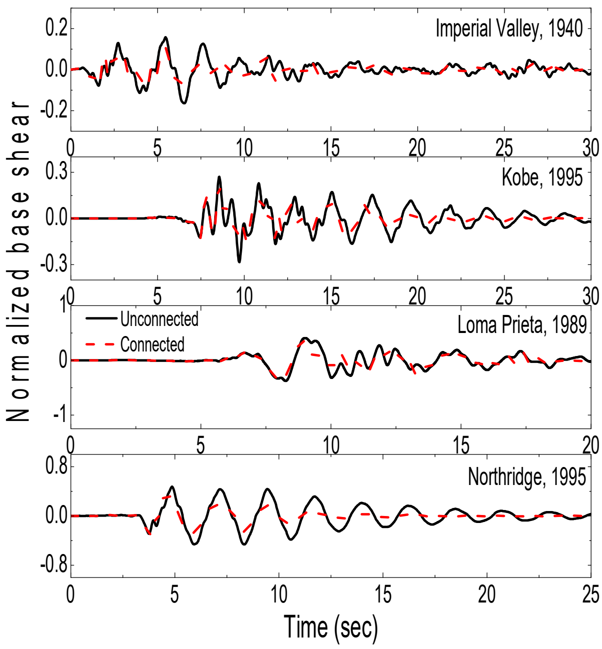



Fig. 6 Time histories of normalized base shear of similar parallel MDOF connected structures

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.

The time histories of the top floor displacement, top floor absolute acceleration and normalized base shear of the two structures connected by Maxwell dampers at all floors with optimum damping coefficient, are shown in Fig. 4, 5, and 6, respectively.

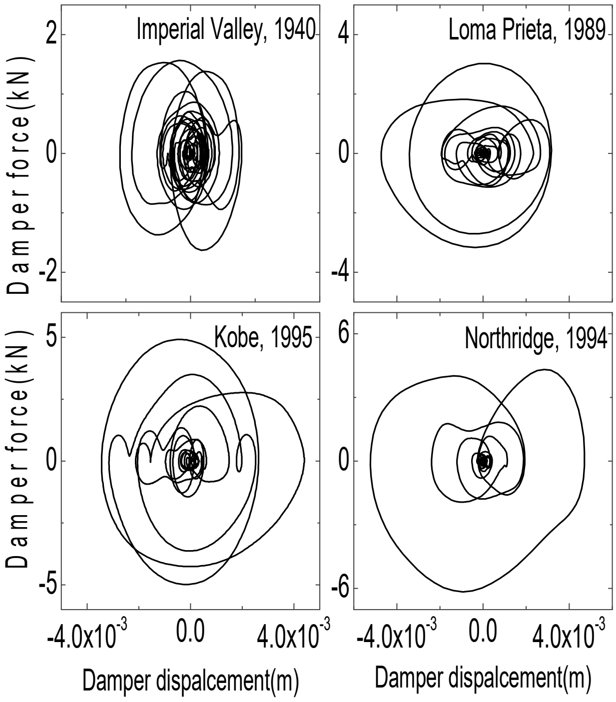



Fig. 7 Damper force-displacement for 8th floor Maxwell damper when parallel structures connected at all floors.

Table 1. Displacement response of similar parallel MDOF structures connected with Maxwell dampers

| Earthquake | Top floor displacement (m) | | | |
|---|---|---|---|---|
| | Case (i) | Case (ii) | Case (iii) | Case (iv) |
| Imperial Valley, 1940 | 0.2567 | 0.0691 (73.09)# | 0.050 (80.52) | 0.0895 (65.14) |
| Kobe, 1995 | 0.3183 | 0.1683 (47.12) | 0.1893 (40.50) | 0.1783 (46.25) |
| Loma Prieta, 1989 | 0.9151 | 0.1991 (78.24) | 0.1876 (79.51) | 0.1748 (80.90) |
| Northridge, 1994 | 0.7908 | 0.2769 (64.98) | 0.3737 (52.75) | 0.3268 (58.68) |

# Quantity within parentheses denotes the percentage reduction.

Table 2. Acceleration response of similar parallel MDOF structures connected with Maxwell dampers

| Earthquake | Top floor acceleration ($m/sec^2$) | | | |
|---|---|---|---|---|
| | Case (i) | Case (ii) | Case (iii) | Case (iv) |
| Imperial Valley, 1940 | 3.6704 | 1.178 (67.85) | 1.2784 (65.17) | 1.8095 (50.70) |
| Kobe, 1995 | 10.2802 | 2.8702 (72.08) | 2.2133 (78.47) | 5.8525 (43.07) |
| Loma Prieta, 1989 | 9.7230 | 4.3374 (55.39) | 3.114 (68.00) | 4.7380 (51.27) |
| Northridge, 1994 | 11.1479 | 4.9037 (56.01) | 4.2975 (61.47) | 6.0299 (45.91) |

Table 3. Normalized base shear of similar parallel MDOF structures connected with Maxwell dampers

| Earthquake | Normalized base shear | | | |
|---|---|---|---|---|
| | Case (i) | Case (ii) | Case (iii) | Case (iv) |
| Imperial Valley, 1940 | 0.1640 | 0.1104 (32.69) | 0.1063 (35.21) | 0.0942 (42.56) |
| Kobe, 1995 | 0.2842 | 0.2134 (24.90) | 0.1684 (40.75) | 0.1055 (62.89) |
| Loma Prieta, 1989 | 0.4092 | 0.3605 (11.89) | 0.3304 (19.25) | 0.3058 (25.28) |
| Northridge, 1994 | 0.4759 | 0.3283 (31.02) | 0.3389 (28.78) | 0.2929 (38.45) |

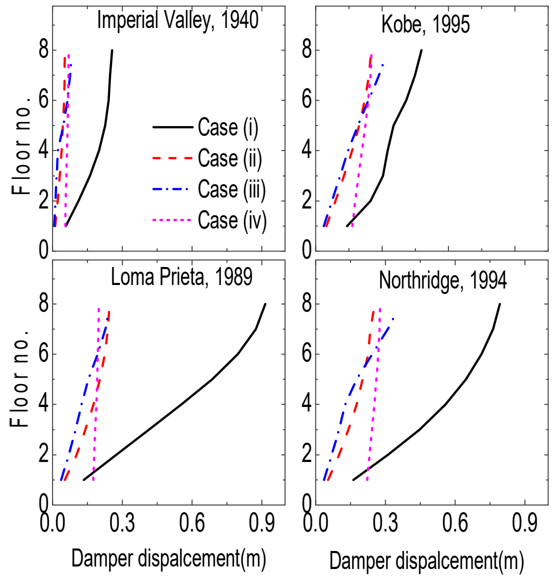



Fig. 8 Variation of floor displacement along the height of the structure

These figures clearly indicate the performance of the Maxwell damper for seismic response control of parallel connected structures. The damper force-displacement relationship for 8th floor Maxwell damper under different earthquake ground motion is shown in Fig. 7.

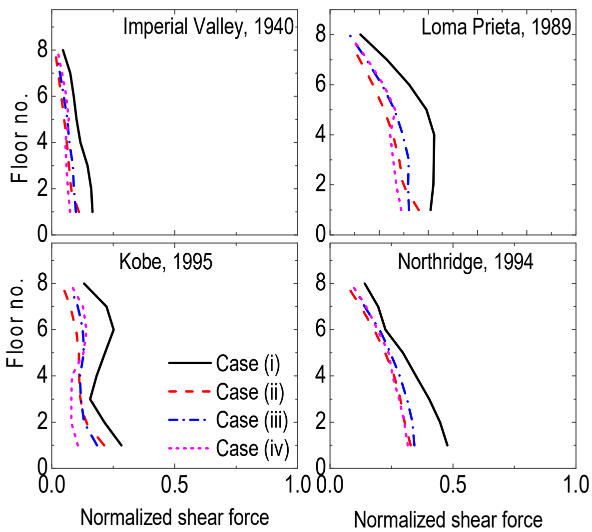



Fig. 9 Variation of floor shear along the height of the structure

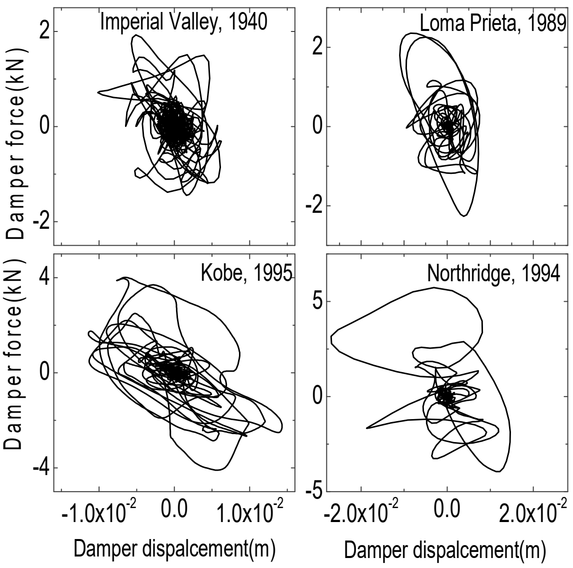



Fig. 10 Damper force-displacement for 8th floor Maxwell damper when parallel structures connected at alternate floor as shown in Fig. (b).

It shows that Maxwell damper effectiveness for energy dissipation during seismic response of the parallel connected structures. The energy dissipation behaviour of Maxwell damper is different during different earthquake ground motion. Thus, the characteristics of the ground motion excitation influence the performance of the Maxwell damper.

The responses of the structures are investigated by considering only eight 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. After many trials are carried out to arrive at the optimal placement of the dampers, the arrangement as shown in Fig. 1(b) and (c) are considered for optimal placement of the dampers. The variation of the displacement and shear forces in all the floors for four different cases when case (i) unconnected, case (ii) connected at all the floors, case (iii) connected at alternate floors as shown in Fig. 1(b) and case (iv) connected at bottom four floors as shown in Fig.1 (c) are shown in Fig. 8 and 9, respectively. It is found from the figure that the dampers are more effective, when they are connected as shown in Fig. 1(b). When the dampers are attached to these floors, the displacement and shear forces in all stories are reduces almost as much as when they are connected at all floors. The damper-force displacement diagram for the top damper when connected as shown in Fig. 1(b) is shown in Fig.10. It shows the effectiveness of the Maxwell damper for energy dissipation when connecting the parallel structures as shown in Fig. 1(b). The reduction in the peak value of the top floor displacement, peak value of the top floor acceleration and peak value of the normalized base shear of the structures, for the structures without dampers , connected with dampers at all floors and connected with 50 % of total Maxwell damper are shown in Table 1, 2 and 3, respectively. It is observed from the tables that the reduction in the responses when structures are connected at all floors is as much as when they are connected with 50 % of the total damper as shown in Fig. 1(b). Thus, it can be concluded that it is not necessary to provide the damper connecting all the floors, even few dampers may result in the same performance.

## 4. Conclusions

The seismic response behavior of two parallel dynamically similar MDOF structures connected with Maxwell dampers is investigated under various earthquake ground motion excitations, considering a linear elastic behavior of the structures. The governing equations of motion are formulated for the coupled structural system. The optimal parameter of the damper and their optimal placement for minimum seismic response of the two structures are studied. The analysis is carried out for parallel structures connected by dampers at all floors as well as connected with 50 % dampers. The major conclusions drawn from the results of this study are as summarized below.

1. The Maxwell damper is found to be effective for seismic response control of dynamically similar parallel connected structures.
2. The stiffness of the Maxwell dampers also affects its performances, which may otherwise increase the response of structures, if it is not selected properly.
3. Lesser dampers at appropriate locations can reduce the seismic response of the parallel connected structures almost as much as when they are connected at all floors.
4. The response reduction, when parallel structures connected with 50 % of total dampers is as much as when they are connected at all floors.

The study can be further explored for two similar parallel connected structures with soil-structure interaction effect.

## Disclosures

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