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Seismic study of buildings with viscoelastic dampers

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Abstract. In this paper, the seismic behavior of a 10-story building equipped with viscoelastic dampers is analyzed. The effects of ambient temperature, the thickness, the total area, and the position of the viscoelastic dampers are studied. Results indicate that the energy-absorbing capacity of viscoelastic damper decreases with increasing the ambient temperature. The thickness and the total area of viscoelastic dampers also affect the seismic mitigation capacity. The thickness cannot be too small, which is not effective in vibration reduction, nor can it be too large, which not only increases the cost but also reduces the seismic resistance. The total area of viscoelastic dampers should be determined properly for optimum damper performance at the most economical design. The mounting position of viscoelastic dampers also influences the structure's seismic performance. Numerical results show that, if properly equipped, the VE dampers can reduce the structural response both floor displacement and story shear force and increase the overall level of damping in structures during earthquakes.

Key words: energy-absorbing device; viscoelastic damper; earthquake engineering; seismic mitigation; energy dissipation; structural dynamics; time-history analysis.

1. Introduction

The use of energy-absorbing devices to dissipate seismically induced kinetic energy is one of the most economical and effective ways to mitigate the effects of earthquakes on structures. Viscoelastic dampers (Keel and Mahmoodi 1986) have been adopted for several tall buildings in the U.S. to reduce wind-induced response. In recent years, both analytical and experimental research (Chang, *et al.* 1991, Tsai and Lee 1993) have demonstrated their effectiveness for seismic hazard mitigation of buildings. More recently, Tsai and Lee (1993) have developed an analytical model, in good agreement with experimental results, to simulate the mechanical behavior of buildings equipped with viscoelastic dampers. The objectives of this study are to further study the seismic effects of the ambient temperature, the thickness, the numbers, and placements of viscoelastic dampers and the seismic behavior of a 10-story building with VE dampers.

2. Analytical model for viscoelastic damper

This analytical model was proposed by Tsai and Lee (1993). The constitutive law for viscoelastic damper at time step $N\Delta t$ is

$$\tau(N\Delta t)=\left[G_0+\frac{G_1(\Delta t)^{-\alpha}}{\Gamma(2-\alpha)}\right]\gamma(N\Delta t)+F(N\Delta t) \tag{1}$$

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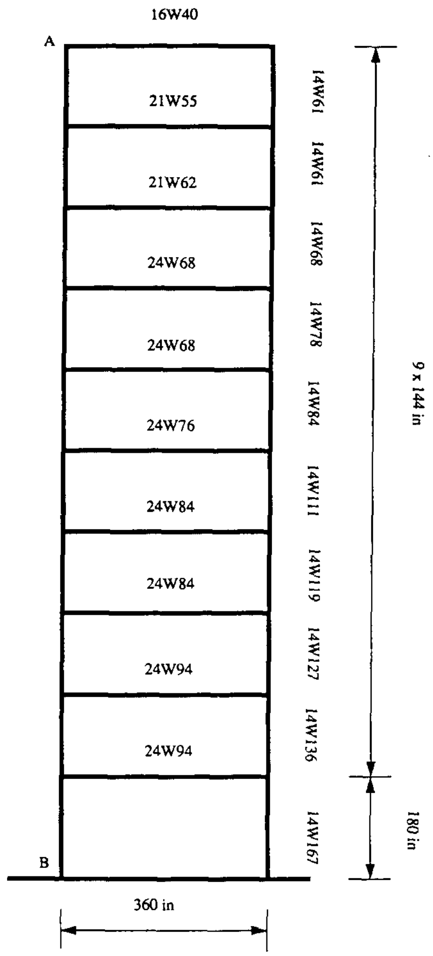

Fig. 1 A 10-story building.

where $\tau(N\Delta t)$=shear stress, $\gamma(N\Delta t)$=shear strain, G_0=G_1=constitutive model parameters, α=to be determined from the experimental data.

In the above equation, the previous time effect of the strain, $F(N\Delta t)$, is defined as

$$F(N\Delta t)=\frac{G_1(\Delta t)^{-\alpha}}{\Gamma(2-\alpha)}\{\{(N-1)^{1-\alpha}+(-N+1-\alpha)N^{-\alpha}\}\gamma(0)$$

$$+\sum_{n=1}^{N-1}\{(N-n-1)^{1-\alpha}-2(N-n)^{1-\alpha}+(N-n+1)^{1-\alpha}\}\gamma(n\Delta t)\} \quad (2)$$

A finite element formulation for viscoelastic dampers (Tsai 1993) is adopted for the numerical study of a 10-story building with VE dampers during earthquakes.

3. The response parameters of the viscoelastic dampers

A 10-story building, constructed with moment resistant steel frames, is shown in Fig. 1. Both the columns and beams have a Poisson's ratio and elastic modulus equal to 0.3 and 3×10^7

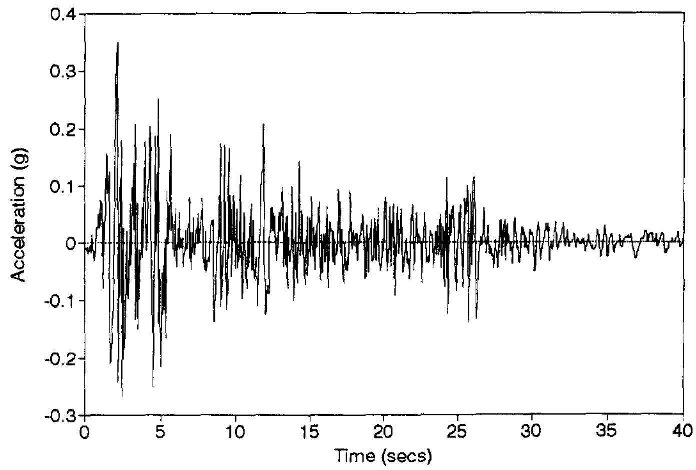

Fig. 2 North-South component of ground motion, El Centro (1940).

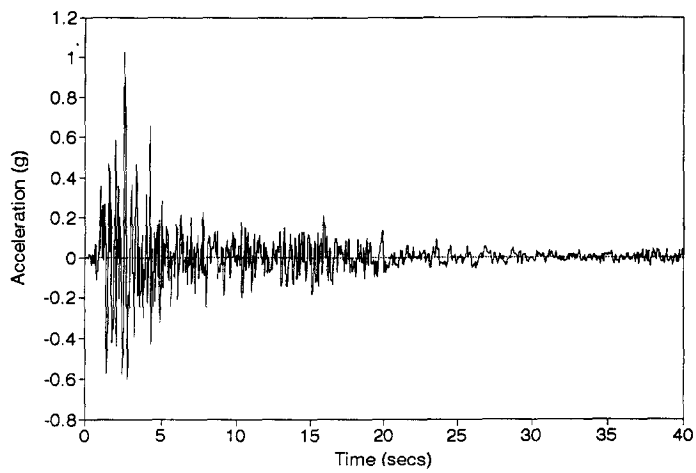

Fig. 3 North-South component of ground motion, San Fernando (1971).

psi (0.2068×10^{12} N/m^2), respectively. The weight of each floor is 25.47 lbs/in (4.4606 N/mm). In the analysis, it is assumed that the floors are rigid in their own plan. The unknown coefficients $A_0 = 7.0741 \times 10^4$ Pa, $\beta = 1.4504 \times 10^{-7}$, $\mu = 3.0$, $\alpha = 0.60$, $\theta = 7.3774 \times 10^5$, $T_o = 28$℃ were adopted. The two selected motion records, shown in Figs. 2-3, include the 1940 EI Centro earthquake, and the 1971 San Fernando earthquake. As shown in Fig. 4, VE dampers are installed on each floor and supported by Chevron braces.

The parameters of this study are the thickness, the total area, the number of viscoelastic dampers, and the ambient temperature. The selected response parameters include (1) the story shear force, which is the total shear shared by the viscoelastic dampers and frame; and (2) the floor displacement. In all figures, the unit of displacement is in inches and the unit of force is in pounds. Tables 1-4 define the symbols which represent the selected conditions. For example, if the number of the viscoelastic dampers were selected as 10, 5, 3, 1, they were assigned as VE10, VE5, VE3, VE1. The total area of the damper at first floor was designated as area 1

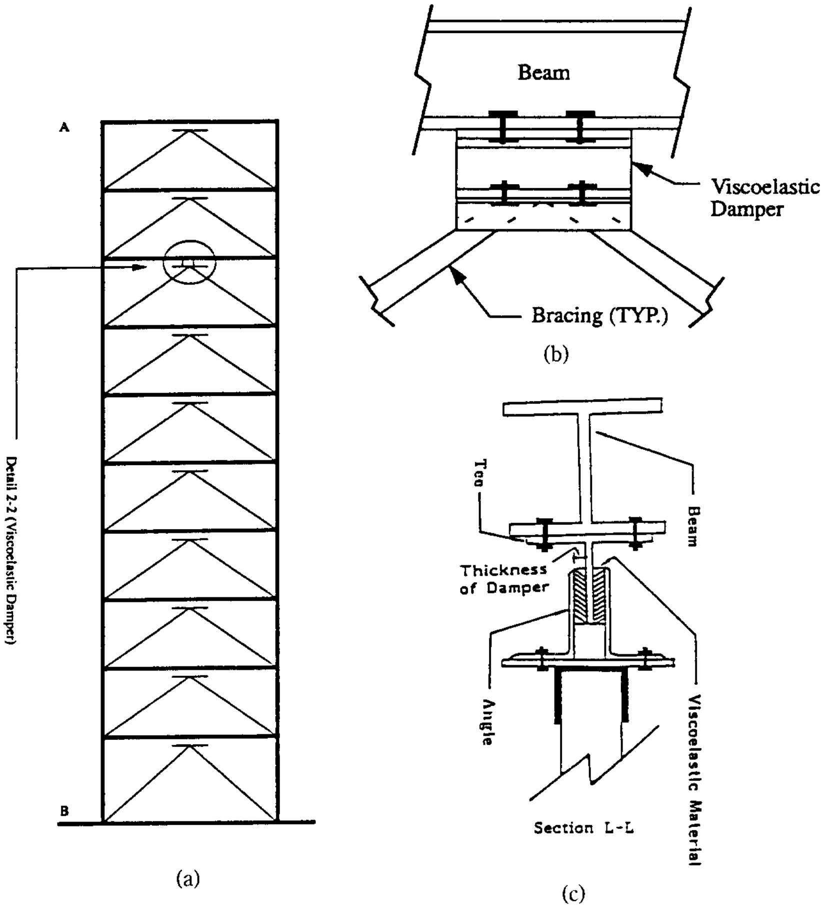

Fig. 4 A 10-story building with proposed arrangement of VE dampers.

Table 1 The symbols of the location of VE dampers

Symbols	Explanation
VE10	Each floor was mounted with a VE damper
VE5	Floors 1, 2, 3, 4, 5 were mounted with a VE damper
VE5(2)	Floors 1, 3, 5, 7, 9 were mounted with a VE damper
VE3	Floors 1, 2, 3 were mounted with a VE damper
VE3(2)	Floors 1, 3, 5 were mounted with a VE damper
VE1	Floor 1 was mounted with a VE damper

Table 2 The symbols of area of VE dampers

Symbol	Area 1 (in^2)	Area 2 (in^2)
a1	220	132
a2	250	150
a3	280	168
a4	310	186
a5	465	279

Table 3 The symbols of thickness of VE dampers

Symbol	Thickness (in)
t1	1.30
t2	1.45
t3	1.60
t4	1.15
t5	1.00
t6	1.38
t7	1.34
t8	1.77

Table 4 The symbols of temperature of VE dampers

Symbol	Temperature (℃)
T0	0
T5	5
T10	10
T15	15
T20	20
T25	25
T30	30
T35	35
T40	40

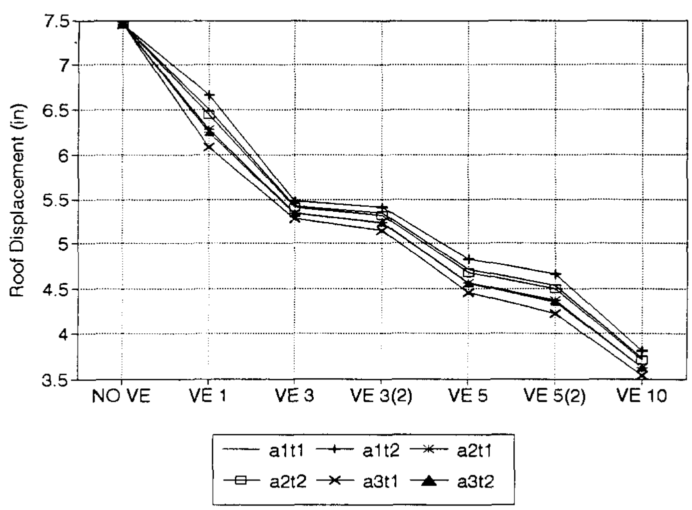

Fig. 5 Comparison of floor displacement when the structure is subjected to El Centro ground motion.

while those for the remaining dampers were assigned as area 2. The area 2 is equal to 60% of the area 1.

4. Positional effects of viscoelastic dampers

The effects of the number of viscoelastic dampers mounted on the structure are shown in

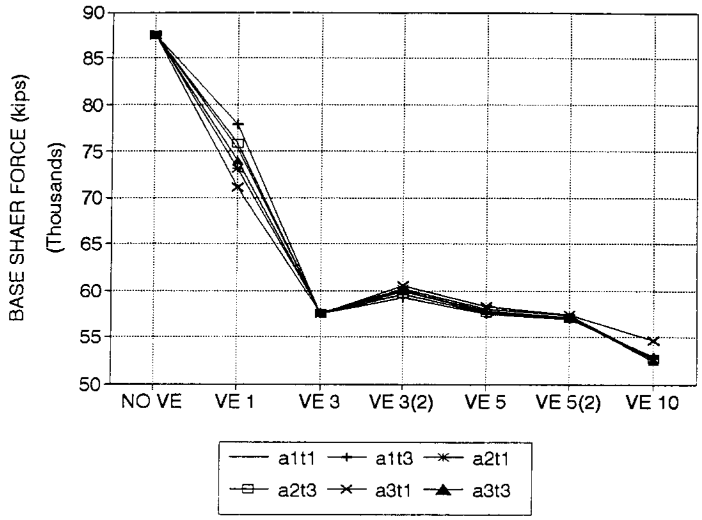

Fig. 6 Comparison of base shear force when the structure is subjected to El Centro ground motion.

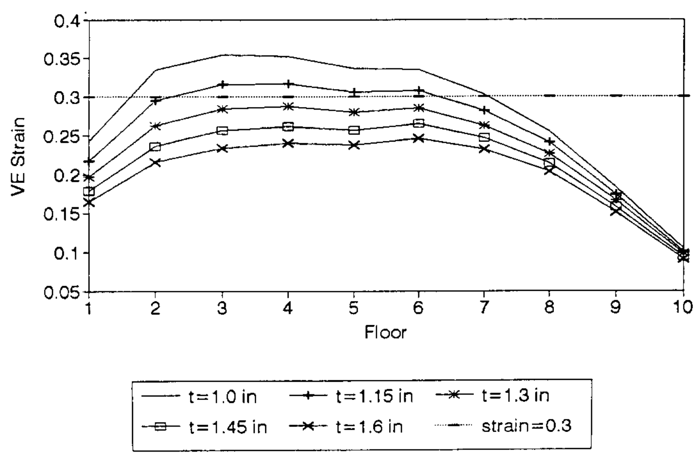

Fig. 7 Comparison between the thickness and the strain while the structure is subjected to El Centro ground motion.

Figs. 5-6. Fig. 5 indicates that when more dampers are mounted on the structure, the smaller maximum roof displacement (MRD) is produced. However, VE5(2) has a smaller MRD than VE5. This indicates that a viscoelastic damper mounted to every other floor starting from the 1st floor performs better than that mounted on the structure from floor 1 to floor 5. The results also show that the structure with VE(a3t1) has the best performance among the six cases and prove that viscoelastic dampers with greater area perform better. On the other hand, decreasing the thickness of viscoelastic dampers has resulted in better performance; however, this does not mean that the thinner the damper, the smaller the MRD responses. When the thickness of the damper is too small, the viscoelastic damper develops strain greater than its performance limit of 0.3. Therefore, the thickness of a viscoelastic damper should be carefully considered so that it will not be too small to induce large strain. At the same time, it should not be too large to increase its cost and to reduce its performance.

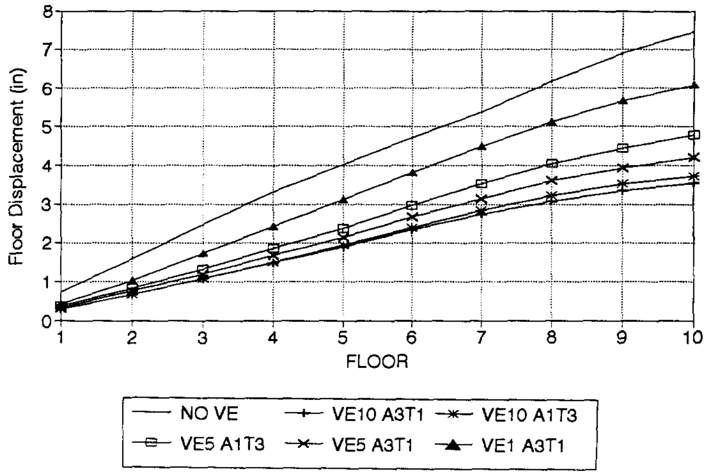

Fig. 8 Comparison of floor displacement when the structure is subjected to El Centro ground motion.

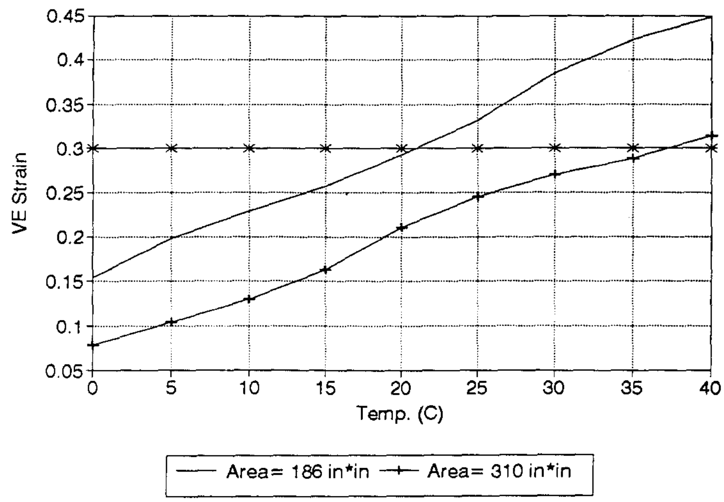

Fig. 9 Comparison of strain at different temperatures while the structure is subjected to El Centro ground motion.

Fig. 5 shows that VE3 reduces about 27% of the roof displacement, and VE10 reduces about 50%, compared to the structure without VE. Although the VE10 produces the smallest base shear force, mounting only one viscoelastic damper to the first floor could effectively reduce both base shear force and roof displacement.

The relations between the thickness of damper and its developed strain were shown in Fig. 7. It indicates that when the thickness are 1.0 in and 1.15 in, the strain measurements are greater than 0.3 which causes the damper to fail to perform properly. Fig. 8 shows the floor displacement when the structure was equipped with various properties of VE dampers during El Centro earthquake.

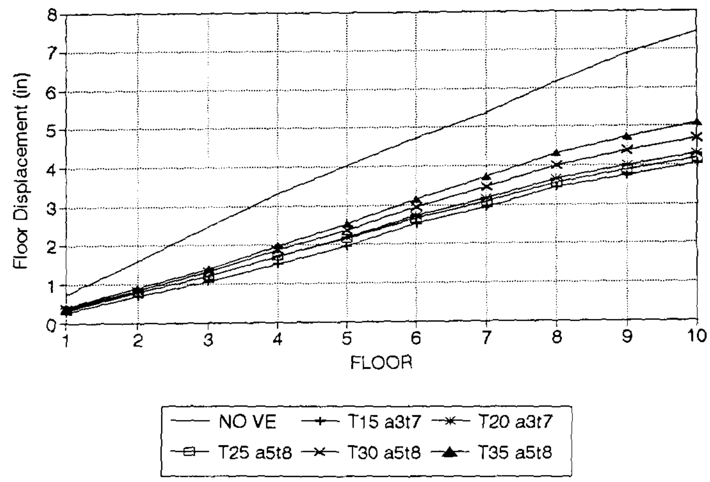

Fig. 10 The response of floor displacement at each floor while the structure is subjected to El Centro ground motion.

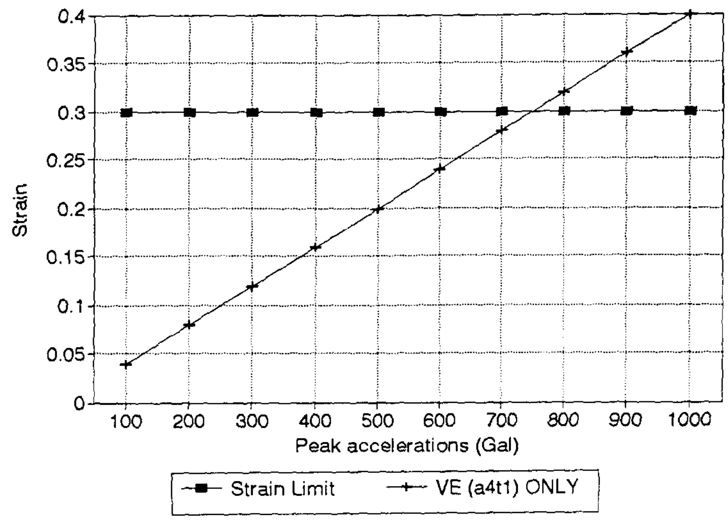

Fig. 11 Comparison of strain measurements when the structure is subjected to the peak acceleration of 100 Gal to 1000 Gal of San Fernando ground motion.

5. Effects of the ambient temperatures

The behavior of the viscoelastic damper is dependent on the ambient temperature. Since the viscoelastic dampers transfer dynamic energy into heat, their temperature rises during earthquake excitation. The temperature increase can affect the capacity of the dampers causing a severe problem. The effect of ambient temperature is, however, very complicated. Temperature increases can reduce the effective performance of the damper while temperature decreases can also increase material stiffness (Chang, *et al.* 1991). Both outcomes are regarded as unfavorable for the design of dampers.

The result of the temperature effects on the developed strain of the viscoelastic dampers is

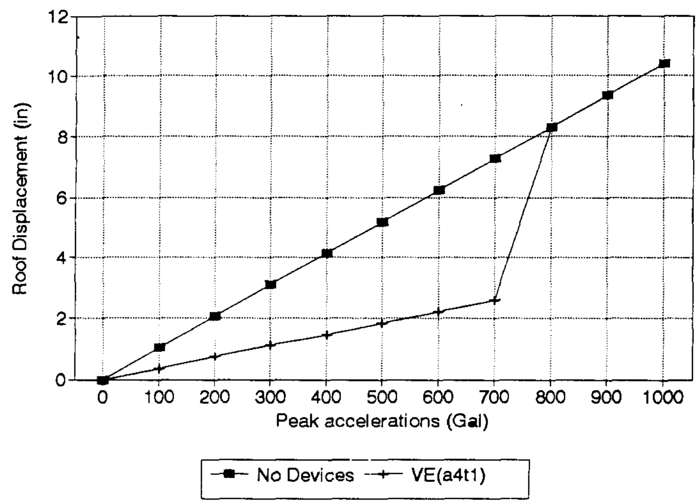

Fig. 12 Comparison of roof displacement when the structure is subjected to the peak acceleration of 100 Gal to 1000 Gal of San Fernando ground motion.

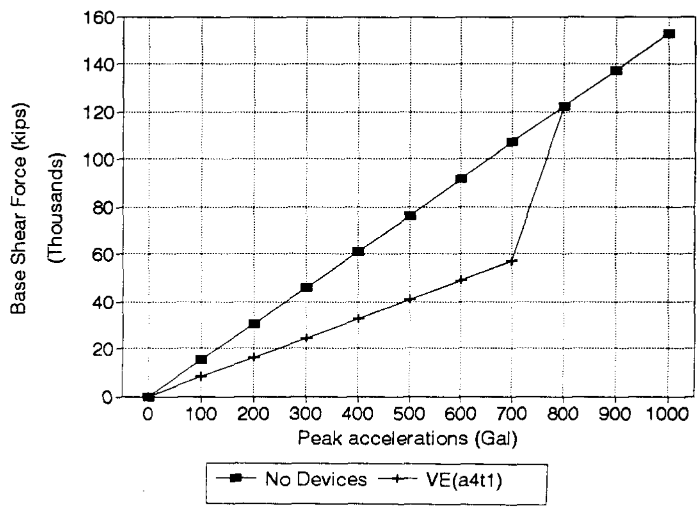

Fig. 13 Comparison of base shear force when the structure is subjected to the peak acceleration of 100 Gal to 1000 Gal of San Fernando ground motion.

shown in Fig. 9. It illustrates that the optimal selection of the viscoelastic damper at the ambient temperature 20°C is not satisfactory when its temperature increases because the dampers develop strain greater than 0.3 during which the dampers fail to improve the seismic resistance. Fig. 10 demonstrates that the thickness and the total area of the damper should be larger when the ambient temperature is higher to reduce its MRD while the thickness and the total area of the damper can be much smaller when the ambient temperature is lower in order to reach the same effects.

The maximum developed strain of the viscoelastic dampers was compared when the structure was subjected to ten different earthquake peak accelerations from 100 Gal to 1000 Gal of the

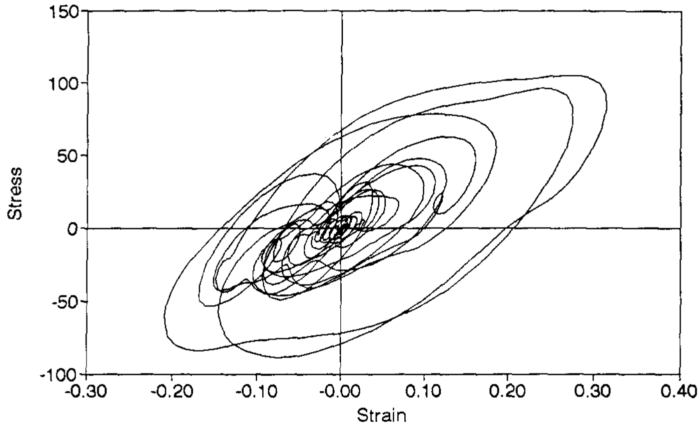

Fig. 14 The relation of stress and strain of dampers at 1st floor when the structure is subjected to San Fernando ground motion.

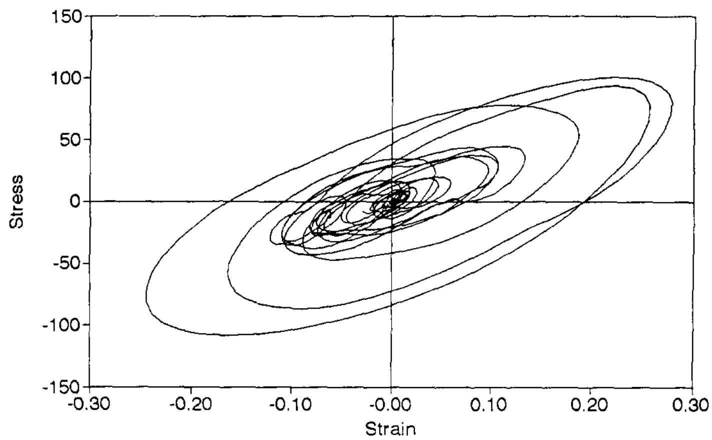

Fig. 15 The relation of stress and strain of dampers at 5th floor when the structure is subjected to San Fernando ground motion.

San Fernando ground motion. Fig. 11 shows that the strain of VE dampers is within its performance limit, 0.3, when the earthquake peak acceleration is less than or equal to 700 Gal of the San Fernando ground motion.

The response (roof displacement and base shear force) of the structure, with and without dampers, was compared when the structure was subjected to ten different earthquake peak acceleration from 100 Gal to 1000 Gal of the San Fernando ground motion. Figs. 12-13 show that the two curves are both linear when the peak acceleration is smaller than or equal to 700 Gal. The curve of the structure with VE dampers has a much smaller gradient. They also show the VE dampers fail to provide proper energy absorbing capacity when the peak acceleration is larger than 800 Gal because the strain measurement is greater than 0.3 which causes the damper to function improperly.

6. Conclusions

Numerical results show that the energy-absorption capacity of the viscoelastic damper decreases

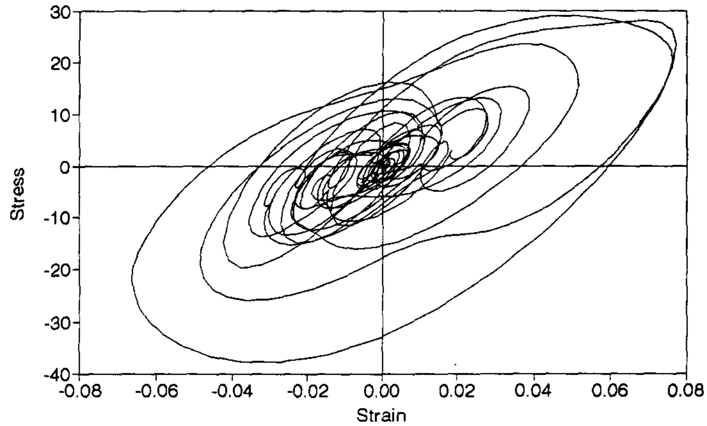

Fig. 16 The relation of stress and strain of dampers at 10th floor when the structure is subjected to San Fernando ground motion.

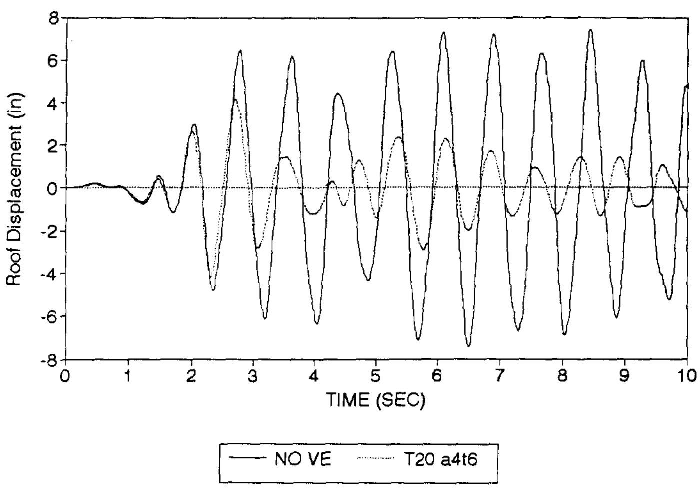

Fig. 17 The response of floor displacement when the structure is subjected to El Centro ground motion.

as ambient temperature increases. Due to temperature effects, the optimal design of viscoelastic dampers may need to be changed for different temperature environments. Therefore, the temperature effect should be considered one of the most important factors in damper design.

Results also show that the thickness of the damper plays an inportant role in improving the seismic resistance. During the design stage, critical decisions must be made about selecting the optimal damper thickness to maintain strain measurements under its limit and to ensure that the damper design is effective and economical. The total area of the viscoelastic dampers should also be determined properly to strengthen its capacity of seismic resistance without high cost. Adding dampers to all stories of the structure is not necessarily the most economical design, but adding a viscoelastic damper to the first floor will effectively reduce the structural response.

Numerical results illustrate that VE dampers located at the lower floors absorb more energy than those at upper floors. Figs. 14-16 show that relationship of stress and strain of the VE

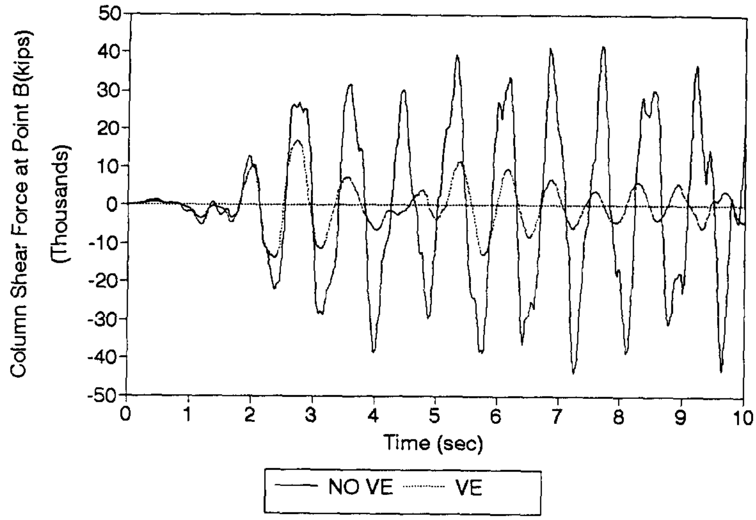

Fig. 18 The response of column shear force at point B when the structure is subjected to El Centro ground motion.

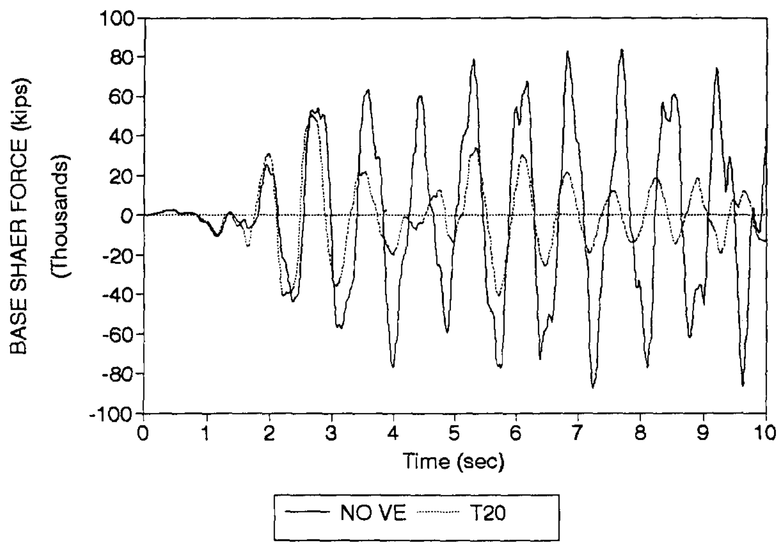

Fig. 19 The response of base shear force when the structure is subjected to El Centro ground motion.

dampers located at the 1st, 5th, and 10th floors, respectively. The time-history responses (roof displacement, column shear force at point B, and base shear force) of the structure, with and without, VE dampers are shown in Figs. 17-19 during El Centro earthquake. They illustrate that both floor displacement and shear stress of the structure are significantly reduced during earthquakes by adding viscoelastic dampers properly. In Fig. 17, the structure with VE generates 13 peaks while the structure without VE generates 12 peaks. The natural frequency is not changed significantly because adding VE dampers to the structure does not generally increase the structure's stiffness.

Fig. 18 indicates that the columns of the structure with VE dampers take a much smaller portion of base shear force compared to those of the structure without VE dampers. The main structural components may be optimized for their required stiffness and load-bearing features at lower cost because the energy-absorption demands on the main structural members are lessened.

A drawback of adopting viscoelastic dampers as energy-absorbing devices for seismic hazard mitigation is the structural response cannot be reduced greatly in the early stages of an earthquake and cannot provide a safe-failure mechanism in the event of strong earthquakes. As shown in Fig. 17, the roof displacement is substantially reduced after the fourth second. Meanwhile, it is not reduced from the first to third seconds. The main reason for this phenomenon is the velocity dependence in these devices is generally regarded as unfavorable. The viscoelastic dampers are made from a velocity proportional viscous material. Because the maximum displacement and the maximum velocity of the dampers never occur at the same time, there exists a conflict between dissipating the energy and developing resisting forces. Therefore, if a peak response occurs during early stages of earthquake excitation, which is generally true for most events, the VE dampers would be unable to reduce its structural response effectively in time. As a result, the structure may suffer severe damage under extreme earthquake loadings.

According to the numerical results, determination of the design properties of viscoelastic dampers is a complex process. Multiple layers of viscoelastic dampers could be considered as an alternative design to overcome the possibility of developing large strain during earthquakes. This design, producing different strains in the viscoelastic damper, will provide reliable energy absorption capacity when subjected to different earthquakes. In addition, a combination of tapered-plate energy absorbers (TPEA) and VE dampers may be considered a reliable energy-absorbing system because each can compensate for the shortcomings of the other device.

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