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Seismic performance of structures connected by viscoelastic dampers

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Abstract

This study investigates the effect of installing viscoelastic dampers (VEDs) in places such as seismic joints or building–sky-bridge connections to reduce earthquake-induced structural responses. To investigate the effectiveness of the proposed scheme, parametric studies are conducted first using single-degree-of-freedom systems connected by VEDs and subjected to white noise and earthquake ground excitations. From the parametric study, it is shown that there exists a certain size of a VED that minimizes the dynamic responses of the structures, and that such a scheme is effective only when the natural frequencies are different enough. Then dynamic analyses are carried out with 5-story and 25-story rigid frames connected to braced-frames. According to the analysis results, the use of VEDs in seismic joints or in sky-bridges can be effective in reducing earthquake-induced responses if the connected structures are designed in such a way that the natural frequencies become quite different. This can be achieved by designing the connected structures to have different structural systems.

Keywords: Viscoelastic dampers; Seismic design; Passive control; Adjacent structures

1. Introduction

Viscoelastic dampers (VEDs) are usually placed in building inter-stories where the relative inter-story drift and velocity are maximized. However, such locations are frequently objected to by architects or building owners because VEDs attached to diagonal or chevron braces frequently interfere with spatial planning and obstruct internal view. These shortcomings would be overcome by installing VEDs across seismic joints or in building–sky-bridge connections as illustrated in Fig. 1, if such scheme is effective enough. In this case the possibility of pounding between adjacent structures can also be removed.

It is not unusual that structures located closely are connected by sky-bridges; the Petronas Towers in Kuala Lumpur, Malaysia, are a good example. Also there are many cases when a large structure is divided horizontally into many smaller pieces by expansion or seismic joints. Expansion joints are usually applied to prevent cracks caused by either temperature change or differential settlement of foundations, etc. In seismic regions, structural parts with different shapes or masses in a single large structure are frequently separated by seismic joints to reduce earthquake-induced load effects, such as torsional loads or higher mode effects, etc. In this case the adjacent structures need to be distanced properly to prevent pounding of structures. As the displacement response generally increases as the structure height increases, the width of seismic joints is widened as the height of connected floors increases. Moreover, as the distance between two adjacent structures increases, the cost for constructing proper seismic joints would also increase.

Recently Zhang and Xu [1] investigated the dynamic characteristics and seismic response of adjacent buildings linked by viscoelastic dampers using a complex mode superposition method. They concluded that if damper parameters are selected appropriately, the modal damping ratios can be increased and therefore the earthquake-induced dynamic responses of both buildings can be significantly reduced. Yang and Lu [2] investigated experimentally the seismic responses of 6-story and 5-story structures

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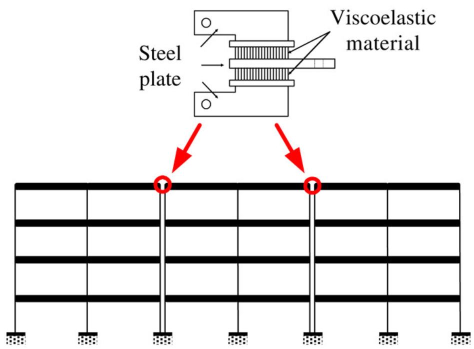
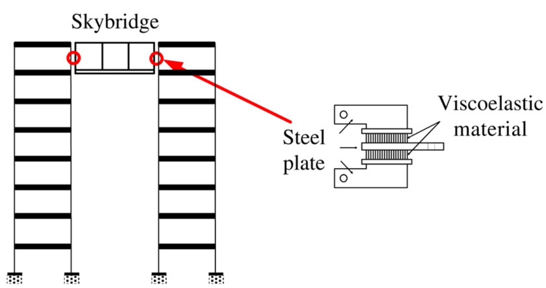


(a) Structures with seismic joints.



(b) Structures connected by a sky-bridge.

Fig. 1. Structures connected by VEDs.

connected by fluid viscous dampers using a seismic simulator. They found that the seismic performance of the two model structures could be significantly increased by the installation of dampers while the natural frequencies of both structures remained almost unchanged. Xu and Yang [3] presented a study of the inelastic seismic response of adjacent buildings linked by fluid dampers. In their study elastic–plastic seismic responses of the two steel frames with and without fluid dampers were computed, and the performance of fluid dampers on controlling the inelastic seismic response of the two steel frames was assessed. Johnson et al. [4] presented a case study of installing viscous dampers across expansion joints in a structure located close to an active fault. According to an analytical study the dampers turned out to be effective at reducing earthquake-induced displacement across expansion joints.

This study investigates the effect of installing viscoelastic dampers (VEDs) between structures in such places as building–sky-bridge connections or across seismic joints to reduce earthquake-induced structural responses. Focus is on the mitigation of earthquake-induced inelastic deformation and hysteretic energy demand. To investigate the effectiveness of the proposed scheme, parametric studies are conducted first in elastic domain using single-degree-of-freedom systems connected by VEDs and subjected to white noise ground excitations. Then a series of nonlinear dynamic time history analyses using earthquake loads are carried out on single-story shear building models to investigate the effect of varying natural period ratio on displacement response, hysteretic energy, and base shear. Finally the

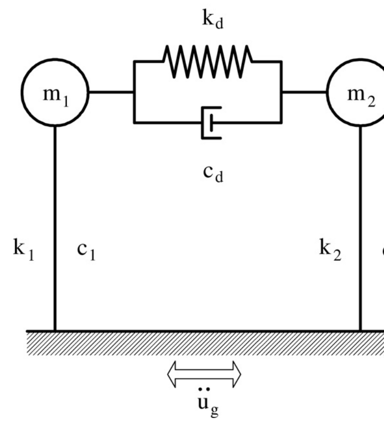


Fig. 2. A 2-DOF structure connected by a VED.

validity of the proposed scheme is verified by dynamic analyses of 5-story and 25-story steel structures connected by viscoelastic dampers.

2. Responses of 2-DOF systems subjected to a white noise ground excitation

VEDs have both elasticity and viscosity, and the behavior of VEDs is usually simulated by the Kellvin model, which models the VED by an elastic spring and a viscous dashpot connected in parallel. In this case the stiffness and the damping constants can be represented as follows [5].

$$k_d = \frac{G'(\overline{\omega})A}{t} \qquad c_d = \frac{G'(\overline{\omega})A}{\overline{\omega}t} \tag{1}$$

where G' and G'' are the storage and the loss moduli of viscoelastic material, respectively, A and t are the shear area and thickness of the layer of viscoelastic material, respectively, and ω is the forcing frequency, for which the fundamental natural frequency of the structure is usually used. The equation of motion of the 2-DOF system connected by a VED, shown in Fig. 2, is expressed as follows:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{Bmatrix} + \begin{bmatrix} c_1 + c_d & -c_d \\ -c_d & c_2 + c_d \end{bmatrix} \begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{Bmatrix} + \begin{bmatrix} k_1 + k_d & -k_d \\ -k_d & k_2 + k_d \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} = - \begin{Bmatrix} m_1 \ddot{u}_g \\ m_2 \ddot{u}_g \end{Bmatrix} \tag{2}$$

where m_1, c_1 and k_1 are the mass, damping and the stiffness of structure 1, respectively, and m_2, c_2 and k_2 are those of structure 2. If the ground excitation is assumed to be a harmonic motion, i.e., $\ddot{u}_g = e^{i\omega t}$, the displacement responses of both the masses are as follows:

$$u_1 = H_1(\omega)e^{i\omega t}, \qquad u_2 = H_2(\omega)e^{i\omega t} \tag{3}$$

where $H(\omega)$ is the complex frequency response function, which can be obtained by the Fourier transformation of a unit impulse response function. By substituting Eq. (3) into Eq. (2) the complex frequency response functions for displacement of the two structures can be derived as follows:

$$H_1(\omega) = \frac{B_1}{A} \qquad H_2(\omega) = \frac{B_2}{A} \tag{4}$$

$$B_1 = m_1 m_2 \omega^2 - \{m_2 c_d + m_1(c_2 + c_d)\}\mathrm{i}\omega - \{m_2 k_d + m_1(k_2 + k_d)\}$$

$$B_2 = m_1 m_2 \omega^2 - \{m_1 c_d + m_2(c_1 + c_d)\}\mathrm{i}\omega - \{m_1 k_d + m_2(k_1 + k_d)\}$$

$$\begin{aligned} A = {} & m_1 m_2 \omega^4 - \{m_2(c_1 + c_d) + m_1(c_2 + c_d)\}\mathrm{i}\omega^3 \\ & - \{m_2(k_1 + k_d) + (c_1 + c_d)(c_2 + c_d) \\ & + m_1(k_2 + k_d) - c_d^2\}\omega^2 + \{(k_1 + k_d)(c_2 + c_d) \\ & + (c_1 + c_d)(k_2 + k_d) - 2c_d k_d\}\mathrm{i}\omega + (k_1 + k_d) \\ & \times (k_2 + k_d) - k_d^2. \end{aligned}$$

Using the frequency response functions, the power spectral density function for response $S_y(\omega)$ is obtained as

$$S_y(\omega) = |H(\omega)|^2 S_X(\omega) \tag{5}$$

where $S_X(\omega)$ is the power spectral density function for excitation. If the ground excitation is assumed to be the white noise with an amplitude of $S_X(\omega) = S_0$, then the mean square response can be computed as follows:

$$E[y_1^2] = \int_{-\infty}^{\infty} |H_1(\omega)|^2 S_0 \,\mathrm{d}\omega$$

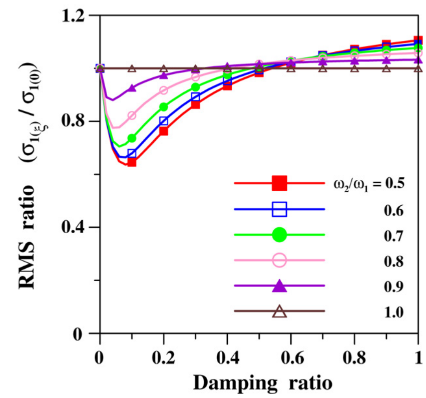
$$E[y_2^2] = \int_{-\infty}^{\infty} |H_2(\omega)|^2 S_0 \,\mathrm{d}\omega. \tag{6}$$

The mean square acceleration responses can be obtained using the complex frequency response function $H(\omega)$:

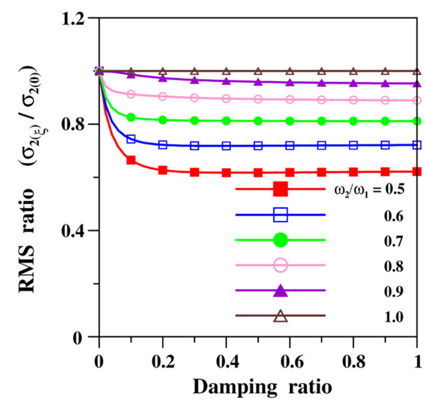
$$H_1(\omega) = \frac{-\{(c_1 + c_d)\mathrm{i}\omega + (k_1 + k_d)\}H_1 + (c_d \mathrm{i}\omega + k_d)H_2}{m_1}$$

$$H_2(\omega) = \frac{(c_d \mathrm{i}\omega + k_d)H_1 - \{(c_2 + c_d)\mathrm{i}\omega + (k_2 + k_d)\}H_2}{m_2}. \tag{7}$$

Figs. 3 and 4 show the ratios of the root-mean-squared (RMS) displacement and acceleration responses of the 2-DOF system with and without VEDs, where $\sigma_1(\xi)$ and $\sigma_1(0)$ are the RMS displacements with and without VEDs, respectively, and those with double dots above represent the acceleration responses. The mass of the structures is fixed to an unit value and the stiffness is varied in accordance with the given natural frequency. The shear storage and loss moduli of viscoelastic material are 0.72 MPa and 0.52 MPa, respectively. In the figures the damping ratio ξ of the added VED is defined as $\xi = \frac{c_d}{2\sqrt{k_1 m_1}}$. It can be observed in Fig. 3 that the displacement response of structure 1 with larger natural frequency (i.e., with higher stiffness in this case) decreases first as the damping ratio increases up to a certain point, then it increases as the added damping further increases until the response ratio becomes larger than one. This implies that the use of a VED with its size larger than a certain value may not be effective in reducing dynamic responses. In the structure with smaller natural frequency (i.e., with smaller stiffness) the displacement responses are always smaller than those of the structure not connected to the neighboring one no matter what the added



(a) Structure 1.



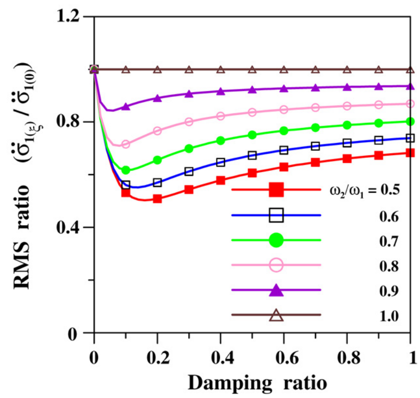
(b) Structure 2.

Fig. 3. Displacement response of 2-DOF structures subjected to white noise input.

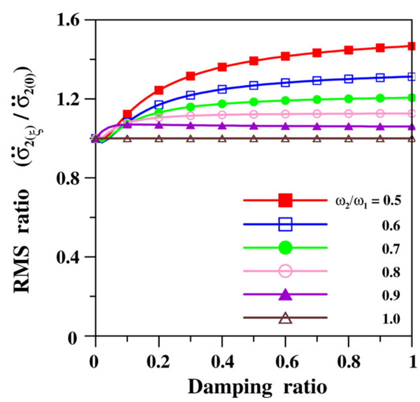
damping and natural frequency ratio are. More specifically, the displacement ratio decreases up to a certain point of added damping, then the response does not change with further increase of added damping. From these observations it can be concluded that there exists a certain amount of added damping which minimizes the displacement response of each connected structure. It also can be noticed that as the difference in natural frequencies of the connected structures increases, the displacement responses generally decrease. Fig. 4 shows the acceleration responses of the two structures, where it can be seen that the acceleration of the structure with larger natural frequency is always smaller than that of the structure with no VEDs, while the opposite is true for the structure with smaller natural frequency. This implies that the placement of VEDs between two structures may not be effective in reducing the force induced in the whole system. It also can be observed that the existence of VEDs does not make any difference when the natural frequencies of the connected structures are the same.

3. Seismic responses of single-story structures connected by VEDs

In this section nonlinear dynamic analyses of single-story structures connected by VEDs and subjected to the

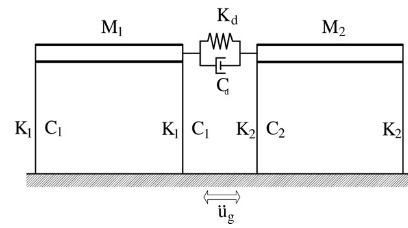


(a) Structure 1.

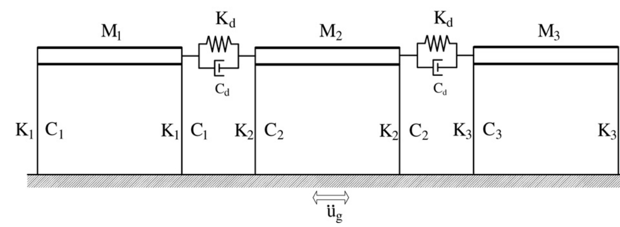


(b) Structure 2.

Fig. 4. Acceleration response of 2-DOF structures subjected to white noise input.

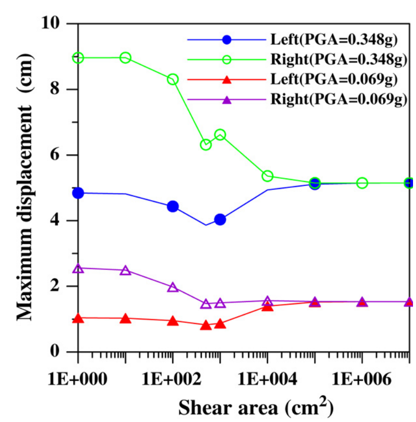


(a) 2-DOF structure.

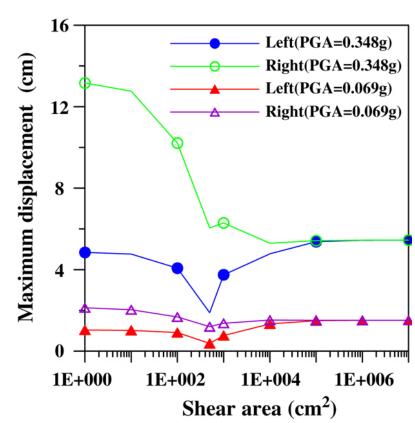


(b) 3-DOF structure.

Fig. 5. Single-story structures connected by VEDs.



(a) Natural periods 0.5–1.0 s.

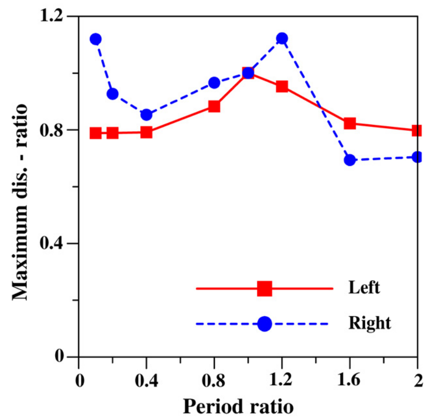


(b) Natural periods 0.5–1.5 s.

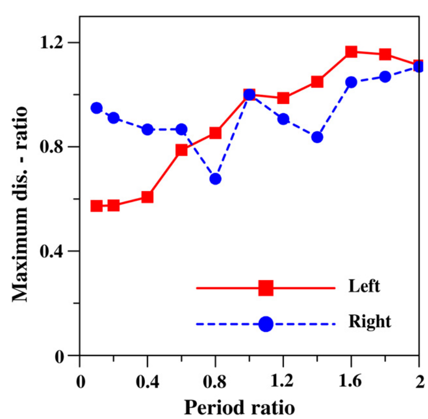
Fig. 6. Variation of maximum displacement of the 2-DOF system with varying shear area of the VEDs.

El Centro earthquake (North–South) were carried out using nonlinear dynamic analysis code DRAIN-2D+ [6]. Fig. 5 shows the single-story shear buildings connected by VEDs. The mass of the structures is fixed to 44 ton and the stiffness is varied in accordance with the desired natural period. It is assumed that a VED is composed of two layers of viscoelastic material with the thickness of each layer taken to be 5 cm.

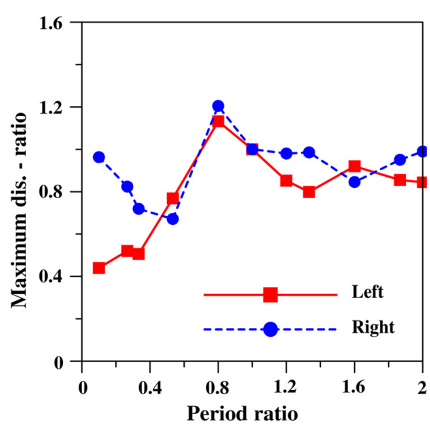
Fig. 6 shows the variation of maximum displacement of the 2-DOF system, shown in Fig. 5(a), with varying shear area of the VEDs. Two levels of El Centro earthquake load, peak ground acceleration (PGA) of $0.348g$ and $0.069g$, were utilized in the analysis. It was observed that under the earthquake of PGA $= 0.348g$ plastic hinges formed in the columns; however, the structure remained elastic when it was subjected to the earthquake with PGA $= 0.069g$. Fig. 6(a) plots the maximum displacement of the structures with natural periods of 0.5 and 1.0 s. It can be observed that the maximum displacement of the structure with larger natural period (structure 2, right-hand side) keeps decreasing as the shear area of the VEDs increases. However, the maximum displacement of the structure with smaller natural period decreases first but then increases as the shear area of the VEDs further increases, which implies that there exists a certain amount of viscoelastic damping that minimizes the maximum displacement. Fig. 6(b) shows the maximum displacement of the structures with natural periods of 0.5 and 1.5 s, in which it can be noticed that the decrease of the maximum displacements is more significant at the optimum shear area of the VEDs when the difference in



(a) $T_1 = 0.5$ s.

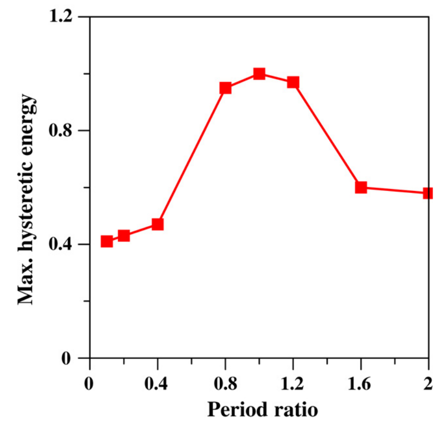


(b) $T_1 = 1.0$ s.

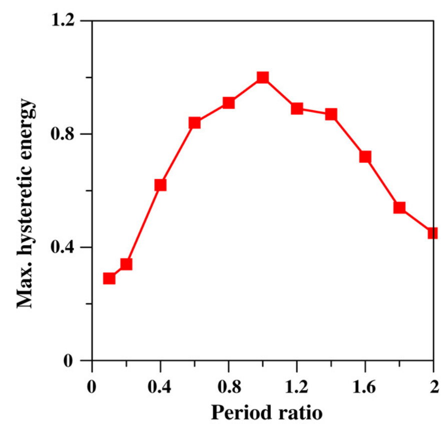


(c) $T_1 = 1.5$ s.

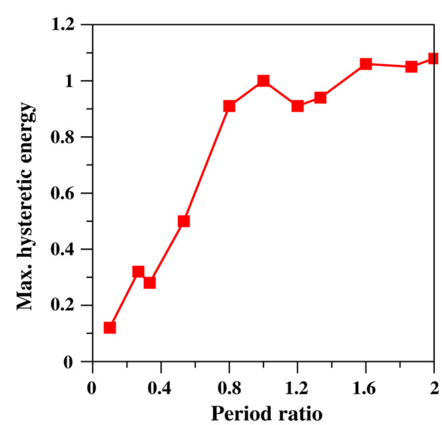
Fig. 7. Ratio of maximum displacements of 2-DOF structures with various natural period ratios.



(a) $T_1 = 0.5$ s.



(b) $T_1 = 1.0$ s.

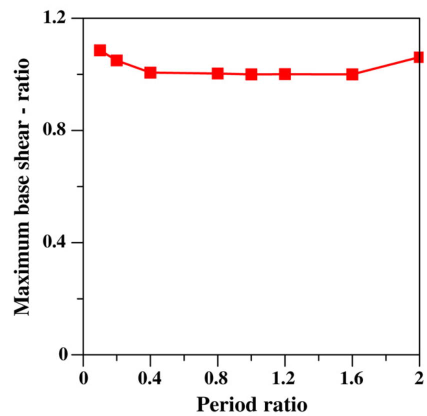


(c) $T_1 = 1.5$ s.

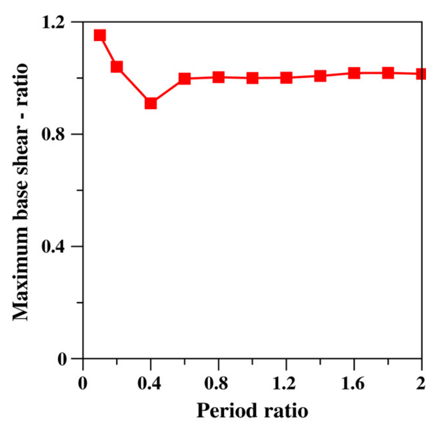
Fig. 8. Ratio of hysteretic energy of 2-DOF structures with various natural period ratios.

natural periods is enlarged. It also can be observed that the displacements of the structure with larger natural period were minimized at the same optimal shear area of the VEDs no matter whether the structure deformed elastically or inelastically. However, the effectiveness of the damper in the reduction of displacement response is slightly larger when the structure behaved inelastically.

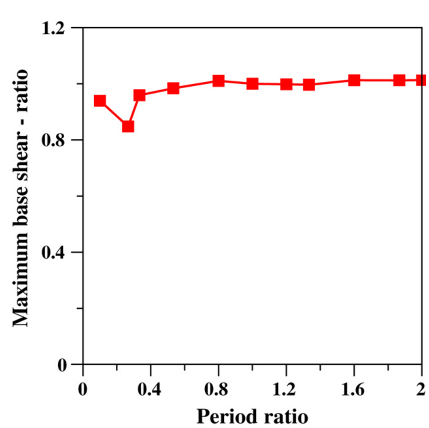
Fig. 7 depicts the variation of maximum displacement ratio of the model structures (i.e., the maximum displacements of the structures with VEDs divided by those of the structures without VEDs) when the natural period of the structure in the left (structure 1) is set to be 0.5, 1.0, and 1.5 s and that of the other structure is varied from 0.1 to 2.0 times that of the structure 1. The same size of VED used previously was used in the analysis. When the natural period of structure 1 is 0.5 s, the displacement ratio is less than 1.0 in most cases except the period ratio of 0.1 and 1.2. When the natural period of structure 1 is 1.0 s, the displacement ratios are generally



(a) $T_1 = 0.5$ s.



(b) $T_1 = 1.0$ s.



(c) $T_1 = 1.5$ s.

Fig. 9. Ratio of base shear of the 2-DOF structures with various natural period ratios.

less than 1 when the period ratio is less than 1, and the opposite is generally true when the period ratio is greater than 1.0. When the natural period of structure 1 is equal to 1.5 s, the displacement ratios are less than 1 except at the period ratio equal to 0.8. It also can be noticed that when the period ratio is 1.0 the displacement ratio is 1.0, which implies that when the natural periods of the two structures are the same the placement of VEDs does not make any difference. The ratios of hysteretic energy, plotted in Fig. 8, show that the reduction in hysteretic energy is significant except when the natural periods of both the structures are very large. The base shear, however, does not change at all or sometimes even increases slightly with the installation of VEDs as shown in Fig. 9.

Fig. 10 presents the analysis results of the 3-DOF structure shown in Fig. 5(b) with various combination of the natural period of each structure. It can be observed that there exists a certain VED shear area that minimizes the maximum displacements of the external stiffer structures, while that of the flexible interior structure decreases almost monotonically as the VED shear area increases.

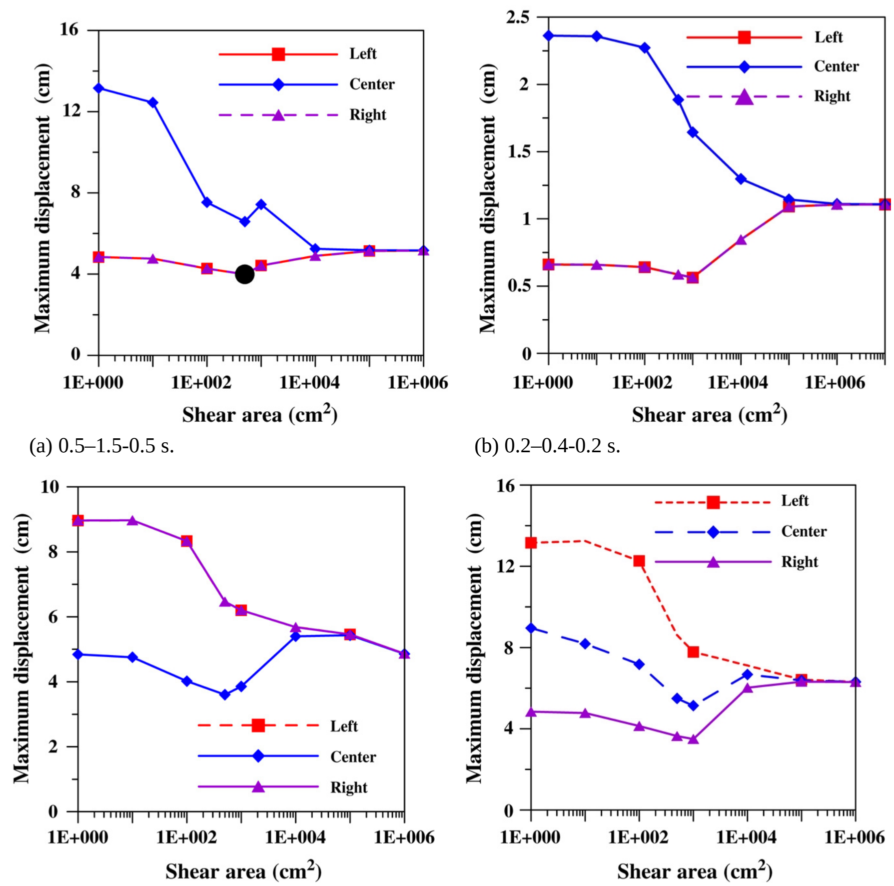
Fig. 11 plots the variation of maximum displacement ratio of the 3-DOF model structure when the natural periods of the two outside structures (structures 1) are set to be 0.5, 1.0, and 1.5 s and that of the structure in the middle is varied from 0.1 to 2.0 times those of structures 1. The trend is, with some exceptions, similar to that of the 2-DOF case; i.e., the maximum displacements of the structures generally decrease as a result of VED installation. Fig. 12 presents the ratio of the hysteretic energy of the 3-DOF structure with viscoelastic dampers. To define the hysteretic energy dissipated in a structure during earthquake excitation, the energy balance equation of a 1-DOF system is presented as follows:

$$\int m\ddot{x}\,\mathrm{d}x + \int \dot{c}x\,\mathrm{d}x + \int f_s(x,\dot{x})\,\mathrm{d}x = -\int m\ddot{x}_g\,\mathrm{d}x \quad (8)$$

where $m, c, f_s\ (x, \dot{x})$ are the mass, damping coefficient, and the restoring force of the structure, and $\ddot{x}_g$ is the ground acceleration. The first and the second terms represent the kinetic and the damping energy, respectively, and the third term is the absorbed energy composed of the recoverable elastic strain energy and the irrecoverable hysteretic energy. The term on the right-hand side corresponds to the seismic input energy. The ratios of the hysteretic energy presented in Fig. 12 show that the hysteretic energy is reduced in all the range of period ratio once the viscoelastic dampers are installed. It also can be noticed that the hysteretic energy further decreases as the difference between the natural periods increases.

4. Analysis of example structures

The parametric study conducted above indicates that the seismic responses of single-story structures connected by VEDs are generally reduced when VEDs are installed between structures. Also observed is that an optimum size of VED which minimizes the overall structural responses does exist. In this section those findings are to be verified by applying VEDs in a 5-story and 25-story structures connected by VEDs. A proper size of VED is first determined and the seismic responses of the structures with and without VEDs are compared.



(a) 0.5–1.5-0.5 s.
(b) 0.2–0.4-0.2 s.
(c) 1.0–0.5-1.0 s.
(d) 1.5–1.0-0.5 s.

Fig. 10. Variation of maximum displacement of 3-DOF system with varying shear area of VEDs.

4.1. Analysis models and earthquake ground motions

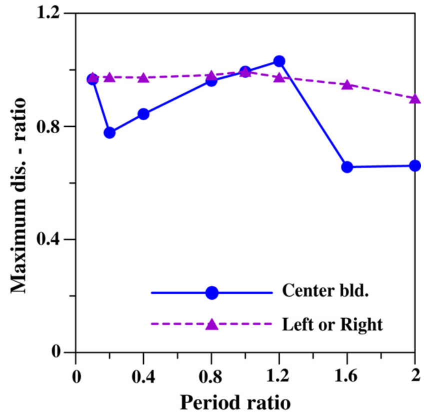
Fig. 13 shows a 5-story analysis model which is divided into three pieces by seismic joints and a 25-story structure connected by VEDs. To enhance the effectiveness of the VEDs, the model structures are designed with braced frames connected to a moment-resisting frame. Each structure is designed in accordance with the Korean design code considering the gravity and the seismic load using the program code MIDAS GEN [7]. The story height and the span length are 4 m and 9 m, respectively, and the yield strength of beams and columns are 24 kN/cm^2 and 33 kN/cm^2, respectively. The modal damping ratios for the first two modes are taken to be 5% of the critical damping. In the 5-story structure, eigenvalue analyses provide that the natural periods of the outside braced frames are 0.43 s and that of the moment frame is 1.53 s. The natural periods of the 25-story structures are 2.15 and 3.25 s for the braced and the rigid frame, respectively. It is assumed that the point plastic hinges occur only at the end of beams and columns and the post-yield stiffness is assumed to be 2% of the initial stiffness. In the analysis the storage modulus and the loss modulus of the viscoelastic material are taken to be 0.72 MPa and 0.52 MPa, respectively, and the thickness of the viscoelastic material is assumed to be 7 cm.

To verify the effectiveness of using VEDs between structures, El Centro (NS, PGA $= 0.348g$) and Northridge earthquake (PGA $= 0.605g$) are used in the nonlinear dynamic analyses. The response spectra of the earthquake loads are given in Fig. 14.

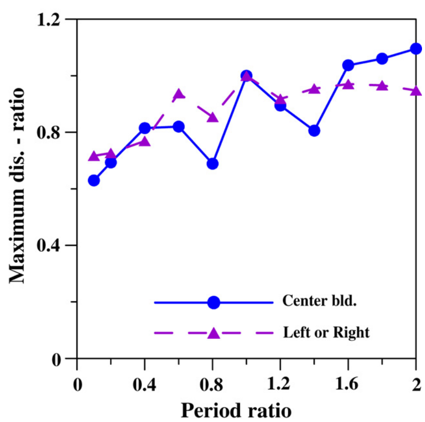
4.2. Seismic responses of the 5-story structure

Two types of VED installation schemes are considered: (i) a VED is installed between the top floors, and (ii) VEDs of the same size are installed in all stories. Eigenvalue analysis of the whole system including VEDs is carried out first to obtain natural frequency of the system, then the natural frequency is used in Eq. (1) to determine the stiffness and damping coefficients of the VEDs.

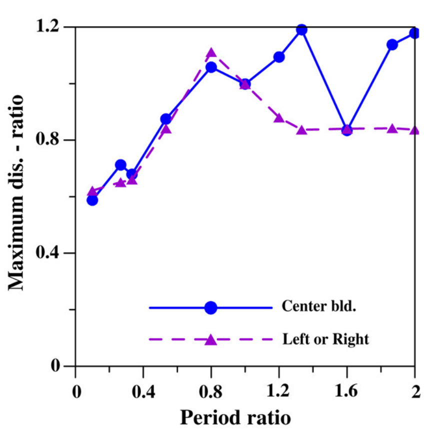
The proper size of a VED for the model structure subjected to the El Centro earthquake is determined from Fig. 15, which plots the variation of maximum displacements as a function of shear area of the VEDs. It is observed that the maximum displacements of the braced frames are minimized at the VED shear areas of 3000 cm^2



(a) $T_1 = 0.5$ s.

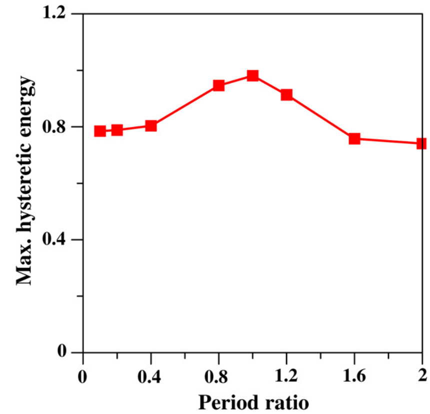


(b) $T_1 = 1.0$ s.

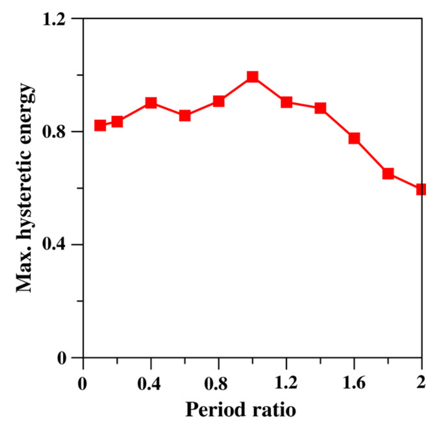


(c) $T_1 = 1.5$ s.

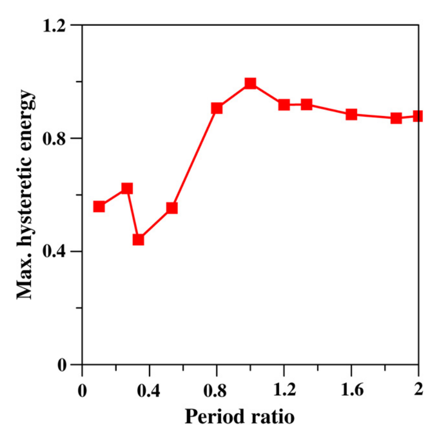
Fig. 11. Variation of Maximum displacement ratio of 3-DOF structures with varying period ratio.



(a) $T_1 = 0.5$ s.



(b) $T_1 = 1.0$ s.

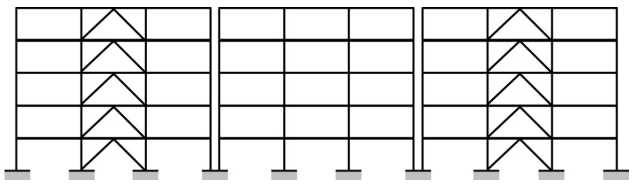


(c) $T_1 = 1.5$ s.

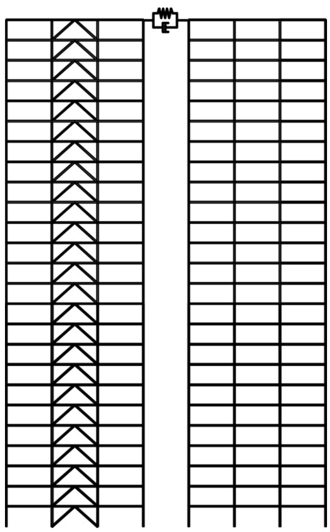
Fig. 12. Variation of hysteretic energy ratio of the 3-DOF structures with varying period ratio.

when a VED is installed between the top floors, and of 4000 cm^2 when VEDs are installed at all floors. About 13% (braced frames) and 53% (rigid frame) of the maximum displacements are reduced when a VED with the optimum size is installed between the top floors. The trends are almost the same when VEDs are installed in all stories; however, the maximum displacements at larger VED shear area are enhanced compared to the case that a VED is installed only at the top floors.

Fig. 16 shows that the relative displacement of the model structure subjected to the El Centro earthquake is significantly reduced by adding VEDs. It also can be observed that the maximum relative displacement, which is about 6 cm, is well within the maximum deformability of VEDs.



(a) 5-story structures.



(b) 25-story structures.

Fig. 13. Analysis model structures connected by viscoelastic dampers.

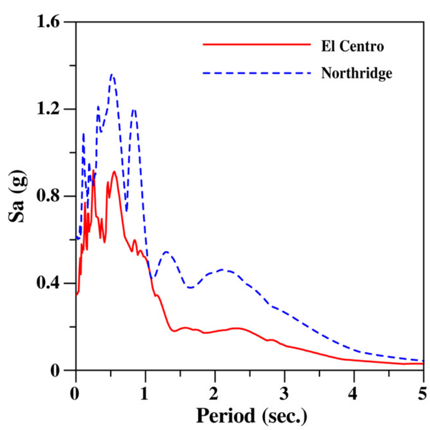
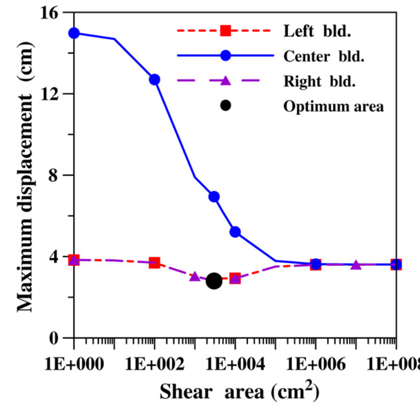
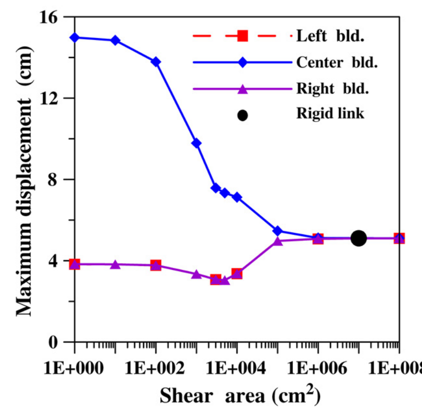


Fig. 14. Pseudo-acceleration response spectra of earthquakes used in the analysis.



(a) VED at the top story.



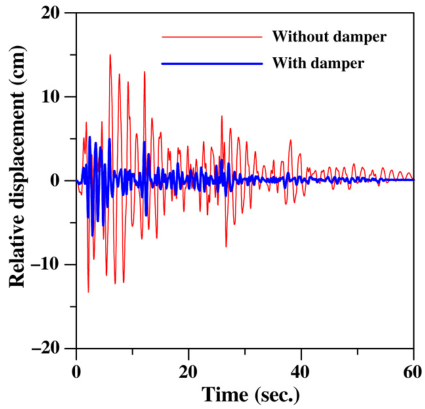
(b) VEDs in all stories.

Fig. 15. Variation of maximum displacement of the 5-story structure for the El Centro earthquake.

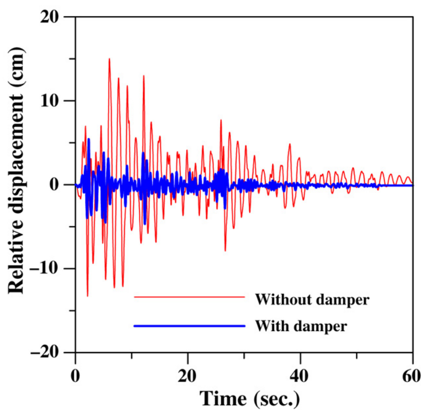
Fig. 17 plots the input and hysteretic energy time histories, which show that the amount of plastic deformation and structural damage is maximum when the frames are connected by rigid link instead of VEDs, and is minimum when a VED is installed. This implies that a VED installed between adjacent structures is more effective in reducing structural damage than separating the structures or connecting them with rigid joints, i.e., designing without seismic joints. It also can be observed that the nonlinear deformation is larger when VEDs are installed in all stories.

Fig. 18 plots the location and size of plastic hinges in structures with and without VEDs, which shows that with the installation of VEDs the size of plastic hinges formed in the second floor beams is significantly reduced. The plastic hinges formed on the third floors disappeared after the VEDs were placed between the structures. No noticeable difference was observed whether the VEDs were located only in the top story or in every story.

To verify the effectiveness of the proposed scheme for another earthquake record, time-history analysis is carried out using Northridge earthquake (PGA $= 0.6047g$). The VEDs are installed only in the top story. According to the variation of the maximum displacements for varying VED shear area (Fig. 19), the same shear area of 3000 cm^2 as for the El Centro earthquake is obtained as the optimum damper size that minimizes the maximum displacements of braced frames. Figs. 20 and 21 plot the time-history of maximum absolute and relative displacements, respectively, with and without VEDs. It can be seen that both the absolute and relative displacements are reduced significantly after VEDs are installed. Fig. 22 plots the input energy, damping energy, and hysteretic energy stored and dissipated in the system with and without VEDs. It can be observed that with the addition of VEDs input energy is increased only slightly

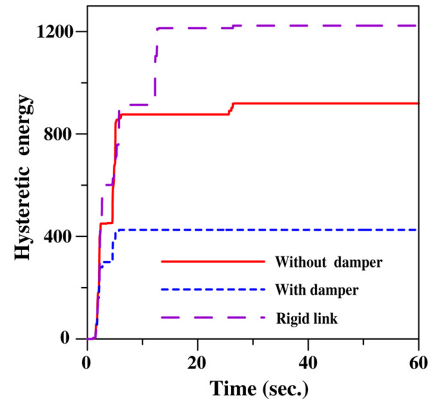


(a) VED in the top story.

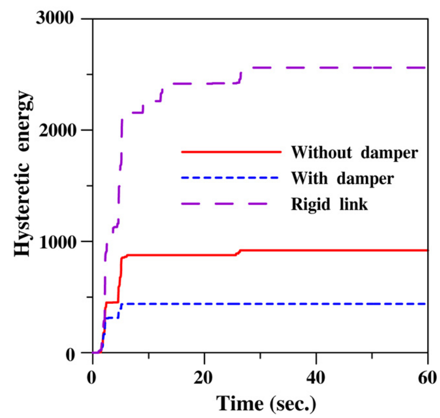


(b) VEDs in all stories.

Fig. 16. Time histories of maximum relative displacements.



(a) VED in the top story.



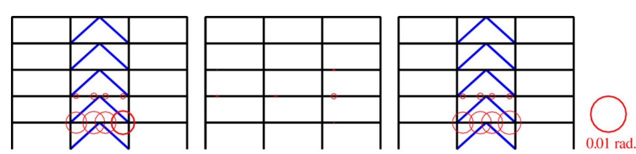
(b) VEDs in all stories.

Fig. 17. Time history of hysteretic energy.

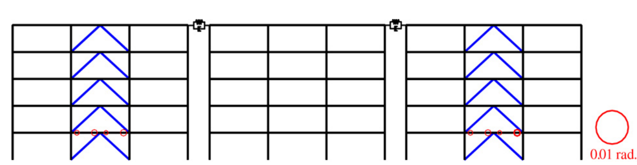
due to the added stiffness from VEDs, whereas the energy dissipation due to added damping is increased significantly, contributing to large reduction in hysteretic energy and plastic deformation. Fig. 23 shows that the amount of plastic deformation is much larger than in the previous case, reflecting the enhanced intensity of the earthquake load. The numerical results show that the proposed method of applying VEDs across seismic joints is also effective for Northridge earthquake.

4.3. Seismic responses of the 25-story structures

The 25-story chevron-braced and rigid-frame structures connected by VEDs at the top floors (described in Fig. 25) are analyzed using the Northridge earthquake. The optimum size of VED is determined from Fig. 24(a), in which it is observed that the maximum displacement of the braced frame is minimized when the VED shear area of a VED reaches 1000 cm^2. The hysteretic energy time histories show that due to the installation of VEDs the hysteretic energy is significantly reduced. Fig. 25 depicts the location and size of plastic hinges before and after the installation of VEDs. The optimum size obtained in Fig. 24 is used in the analysis. It can be noticed that when the two buildings are not connected



(a) Without VEDs.



(b) With VEDs at the top story.

Fig. 18. Size and location of plastic hinges for the El Centro earthquake.

by VEDs, the plastic hinges are formed mainly at lower stories in the braced frame and at higher stories in the framed structure. This can be explained by the fact that in the braced frame the first mode is dominant, while higher modes participate significantly in the rigid frame. After the VEDs are installed the number and size of plastic hinge are noticeably reduced in both structures.

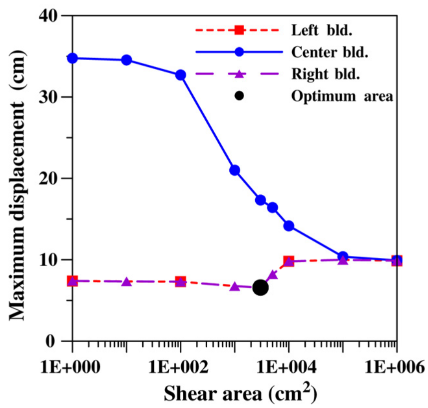


Fig. 19. Variation of maximum displacement for the Northridge earthquake.

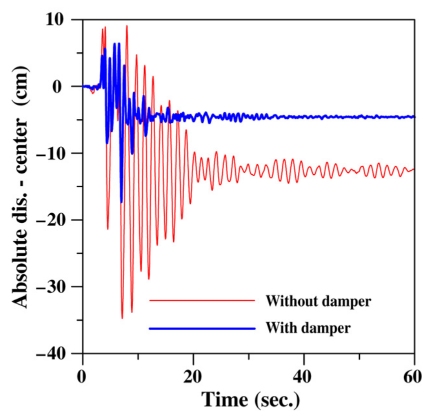


Fig. 20. Maximum displacement time history of rigid frame.

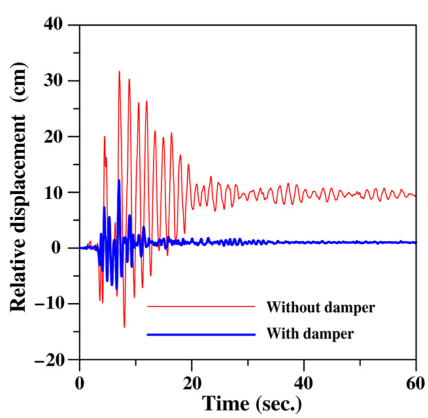
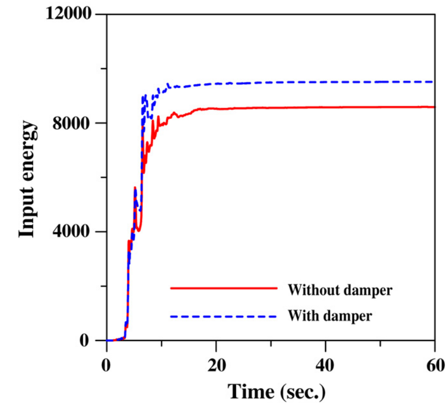
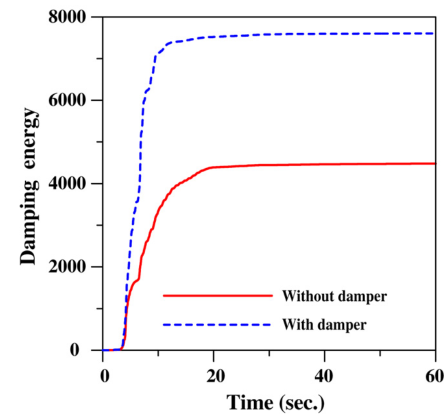


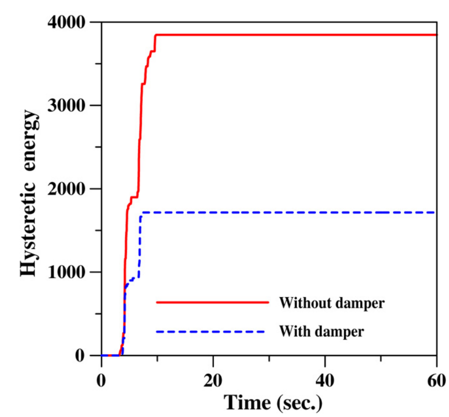
Fig. 21. Time history of roof–story relative displacement.



(a) Input energy.



(b) Damping energy.

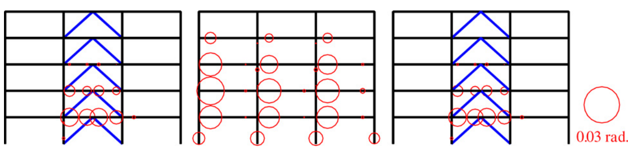


(c) Hysteretic energy.

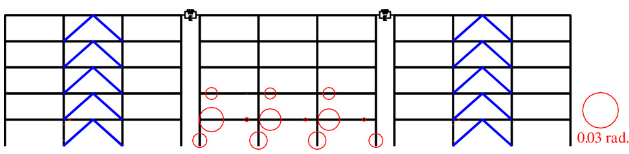
Fig. 22. Energy time histories for Northridge earthquake.

5. Conclusion

This study investigates the effect of installing viscoelastic dampers between structures in seismic joints or in sky-bridges to reduce earthquake-induced dynamic responses. According to elastic and inelastic analysis results it was found that there exists a certain amount of viscoelastic damping which minimizes the maximum displacements. When the optimum size of VED is installed the relative as well as the absolute displacements of connected structures can be significantly reduced, if the natural frequencies of the connected structures are different enough. The difference in natural frequencies can be achieved by designing the structures to have different structure systems. It was also observed that the hysteretic energy and the plastic deformation were significantly reduced as a result of VED installation, and the effect was more enhanced for an earthquake with larger intensity. However, the seismic

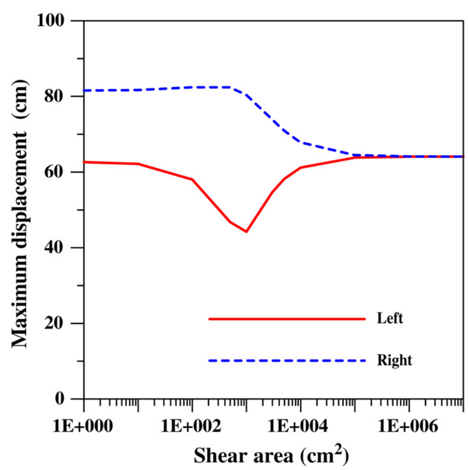


(a) Without dampers.

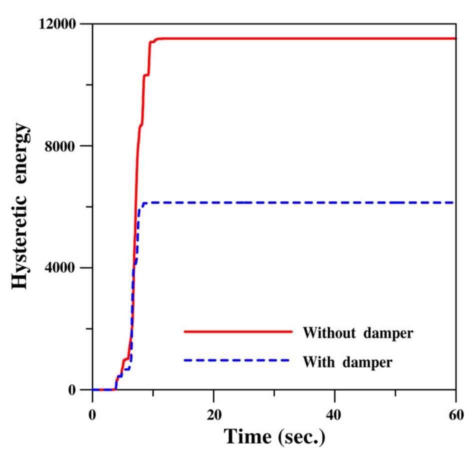


(b) With dampers.

Fig. 23. Location and size of plastic hinges for the Northridge earthquake.

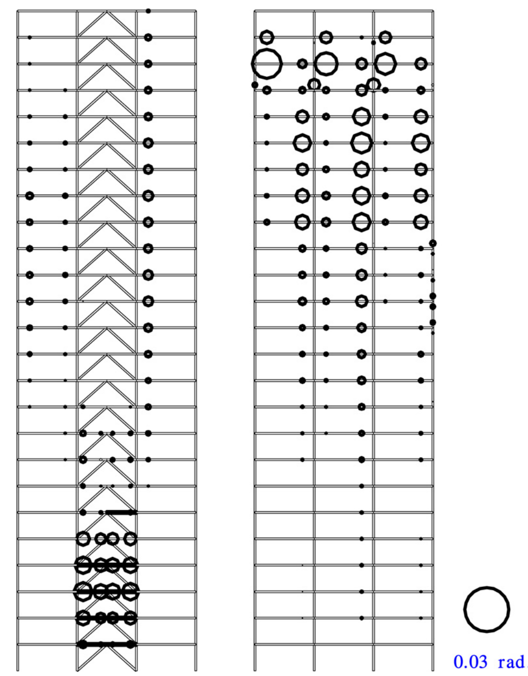


(a) Variation of maximum displacement.

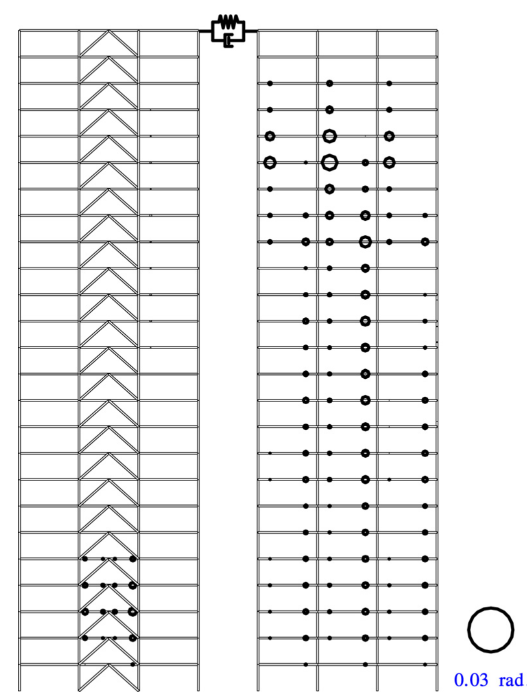


(b) Time history of hysteretic energy.

Fig. 24. Response of the 25-story structures connected by VEDs at the top floors.



(a) Without viscoelastic damper.



(b) With viscoelastic damper.

Fig. 25. Plastic hinge formation in the 25-story model structures.

base shear did not decrease significantly. For preliminary design of structures connected by viscoelastic dampers, it would be convenient to prepare a diagram or a design aid, such as a design spectrum, which plots the optimum size of viscoelastic dampers, normalized by the mass of a structure for various combination of natural frequencies of the connected structures.

Acknowledgements

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