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SEISMIC RESPONSE OF ADJACENT BUILDINGS CONNECTED WITH DAMPERS

A.V. BHASKARARAO [1] and R.S. JANGID [2]

SUMMARY

Connecting the adjacent buildings with dampers not only mitigates the structural response, but also avoids pounding. In this paper, the structural response of two adjacent buildings connected with various types of dampers under different earthquake excitations is studied. A formulation of the equations of motion for multi-degree of freedom model of buildings connected with dampers is presented. The effectiveness of various types of dampers, viz., viscous, viscoelastic and friction dampers in terms of the reduction of structural responses (i.e., displacement, acceleration and shear forces) of connected adjacent buildings is investigated. A parametric study is also conducted to investigate the optimum parameters of the dampers for adjacent buildings of different heights. In addition, the optimal placement of the dampers, rather than providing the dampers at all the floor levels, is also studied. Results show that connecting the adjacent buildings of different fundamental frequencies by passive dampers can effectively reduce the earthquake-induced responses of either building. There exist optimum damper properties for minimum earthquake response of the buildings. In addition, it is not necessary to connect the two adjacent buildings by dampers at all floors but lesser dampers at appropriate locations can also significantly reduce the earthquake response of the combined building system.

INTRODUCTION

Increasing population and growing social and commercial activities but limited land resources available in a modern city lead to more and more buildings being built closely to each other. These buildings, in most cases, are separated without any structural connections. Hence, wind-resistant or earthquake-resistant capacity of each building mainly depends on itself. The ground motion during earthquakes causes damage to the structure by generating inertial forces caused by the vibration of the buildings masses. Tall structures are extremely 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

[1] Research Scholar, Indian Institute of Technology Bombay, Mumbai, INDIA
[2] Associate Professor, Indian Institute of Technology Bombay, Mumbai, INDIA.
Email: rsjangid@civil.iitb.ac.in

earthquake as observed in the 1985 Mexico City earthquake, the 1989 Loma Prieta earthquake, and many others.

To prevent mutual pounding between adjacent buildings during an earthquake, Westermo [1] suggested using hinged links to connect two neighboring floors if the floors of adjacent buildings are in alignment. It is obvious that this 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 [2] investigated the optimal values for the distribution of viscous dampers interconnecting 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. Xu et al. [3] and Zhang and Xu [4] 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 [5] 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. Hongping and Hirokazu [6] examined the dynamic characteristics of two single-degree-freedom systems coupled with a visco-elastic coupling element 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 parameters of the system on the optimal parameters and control effectiveness. Ni *et al*. [7] 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. Although, the above studies confirm that the dampers are effective in reducing the earthquake response of buildings, however, there is need to study the comparative performance of different dampers, optimum parameters for minimum earthquake response and optimum placement of dampers.

PROBLEM FORMULATION

Connected with viscoelastic dampers

The equations are first formulated for the multi-degrees-of-freedom (MDOF) structures connected with the viscoelastic dampers. Later, the same formulation can be used, when connected with viscous dampers or friction dampers with some modifications.

Assumptions and limitations

Two buildings are assumed to be symmetric buildings with their symmetric planes in alignment. The ground motion is assumed to occur in the direction of the symmetric planes of the buildings so that the problem can be simplified as a two-dimensional problem as shown in Figure 1. Each building is modeled as a linear multi-degree of freedom system where the mass is concentrated at each floor and the stiffness is provided by the mass less walls or columns. This assumption indicates that earthquake excitation considered here is not severe or due to the significant increase of energy absorbing capacity the buildings are able to retain elastic and linear properties under the earthquake.

The floors of each building are at the same level, but the number of story in each building can be different. Each viscoelastic damper device is modeled as a combination of a linear spring proportional to the relative displacement and a linear dashpot proportional to the relative velocity between the two connected floors. 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. Neglecting soil-structure interactions limits the applicability of the results to buildings on stiff, firm ground and less restrictively to buildings whose foundations are not massive (e.g. footing foundations).

Equations of motion

Let Building1 and Building2 have $n+m$ and n stories, respectively as shown in Figure 1. The mass, shear stiffness, and damping coefficients for the ith story are m_{i1}, k_{i1} and c_{i1} for Building1 and m_{i2}, k_{i2} and c_{i2} for Building2, respectively. The damping coefficient and stiffness coefficient of the damper at the ith floor are c_{di} and k_{di}, respectively. The structural model is then taken to be a $(2n+m)$ degrees-of-freedom system. The equations of motion of the connected system are expressed in the matrix form as

$$\mathbf{M}\ddot{\mathbf{X}} + (\mathbf{C} + \mathbf{C_D})\dot{\mathbf{X}} + (\mathbf{K} + \mathbf{K_D})\mathbf{X} = -\mathbf{M}\,\mathbf{I}\,\ddot{x}_g \qquad (1)$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices of the combined building system, respectively; $\mathbf{C_D}$ and $\mathbf{K_D}$ are the additional damping and stiffness matrices due to the installation of the viscoelastic dampers; $\mathbf{X}$ is the relative displacement vector with respect to the ground and consists of Building1's displacements in the first $n+m$ positions and Building2's displacements in the last n positions; $\mathbf{I}$ is a vector with all its elements equal to unity; and $\ddot{x}_g$ is the ground acceleration at the foundations of the structures.

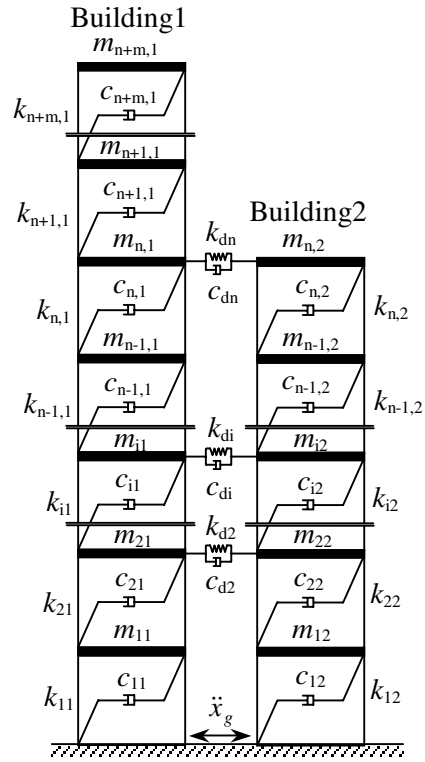

Figure 1. Structural model of adjacent buildings with connected dampers.

The details of each matrix are given under.

$$\mathbf{M} = \begin{bmatrix} \mathbf{m}_{n+m,n+m} & \mathbf{o}_{n+m,n} \\ \mathbf{o}_{n,n+m} & \mathbf{m}_{n,n} \end{bmatrix} ; \quad \mathbf{K} = \begin{bmatrix} \mathbf{k}_{n+m,n+m} & \mathbf{o}_{n+m,n} \\ \mathbf{o}_{n,n+m} & \mathbf{k}_{n,n} \end{bmatrix} ; \quad \mathbf{C} = \begin{bmatrix} \mathbf{c}_{n+m,n+m} & \mathbf{o}_{n+m,n} \\ \mathbf{o}_{n,n+m} & \mathbf{c}_{n,n} \end{bmatrix} \qquad (2)$$

$$\mathbf{C_D} = \begin{bmatrix} \mathbf{c_d}_{(n,n)} & \mathbf{o}_{(n,m)} & -\mathbf{c_d}_{(n,n)} \\ \mathbf{o}_{(m,n)} & \mathbf{o}_{(m,m)} & \mathbf{o}_{(m,n)} \\ -\mathbf{c_d}_{(n,n)} & \mathbf{o}_{(n,m)} & \mathbf{c_d}_{(n,n)} \end{bmatrix} ; \quad \mathbf{K_D} = \begin{bmatrix} \mathbf{k_d}_{(n,n)} & \mathbf{o}_{(n,m)} & -\mathbf{k_d}_{(n,n)} \\ \mathbf{o}_{(m,n)} & \mathbf{o}_{(m,m)} & \mathbf{o}_{(m,n)} \\ -\mathbf{k_d}_{(n,n)} & \mathbf{o}_{(n,m)} & \mathbf{k_d}_{(n,n)} \end{bmatrix} \qquad (3)$$

$$\mathbf{m}_{n+m,n+m} = \begin{bmatrix} m_{11} & & & & & \\ & m_{21} & & & & \\ & & \dots & & & \\ & & & \dots & & \\ & & & & m_{n+m-1,1} & \\ & & & & & m_{n+m,1} \end{bmatrix} ; \quad \mathbf{m}_{n,n} = \begin{bmatrix} m_{12} & & & & & \\ & m_{22} & & & & \\ & & \dots & & & \\ & & & \dots & & \\ & & & & m_{n-1,2} & \\ & & & & & m_{n2} \end{bmatrix} \qquad (4)$$

$$\mathbf{k}_{n+m,n+m} = \begin{bmatrix} k_{11}+k_{21} & -k_{21} & & & & & \\ -k_{21} & k_{21}+k_{31} & -k_{31} & & & & \\ & & \ldots\ldots & & & & \\ & & & \ldots\ldots & & & \\ & & & -k_{n+m-1,1} & k_{n+m-1,1}+k_{n+m,1} & -k_{n+m,1} \\ & & & & -k_{n+m,1} & k_{n+m,1} \end{bmatrix} \tag{5}$$

$$\mathbf{k}_{n,n} = \begin{bmatrix} k_{12}+k_{22} & -k_{22} & & & & \\ -k_{22} & k_{22}+k_{32} & -k_{32} & & & \\ & & \ldots\ldots & & & \\ & & & \ldots\ldots & & \\ & & & -k_{n-1,2} & k_{n-1,2}+k_{n2} & -k_{n2} \\ & & & & -k_{n2} & k_{n2} \end{bmatrix} \tag{6}$$

$$\mathbf{c}_{n+m,n+m} = \begin{bmatrix} c_{11}+c_{21} & -c_{21} & & & & \\ -c_{21} & c_{21}+c_{31} & -c_{31} & & & \\ & & \ldots\ldots & & & \\ & & & \ldots\ldots & & \\ & & & -c_{n+m-1,1} & c_{n+m-1,1}+c_{n+m,1} & -c_{n+m,1} \\ & & & & -c_{n+m,1} & c_{n+m,1} \end{bmatrix} \tag{7}$$

$$\mathbf{c}_{n,n} = \begin{bmatrix} c_{12}+c_{22} & -c_{22} & & & & \\ -c_{22} & c_{22}+c_{32} & -c_{32} & & & \\ & & \ldots\ldots & & & \\ & & & \ldots\ldots & & \\ & & & -c_{n-1,2} & c_{n-1,2}+c_{n2} & -c_{n2} \\ & & & & -c_{n2} & c_{n2} \end{bmatrix} \tag{8}$$

$$\mathbf{c}_{\mathbf{d}(n,n)} = \begin{bmatrix} c_{d1} & & & & & \\ & c_{d2} & & & & \\ & & \ldots & & & \\ & & & \ldots & & \\ & & & & c_{d,n-1} & \\ & & & & & c_{dn} \end{bmatrix} \; ; \; \mathbf{k}_{\mathbf{d}(n,n)} = \begin{bmatrix} k_{d1} & & & & & \\ & k_{d2} & & & & \\ & & \ldots & & & \\ & & & \ldots & & \\ & & & & k_{d,n-1} & \\ & & & & & k_{dn} \end{bmatrix} \tag{9}$$

$$\mathbf{X}^{\mathbf{T}} = \left\{ x_{11}, x_{21}, x_{31}, \ldots\ldots\ldots, x_{n+m-1,1}, x_{n+m,1}, x_{12}, x_{22}, x_{32}, \ldots\ldots\ldots, x_{n-1,2}, x_{n2} \right\} \tag{10}$$

'**o**' is the null matrix.

The corresponding equations of motions, when the two adjacent buildings are connected with viscous dampers, can simply be obtained by making $\mathbf{K_D}$ equal to null matrix in the equation (1).

Connected with friction dampers

There had been considerable interest in the past to investigate the vibration control of structures using the sliding systems [8-11]. From these studies, it was established that there exist two states of modes, namely non-slip and slip mode. It is interesting to note that the similar modes can also be observed in the case of adjacent buildings connected with friction damper. When the adjacent buildings, connected with the friction damper, are excited to ground motion, the connected floors may move together sticking with each other or slippage may occur between the two floors depending on the system parameters and the excitation. When the slippage does not occur, the floors are said to be in *non-slip mode* and when slippage occurs, they are said to be in *slip mode*.

Utilizing a fictitious spring Yang et al. [12] studied the response of MDOF structures on sliding supports. The force in the fictitious spring is used to model the friction force under the foundation raft. The spring was assumed to be having a very large stiffness during the non-slip mode and zero stiffness during the slip mode. The same concept is used here to model the friction dampers connecting the adjacent buildings, i.e., the friction damper is modeled as a *fictitious spring* having very high stiffness (k_d) during non-slip mode and zero stiffness during slip mode as shown in Figure 2. The force in the friction damper (f_d), equal to the force in the fictitious spring, is then equal to the product of its stiffness and the relative displacement between the two buildings. The slip takes place whenever the force in the damper exceeds the slip force (f_s), which is the limiting force in the friction damper. When the velocities of any two connected floors are same and the force in that connecting damper becomes less than its slip force, those two floors again undergo into the non-slip mode. The equations of motion for this approach can be written as follows.

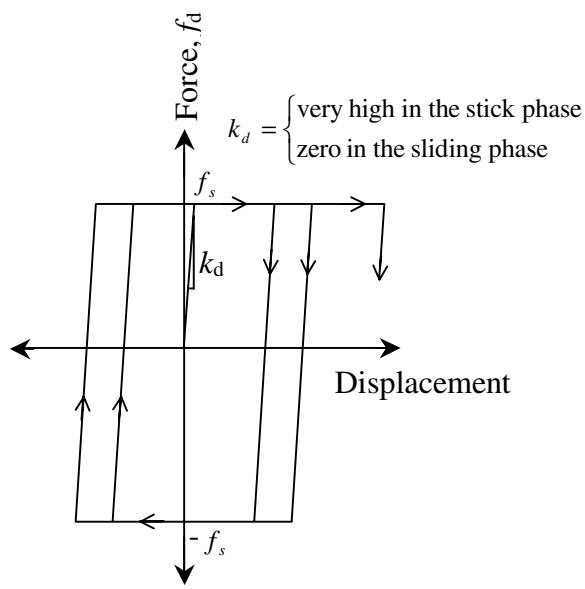

Figure 2. Modeling of friction force in the damper using fictitious spring concept.

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = -\mathbf{M}\,\mathbf{I}\,\ddot{x}_g + \mathbf{F_D} \tag{11}$$

Where all parameters are as defined earlier and

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

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

f_{di} is the force in any i^{th} damper connecting the floors i of the Building1 and Building2 and is calculated based on its phase of motion.

Non-slip mode

When the force in a friction damper does not exceed the slip force, the connected floors vibrate in non-slip mode. Initially all the dampers are in non-slip mode. During non-slip mode, the friction damper is assumed as a fictitious spring with a very high stiffness and the force in any i^{th} damper is calculated using the equation

$$f_{di} = k_{di}\left(x_{i2} - x_{i1}\right)\mathrm{sgn}(\dot{x}_{i2} - \dot{x}_{i1}) \;\; \leq \;\; f_{si} \tag{14}$$

Where f_{si} is the slip force in the ith damper. If the absolute value of this force in the friction damper is less than or equal to the slip force of that damper, then the corresponding connected floors are in non-slip mode. Here, the value of k_{di} is taken as 5000 times the inter-story stiffness of the Building1.

Slip mode

When the force in a friction damper exceeds its slip force, the corresponding connected floors vibrate in slip mode. During this mode, the stiffness of that damper will be made equal to zero and the force in that damper is limited to that slip force. Hence, during the slip mode

$$f_{di} = f_{si}\ \mathrm{sgn}(\dot{x}_{i2} - \dot{x}_{i1}) \tag{15}$$

Whenever the velocities of any two connected floors are equal and the force in that friction damper becomes less than its slip force, those two floors again go into the non-slip mode. After each time step, the modes of all the dampers are checked and accordingly the forces in the dampers are calculated. The above equations are solved using the Newmark's linear acceleration method.

RESULTS AND DISCUSSION

For the present study, two adjacent buildings with 20 and 10 stories are considered. The floor mass and inter-story stiffness are considered to be uniform for both buildings. The mass and stiffness of each floor are chosen such that to yield a fundamental time period of as 1.9sec and 0.9 sec of Building1 and Building2, respectively. The damping ratio of 2% is considered for both buildings. Thus, the Building1 may be considered as soft building and Building2 as stiff building. For the uncontrolled system the first three natural frequencies corresponding to first three modes of the building1 are 3.3069, 9.9014, 16.4378 rad/s and that of the Building2 are 6.9813, 20.7880, 34.1303 rad/s respectively. These frequencies clearly show that the modes of the buildings are well separated. The earthquake time histories selected to examine the seismic behavior of the two buildings are: N00S component of El Centro, 1940, N00S component of Kobe, 1995, N90S component of Northridge, 1994 and N00E component of Loma Prieta, 1989. The peak ground acceleration of El Centro, Kobe, Northridge and Loma Prieta earthquake motions are 0.32g, 0.86g, 0.84g and 0.57g, respectively (g is the acceleration due to gravity).

Connected with viscous dampers

The adjacent buildings considered above are first connected with viscous dampers at all the floor levels. To arrive at the optimum damper damping coefficient of the dampers, the variation of the top floor relative displacements, top floor absolute accelerations and base shears of the two buildings are plotted with the damper damping coefficient and are shown in Figure 3 for all the four earthquakes considered. The base shear and damper damping coefficient are normalized with respect to the weight of a floor and damping coefficient of the Building1 respectively. It can be observed that the responses of both the buildings are reduced up to a certain value of the damping, after which they are again increased. Therefore, it is clear from the figures that the optimum damper damping coefficient exists to yield the lowest responses of both the buildings. As the optimum damper damping coefficient is not the same for both the buildings, the optimum value is taken as the one, which gives the lowest sum of the responses of the two buildings. In arriving at the optimum value, the emphasis is given on the displacements and base shears of the two buildings and at the same time care is taken that accelerations of the buildings, as far as possible, are not increased. From the figures, it can be observed that the responses are reduced drastically when the ratio of the damping is 2.273. For ratios higher than this, the performance of the dampers is reduced. At very high damping ratios, the two buildings behave as though they are almost rigidly connected. As a result, the displacements and the velocities of the two buildings become the same. On the other hand, if the damping value is reduced to zero, the two buildings return to the unconnected condition. Hence, the optimum damper damping ratio is taken as 2.273. The time variation of the top floor displacement and base shear responses of the two buildings connected by viscous dampers with optimum

damping at all the floors is shown in Figures 4 and 5. These figures clearly indicate the effectiveness of dampers in controlling the earthquake responses of both the buildings.

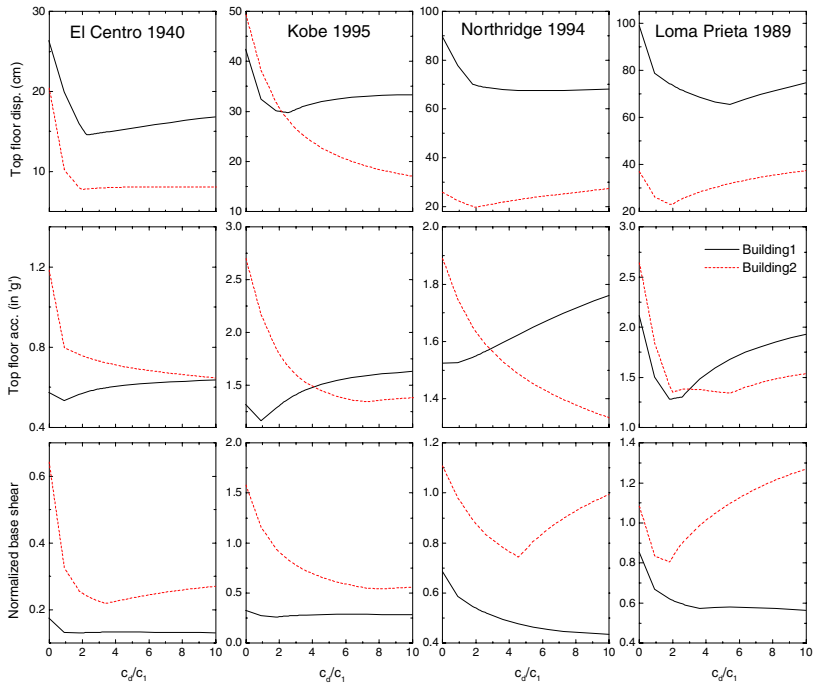

Figure 3. Effect of the damping of the dampers on the responses(Opt c_d/c_1=2.273).

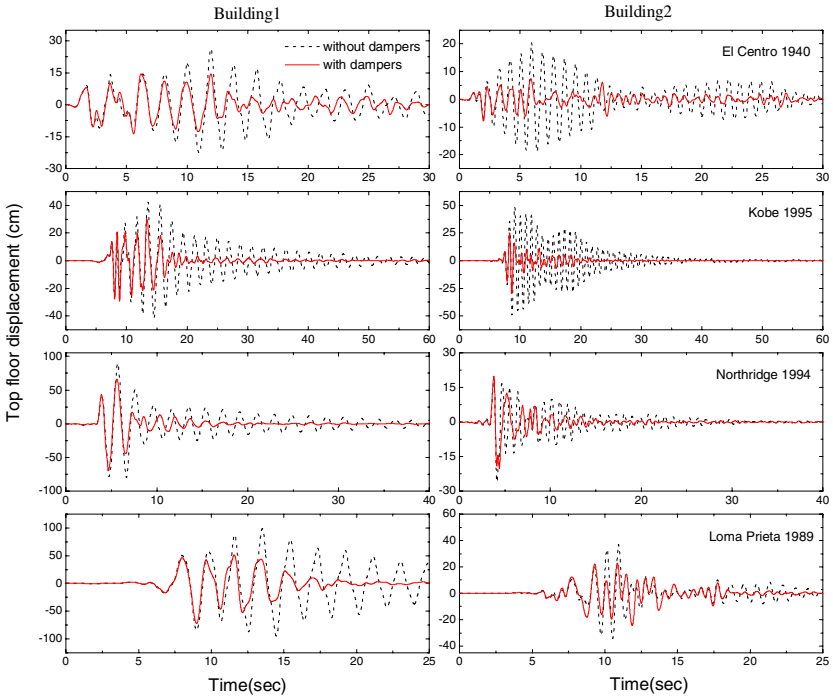

Figure 4. Time histories of top floor displacements of the two buildings.

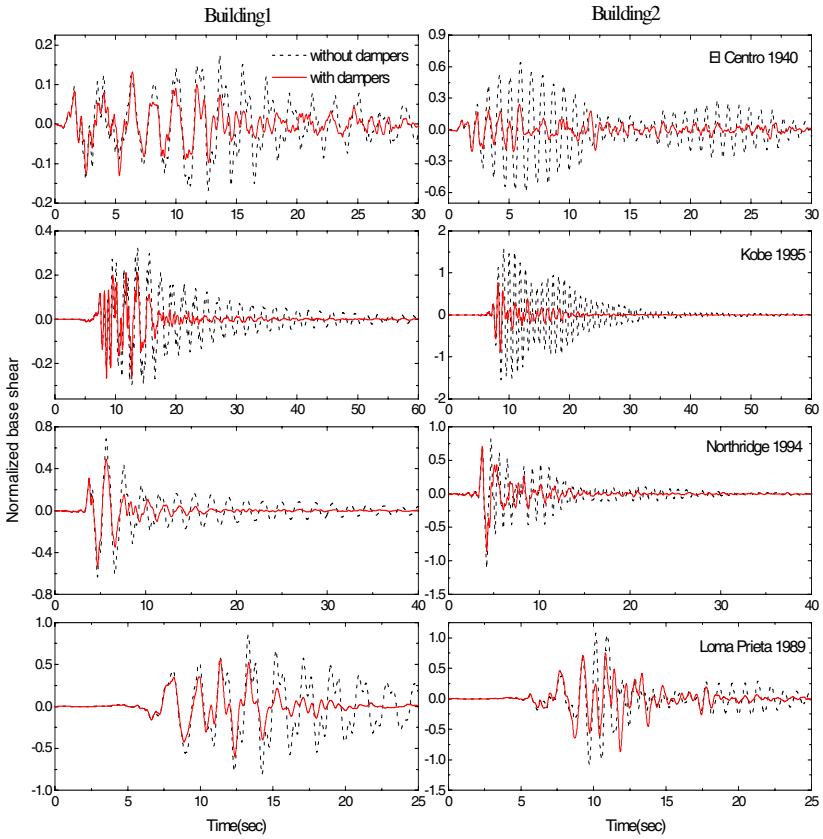

Figure 5. Time histories of base shears of the two buildings.

In order to minimize the cost of dampers, the responses of the adjacent buildings are investigated by considering only five dampers (i.e., 50% of the total) with optimum damping obtained above at selected floor locations. The floors whichever has the maximum relative displacement are selected to place the dampers. Many trials are carried out to arrive at the optimal placement of the dampers, among which Figures 6 and 7 show the variation of the displacements and shear forces in all the floors for four different cases, when (i) unconnected, (ii) connected at all the floors, (iii) connected at 6,7,8,9 and 10 floors and (iv) connected at 2,4,6,8 and 10 floors. It can be observed from the figures that the dampers are more effective when they are placed at 6,7,8,9 and 10 floors. When the dampers are attached to theses floors, the displacements and shear forces in all the stories are reduced almost as much as when they are connected at all the floors. Hence, 6,7,8,9 and 10 floors are considered for optimal placement of the dampers. The reductions in the peak top floor displacements, peak top floor accelerations and normalized base shears of the two buildings for without dampers, connected with viscous dampers at all floors and connected with only five viscous 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 decrease in the reduction of the responses of the two buildings with only 50% dampers is not more than 10% of that obtained for the buildings with dampers connected at all the floors.

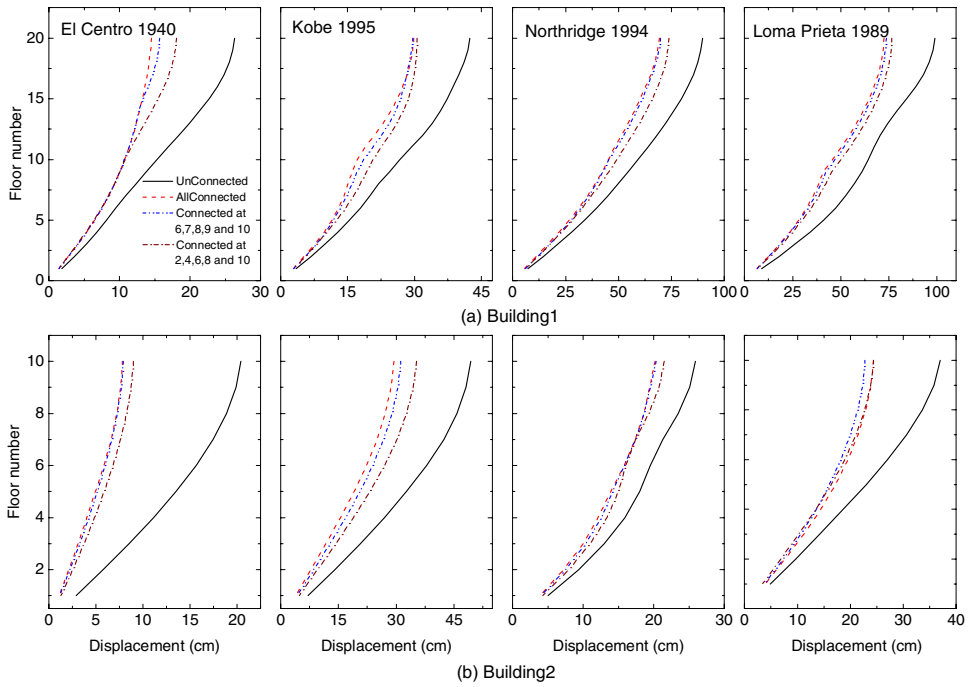

Figure 6. Variation of the displacements along the floors.

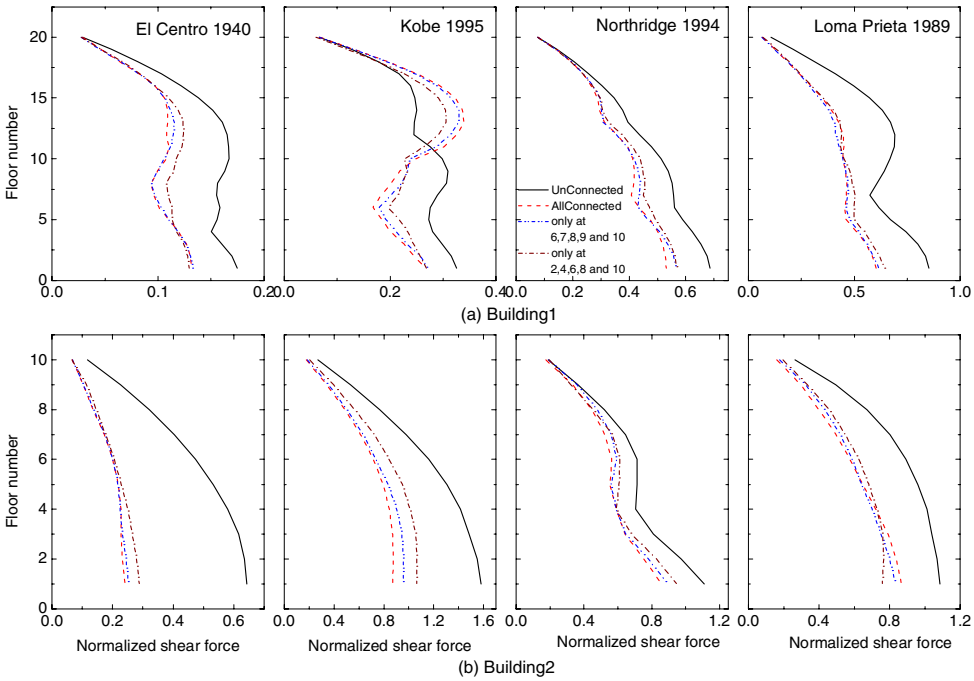

Figure 7. Variation of shear forces along the floors.

Table 1. Seismic Responses of the two buildings for different earthquakes when connected with viscous dampers

Earthquake	Building	Response quantities								
		Top floor displacement (cm)			Top floor acceleration (in 'g')			Normalized base shear		
		Un-connected	Connected at all floors	Connected at 5 floors*	Un-connected	Connected at all floors	Connected at 5 floors*	Un-connected	Connected at all floors	Connected at 5 floors*
El Centro, 1940	1	26.33	14.57 (44.67)#	15.69 (40.41)	0.57	0.57 (0.0)	0.56 (2.9)	0.17	0.13 (24.75)	0.13 (24.12)
	2	20.43	7.83 (61.67)	7.92 (61.23)	1.19	0.75 (36.74)	0.77 (35.36)	0.64	0.24 (62.51)	0.25 (60.74)
Kobe, 1995	1	42.42	29.87 (29.59)	29.64 (30.13)	1.31	1.31 (0.0)	1.31 (0.0)	0.33	0.27 (17.75)	0.27 (16.87)
	2	49.36	29.41 (40.42)	31.24 (36.71)	2.70	1.73 (35.79)	1.82 (32.63)	1.58	0.87 (44.88)	0.96 (39.43)
Northridge, 1994	1	89.61	69.22 (22.75)	69.83 (22.07)	1.52	1.52 (0.0)	1.52 (0.0)	0.69	0.53 (22.56)	0.57 (17.43)
	2	25.88	20.15 (22.14)	20.34 (21.41)	1.89	1.61 (14.67)	1.64 (13.45)	1.11	0.86 (22.67)	0.89 (19.35)
Loma Prieta, 1989	1	98.95	72.50 (26.73)	73.66 (25.56)	2.11	1.29 (38.78)	1.31 (38.11)	0.85	0.60 (29.10)	0.62 (27.61)
	2	36.99	24.41 (34.01)	22.78 (38.42)	2.64	1.37 (48.32)	1.46 (44.77)	1.08	0.87 (20.00)	0.83 (23.01)

* connected at the floors 6,7,8,9 and 10. # quantity within the parentheses denotes the percentage reduction

Connected with viscoelastic dampers

The seismic behavior of the two buildings is next examined when connected with viscoelastic dampers. The same optimum damping obtained above for viscous dampers is considered for the viscoelastic dampers also and the effect of the stiffness of the dampers on the responses is studied. The variations of the top floor displacements and base shears with the stiffness of the dampers, normalized with respect to the stiffness of the first building, are shown in Figure 8. It can be observed from the figures that the advantage we get due to viscoelastic dampers over and above the viscous dampers is very meager and can be neglected in this case. It is seen from the graphs, there is much reduction in the responses of the buildings for a stiffness ratio of less than 0.002 compared with that of unlinked buildings. It can also be seen that if the stiffness ratio is less than 1×10^{-4}, the stiffness of the damper has no effect on the responses of the buildings and it is observed that the frequencies of both the buildings are unaltered. 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 buildings. Therefore, the ratio of 1×10^{-4} is selected as the optimum stiffness ratio for the dampers. If the stiffness ratio is increased beyond 0.002, it is seen that the strong damper stiffness reduces the relative displacement and the velocity of the damper and hence the performance of the dampers deteriorates. Moreover, the top floor displacement and the base shear of the stiff building may increase compared to that of unlinked condition. When the stiffness ratio is increased beyond 0.5, the relative displacement and velocity between the adjacent buildings become nearly zero due to very stiff damper, which implies that the two buildings behave as rigidly connected and hence, the damper losses it's effectiveness completely. It can be concluded that the reductions in the responses of the two buildings when connected with viscoelastic dampers are more or less the same as obtained when connected with viscous dampers and the stiffness of the dampers should be chosen such that it should not affect the dynamic characteristics of the two buildings.

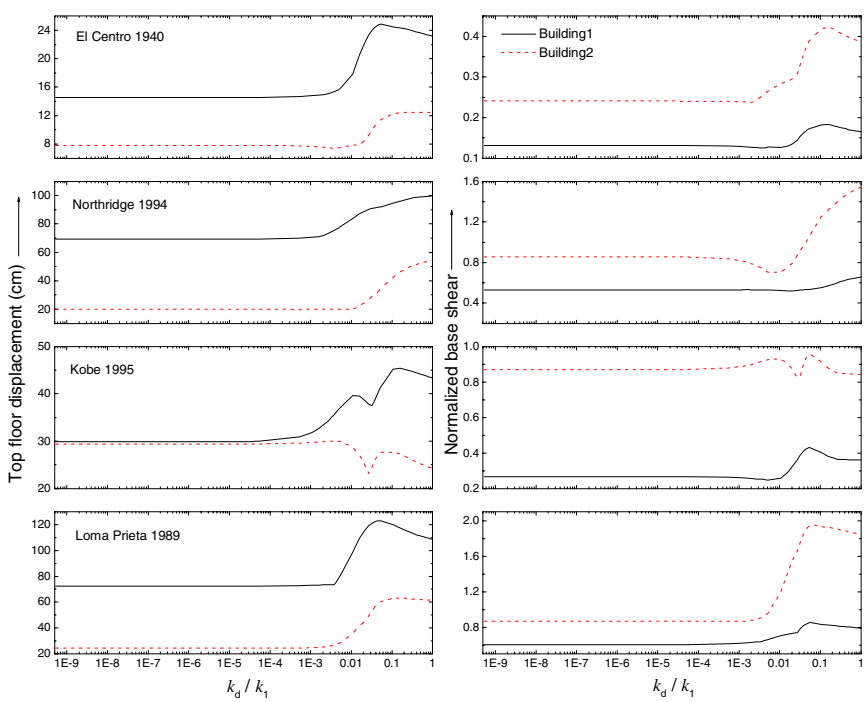

Figure 8. Effect of stiffness of the damper on the responses (Opt k_d / k_1=1x10^{-4}).

Connected with friction dampers

In the third case, the seismic behavior of the two buildings when connected with the friction dampers is investigated. The slip force is normalized with the weight of a floor to get the normalized slip force ($\bar{f}_s$). Figure 9 shows the variation of the responses with the normalized slip force, when both the buildings are connected with friction dampers at all the floors. It can be seen that the drastic reduction in the responses of the buildings up to certain slip force, after which the responses are increased, showing that there exists an optimum value of slip force in the friction dampers. From the figures, the optimum normalized slip force may be considered as 0.204. To arrive at the optimum placement of the friction dampers, the same procedure that followed for viscous dampers is followed and here also it is observed that when dampers are placed at 6,7,8,9 and 10 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 obtained when the two buildings are unconnected, connected with friction dampers at all the floors and connected with only 5 friction dampers at optimal locations are presented in Table 2. These reductions in the responses are in the same range as that obtained when connected with viscous dampers.

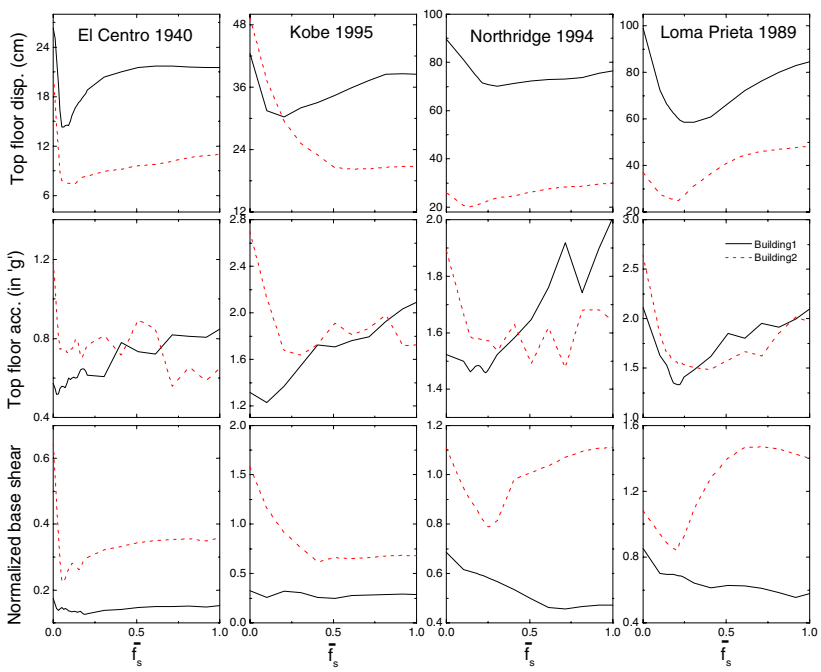

Figure 9. Effect of slip force on the responses (Opt $\bar{f}_s$=0.204).

Table 2. Seismic Responses of the two buildings for different earthquakes when connected with friction dampers

Earthquake	Building	Response quantities								
		Top floor displacement (cm)			Top floor acceleration (in 'g')			Normalized base shear		
		Unconnected	Connected at all floors	Connected at 5 floors*	Unconnected	Connected at all floors	Connected at 5 floors*	Unconnected	Connected at all floors	Connected at 5 floors*
El Centro, 1940	1	26.33	14.30 (45.69)#	15.27 (42.03)	0.57	0.55 (3.00)	0.48 (15.51)	0.17	0.14 (18.94)	0.15 (10.97)
	2	20.43	7.64 (62.60)	8.49 (58.42)	1.19	0.75 (36.78)	0.79 (32.91)	0.64	0.22 (65.28)	0.29 (53.50)
Kobe, 1995	1	42.42	30.30 (28.58)	30.32 (28.54)	1.31	1.37 (-4.32)	1.31 (0.0)	0.33	0.32 (1.34)	0.28 (11.74)
	2	49.36	29.48 (40.28)	32.56 (34.04)	2.70	1.67 (37.85)	1.89 (29.68)	1.58	0.92 (41.87)	1.02 (35.39)
Northridge, 1994	1	89.61	72.35 (19.26)	77.28 (13.76)	1.52	1.48 (2.96)	1.52 (1.18)	0.69	0.59 (13.14)	0.63 (8.29)
	2	25.88	21.47 (17.06)	21.35 (17.50)	1.89	1.57 (16.58)	1.61 (14.61)	1.11	0.83 (24.76)	0.88 (19.98)
Loma Prieta, 1989	1	98.95	60.82 (38.54)	63.94 (35.38)	2.11	1.34 (36.78)	1.54 (27.25)	0.85	0.69 (18.98)	0.70 (17.91)
	2	36.99	25.02 (32.35)	26.68 (27.86)	2.64	1.56 (40.90)	1.65 (37.57)	1.08	0.84 (22.28)	0.91 (16.11)

* connected at the floors 6,7,8,9 and 10. # quantity within the parentheses denotes the percentage reduction

CONCLUSIONS

From the trends of the results of the present study, following conclusions are drawn:

1. The dampers are found to be very effective in reducing the earthquake responses of the adjacent buildings and also helpful in avoiding the pounding phenomenon.
2. There exits optimum parameters for the dampers for minimum earthquake response of the buildings.
3. The advantage of viscoelastic dampers over and above the viscous dampers is very less and there is a possibility of increase in the base shear of stiff building when stiffness of the dampers is not taken properly.
4. The reductions in the responses when connected with the friction dampers are in the same range as that obtained when connected with viscous dampers.
5. It is not necessary to connect the two adjacent buildings by dampers at all floors but lesser dampers at appropriate locations can significantly reduce the earthquake response of the combined system almost as much as when they are connected at all the floors.
6. The neighboring floors having maximum relative displacement should be chosen for optimal dampers locations.

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