Dynamic analyses of adjacent buildings connected by fluid viscous dampers

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Abstract

Building structures are often built close to each other because of lack of available land in metropolitan cities. In this study, the effectiveness of fluid viscous dampers is investigated in terms of the reduction of displacement, acceleration and shear force responses of adjacent buildings. The specific objectives of this investigation are carried out in three parts namely: (1) to formulate the equations of motion for the two adjacent buildings connected with viscous dampers; (2) to find out the effectiveness of fluid viscous dampers in consideration of the three-dimensional vibration mitigation analysis when the dampers are connected at all the floors, using both a response spectrum analysis and a time-history analysis; and (3) to investigate the optimal placement of the fluid viscous dampers instead of placing them at all the floors in order to minimise the cost of the dampers. Results show that by using 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. Analysis results of this study show that placing fluid viscous dampers at selected floors will result in a more efficient structural system to mitigate earthquake effects.
Keywords: adjacent buildings, fluid viscous joint dampers, earthquake excitations, time-history analysis, parametric study.

1 Introduction

In civil structures, the aim is to protect them from large seismic events through providing redundancies. In recent years, medium and high-rise structures have begun installing control systems, such as passive, active and semiactive devices

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to reduce responses. In ultrahigh-rise buildings, controlling with these devices is difficult and relatively flexible due to large energy requirements.

Coupled building control was suggested for adjacent building to exert forces upon one another. This concept was first introduced by Klein et al. [1] nearly three decades ago. Christenson et al. [2] proposed that coupled building research has gradually achieved momentum from planned research concepts to real implementation. Various control strategies are investigated by a number of researchers and full-scale applications are beginning to appear. According to Seto [3], coupling buildings has been indicated to become a workable choice for the protection of adjacent flexible structures. For passive controls, many strategies have been studied for both high- and low-rise adjacent buildings. Gurley et al. [4] and Sugino et al. [5] have each studied the case of adjacent tall structures with passive devices, while Luca and De Barros [6], Xu et al. [7] have studied connecting low-to medium rise structures with passive devices. Mitigating seismic response of adjacent structures connected with active control devices has been investigated by Seto and Mitsuta [8].

Xu et al. [7] studied the dynamic response of damper-connected adjacent buildings under earthquake excitation. They observed that the ground acceleration due to earthquake is regarded as a stochastic process, and a pseudo-excitation algorithm in the frequency domain is implemented in a computer program to handle non-classical damping properties of the system. They also proposed that the optimum damper properties can be found through parametric studies.

The effectiveness of the fluid damper-defined Maxwell model and the effectiveness of the viscoelastic damper-defined Voigt model in coupled high-rise buildings under earthquake-induced movement were investigated by Zhang and Xu [9]. In their study, the Maxwell model-defined fluid dampers could be the same as that connected by the Voigt model-defined viscoelastic dampers, and the seismic response of adjacent buildings was determined by the pseudo-excitation method. The studies demonstrated that parameters of fluid dampers could reduce the seismic response of adjacent buildings if damper properties are appropriately selected. Moreover, using the dampers with optimal parameters to link the adjacent buildings can increase the modal damping ratios. Thus, optimal parameters of passive element such as damping and stiffness under different earthquake excitations can influence the structural parameters of the system.

In order to investigate the effectiveness of linear viscous dampers vibration mitigation, this paper presents a three dimensional analysis of the response of two neighbouring buildings under various earthquake excitations. The four example models are presented in this application. Moreover, the buildings are connected with fluid viscous dampers placed at different levels. The effectiveness of fluid joint dampers is then investigated in terms of the reduction of displacement, acceleration and shear force responses of adjacent buildings. Finally, an extensive parametric study is carried out to find the optimum damper placements in adjacent buildings both having the same stiffness ratios and having different stiffness ratios.

2 Formulation

The theoretical formulation for modelling two adjacent buildings connected by viscous dampers is presented. The efficiency of fluid viscous dampers for the coupled building into equations of motion is shown by using the MDOF coupled building model in Figure 1.

2.1 Equations of motion

Building A and Building B have n + m stories and n stories, respectively, as shown in Figure 1. The mass, damping coefficient and shear stiffness values for the ith storey are mi,1, ci,1 and ki,1 for Building A and mi,2, ci,2 and ki,2 for Building B, respectively. The stiffness of viscous damper and the coefficient of damping at the ith floor are represented as kd,i and cd,i, respectively.

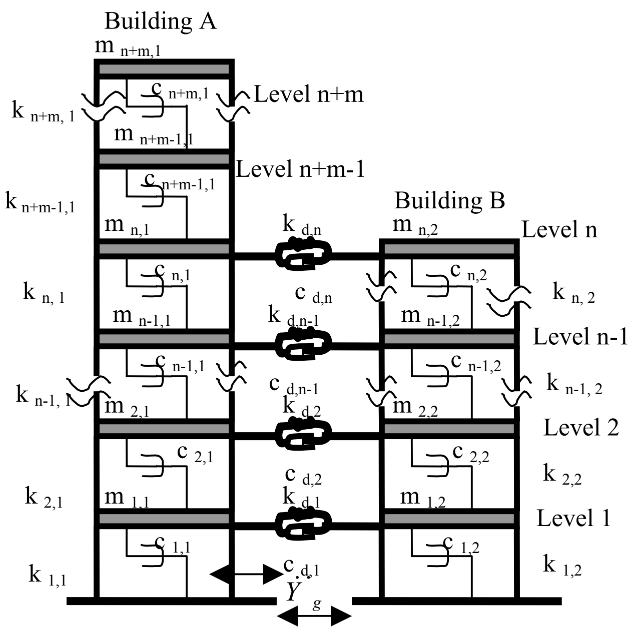

Figure 1: Structural model of coupled buildings with joint dampers.

The dynamic model of the coupled buildings is taken to have a 2n+m degrees of freedom system. The equations of motion for this system are expressed as follow:

$$M\ddot{Y} + (C + C_d)\dot{Y} + (K + K_d)Y = - MI\,\ddot{y}_g \tag{1}$$

where M, C and K are the mass, damping and stiffness matrices of the coupled buildings, respectively; Cd and Kd are the additional damping and stiffness matrices consisting of the installation of the fluid viscous damper; Y is the relative displacement vector with respect to the ground and consists of Building A's displacements in the first n + m positions and Building B's displacements in the last n positions; I is a unity matrix with all its diagonal elements equal to unity and rest equal to 0; $\ddot{y}_g$ is the earthquake acceleration at the foundations of the buildings. The details of each matrix are shown as follows:

$$M=\begin{bmatrix} m_{n+m,n+m} & 0_{n+m,n} \\ 0_{n,n+m} & m_{n,n} \end{bmatrix};K=\begin{bmatrix} K_{n+m,n+m} & 0_{n+m,n} \\ 0_{n,n+m} & K_{n,n} \end{bmatrix};$$

$$C=\begin{bmatrix} C_{n+m,n+m} & 0_{n+m,n} \\ 0_{n,n+m} & C_{n,n} \end{bmatrix} \tag{2}$$

$$C_d=\begin{bmatrix} c_{d(n,n)} & 0_{(n,m)} & -c_{d(n,n)} \\ 0_{(m,n)} & 0_{(m,m)} & 0_{(m,n)} \\ -c_{d(n,n)} & 0_{(n,m)} & c_{d(n,n)} \end{bmatrix};K_d=\begin{bmatrix} k_{d(n,n)} & 0_{(n,m)} & -k_{d(n,n)} \\ 0_{(m,n)} & 0_{(m,m)} & 0_{(m,n)} \\ -k_{d(n,n)} & 0_{(n,m)} & k_{d(n,n)} \end{bmatrix} \tag{3}$$

$$Y^T = \left[y_{11}, y_{21}, \ldots, y_{n+m-1,1}, y_{n+m,1}, y_{12}, y_{22}, \ldots, y_{n-1,2}, y_{n,2}\right] \tag{4}$$

And 0 is described as a zero matrix. For the time domain analysis, the above equations can be used directly for any given time history record of ground motion.

2.2 Computer program and earthquake data

Analytical modelling of the fluid viscous dampers is accomplished by using the SAP 2000n package program [10]. The aim of the analysis is to provide the amount of reduction in the seismic response of the adjacent buildings by using fluid viscous dampers installed at each storey level. Additionally, the amount of reduction by using fluid viscous dampers installed at few storey levels is investigated for determining the optimum placement of the dampers.

All earthquake records with the same time intervals have been selected in order to examine the behaviour of fluid viscous damper. The earthquake time histories selected to investigate the dynamic analysis of the two buildings in four example applications are: the 1940 El Centro Earthquake, the 1994 Northridge Earthquake, the 1989 Loma Prieta earthquake and the 1995 Kobe Earthquake.

All the aforementioned earthquakes have their original duration of 60 s taken at a total of 3000 time records at an interval of Δt =0.02 s. Without varying the total time number, the time interval Δt of the earthquake can be varied to alter the predominant frequency of the input motion. However, in this study, the time interval Δt is selected as 0.02 s. The time history responses including horizontal displacements, velocities, accelerations and internal forces at all joints and members in all degrees of freedom have been computed.

2.3 Modelling the fluid viscous dampers

In this study, the fluid viscous dampers have been modelled by the linear properties (LPROP) and linear link (LLINK) data forms of the SAP 2000n computer program. In addition to, LLINK for fluid viscous damper is designed as hinging in the X and Y directions. For each deformational degree of freedom, independent damping properties may be specified. The linear damper behaviour is given by

$$F_T = C\,V^{c\,exp} + K\,D_k = F_D + F_E \tag{5}$$

Where F_T is the total output force provided by the damper, C is the damping coefficient, K is the spring constant, V and D_k are the velocity across the damper and the displacement across the spring, respectively, c exp is the damping exponent. The damping exponent must be positive. The practical range between c exp=0.5 and 2.0 is determined. In the numerical data of this study, c exp is taken as unity. It is evident that F_T consists of two parts. The first is the damping force F_D which equals $C\,V^{c\,exp}$. The second is the restoring force F_E which equals K Dk. Eq. 5 shows that the damper is linear. For the analytical modelling, four earthquakes are applied to the four example buildings. Furthermore, the fluid viscous dampers are modelled by SAP 2000n computer program. Section 3 presents the application of four example buildings.

3 Application to example buildings

In order to investigate the effects of the fluid viscous damper for adjacent buildings, four example models are presented in this application. All examples have some different characteristics. For example, Example 1 consists of one 10-storey building and one 5-storey building having the same floor elevations with dampers connecting two neighbouring floors which have the same stiffness and the same structural damping ratio, while Example 2 consists of one 15-storey building and one 10-storey building having the same floor elevations with dampers linking two adjacent floors which have different stiffness coefficient because of using different size of columns and beams. Example 3 consists of two 20-storey buildings having the same elevations with dampers connecting two neighbouring floors which have the same stiffness and the same structural damping ratio. Finally, Example 4 consists of two 20-storey buildings having different shear stiffness. The damper stiffness and the damper coefficient in all the four cases are the same of $k_d = 1.0 \times 10^5\ N/m$ and the same of $c_d = 1.0 \times 10^6\ N \times s/m$. Table 1 shows the sizes of columns and beams in the buildings for all examples mentioned above.

For all modes, both buildings have damping ratios 5% of the critical structural damping (ζ=0.05). In this way, the structural damping coefficient in SAP 2000n is automatically calculated from the expression shown below.

$$[C] = diag\,(2\,M\,\zeta\,w) \tag{6}$$

where [C] is the modal damping matrix, M, ζ and w are the modal mass, the damping ratio and natural frequency, respectively. The typical slab loads at each storey of all examples have one point load on one-third span points for all beams

54 kN from the secondary beams and a uniformly distributed load of 59.1 kN/m along the beams throughout. The following section shows the results of these four examples to understand the effectiveness of fluid viscous damper for the different types of adjacent buildings.

Table 1: The sizes of columns and beams in the buildings for each example.

Example	Building A		Building B	
No	Beams (mm)	Columns (mm)	Beams (mm)	Columns (mm)
1	300x500	500x500	300x500	500x500
2	300x700	600x600	300x600	500x500
3	300x700	600x600	300x700	600x600
4	300x700	600x600	300x600	500x500

4 Results

In this paper, the numerical study is carried out in three sections. All obtained results are evaluated by SAP 2000n computer program, using both frequency domain and time domain. This section presents the effectiveness of fluid viscous dampers investigated in terms of the reduction of displacement, acceleration and shear force responses of the coupled buildings in four different examples. Moreover, optimum placement of dampers for all examples is determined, creating some cases on linking dampers.

4.1 Results in frequency domain

In this paper, the graphs of the examples which show the displacement-frequency in Lome Prieta 1989 and the acceleration-frequency in Northridge 1994 are presented separately for each example. Figure 2 shows that amplitudes of top floor displacement in all examples are reduced by using damper for both building. The displacements in the lowest natural frequencies for buildings connected by dampers become higher with increasing frequency in all earthquakes when it is compared with buildings unconnected by dampers.

Frequency domain is graphically evaluated in terms of the spectral density functions of acceleration for the four example buildings as shown Figure 3. In Example 1 and Example 2, it can be clearly seen that by using damper for the lower Building B is more beneficial than the higher Building A. In Example 3, it can be observed that the peaks are slowly changed, although the buildings have the same dynamic characteristics.

However, using damper does not help to mitigate the response of top floor acceleration. In Example 4, the effectiveness of dampers in the building having the strong stiffness is more valuable than Building B.

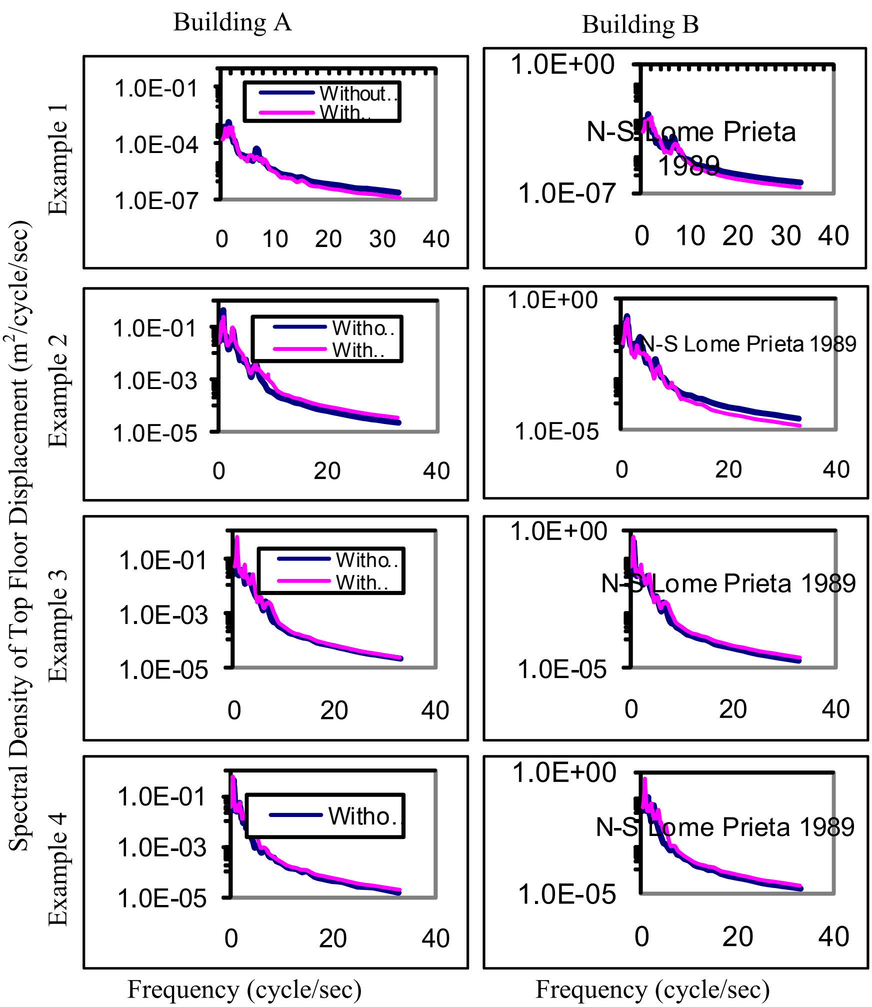

Figure 2: Spectral density of top floor displacements of two adjacent buildings for all examples.

4.2 Results in time domain

In time domain, Figure 5 shows that dampers in all examples provide mitigating the response of top floor displacements in terms of time factor.

In Example 1 and Example 2, it is shown that the amplitudes of displacement are reduced significantly in N-S direction, while the unlinked and the linked buildings are the same the reduction of the amplitude of displacement in E-W direction. The maximum reduction of the top floor displacement is 50% in Example 1, while the reduction is almost 35% in Example 2. Example 3 shows that the using damper for high adjacent buildings having the same characteristics cannot be reduced to the amplitude of displacements. Example 4 investigates that the absolute displacements in terms of floor number are mitigated using fluid dampers for high adjacent buildings having different shear stiffness.

Figure 6 demonstrates the shear force-time graphs for all examples in N-S direction using the Lome Prieta 1989 earthquake. The dampers can mitigate the amplitudes of shear forces in the related earthquake which is in N-S direction. The amplitudes of the forces for earthquakes mentioned above in E-W direction are not reduced.

As shown in Figure 4, the reduction of shear forces for Example 4 is more than Example 3. After the first ten seconds, the peak responses of the buildings in N-S direction in both earthquakes are reduced with the peak response reduction range from 10% to 20%.

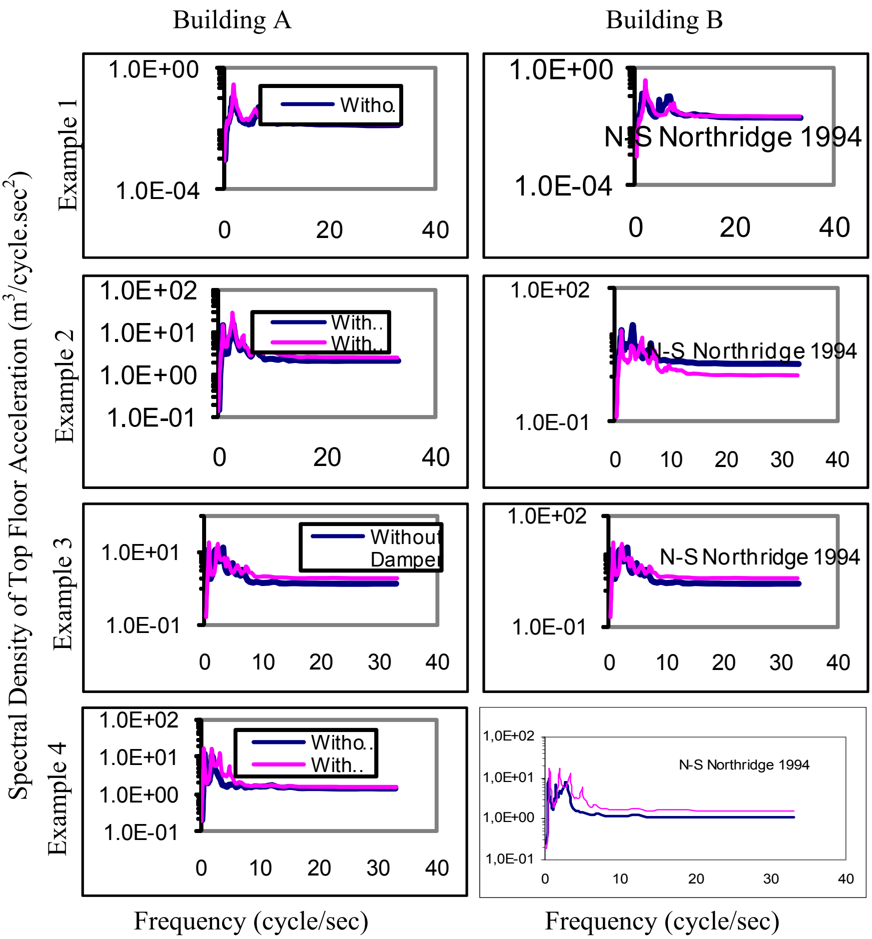

Figure 3: Spectral density of top floor acceleration of two adjacent buildings for all examples.

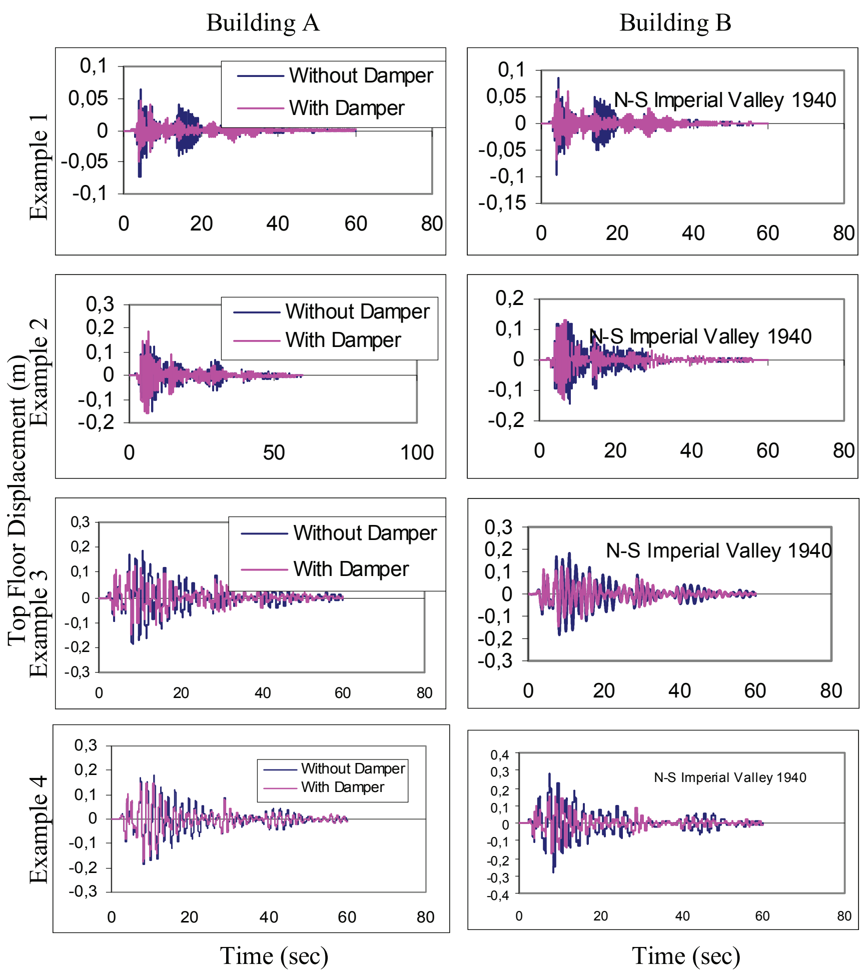

Figure 4: Time histories of top floor displacements of the two adjacent buildings for all examples.

4.3 Optimum placement of dampers

In order to investigate the effect of damper position on the behaviour of the buildings, for each example, four cases of damper placements were investigated. Case (i) represents the central case where the buildings are not connected. In Case (ii), the dampers are placed in all floors. The dampers in Case (iii) are placed at odd floors. Finally, the dampers in Case (iv) are placed in the floors above the middle of the shorter buildings. Figure 6 demonstrates the variation of the displacements along the floors for all examples.

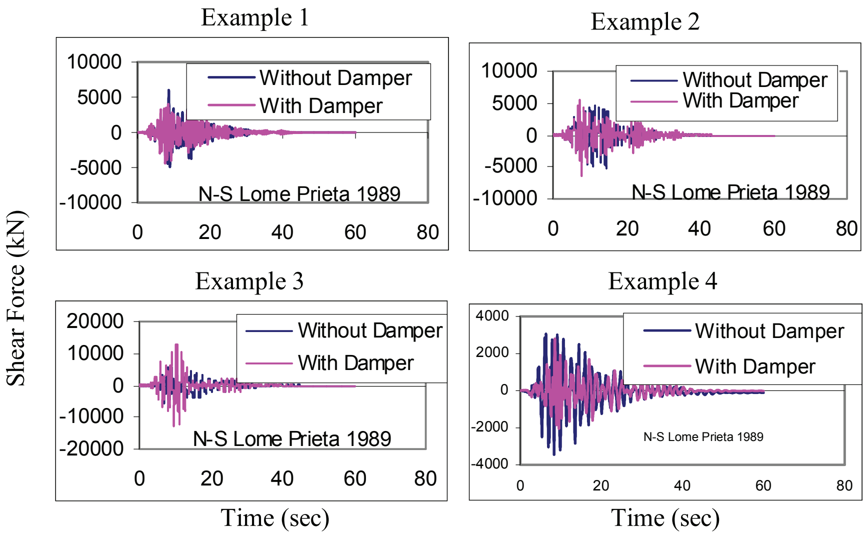

Figure 5: Shear force- time graphs in N-S and E-W directions for all examples.

All examples calculated in each case show that the dampers at suitable placements can reduce significantly the seismic responses of the coupled system. This reduces the cost of the dampers to a greater level.

5 Conclusions

Based on findings the present studies, the following conclusions can be drawn:

- Dampers have a major role in controlling the earthquake responses of the adjacent buildings except the buildings having the same characteristics including height.
- The effectiveness of fluid viscous dampers becomes less important for the taller buildings than the shorter buildings.
- The efficiency of fluid viscous dampers becomes more beneficial for the adjacent buildings having the different height than those of the same heights.
- For lower buildings, lesser dampers at appropriate placements can be more effective than dampers at all floors.
- For higher buildings, it can be the opposite of the situation in some big earthquakes.

Finally, it can be concluded that placing appropriate fluid viscous dampers between adjacent buildings improves the behaviour of buildings to earthquakes.

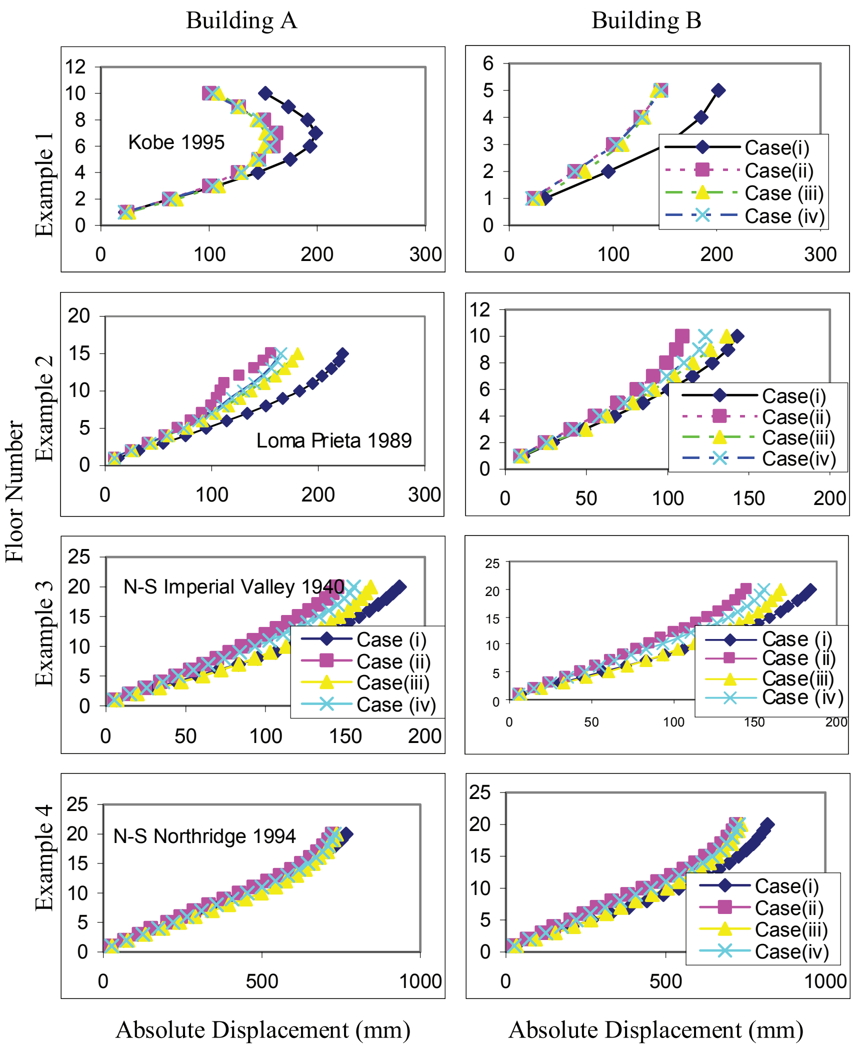

Figure 6: Variation of the displacements along the floors for all examples.

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