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Shaking table study of a 2/5 scale steel frame with new viscoelastic dampers

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Abstract. Viscoelastic (VE) dampers have shown to be capable of providing structures with considerable additional damping to reduce the dynamic response of structures. However, the VE material appears to be sensitive to the variations in ambient temperature and vibration frequency. To minimize these effects, a new VE material has been developed. This new material shows less sensitivity to variations in vibration frequency and temperature. However, it is highly dependent on the shear strain. Experimental studies on the seismic behavior of a 2/5 scale five-story steel frame with these new VE dampers have been carried out. Test results show that the structural response can be effectively reduced due to the added stiffness and damping provided by the new type of VE dampers under both mild and strong earthquake ground motions. In addition, analytical studies have been carried out to describe the strain-dependent behavior of the VE damper. The dynamic properties and hysteresis behavior of the dampers can be simulated by a simple bilinear model based on the equivalent dissipated energy principle proposed in this study.

Key words: VE damper; hysteresis; energy dissipation; shaking table study.

1. Introduction

Comprehensive analytical and experimental studies on seismic structural response attenuation using energy-absorbing devices, such as ADAS (added damping and stiffness) elements, viscoelastic (VE) dampers, viscous fluid dampers, and Pall friction devices *etc*., have been carried out in recent years (ATC17-1 1993, Earthquake Spectra 1993). Among these devices, VE dampers have shown to be capable of providing structures with considerable added damping to dissipate the seismic input energy and effectively reduce the response of structures subjected to wind loads or earthquake ground motions for both steel and reinforced concrete structures (Chang *et al*. 1995, Shen *et al*. 1995). The ductility demand of the viscoelastically damped structures under strong earthquakes can therefore be greatly reduced by proper utilization of the VE dampers (Chang *et al*. 1996).

It is well known that the dynamic properties of VE dampers vary with the change of the damper temperature and the vibration frequency. Recently, a new viscoelastic material has been developed.

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This new VE material is insensitive to temperature and frequency within the normal operation range, but is strongly strain dependent. When the deformation is small, the VE damper behaves viscoelastically. When the deformation is large, the hyteresis behavior of the VE damper becomes similar to that of a yielding-type energy dissipation device. In this study, the results of a shaking table study on a 2/5 scaled five-story steel frame with VE dampers made of the above mentioned new VE material are described. The dynamic responses of the steel frame with and without dampers under different intensities of scaled earthquake ground motions are compared. Although this new material is less sensitive to temperature and frequency change, numerical methods are proposed to consider these effects on the dynamic property of dampers. A simple bilinear model based on an equivalent dissipated energy principle is used to describe the hysteresis behavior of the new VE dampers, and the accuracy of the model is verified by comparing the simulated structural responses with the experimental results.

2. Material behavior

2.1 Damper test

Before proceeding to the shaking table test, sinusoidal cyclic loading tests on the dynamic behavior of the VE damper is carried out. A sketch of the VE damper used in the study is shown in Fig. 1. The test frequency and maximum strain range from 0.1 Hz to 5 Hz and 5% to 50%, respectively. The effect of ambient temperature is demonstrated by Fig. 2(a). It is seen that even though the ambient temperature increases substantially from 21^{o}C to 36^{o}C, the decrease of energy dissipation capacity of the VE dampers is significantly smaller than that studied before (Chang *et al*. 1992). Fig. 2(b) shows typical hysteresis loops of the damper under 1.0 Hz and 5.0 Hz sinusoidal excitations with maximum strains equal to 5%, 10%, and 50%. It is shown that the hysteresis loops stabilize after the second cycle. It is also seen that the VE damper behaves viscoelastically when the maximum damper strain is small. As the maximum damper strain increases, the shape of hyteresis loops becomes similar to that of a yielding-type energy dissipation device. Also, the first cycle usually has the largest loop area as compared to the subsequent cycles. In addition, it is observed

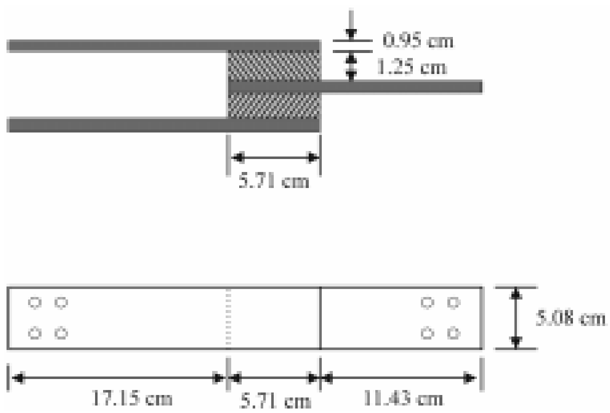
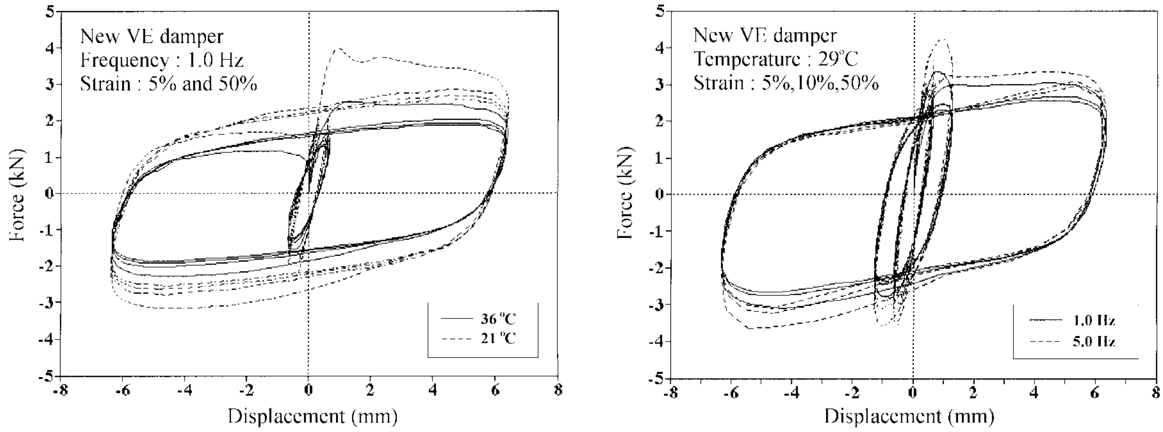


Fig. 1 The VE damper used in the study



(a) (b)

Fig. 2 (a) The effect of ambient temperature on damper properties; (b) Typical hysteresis loops of the damper under sinusoidal excitations

that the maximum damper force, except for the first cycle, is insensitive to the maximum displacement, and is slightly dependent on the vibration frequency. The damper force gradually returns to zero after the end of the displacement control test.

In addition to the sinusoidally cyclic loading tests, monotonic loading tests were also carried out to estimate the yield strain of the dampers, as will be described later.

2.2 Strain dependence

From the damper test results, it is clear that the most important characteristic of the dampers is its strain dependence. It is observed that the natural logarithm of energy dissipation per unit volume for the second cycle is nearly independent of the vibration frequency, but varies with maximum strains. To account for the strain dependence, the following equation is proposed to describe the energy dissipation capacity of the dampers:

$$\ln(E_d)=\frac{\left(b\gamma^{\beta}\sin\frac{\beta\pi}{2}\right)}{\left(1+b\gamma^{\beta}\cos\frac{\beta\pi}{2}\right)}-4.976 \text{ in N/mm}^2 \text{ unit} \tag{1a}$$

where E_d is the dissipated energy per cycle of the dampers for a unit volume; γ is the maximum strain; b and β are constants determined from test data, and $0<\beta<1$. It is noted that Eq. (1a) is derived from the fractional Kelvin model (Kasai *et al*. 1993, Chang *et al*. 1998). The values of b and β are equal to 47.585 and 0.900, respectively, from regression results. Therefore, the value of E_d can be determined from

$$E_d=0.0069\exp\left[\frac{\left(b\gamma^{\beta}\sin\frac{\beta\pi}{2}\right)}{\left(1+b\gamma^{\beta}\cos\frac{\beta\pi}{2}\right)}\right] \quad \text{in N/mm}^2 \text{ unit} \tag{1b}$$

2.3 Frequency dependence

Test results also show that the maximum stress is nearly independent of the maximum strain but is slightly affected by the vibration frequency. Therefore, by neglecting the effect of maximum strains, the equation proposed in Eq. (1a) can be modified to describe the maximum damper stress which is frequency dependent. The frequency-dependent maximum shear stress is expressed as

$$F_{vm}=0.0069\frac{\left(p\omega^{\lambda}\sin\frac{\lambda\pi}{2}\right)}{\left(1+p\omega^{\lambda}\cos\frac{\lambda\pi}{2}\right)} \quad \text{in N/mm}^2\text{ unit} \tag{2}$$

where F_{vm} is the maximum damper stress; ω is the vibration frequency with units in radians; p and λ are constants determined from test data, and $0 < \lambda < 1$. Regression results give values of p and λ equal to 94.630 and 0.995, respectively. The maximum stress predicted by Eq. (2) together with the energy dissipation per unit volume estimated by Eq. (1b) will be used to construct an analytical model for the dampers in simulating the seismic structural responses.

3. Test setup and test programs

The test model is a 2/5 scaled five-story steel frame with story heights of 0.91 m for the first story and 1.19 m for the rest of the stories, as shown in Fig. 3. The plan dimension is 1.32 m $\times$ 1.32 m. A lumped-mass system with weights of 5.84 kN for the roof and 5.66 kN for the rest of the floors is used to simulate the prototype structure. Table 1 lists the section properties of beams, columns and braces of the test frame in the direction of input ground motions. Several scaled earthquakes,

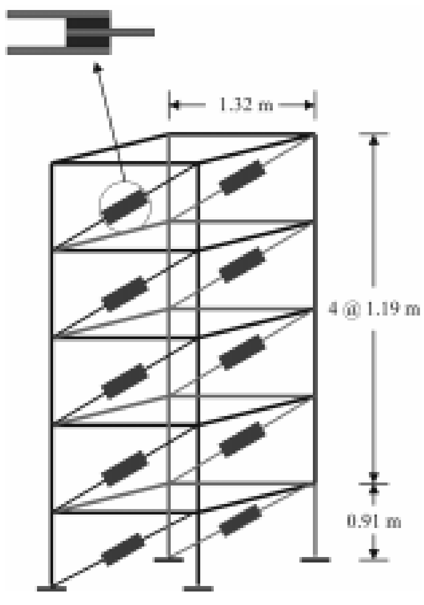


Fig. 3 The 2/5 scale five-story viscoelastically damped frame

Table 1 Section properties of beams, columns and braces for the 2/5 scale five-story steel frame

	Beam	Column	Damper brace
A (mm^2)	709.68	1419.35	1167.74
I_x (mm^4)	1065.6×10^3	653.5×10^3	
Z_x (mm^3)	22286.4	13929.0	

	Damper size
thickness (mm)	12.5
area (mm^2)	57.1×50.8 = 2900.7

including El Centro (1940), Hachinohe (1968), Sylmarff, Newhall (Darragh *et al*. 1994) and Kobe (AIJ 1995) earthquakes, were used in the experimental study. Each input ground motion was imposed to the test model in the horizontal direction parallel to the frame with VE dampers.

The test setup and instrumentation were designed to measure the floor accelerations, lateral floor displacements, beam and column strains, and damper force-deformations. In general, low-level white noise excitation tests were carried out to identify the dynamic characteristics of the structure before and after every major earthquake simulation test.

Test Series I was aimed at studying the dynamic characteristics and seismic response of the 2/5 scaled steel frame without added VE dampers. In this paper, the steel frame with and without VE dampers is defined as damped and undamped frame, respectively. The peak ground acceleration (PGA) was limited to 0.12g to prevent from damaging the undamped frame. In Test Series II, the peak ground accelerations of the input ground motions were generally scaled up to investigate the seismic responses of the model structure with added dampers under medium to strong ground excitations. In this stage, the model steel frame is kept in the elastic range. A preliminary analytical study indicates that, assuming a yield stress of 25 kN/cm^2 for the steel members, the steel structure without added dampers might be damaged under 0.34g El Centro earthquake ground motions. Therefore, only the structure with dampers was tested when the PGA is greater than 0.12g.

In Test Series III, seismic simulation tests were again conducted on the steel frame with dampers under Hachinohe and El Centro earthquake ground motions. The value of PGA is scaled up gradually to a maximum value of 0.7g for the Hachinohe earthquake and 1.2g for the El Centro earthquake in order to examine the inelastic behavior of the structure with added dampers. All of the tests were performed under a room temperature of about 25^{o}C.

4. Test results

4.1 Dynamic characteristics of structures

The dynamic characteristics of the model structure with and without dampers were identified using 0.12g white noise excitations. Fig. 4 shows the transfer function of the frame with and without added VE dampers. It is seen that the spectral responses of the structure with dampers is smaller than that of the frame without dampers, and the higher mode responses of the frame with dampers become insignificant as compared to those of the frame without dampers. The fundamental frequency and first modal damping ratio of the frame without dampers are about 2.64 Hz and 1%.

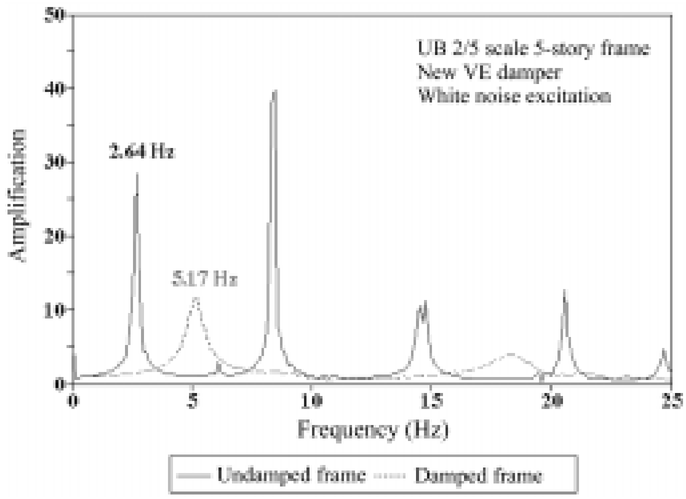
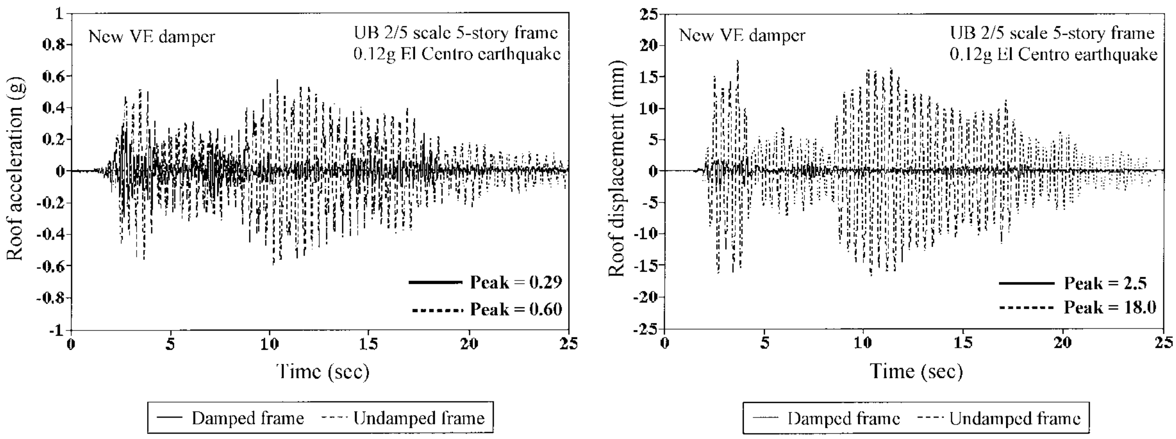


Fig. 4 The transfer functions of both damped and undamped frame

When the VE dampers were added to the frame, the fundamental frequency and first modal damping ratio increase to 5.17 Hz and 4%. The increase of damping ratio is only moderate due to the high initial stiffness and small amount of viscous damping provided by the dampers.

4.2 Structural responses

The lateral roof accelerations and displacements of the frame with and without dampers under the scaled 0.12g El Centro earthquake are shown in Figs. 5(a) and 5(b), respectively. As shown in these figures, the structural responses can be effectively reduced when the VE dampers were added to the frame. Since the new VE damper has high initial stiffness, the displacements of the first few cycles



(a) (b)

Fig. 5 (a) Lateral roof accelerations of damped and undamped frame under the scaled 0.12g El Centro earthquake, (b) Lateral roof displacements of damped and undamped frame under the scaled 0.12g El Centro earthquake

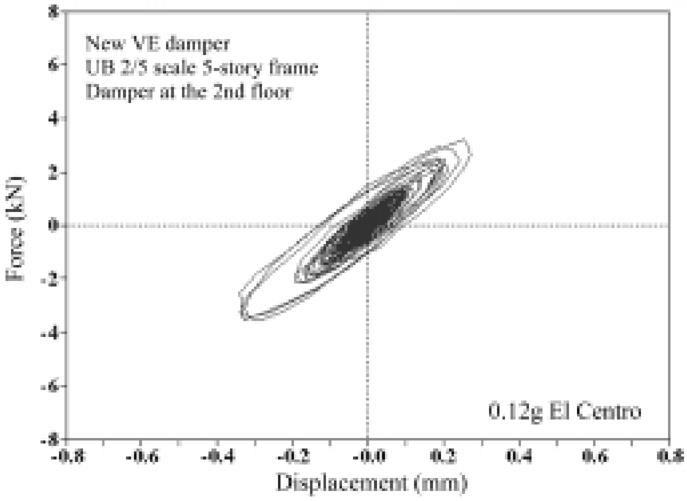


Fig. 6 Force-displacement loops of the damper under the scaled 0.12g El Centro earthquake

can also be considerably reduced, which is different from what was observed in a previous study (Mahmoodi 1969, Chang *et al*. 1996). The force-deformation curve of the damper at the second floor of the viscoelastically damped frame is shown in Fig. 6. It is clear that the VE dampers behave viscoelastically with small hysteresis loops when the intensities of input excitations are moderate. Hence, instead of mainly providing additional damping to structures as the traditional VE dampers do, the new VE damper also increases the lateral stiffness of structures under moderate seismic excitations.

When the PGA of the input earthquake is greater than 0.12g, numerically simulated responses of the frame without dampers are used to compare with the corresponding experimental results of the damped frame, as explained earlier. Fig. 7 shows the numerically simulated response of the

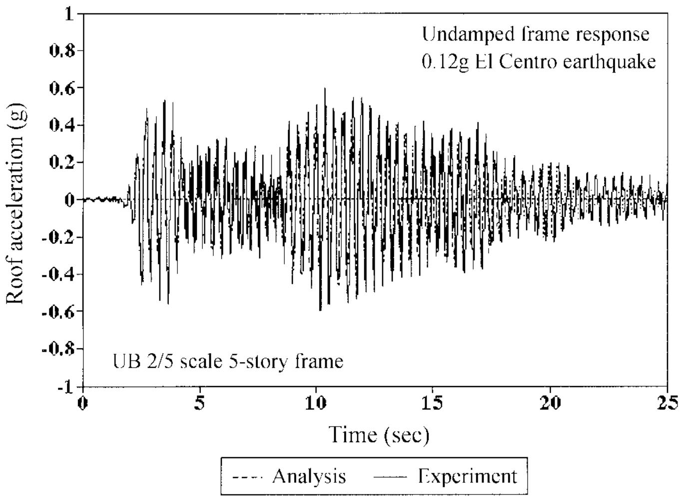


Fig. 7 Simulated responses of the undamped frame under the scaled 0.12g El Centro earthquake

Table 2 Response envelopes under scaled El Centro earthquakes

Floor acceleration (g)									
	Damped frame(1)			Undamped frame(2)			Reduction((2)-(1))/(2)		
Floor	0.12g	0.36g	0.60g	0.12g	0.36g	0.60g	0.12g	0.36g	0.60g
5	0.29	0.60	1.07	0.60	1.41	1.96	0.52	0.57	0.45
4	0.26	0.57	1.05	0.50	1.27	1.52	0.48	0.55	0.31
3	0.21	0.47	0.76	0.44	1.20	1.89	0.52	0.61	0.60
2	0.18	0.40	0.66	0.37	0.97	1.32	0.51	0.59	0.50
1	0.13	0.32	0.56	0.21	0.70	1.25	0.38	0.54	0.55
Floor displacement (mm)									
	Damped frame(1)			Undamped frame(2)			Reduction((2)-(1))/(2)		
Floor	0.12g	0.36g	0.60g	0.12g	0.36g	0.60g	0.12g	0.36g	0.60g
5	2.54	10.11	24.71	17.98	47.22	76.58	0.88	0.79	0.68
4	2.02	9.14	22.76	15.52	41.86	71.83	0.87	0.78	0.68
3	1.70	7.89	19.18	12.24	33.45	61.60	0.86	0.76	0.69
2	1.08	5.33	12.65	7.70	20.93	36.83	0.86	0.75	0.66
1	0.50	2.03	4.51	2.59	6.55	8.61	0.81	0.69	0.48

undamped frame under the scaled 0.12g El Centro earthquake as well as the test result. The floor acceleration and displacement response envelopes of the steel frame with and without dampers subjected to scaled El Centro earthquakes with various PGA values are listed in Table 2. As observed from Table 2, the reduction of floor accelerations is generally between 40% and 60%. The steel frame remains elastic under the scaled 0.6g El Centro earthquake and the dampers dissipate the seismic input energy through a visco-plastic type of hysteresis behavior, as shown in Fig. 8. However, as indicated by the results of numerical simulation, the undamped frame yields under the scaled earthquake when the PGA is larger than 0.34g.

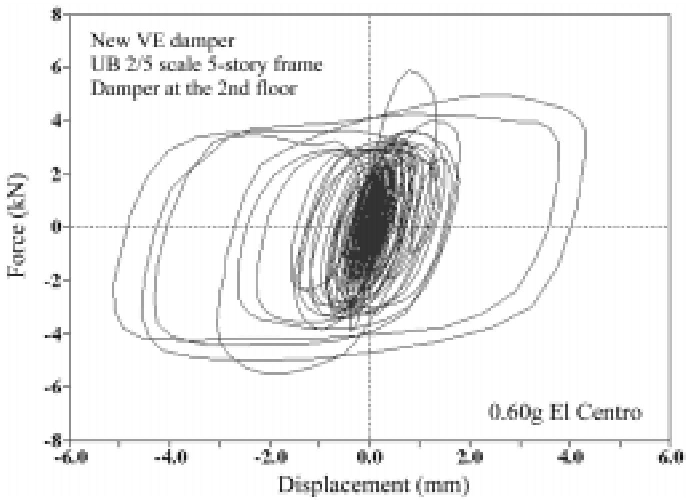


Fig. 8 Force-displacement loops of the damper under the scaled 0.60g El Centro earthquake

Furthermore, the reduction of floor displacements decreases when the intensity of the scaled earthquake increases. This is because the damper stiffness decreases when its deformation increases, as observed in Fig. 8. However, unlike the damped structure, the undamped structure is expected to yield severely under the scaled 0.6g El Centro earthquake, as shown in Fig. 9.

The seismic simulation tests were terminated at the scaled 1.2g El Centro earthquake, under which the table suddenly shut down due to the limitations of the shaking table. Hence, the damped frame only experienced some major peaks of the extremely strong earthquake. Nevertheless, the damped frame yielded slightly and a minor crack was observed at the lower end of the column fixed on the table. Fig. 10(a) shows the moment-curvature loops of the base story column. However, the VE dampers still exhibit metal-like hysteresis behavior even under this extremely strong earthquake, as shown in Fig. 10(b).

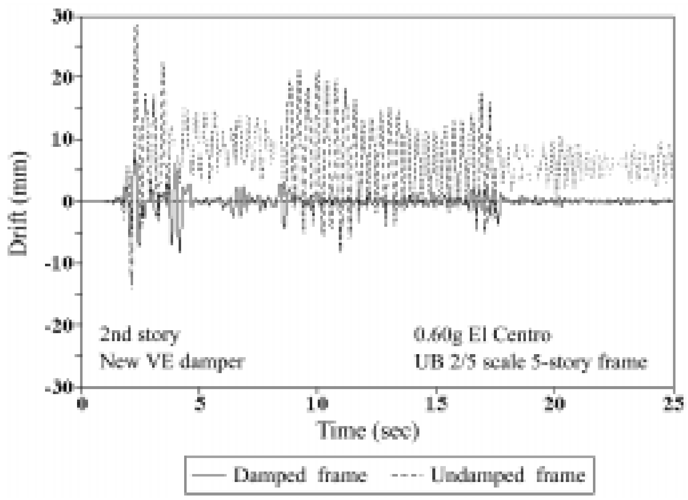


Fig. 9 The 2nd-story drift of both damped and undamped frame under the scaled 0.60g El Centro earthquake

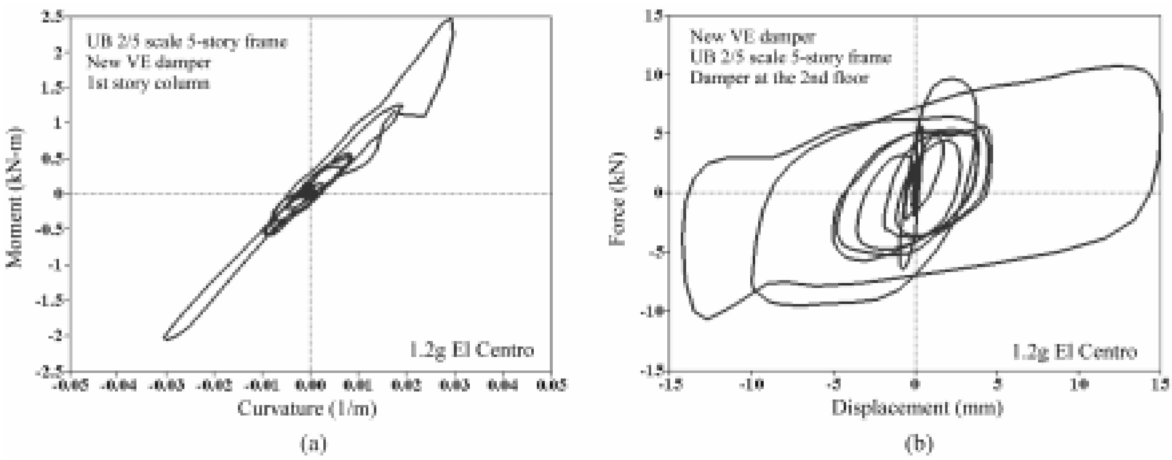


Fig. 10 (a) Moment-curvature loops of the base story column under the scaled 1.2g El Centro earthquake, (b) Force-displacement loops of the damper under the scaled 1.2g El Centro earthquake

5. Analytical simulation

5.1 Bilinear model

Because the new VE damper material exhibits metal-like, nearly bilinear hysteresis loops under large deformations, a simple bilinear model is adopted to simulate the damper behavior when the damped frame is subjected to large earthquake ground motions. According to the material test results, an assumption that the damper is temperature, frequency and strain dependent is made in the bilinear model. In addition to the yield strain, there are three major parameters to be determined in the bilinear model, i.e., the initial stiffness, the post stiffness and the characteristic strength. From the results of monotonic loading tests, the yield strain of the damper is estimated to be 0.036 in this study.

The characteristic strength, Q_d, is defined by

$$Q_d=\frac{E_d}{4(\gamma-\gamma_y)} \tag{3}$$

where γ_y is the yield strain, and the value of E_d is determined by Eq. (1b). Thereafter, the post modulus, G_2, can be determined from

$$G_2=\frac{F_{vm}-Q_d}{\gamma} \tag{4}$$

where F_{vm} is computed by Eq. (2), and the elastic modulus, G_1, is then estimated by

$$G_1=\frac{F_{vm}-G_2(\gamma-\gamma_y)}{\gamma_y} \tag{5a}$$

or

$$G_1=G_2+\frac{Q_d}{\gamma_y} \tag{5b}$$

Consequently, the effective modulus of dampers, which is used to estimate the effective vibration frequency of the damped frame, is calculated by

$$G_{eff}=\frac{F_{vm}}{\gamma} \tag{6}$$

It should be pointed out that the effective natural frequency of the damped frame is calculated based on the effective stiffness of the VE dampers and elastic stiffness of the undamped frame. The effective stiffness of VE dampers is determined by

$$K_{v,\,eff}=G_{eff}A_v/t_v \tag{7}$$

where A_v and t_v are the shear area and thickness of the VE dampers, respectively.

5.2 Seismic structural response analysis

As indicated earlier, because the damper property is frequency dependent for the maximum stress and is strain dependent for its characteristic strength, the dynamic behavior of the damped frame is indeed nonlinear. For practical applications, the effective vibration frequency is used and an iteration procedure is needed for the estimation of these parameters. The iteration process begins with an initial guess of maximum damper strain equal to the yield strain and a trial effective frequency equal to the natural vibration frequency of the undamped frame. Thereafter, the maximum stress and dissipated energy are estimated by Eqs. (2) and (1b), and the three parameters are calculated by Eqs. (3), (4) and (5). From eigenvalue and structural response analyses, a new effective natural frequency and maximum damper strain can be obtained. If the current maximum damper strain is not close to the previous one, the analysis is repeated based on the new effective natural frequency and current maximum strain. This iteration procedure is presented in Fig. 11.

As an example, when the damped frame is subjected to the scaled 1.0g El Centro earthquake ground motion, the damper parameters obtained from the iteration procedure are: maximum damper strain γ_{max}=140%, effective natural frequency f_{eff}=2.94 Hz, characteristic strength Q_d=0.391 N/mm^2, elastic modulus G_1=11.15 N/mm^2, and post modulus G_2=0.278 N/mm^2. The estimated elastic stiffness K_1 and post stiffness K_2 of the VE dampers are equal to 5174.8 N/mm and 129.0 N/mm, respectively. The structural analysis is conducted by using the DRAIN-2D+ program (Tsai and Li 1994). The Young's modulus and Poisson's ratio of the steel frame are 2.0E11 N/m^2 and 0.3,

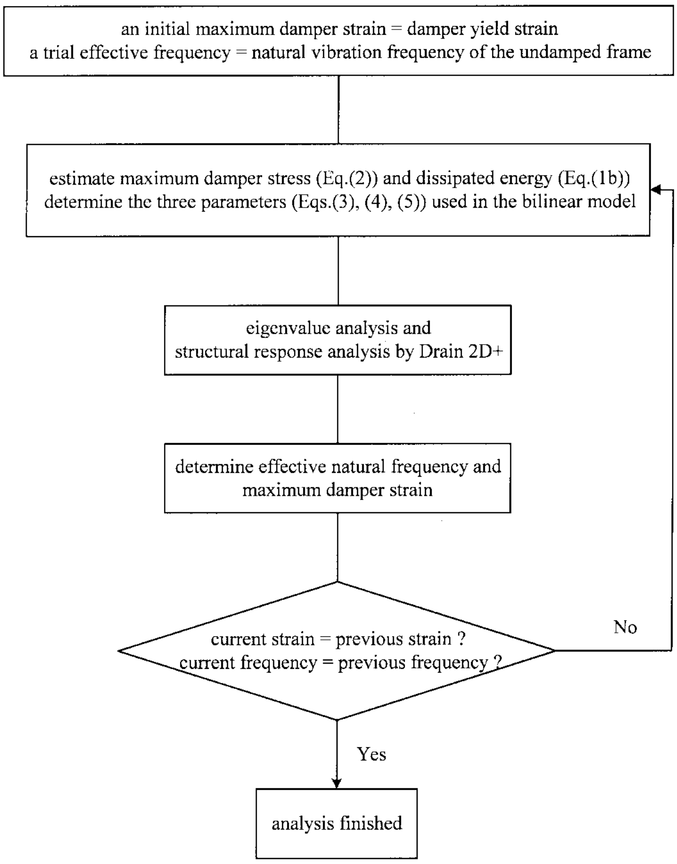


Fig. 11 The iteration procedure for seismic response analysis of damped structures

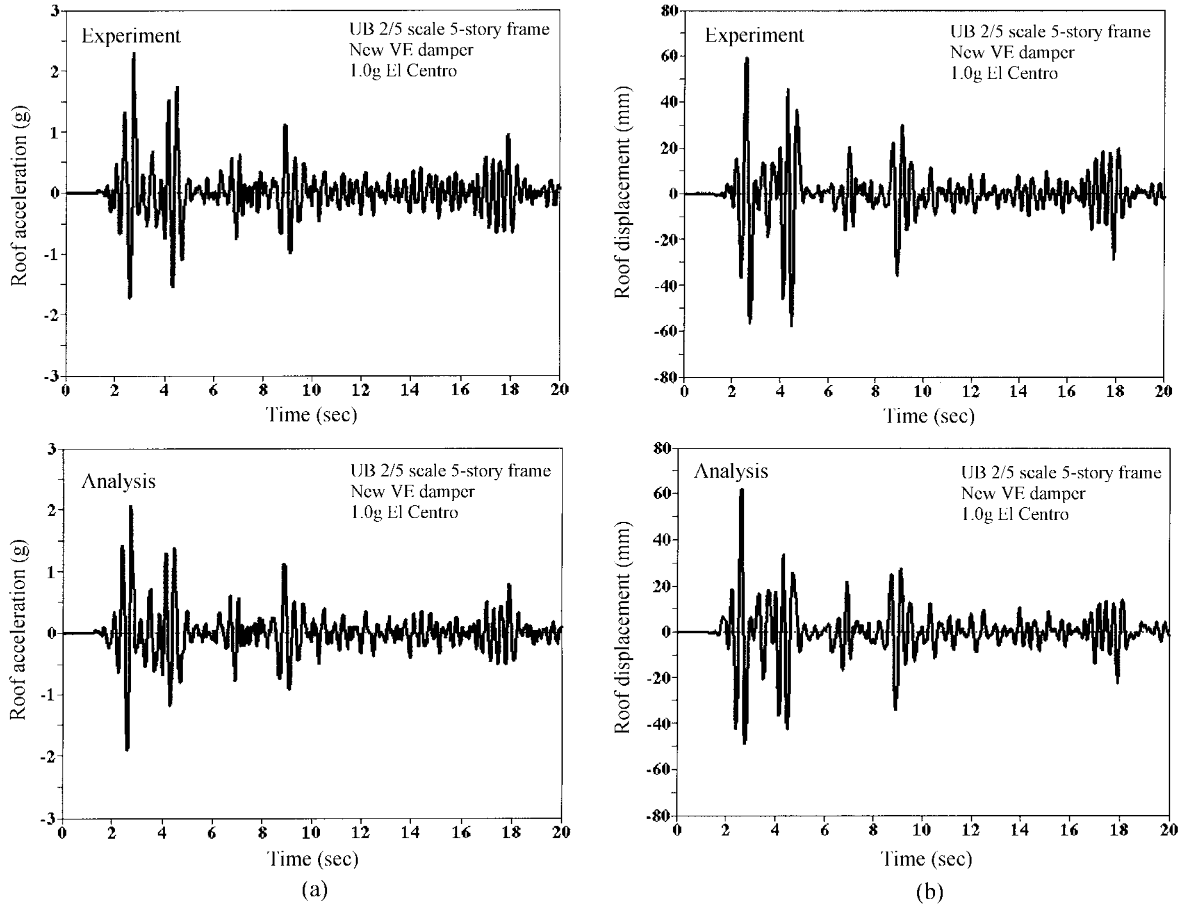


Fig. 12 (a) Simulated roof acceleration of the damped frame under the scaled 1.0g El Centro earthquake; (b) Simulated roof displacement of the damped frame under the scaled 1.0g El Centro earthquake

respectively, in the analysis. The simulated roof acceleration and displacement and the corresponding experimental results of the damped frame under the scaled 1.0g El Centro earthquake are shown in Figs. 12(a) and 12(b). It is seen that they are in good agreements.

6. Conclusions

Experimental studies on the seismic behavior of a 2/5 scale five-story steel frame with a new type of VE dampers have been carried out under a few recorded earthquake ground motions scaled to various peak ground accelerations. The VE dampers used are slightly sensitive to frequency and temperature, but are strain dependent. When the deformation is small, the VE damper behaves viscoelastically. When the deformation is large, the hysteresis behavior of the VE damper becomes similar to that of a yielding-type energy dissipation device. The experimentally obtained responses of the damped frame were compared to those of the undamped frame. Under mild earthquake ground motions, the additional high stiffness and moderate structural damping contributed by the dampers effectively reduce the seismic responses of the structure as compared to the no-damper case. The reduction of structural responses under strong earthquake excitations is achieved by the high energy dissipation capacity of the dampers, which exhibit metal-like hysteresis behavior. Hence, instead of mainly providing additional damping to the structures as the traditional VE dampers do, the new VE damper significantly increases the lateral stiffness of the structures with a moderate increase of damping ratio under mild seismic excitations, while it offers large hysteretic damping to the structures under strong earthquake ground motions.

Based on an equivalent dissipated energy principle, a simple bilinear model with modal parameters estimated by the proposed approach is used to predict the dynamic response of the damped structures. The structural response obtained from numerical analyses is in general consistent with the experimental results. The peak response of structures with added dampers made of the new VE material can be estimated by the proposed simple bilinear model.

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