New installation scheme for viscoelastic dampers using cables

Hyunhoon Choi and Jinkoo Kim

Abstract: Passive energy dissipation devices, such as, viscous, viscoelastic, and friction devices are generally installed in buildings using diagonal or chevron braces. To increase the effective damping force and to reduce the damper volume, various magnifying system of the damper displacement, such as, toggle brace system and scissor-jack-damper configuration have been developed with increase in installation cost. In this study, new installation scheme for passive dampers was proposed using cables installed in such a way that relative displacement equal to storey displacement occurs between the cable and the structure when the structure is subjected to lateral load. The cables can be installed continuously or discretely between base and top storey of the structure. To verify the validity of the proposed method nonlinear dynamic analysis of model structures with viscoelastic dampers installed using the proposed configuration scheme was carried out using three earthquake records and two sinusoidal forces. According to the analysis, the proposed method resulted in significant reduction in the size of dampers compared with the conventional installation methods.

Key words: viscoelastic dampers, seismic analysis, cable, passive control.

Résumé : Les dispositifs passifs de dissipation d'énergie, tels que les amortisseurs visqueux, viscoélastiques et à friction, sont généralement installés dans les bâtiments en utilisant des entretoises diagonales ou en chevron. Afin d'accroître la force efficace d'amortissement et de réduire le volume de l'amortisseur, divers systèmes d'amplification du déplacement de l'amortisseur, tels qu'un système d'amortisseurs pour contreventements à fixations grenouillères et des amortisseurs à vérin hydraulique ont été développés avec l'augmentation du coût d'installation. Dans cette étude, un nouveau plan d'installation des amortisseurs passifs est proposé qui utilise des câbles installés de manière à ce qu'un déplacement relatif égal au déplacement des étages survienne entre le câble et la structure lorsque cette structure est soumise à une charge latérale. Les câbles peuvent être installés en continu ou en discontinu entre la fondation et l'étage supérieur de la structure. Pour vérifier la validité de la méthode proposée, une analyse dynamique non linéaire des structures de modèles avec amortisseurs viscoélastiques installés en utilisant la configuration proposée a été réalisée en utilisant les registres de trois séismes et de deux forces sinusoïdales. Selon les résultats de l'analyse, la méthode proposée permet de réduire significativement la dimension des amortisseurs par rapport aux méthodes conventionnelles d'installation.

Mots-clés : amortisseurs viscoélastiques, analyse sismique, câble, contrôle passif.

Introduction

For the last few decades, there has been progressin research, development, and implementation of various energy dissipation devices to reduce the response and vibration produced by wind as well as seismic disturbances. Among the energy dissipation devices, passive damping systems have been adopted widely in the engineering field. They include viscous and viscoelastic dampers (VEDs), friction dampers, metallic yielding dampers, seismic isolation systems, and tuned mass dampers. The main advantages of employing passive damping devices are to mitigate structural vibration most economically and effectively with high reliability. The performance of passive damping devices has been verified through extensive analytical and experimental research. The influence of VEDs properties on structural response were evaluated (Kim and Bang 2002; Lin and Chopra 2003; García et al. 2007). Xu et al. (2004) proposed a synthetic optimization method to determine the optimal parameters and location of dampers using numerical analysis and shaking table test of a reinforced concrete structure. The displacement-based design procedures for supplemental dampers were proposed in the context of performance-based seismic design (Lin et al. 2003; Kim and Choi 2006). Min et al. (2004) conducted a full-scale test of a five-storey steel structure to verify the effectiveness of VEDs. Recently, Ahn et al. (2008) reported practical issues and solutions on the installation of VEDs in a high-rise building structure.

The damping force in a passive device is a function of the displacement between each end of the device. When passive dampers are installed with supporting braces between two storeys, the energy dissipation capacity will be limited because the damper displacements are less than or equal to the interstorey drift. To increase the effective damping force or to reduce the damper volume, the magnifying system of damper displacement has been developed. Toggle-brace-

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Fig. 1. General installation scheme of passive dampers: (*a*) diagonal brace, (*b*) inverse V.

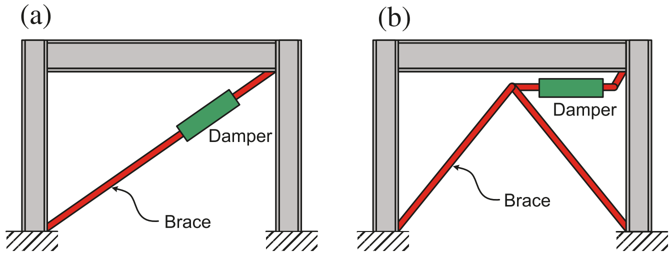
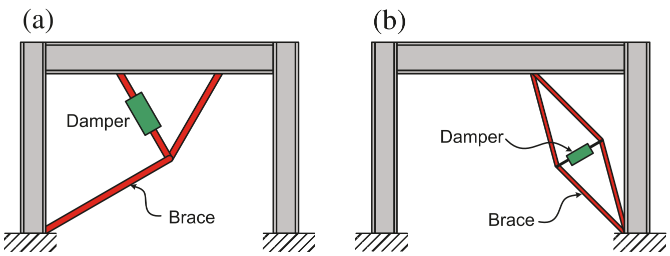


Fig. 2. Installation of dampers using displacement amplifiers: (*a*) toggle system, (*b*) scissor-jack.



damper system proposed by Constantinou et al. (2001) offers advantages that overcome these limitations. Also, Sigaher and Constantinou (2003) performed experimental and numerical studies to demonstrate the effectiveness of the scissor-jack-damper configuration with compactness and near-vertical installation. However, the disadvantage of both displacement magnifying systems is that they require higher cost as well as sophisticated techniques in their analysis and detailing. Also, the systems require more space for installation, which may be a critical issue in residential or commercial buildings.

This paper proposed a new installation scheme for passive dampers using cables installed in such a way that relative displacement occurs between the cable and the structure when the structure is subjected to lateral load. While dampers are generally installed between storeys in conventional methods, the dampers are installed parallel to the storey level in the proposed scheme. In case the cable is placed continuously throughout all storeys, the relative movement between a damper and the cable in a certain storey is the accumulation of the interstorey drifts of the storeys located down below. Therefore, the relative movement between the damper and the cable corresponds to the storey displacement, not to the interstorey drift as in the conventional installation scheme for dampers. This may result in a huge advantage when the structure deforms mainly in fundamental mode of vibration. The cables can be installed continuously or discretely between the base and the top storey depending on the vibration characteristics of the structure. To verify the validity of the proposed method, a nonlinear dynamic analysis was carried out using three different earthquake records and two sinusoidal forces for model structures with viscoelastic dampers that are installed using the proposed configuration scheme.

Installation of passive dampers

Passive dampers are generally installed between storeys by diagonal or chevron braces, as shown in Fig. 1*a* and 1*b*. However, those installation methods may result in deformation in dampers that are not large enough to dissipate significant vibration energy. To enhance damper deformation various toggle systems shown in Fig. 2 have been developed. Table 1 shows the relative deformation in a viscous damper when unit lateral displacement occurs in a single storey structure with the damper installed by various schemes (Sigaher and Constantinou 2003). The resultant damping ratio of the structure is also presented. It can be observed that by using the amplifiers the relative deformation of a damper and damping ratio of a structure can be significantly increased. However, additional cost and space are required for increased performance of the damper.

Installation scheme for a damper using cable

Figure 3 depicts a cable installed in a single storey frame using frictionless pulleys or toothed wheels. When the structure is deformed laterally, the points *a*, *b*, and *c* before deformation move to *a*′, *b*′, and *c*′ after deformation. Viscoelastic dampers can be installed horizontally along the beam, as shown in Fig. 4; the two outer steel plates of the damper are fixed to the beam and the inner plate is connected to the cable. Viscoelastic material is inserted between the steel plates. The dampers are activated when the structure is displaced laterally and relative displacement occurs between the structure and the cable and consequently between the outer plates and inner plate of the viscoelastic dampers. Vibration energy is dissipated through repeated shear deformation of the viscoelastic materials placed between steel plates. Compared with conventional installation schemes for dampers, the cable-damper system requires smaller space for installation because cables can be easily hidden within partition walls and the dampers can be installed parallel to floor beams hidden above the ceilings. Moreover, only small holes punctured through the slabs are necessary to install the system throughout the multiple storeys.

Figure 5 depicts the movement of cable when the two-storey structure deforms in its first and the second modes of vibration. When the structure deforms in the first mode, the interstorey drifts correspond to the reduced lengths of the first- and the second-storey diagonal cables *b*–*c*′ and *d*′–*e*. The reduced length of the cable *b*–*c*′ is equal to the relative displacement at the second-storey damper, u_{d1}. As the cable in the first and the second storeys is continuous, the relative movement between the roof beam and the cable, u_{d2}, is the summation of the interstorey drifts of the first and the second storeys, which is the displacement of the storey at the roof. However, when the structure deforms in the second vibration mode, the length of the first-storey diagonal *b*–*c*′ decreases and the length of the second-storey diagonal *d*′–*e* increases. Therefore, the relative movement of the roof beam and the cable, u_{d2}, is the difference between the two interstorey drifts. If the interstorey drifts of the first and the second storeys are the same, the displacement of the second storey is zero and the viscoelastic damper installed in the roof beam do not deform at all.

Table 1. Amplification factor and damping ratio for various shape of damper installation (data from Sigaher and Constantinou 2003).

Installation shape	Diagonal	Inverse V	Upper toggle	Scissor-jack
Amplification factor	0.80	1.00	3.19	2.52
Damping ratio	0.03	0.05	0.51	0.32

Fig. 3. Deformed shape of a frame with a tendon.

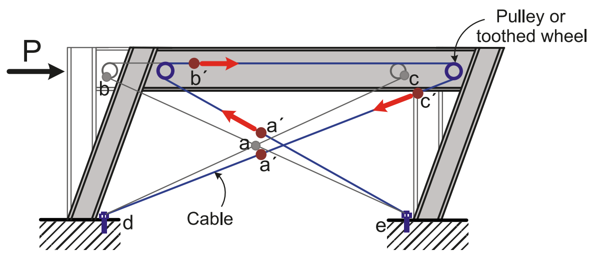
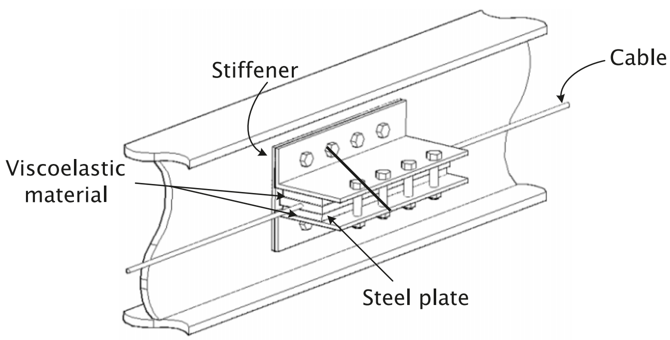


Fig. 4. Details of viscoelastic dampers connected to a steel beam and cables.



The cable can be installed continuously throughout the storeys or can be divided into many pieces depending on the shape of building deformation. In Fig. 6*a*, the cable is composed of only one piece, in which the relative movement between the beam of a storey and the cable parallel to the beam is approximately equal to the lateral displacement at that storey. This installation scheme (Alt-1) results in the largest deformation in the dampers, especially in the dampers located in the higher storeys, when the structure deforms in the first vibration mode. However, when the structure deforms to the higher modes of vibration, the relative movement between the structure and the cable may decrease especially in the higher storeys, as shown in Fig. 5*b*, and consequently the effectiveness of the continuous installation of cable may also decrease. In Fig. 6*b*, the cables are discontinuous between the second and the third storeys. In this case, the relative deformation in the damper located in the fourth storey is the accumulation of the interstorey drifts of only the third and the fourth storeys; i.e., it is not affected by the interstorey drifts to the opposite direction occurred in the first and the second storeys. This installation scheme (Alt-2) has more advantage when the structure deforms in the higher modes of vibration.

Analytical modeling of model structures

Model structures and earthquake loads

To verify the effectiveness of the proposed installation scheme for dampers, six- and 15-storey steel moment-resisting frames were prepared and visclelastic dampers were installed using cables. Figure 7 shows the six-storey structure with 8 m span length and 3 m storey height. The yield strength of the beams and columns are 235 and 325 N/mm^2, respectively, and 3% of inherent damping was assumed. The storey weight was assumed to be 188 kN. The structural members selected for the model structures are listed in Table 2. Table 3 presents the natural periods and mass participation factors of the model structures computed from eigenvalue analysis. The VEDs were placed in every two or three storeys with continuous (Alt-1 scheme) or discontinuous (Alt-2 scheme) cables. In the 15-storey structure, dampers were installed in every three and five storeys.

Figure 8 shows the acceleration time histories of the 1940 El Centro, 1989 Loma Prieta, and 1994 Northridge earthquakes, which are frequently used in the seismic performance evaluation of building structures. Nonlinear time-history analyses of the model structures subjected to the ground excitations were carried out using the nonlinear analysis program code Drain-2DX (Prakash and Powell 1994). It was assumed in the analysis that the beams and columns have bilinear force–deformation relationship with post-yield stiffness ratio of 0.02. Point-plastic hinges were applied at structural elements to consider material nonlinearity of the structure. Hysteretic behaviour of dampers was modeled using the stiffness and damping coefficients of truss elements.

Effect of cable stiffness

When dampers are installed between storeys using steel braces, it is generally assumed for simplicity that the braces are rigid and all deformation is concentrated in the dampers. However, when the dampers are installed using cable, even though the elastic modulus of cable is higher than that of steel braces made of mild steel, the stiffness of cable may not be large enough to be considered as rigid because the length of cable is generally very long compared with installation braces. Therefore, it would be necessary to consider the stiffness of cable as well as dampers in the computation of structural responses. If dampers are installed in the n locations, as shown in Fig. 7*b*, the lateral stiffness of the cable, K_{cl}, can be obtained as follows:

$$[1] \qquad \frac{1}{K_{cl}} = \frac{2n-1}{K_{ch}} + \frac{2n}{K_{cd}\cos^2\theta}$$

where K_{ch} is the axial stiffness of the horizontal cables and K_{cd} is the stiffness of the diagonal cables with slope θ with the horizontal axis. When cable is installed continuously from the first to the top storeys and dampers are located at two locations, as shown in Fig. 7*c*, the stiffness of cable can be obtained from two horizontal components and four diagonal components of cable connected in series.

Fig. 5. Movement of the cable at lateral deformation of the structure: (*a*) first-mode deformation, (*b*) second-mode deformation.

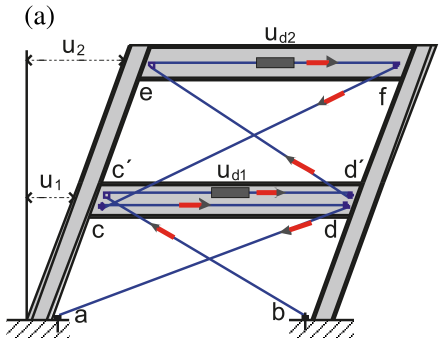
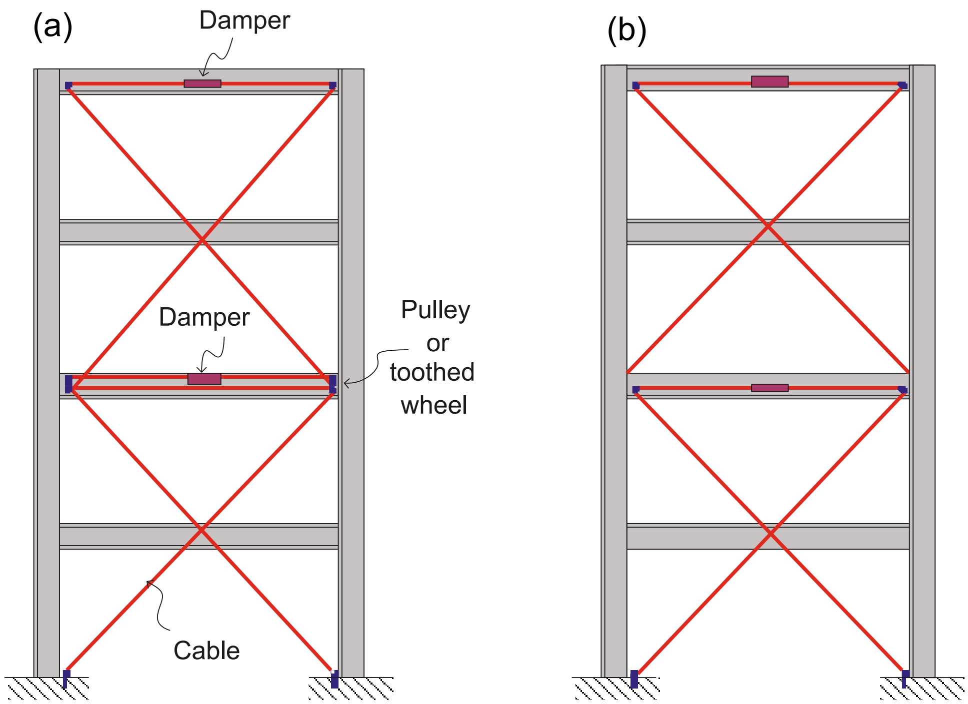


Fig. 6. Installation scheme for viscoelastic dampers: (*a*) continuous tendon (Alt-1), (*b*) discontinuous tendons (Alt-2).



Analysis of model structures

Equivalent damping ratio of model structures

The stiffness K_d and damping coefficient C_d of a viscoelastic damper can be obtained as follows (Soong and Dargush 1997):

$$[2] \qquad K_d = \frac{G'A}{t} \quad C_d = \frac{G'A}{\omega t}$$

where G' is the shear storage modulus, G'' is the shear loss modulus, A is the cross-sectional area, t is the thickness of the damper, and ω is the forcing frequency. The equivalent damping ratio, ζ_d, of a structure with viscoelastic dampers can be expressed as follows (FEMA 2000; Kim and Choi 2006):

$$[3] \qquad \zeta_d = \frac{1}{4\pi}\frac{E_{DV}}{E_S} = \frac{1}{4\pi}\frac{T_{eff,d}\sum_{i=1}^{N} C_{di}\cos^2\theta_i(u_i - u_{i-1})^2}{\sum_{i=1}^{N} m_i u_i^2}$$

where E_S is the maximum strain energy of a structure with a viscoelastic damper (VED), E_{DV} is the dissipated energy by dampers, $T_{eff,d}$ is the effective natural period of a structure with a VED, θ is the slope of a VED, and m_i and u_i are the mass and displacement of ith storey, respectively. If the same dampers are installed in every storey, the damping coefficient of each damper to provide the target damping ratio ζ_d can be obtained as follows from eq. [3]:

$$[4] \qquad C_d = \frac{4\pi\zeta_d \sum_{i=1}^{N} m_i u_i^2}{T_{eff,d}\sum_{i=1}^{N} \cos^2\theta_i(u_i - u_{i-1})^2}$$

By using eqs. [2] and [4], the stiffness of a damper can be obtained from the following relationship:

$$[5] \qquad K_d = \frac{G'\omega}{G'} C_d$$

Fig. 7. Six-storey model structure: (*a*) no damper, (*b*) dampers in every two storeys, (*c*) dampers in every three storeys.

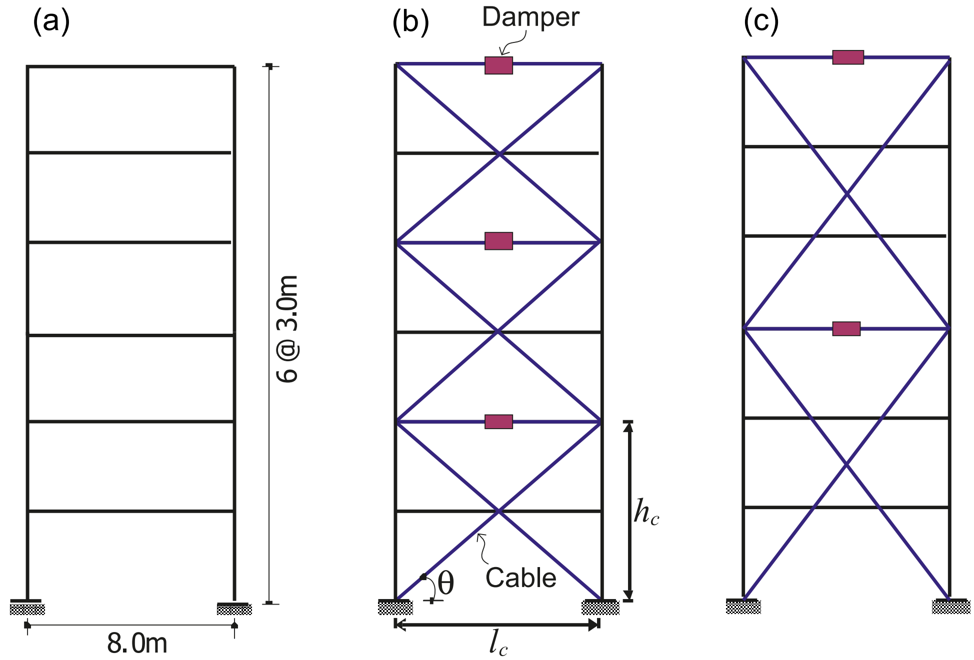


Table 2. Member size (mm): (*a*) six-storey model structure, (*b*) 15-storey model structure.

Storey	Columns	Beams
Six-storey model structure		
4∼6	H394×398×11×18	H396×199x 7×11
1∼3	H400×400×13×21	H400×200x 8×13
15-storey model structure		
13∼15	H394×398×11×18	H396×199x 7×11
10∼12	H400×400×13×21	H400×200x 8×13
7∼9	H406×403×16×24	H400×200x 8×13
4∼6	H414×405×18×28	H450×200x 9×14
1∼3	H414×405×18×28	H500×200×10×16

Table 3. Dynamic characteristics of model structures.

Models	Vibration modes	1	2	3
Six-storey	Period (s)	1.07	0.32	0.16
	Effective mass (%)	77.0	12.6	5.4
15-storey	Period (s)	2.42	0.83	0.46
	Effective mass (%)	74.3	12.0	5.0

In this study, the dampers were designed for the target damping ratio of 10% of critical damping. The required stiffness and damping coefficients of a damper to meet the target damping ratio was determined based on the assumption that the structure deforms proportional to the first mode of vibration and that all dampers have the same size. Table 4 shows the required damping coefficients of dampers to meet the target damping ratio. The required damping coefficients for a VED installed by conventional inverted V-type steel braces were also computed for comparison. It can be observed that the damping coefficients of the proposed installation scheme required to meet the same modal damping ratio are significantly smaller than that of the conventional damper installation method using steel braces. Especially, the continuous installation of cable (Alt-1 scheme) resulted in smaller damping coefficients than those required by discontinuous installation of cable (Alt-2 scheme). The results correspond to the findings of Sigaher and Constantinou (2003) that the damping ratio can be amplified if a proper technique is provided to enhance the relative deformation of dampers.

Effect of cable stiffness on structural responses

When dampers are installed using cable, the relative de-

Fig. 8. Ground acceleration records used in the analysis: (*a*) El Centro earthquake, (*b*) Loma Prieta earthquake, (*c*) Northridge earthquake.

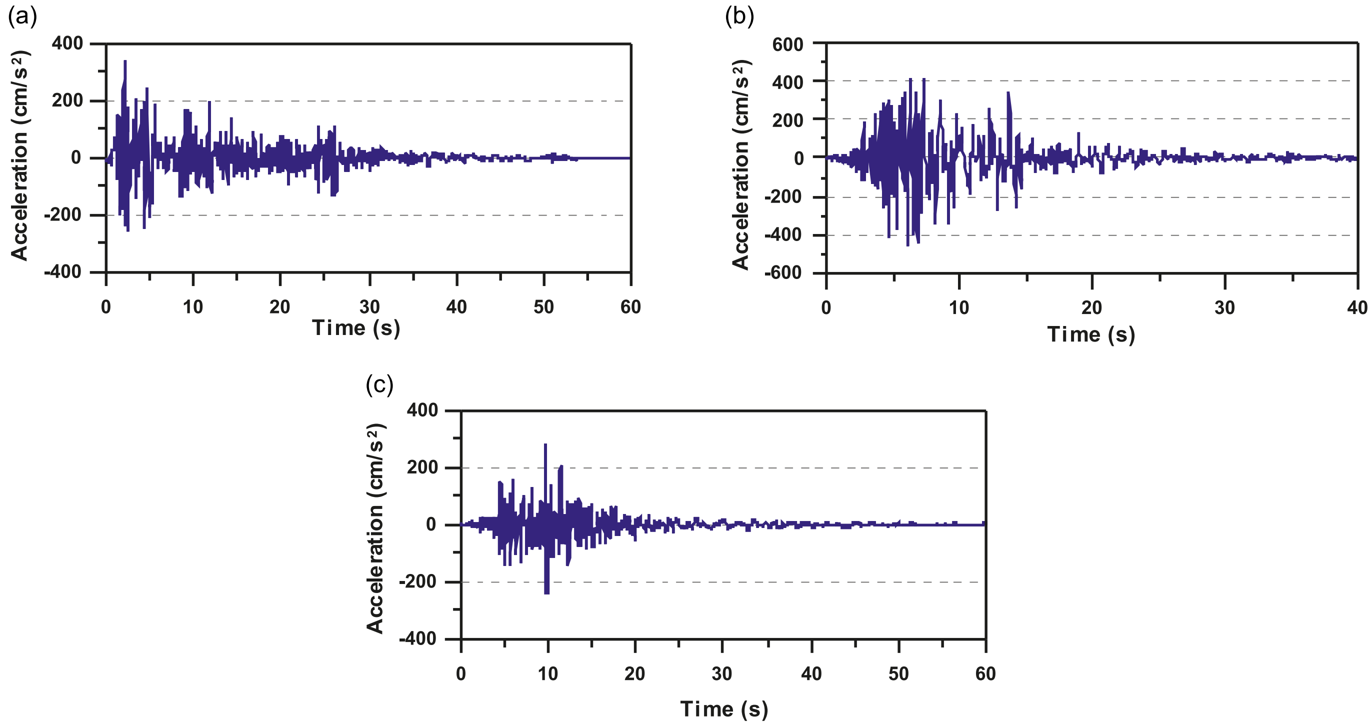


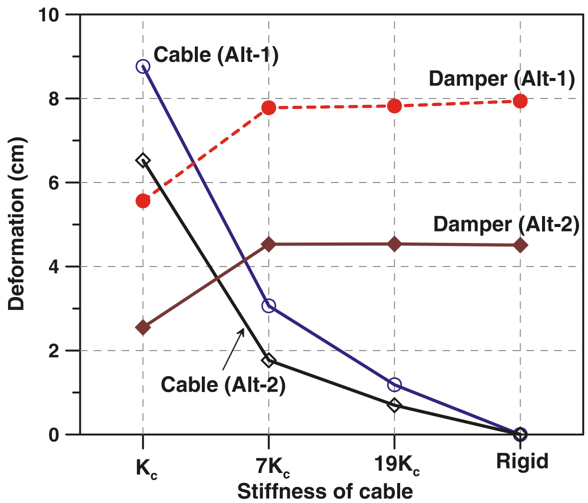
Table 4. Damping coefficients of viscoelastic dampers: (*a*) six-storey, (*b*) 15-storey.

		Alt-1		Alt-2	
Installation type	Inverse V	E2*	E3†	E2	E3
Six-storey model structure					
C_d	3.80	0.42	0.53	1.98	1.37
$\sum_{i=1}^{N} C_{di}$	22.83	1.26	1.07	5.93	2.73
15-storey model structure					
C_d	9.33	0.29	0.42	3.18	1.98
$\sum_{i=1}^{N} C_{di}$	139.97	1.43	1.25	15.90	5.93

*Dampers located in every two storeys (3 dampers) (Fig. 7*b*).
†Dampers located in every three storeys (2 dampers) (Fig. 7*c*).

formation in dampers will be maximized if the relative stiffness of cable is much larger than that of the damper. Otherwise, the cable will also deform and the relative deformation in dampers will decrease, resulting in decrease in effectiveness of the dampers and increase in structural responses. In this section, the effect of cable stiffness on structural responses was investigated. The unit diameter and cross-sectional area of a tendon are 15.2 mm and 138.7 mm^2, respectively. Cables made of one tendon (K_c), seven tendons ($7K_c$), and 19 tendons ($19K_c$) were applied to install VED in the six-storey structure, and the structure was analyzed using the El Centro earthquake. Figure 9 depicts the deformation in the cable and the dampers as the stiffness of the cable varies. It can be observed that as the stiffness of the cable increases the deformation in the cable decreases and the deformation in the dampers increases. It also can be noticed that when the cable stiffness is larger than $7K_c$, the deformation in the dampers does not change significantly. When the cable is installed continuously throughout the structure (Alt-1 scheme), the deformations in both the cable and the dampers are larger than when the cable is installed divided into two pieces (Alt-2 scheme). This is because the structure deformation was similar to the first mode of vibration. Figure 10 depicts the maximum storey displacements of the model structure with different cable stiffness. It can be observed that as the stiffness of cable increases the storey displacement decreases. The difference between using the cable composed of 19 tendons and the rigid cable turned out to be less than 10%. Therefore, the cable may be considered as rigid in the response analysis of a structure with dampers when the stiffness of cable is large enough. The relative stiffness of cable can be enhanced by installing many dampers with small stiffness (and small damping coefficient) instead of a few dampers with large stiffness (and large

Fig. 9. Deformation of cable and damper at various cable stiffness.



damping coefficient), and by applying discontinous installation scheme of cables to reduce the length of each cable.

Response for sinusoidal ground acceleration

To investigate the response characteristics of the model structure with a VED installed by high-strength cables, the model structures were analyzed using a sinusoidal ground excitation with its forcing frequency equal to the first and the second natural frequencies of the structure. The dampers were located in every three storeys (E3) in the six-storey structure and in every five storeys (E5) in the 15-storey structure. Both the Alt-1 and Alt-2 installation schemes were applied; in the Alt-2 installation scheme, the cable was disconnected in every three storeys in the six-storey structure and in every five storeys in the 15-storey structure. The structures with VED installed in every storey by inverted-V type steel braces were also analyzed for comparison. The damping coefficient of each damper in each scheme was determined so that the added damping became 5% of critical damping. It was assumed in the analysis that the cable is rigid. Figure 11 shows the maximum storey displacements of the six-storey structure with three different damper configurations. It can be observed that when the forcing frequency is equal to the first modal frequency of the structure, the analysis results are almost identical regardless of the installation scheme. However, when the structure was excited by ground excitation with forcing frequency equal to the second mode of vibration, the Alt-1 installation scheme resulted in the largest storey displacements. In the 15-storey structure, the difference between the Alt-1 and the Alt-2 schemes was somewhat reduced, as shown in Fig. 12, since vibration modes higher than the second mode also participated in the response.

Response analysis for earthquake ground excitations

Figures 13 and 14 show the nonlinear time-history analysis results of the six-storey structure (*i*) without dampers; (*ii*) with a damper in every storey installed by inverted V-type steel braces (All); and (*iii*) with dampers in every two (E2) and three (E3) storeys. The damping coefficients of a VED, which are presented in Table 4, were determined so that 10% of critical damping was achieved in each damper installation scheme. Figure 13 shows the analysis results of the structure with continuous cable throughout the storeys (Alt-1). It can be observed that with a VED installed by the three different schemes the lateral storey displacements of the model structure were reduced significantly. The structure with a damper in every storey showed smallest displacement in the upper storeys. However, the storey displacements of the structure with less number of dampers and with significantly less amount of damping material installed by the proposed scheme were also reduced similarly. The analysis results of the six-storey structure with a VED installed by discontinuous cables, depicted in Fig. 14, shows that the storey displacements of the model structure with the three different damper installation schemes are almost identical. This can be expected since the dampers were designed to provide the same modal damping ratio in each scheme.

Figures 15 and 16 show the analysis results of the 15-storey structure with Alt-1 and Alt-2 cable installation schemes, respectively. It can be observed that because of the participation of higher modes, the maximum storey displacements obtained by Alt-1 damper installation scheme turned out to be higher than those obtained by the other installation schemes. The results of the Alt-2 scheme with a VED and discontinuous cables installed in every three storeys are almost identical to those obtained in the structure with a damper in every storey installed by conventional steel braces. However, it should be noticed that to have the same response reduction effect, the overall damping coefficient (which is generally proportional to the amount of viscoelastic material used) required in the Alt-2 scheme corresponds only to 12% of the damping coefficient required for conventional method of damper installation.

Figures 17 and 18 plot the hysteresis loops of the dampers located in the second and the sixth storey of the six-storey model structure when it was subjected to the El Centro earthquake. The dampers were installed in every other storey by both Alt-1 and Alt-2 schemes. When the Alt-1 installation scheme was applied, the deformation in the damper located in the top storey corresponds to the storey displacement at the top storey, and consequently produces larger hysteresis loops than those of the dampers in the second storey, as shown in Fig. 17. The hysteretic behavior of the second-storey damper resulted in smaller loops since the relative deformation in the damper was equal to the storey displacement of the second storey. When the dampers were installed by cables discontinuous in every two storeys, the shear deformation in the sixth-storey damper was equal to the relative displacement between the fourth and the sixth storeys and the deformation in the second-storey damper was equal to the storey displacement of the second storey. This resulted in similar hysteresis loops in the second and the sixth storey dampers, as shown in Fig. 18. It also can be observed that the dampers used in the Alt-2 scheme experiencd larger damping force, as the damping coefficient of the dampers used in the Alt-2 scheme is larger than that of the dampers in the Alt-1 installation scheme. In tall buildings, in which many vibration modes contribute to seismic responses, the use of multiple installation schemes for dampers may provide enhanced performance against earthquake loads.

Fig. 10. Interstorey displacement of the six-storey structure with various tendon strength: (*a*) Alt-1 scheme, (*b*) Alt-2 scheme.

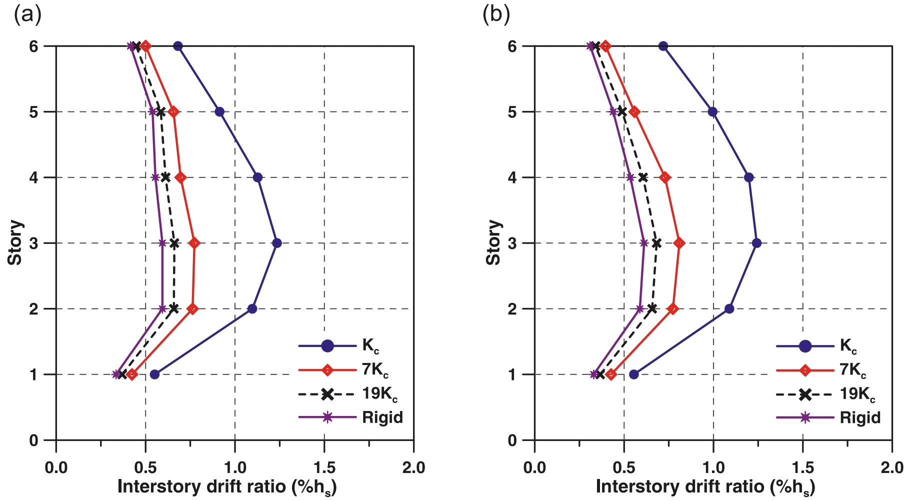


Fig. 11. Maximum storey displacement of the six-storey model structure subjected to sinusoidal.

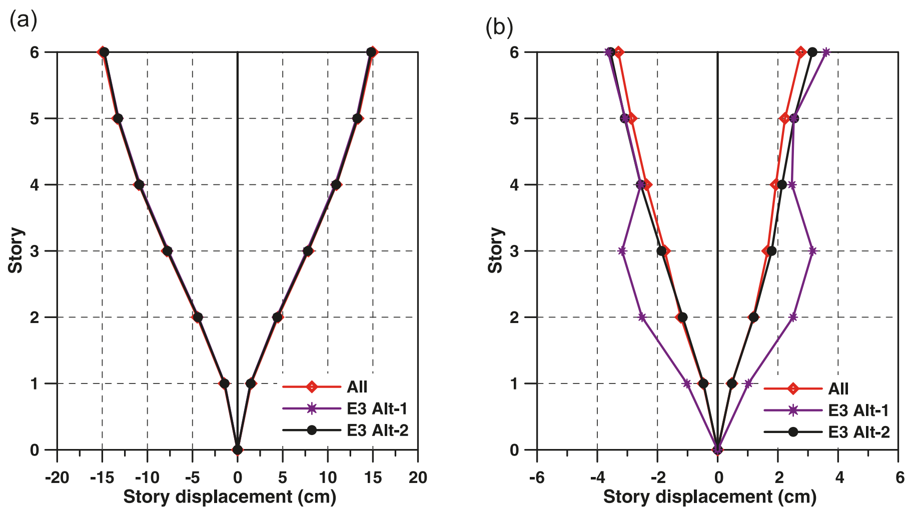


Fig. 12. Maximum storey displacement of the 15-storey model structure subjected to sinusoidal

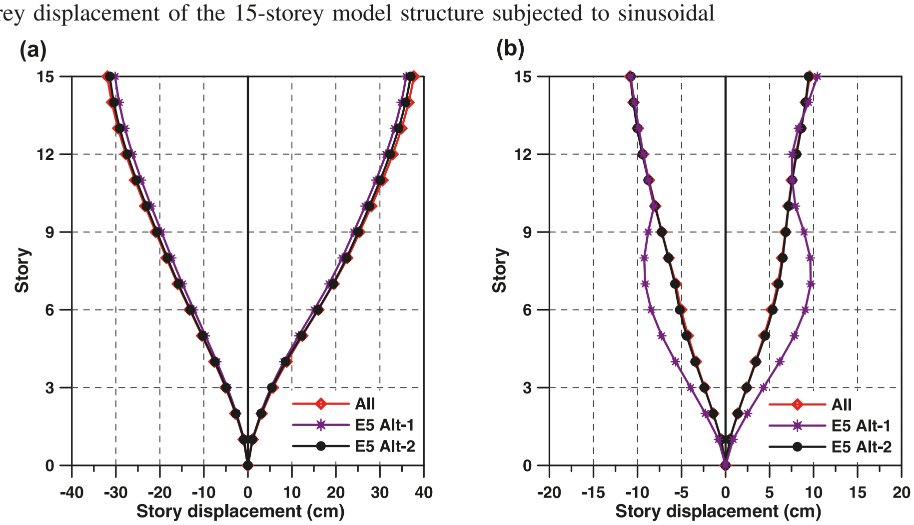


Fig. 13. Interstorey drift of the six-storey structure with dampers installed by Alt-1 scheme: (*a*) El Centro earthquake, (*b*) Loma Prieta earthquake, (*c*) Northridge earthquake.

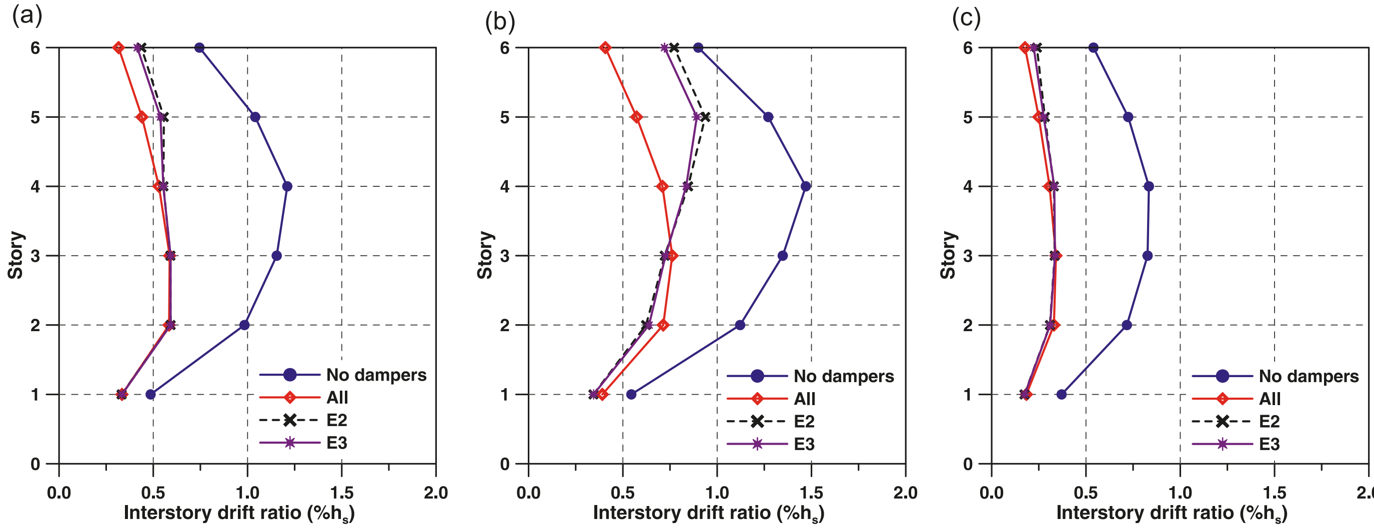
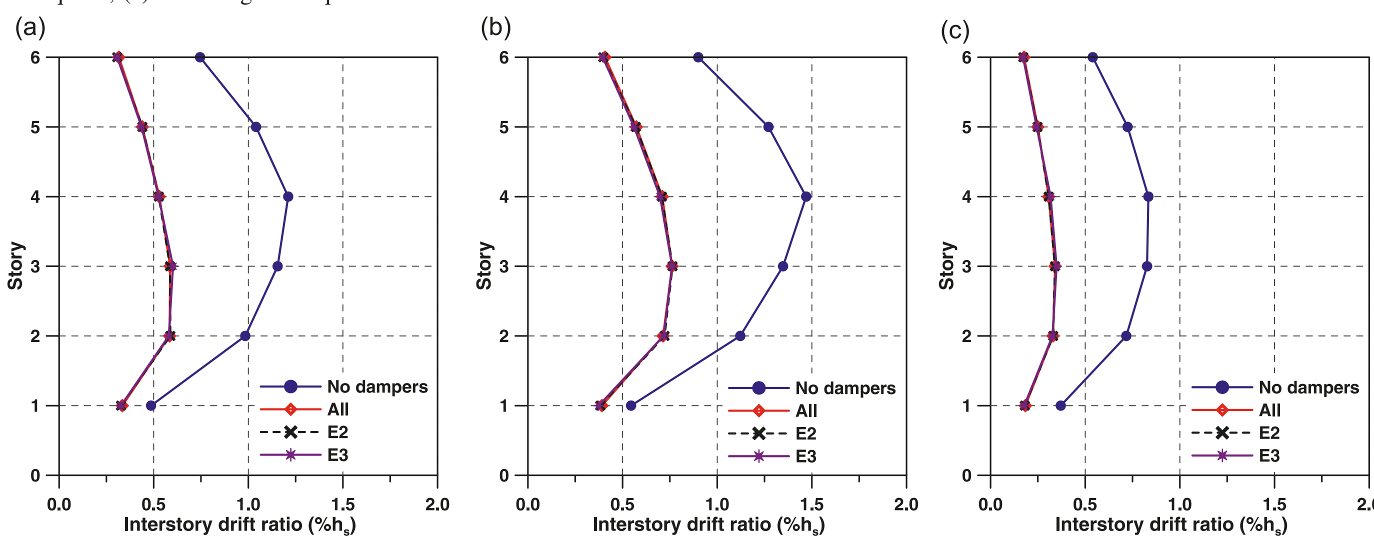


Fig. 14. Interstorey drift of the six-storey structure with dampers installed by Alt-2 scheme: (*a*) El Centro earthquake, (*b*) Loma Prieta earthquake, (*c*) Northridge earthquake.



Conclusions

In this study, new installation scheme for passive dampers was proposed using cables installed in such a way that large relative displacement occurs between the cable and the structure, when the structure is subjected to lateral load. The cables can be installed continuously or discretely between base and top of structures. When continuous cable is used, the shear deformation experienced by each damper is equal to the displacement of the storey, in which the damper is located, not to the interstorey drift as in the conventional method of damper installation using steel braces. This can be an advantage compared with conventional method when the structure deforms primarily in accordance with the first mode of vibration. The effectiveness of the continuous installation scheme will decrease when higher vibration modes participate significantly in the structural responses. In this case, the effectiveness of dampers can be enhanced by installing dampers using cables continuous for only a few storeys.

To verify the validity of the proposed method, nonlinear dynamic analysis of model structures with viscoelastic dampers that are installed using the proposed configuration scheme was carried out. In the analysis, three different earthquake records and two sinusoidal forces were used. According to the results of the analysis,. the proposed method resulted in significant reduction in the size of dampers compared with the conventional installation methods to achieve the same response reduction effect. As the effectiveness of the proposed damper installation scheme depends on the stiffness of the cable relative to that of the damper, the cable is required to be stiff enough to maximize the vibration reduction effect. Even though the effectiveness of the proposed installation scheme has been verified in this paper by numerical analysis of simplified two-dimensional moment frames, further research is still required to evaluate the applicability of the proposed method through experiments or analysis of more realistic structural models. Also, as the cur-

Fig. 15. Interstorey drift of the 15-storey structure with dampers installed by Alt-1 scheme: (*a*) El Centro earthquake, (*b*) Loma Prieta earthquake, (*c*) Northridge earthquake.

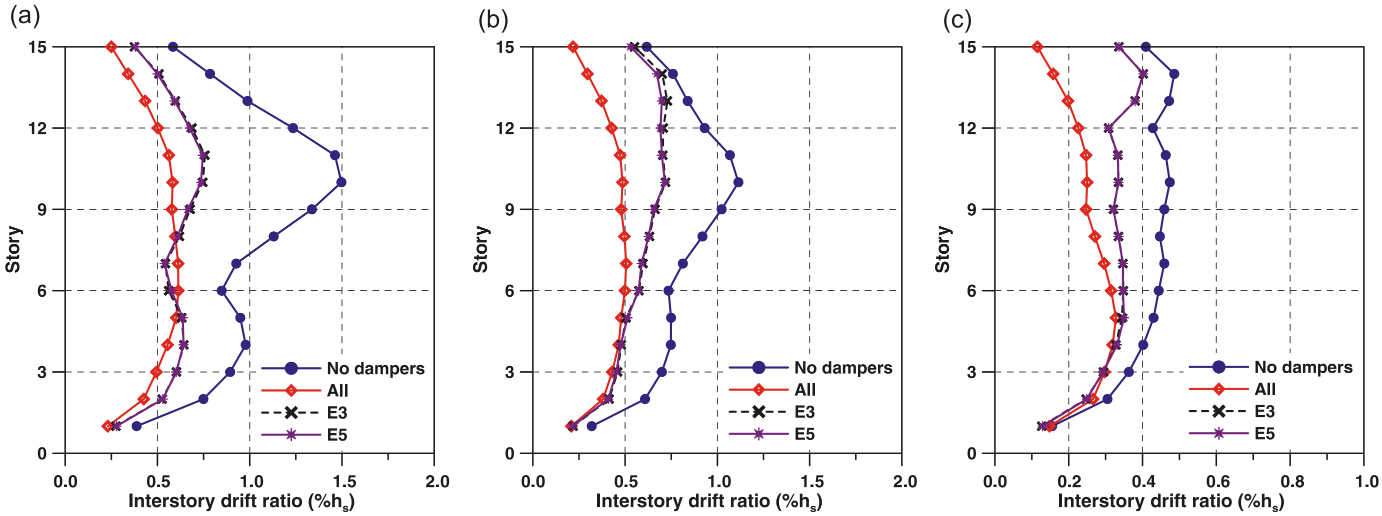


Fig. 16. Interstorey drift of the 15-storey structure with dampers installed by Alt-2 scheme: (*a*) El Centro earthquake, (*b*) Loma Prieta earthquake, (*c*) Northridge earthquake.

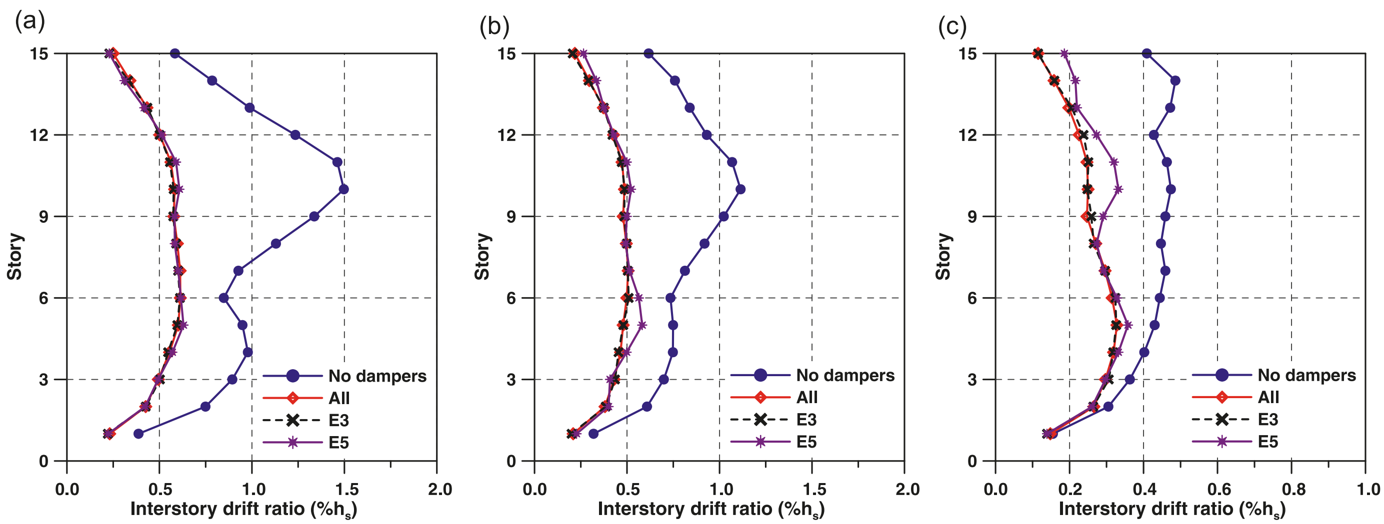


Fig. 17. Hysteresis loop of the six-storey model structure (E2) with dampers installed by Alt-1 scheme subjected to El Centro earthquake: (*a*) top storey, (*b*) second storey.

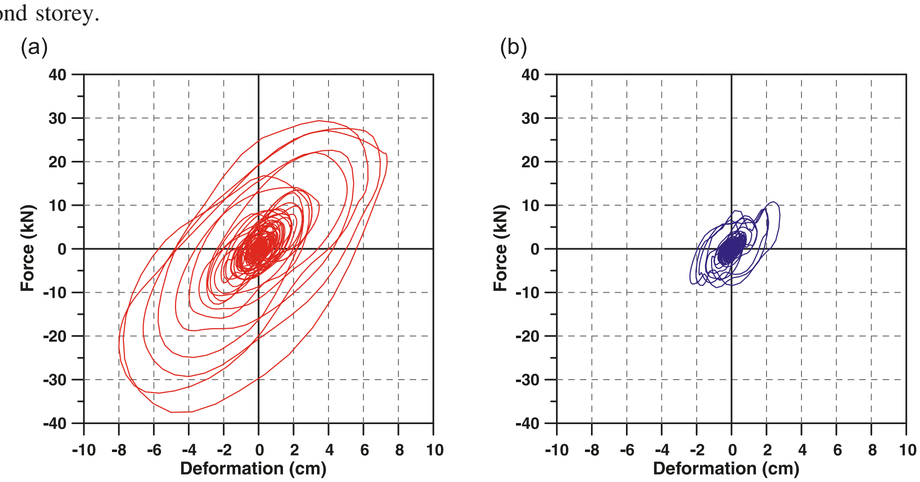
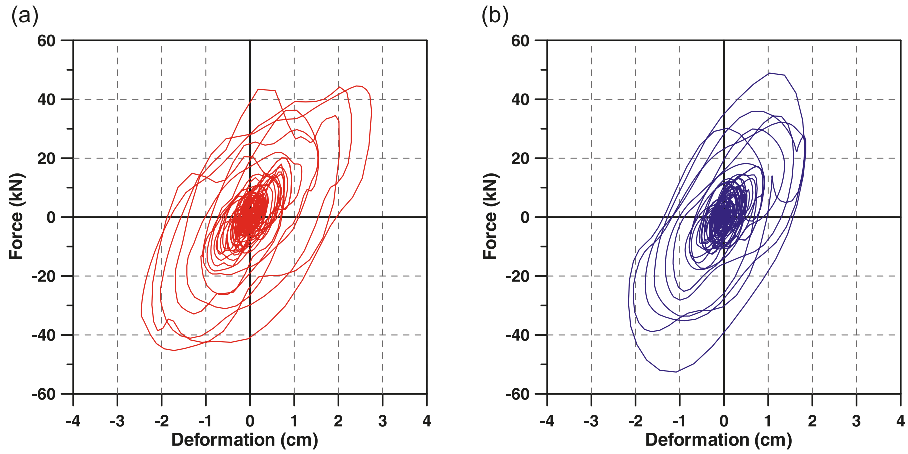


Fig. 18. Hysteresis loop of the six-storey model structure (E2) with dampers installed by Alt-2 scheme subjected to El Centro earthquake: (*a*) top storey, (*b*) second storey.



rent study was limited to conceptual stage of investigation, further study is needed for practical implementation of the cable-damper system in real structures.

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References

Ahn, S.K., Min, K.W., Park, J.H., Lee, S.H., Lee, D.G., Oh, J.K., Kim, K.S., and Lee, S.K. 2008. Practical issues and solutions on installation of viscoelastic dampers in a 46-storey reinforced concrete building structure. Structural Design of Tall and Special Buildings, **17**(1): 231–243. doi:10.1002/tal.353.

Constantinou, M.C., Tsopelas, P., Hammel, W., and Sigaher, A.N. 2001. Toggle-brace-damper seismic energy dissipation systems. Journal of Structural Engineering, **127**(2): 105–112. doi:10.1061/(ASCE)0733-9445(2001)127:2(105).

FEMA. 2000. Prestandard and commentary for the seismic rehabilitation of buildings, FEMA-356, Federal Emergency Management Agency, Washington, D.C.

García, M., de la Llera, J.C., and Almazán, J.L. 2007. Torsional balance of plan asymmetric structures with viscoelastic dampers. Engineering Structures, **29**(6): 914–932. doi:10.1016/j.engstruct.2006.06.022.

Kim, J., and Bang, S. 2002. Optimum distribution of added viscoelastic dampers for mitigation of torsional responses of plan-wise asymmetric structures. Engineering Structures, **24**(10): 1257–1269. doi:10.1016/S0141-0296(02)00046-9.

Kim, J., and Choi, H. 2006. Displacement-based design of supplemental dampers for seismic retrofit of a framed structure. Journal of Structural Engineering, **132**(6): 873–883. doi:10.1061/(ASCE)0733-9445(2006)132:6(873).

Lin, W.-H., and Chopra, A.K. 2003. Asymmetric one-storey elastic systems with non-linear viscous and viscoelastic dampers: Earthquake response. Earthquake Engineering & Structural Dynamics, **32**(4): 555–577. doi:10.1002/eqe.237.

Lin, Y.Y., Tsai, M.H., Hwang, J.S., and Chang, K.C. 2003. Direct displacement-based design for building with passive energy dissipation systems. Engineering Structures, **25**(1): 25–37. doi:10.1016/S0141-0296(02)00099-8.

Min, K.W., Kim, J., and Lee, S.H. 2004. Vibration tests of 5-storey steel frame with viscoelastic dampers. Engineering Structures, **26**(6): 831–839. doi:10.1016/j.engstruct.2004.02.004.

Prakash, V., and Powell, G.H. 1994. DRAIN-2DX: Base program user guide. Earthquake Engineering Research Center, Department of Civil Engineering, University of California, Berkeley, Calif.

Sigaher, A.N., and Constantinou, M.C. 2003. Scissor-jack-damper energy dissipation system. Earthquake Spectra, **19**(1): 133–158. doi:10.1193/1.1540999.

Soong, T.T., and Dargush, G.F. 1997. Passive energy dissipation systems in structural engineering. John Wiley & Sons, New York.

Xu, Z.-D., Zhao, H.-T., and Li, A.-Q. 2004. Optimal analysis and experimental study on structures with viscoelastic dampers. Journal of Sound and Vibration, **273**(3): 607–618. doi:10.1016/S0022-460X(03)00522-4.