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A synthetic optimization analysis method on structures with viscoelastic dampers

Zhao-Dong Xu[a,*], Ya-Peng Shen[b], Hong-Tie Zhao[c]

[a]RC & PC Key Laboratory of Education Ministry, Civil Engineering Institute, Southeast University, Nanjing, China
[b]Institute of Architecture and Mechanics, Xian Jiaotong University, Xian, China
[c]Civil Engineering Institute, Xian Architecture and Technology University, Xian, China

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Abstract

The paper introduces a synthetic optimization analysis method of structures with viscoelastic (VE) dampers, namely the simplex method. The optimal parameters and location of VE dampers can be determined by this method. Numerical example and a shaking table test about reinforced concrete structures with VE dampers show that the seismic responses of structures will be reduced more effectively when the parameters and location of VE dampers are designed in accordance with the results calculated by the simplex method.

Keywords: Viscoelastic damper; Optimization; Simplex method; Shaking table test

1. Introduction

Viscoelastic (VE) dampers are among the earliest types of passive dampers, which have been successfully installed in a number of tall buildings and other structures to reduce the responses due to wind and earthquake. Analytical and experimental studies on the behaviors of VE dampers are carried out [1–4]. At the same time, analytical investigations of the use of VE dampers in civil engineering structures have been processed [5,6], and experimental studies using shaking table have also been conducted [7–12]. Analytical and experimental results show that the structural damping is increased notably and responses of structures due to strong earthquakes can be reduced significantly.

Optimization analysis about structures with VE dampers, including optimization of VE dampers' parameters and optimization of VE dampers' location in the structure, is an important task, because rational parameters and location of VE dampers will lead to most effective shock absorption. Many investigators have investigated optimal designs for building vibration control [13–18], and significant progress in this aspect has been made. However, there are few synthetic optimization researches on structures with VE dampers. Synthetic optimization considering structures and VE dampers can make structures and dampers work in phase, and reducing responses of structures more effectively.

In this paper, the simplex method, a synthetic optimization method for structures with VE dampers, which optimizes parameters and location of VE dampers under the fixed goal, is firstly introduced. Then through a numerical example and a shaking table test about reinforced concrete structure with VE dampers, it can be concluded that the simplex method can act as the comprehensive optimization method of structures with VE dampers and the shock absorption effect of VE dampers is best when the location of VE dampers is optimal.

2. Properties of VE dampers

A typical VE damper is shown in Fig. 1, which is made up of two VE layers bonded between three steel plates. The mechanical properties of VE dampers are rather complex and may vary with environmental temperature and excitation frequency [19].

Under a given harmonic strain or stress excitation, energy dissipation per cycle of VE dampers can be

* Corresponding author. Tel.: +86-25-3794253.
E-mail address: xuzhdgyq@seu.edu.cn (Z.-D. Xu).

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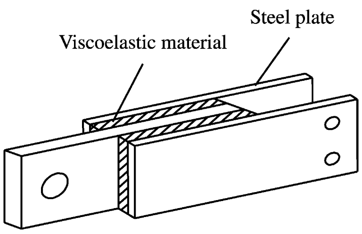

Fig. 1. The ordinary viscoelastic damper.

expressed as

$$E_d = \pi\gamma_0^2 G_1 \eta V \tag{1}$$

where γ_0 is the shear strain amplitude, η is the loss factor ($\eta = G_2/G_1$), G_1 is the storage modulus, G_2 is the loss modulus, V is the volume of VE material ($V = n_v A_v h_v$), n_v is the number of viscoelastic layer, in this paper, $n_v = 2$, A_v and h_v are the area and the thickness of viscoelastic layer, respectively. If the storage modulus G_1 and the loss factor η are determined, the stiffness k_d and the damping c_d of VE dampers can be written as

$$k_d = \frac{n_v G_1 A_v}{h_v} \tag{2}$$

$$c_d = \frac{n_v G_1 \eta A_v}{\omega h_v} \tag{3}$$

where ω is the excitation frequency.

3. Optimization analysis on structures with VE dampers

The optimal solution can be found by iterative computation in the simplex method. When a basic feasible solution is not optimal, another more optimal solution should be determined, so that the objective function decreases [20].

Suppose $\mathbf{A} = (\mathbf{A}_B, \mathbf{A}_N)$, where $\mathbf{A}_B$ is one base of $\mathbf{A}$. Then

$$\mathbf{x} = \begin{bmatrix} \mathbf{A}_B^{-1}(\mathbf{b} - \mathbf{A}_N\mathbf{x}_N) \\ \mathbf{x}_N \end{bmatrix} \geq 0$$

is the feasible field composed of all x.

$$\mathbf{x}' = \begin{bmatrix} \mathbf{A}_B^{-1} \\ 0 \end{bmatrix}$$

is the basic feasible solution corresponding to the base $\mathbf{A}_B$. The objective functions about $\mathbf{x}'$ and $\mathbf{x}$ can be written as

$$J(\mathbf{x}') = \mathbf{C}^\tau \mathbf{x}' = (\mathbf{C}_B^\tau, \mathbf{C}_N^\tau)\begin{bmatrix} \mathbf{A}_B^{-1} b \\ 0 \end{bmatrix} = \mathbf{C}_B \mathbf{A}_B^{-1}\mathbf{b} \tag{4}$$

$$J(\mathbf{x}) = (\mathbf{C}_B^\tau, \mathbf{C}_N^\tau)\begin{bmatrix} \mathbf{A}_B^{-1}(b - \mathbf{A}_N\mathbf{x}_N) \\ 0 \end{bmatrix}$$
$$= \mathbf{C}_B\mathbf{A}_B^{-1}\mathbf{b} + (\mathbf{C}_N^\tau - \mathbf{C}_B^\tau \mathbf{A}_B^{-1}\mathbf{A}_N)\mathbf{x}_N \tag{5}$$

where $\mathbf{C} = (\mathbf{C}_1, \ldots, \mathbf{C}_n)^\tau = (\mathbf{C}_B^\tau, \mathbf{C}_N^\tau)$. If $\mathbf{C}_N^\tau - \mathbf{C}_B^\tau\mathbf{A}_B^{-1}\mathbf{A}_N \geq 0$, $\mathbf{x}'$ is the optimal solution. If $\mathbf{C}_N^\tau - \mathbf{C}_B^\tau\mathbf{A}_B^{-1}\mathbf{A}_N$ has negative component, $\mathbf{x}'$ is not the optimal solution.

When $\mathbf{x}'$ is not the optimal solution, one column vector in matrix $\mathbf{A}_B$ should be exchanged with one column vector in matrix $\mathbf{A}_N$, and the matrix $\mathbf{A}_B^+$ is formed, the basic feasible solution $\mathbf{x}'_+$ corresponding to $\mathbf{A}_B^+$ can be solved. The detailed process is described as follows

$$\tilde{\mathbf{A}}_N = \mathbf{A}_B^{-1}\mathbf{A}_N = (\mathbf{A}_B^{-1}a^{(m+1)}, \ldots, \mathbf{A}_B^{-1}a^{(n)})$$
$$= (\tilde{a}^{(m+1)}, \ldots, \tilde{a}^{(n)}) \tag{6}$$

$$\tilde{\mathbf{C}}_N^\tau = \mathbf{C}_N^\tau - \mathbf{C}_B^\tau\mathbf{A}_B^{-1}\mathbf{A}_N = (\tilde{c}_{m+1}, \ldots, \tilde{c}_n) \tag{7}$$

where $\tilde{c}_i = c_i - c_B^\tau \tilde{a}^{(i)}$, $i \in N = \{m+1, \ldots, n\}$. Assume $\tilde{c}_p = \min_{i\in N} \tilde{c}_i$, if $\tilde{c}_p \geq 0$, stop calculation and $\mathbf{x}'$ is the optimal solution, otherwise, continue calculation. Choose the component x_p and the corresponding column $a^{(p)}$. Assume $\mathbf{x}_N = (0, \ldots, 0, x_p, 0, \ldots, 0)^\tau$, then

$$\mathbf{x}_B = \mathbf{A}_B^{-1}\mathbf{b} - \mathbf{A}_B^{-1}\mathbf{A}_N\mathbf{x}_N = \tilde{b} - \tilde{a}^{(p)}x_p \tag{8}$$

If $\tilde{a}^{(p)} \leq 0$, $\mathbf{x}_B$ increases with x_p, the feasible field has no limits, the objective function $J(x) \to -\infty$, and the optimal solution does not lie. If $\tilde{a}^{(p)}$ has positive component $\tilde{a}_q^{(p)}$, when $x_p = (\tilde{b}_q/\tilde{a}_q^{(p)}) = \min_{\tilde{a}_q^{(p)}>0} (\tilde{b}_i/\tilde{a}_i^{(p)})$, the qth component of $\mathbf{x}_B$ $x_q = \tilde{b}_q - \tilde{a}_q^{(p)}x_p = 0$, the other components should be positive in order to insure $\mathbf{x}_B \geq 0$. a_q is chosen to exchange with a_p, and the new base $\mathbf{A}_B^+$ can be written as

$$\mathbf{A}_B^+ = \mathbf{A}_B + (a^{(p)} - a^{(q)})\mathrm{e}^{(q)\tau} \tag{9}$$

where $\mathrm{e}^{(q)\tau} = (0, \ldots, 0, 1, 0, \ldots, 0)$, the qth element is 1 and the others are 0. The basic solution corresponding to $\mathbf{A}_B^+$ can be got

$$\mathbf{x}'_+ : x_i = \tilde{b}_i - \frac{\tilde{b}_q}{\tilde{a}_q^{(p)}}\tilde{a}_i^{(p)}, \qquad i \in B = \{1, \ldots, m\} \tag{10}$$

$$x_p = \frac{\tilde{b}_q}{\tilde{a}_q^{(p)}} \tag{11}$$

$$x_i = 0, \qquad i \in N, \ i \neq p \tag{12}$$

In order to describe the simplex method clearly, the calculation block diagram is shown as in Fig. 2.

For frame structures, VE dampers are usually attached to braces. In consideration of the stiffness of braces, the damper-brace system can be treated as a damper and a spring being connected in series. In order to assure that VE dampers function effectively, the stiffness of braces is usually strong. Accordingly the stiffness of braces can be neglected to simplify calculation, and the equations of motion of the structure with VE dampers can be written as

$$\mathbf{M}\ddot{\mathbf{y}} + \mathbf{C}\dot{\mathbf{y}} + \mathbf{K}\mathbf{y} = -\mathbf{M}\Gamma\ddot{x}_g - \mathbf{B}\mathbf{f}_d \tag{13}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrixes of the structure, respectively, $\mathbf{y}$ is the vector of

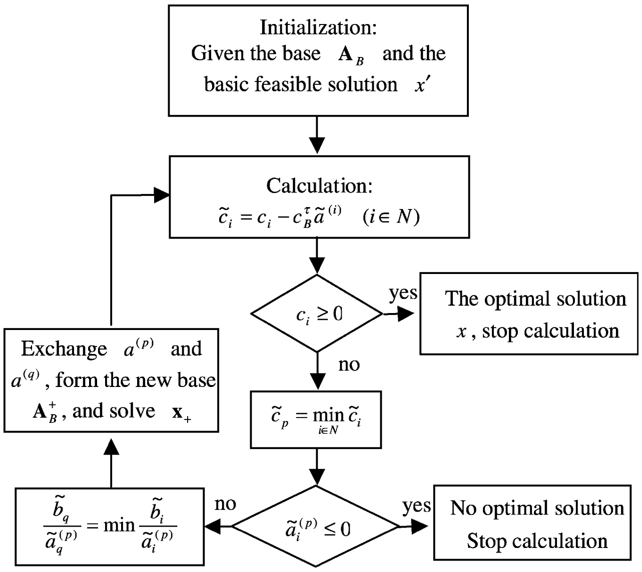

Fig. 2. The calculation block diagram of the simplex method.

the relative displacements of the floors of the structure, Γ is the column vector of ones, $\ddot{x}_g$ is the earthquake acceleration excitation, $\mathbf{B}$ is the matrix determined by the placement of VE dampers in the structure, $\mathbf{f}_\mathrm{d} = [f_{\mathrm{d}1}, f_{\mathrm{d}2}, \ldots, f_{\mathrm{d}n}]^\mathrm{T}$ is the vector of control forces produced by VE dampers, and $f_{\mathrm{d}n}$ is the control force of the nth floor.

The control force $f_{\mathrm{d}n}$ can be calculated according to the Kelvin model [21], in which VE dampers are assumed to have a spring component augmented by a Newtonian viscosity component and its relationship between force and displacement can be expressed as

$$f_{\mathrm{d}n} = k_{\mathrm{d}n}\Delta_{\mathrm{d}n} + c_{\mathrm{d}n}\dot{\Delta}_{\mathrm{d}n} \tag{14}$$

$$\Delta_{\mathrm{d}n} = \Delta_n \cos\theta, \qquad \dot{\Delta}_{\mathrm{d}n} = \dot{\Delta}_n \cos\theta \tag{15}$$

where $k_{\mathrm{d}n}$ and $c_{\mathrm{d}n}$ are the stiffness and the damping of VE dampers in the nth floor, which can be determined by Eqs. (2) and (3), respectively. $\Delta_{\mathrm{d}n}$ and $\dot{\Delta}_{\mathrm{d}n}$ are the displacement and velocity produced by VE dampers in the nth floor, respectively. Δ_n and $\dot{\Delta}_n$ are the interstory drift and interstory velocity of the nth floor, respectively. θ is the angle between the braces and the horizontal axis.

For the structure with VE dampers, if the location and dimensions of VE dampers are regarded as optimization parameter vector $\mathbf{x}$, the optimal solution of the structure with VE dampers can be found by the simplex method. Under some constraint conditions, a series of optimization parameters are sought so that the objective function value is minimum and the structure system is optimal. The aims of optimal design for the structure with VE dampers are mainly the following two aspects: (1) When the seismic responses of the structure with VE dampers satisfies the given demand, the number of VE dampers should be as few as possible; (2) In order to assure that VE dampers function effectively, the stiffness of VE dampers cannot be too strong compared with that of braces. So according to the design aims the objective function should be written as

$$J = \alpha_1 \frac{\theta_m}{[\theta]} + \alpha_2 \frac{\Delta_m}{[\Delta]} + \alpha_3 \frac{\sum_{i=1}^{n} n_{\mathrm{d}_i}}{n_{\mathrm{d}_0}} + \alpha_4 \frac{k_\mathrm{d}}{k_{\mathrm{d}_0}} \tag{16}$$

where θ_m and Δ_m are the maximum interstory drift angle and the maximum interstory drift, respectively, $[\theta]$ and $[\Delta]$ are the limits of elastic interstory drift angle and elastic interstory drift, respectively, n_{d_i} is the number of VE dampers in the ith floor, n_{d_0} is the sum of the initial setting VE dampers, k_{d_0} is the initial setting stiffness of VE dampers, which is determined by experience, α_1, α_2, α_3 and α_4 are the weight coefficients, which are dependent on the importance of each component, 0.28, 0.22, 0.27 and 0.23 are adopted, respectively, in this paper. It must be noted that the initial location of VE dampers is based on well distribution of the stiffness of each floor of structures with dampers, and it can be determined by calculating roughly for the stiffness of structures and the initial setting stiffness of VE dampers.

The constraint condition, which the frame structures must be satisfied, is $\theta_i \leq 1/450$, and the constraint condition, which the VE damper must be satisfied, is $k_\mathrm{d} \leq \alpha \min(k_i)$, where α is the coefficient, in this paper, $\alpha = 0.1$, k_i is the stiffness of the ith floor of structures.

The maximum interstory drift Δ_m can be substituted by the standard deviation of interstory drift calculated by the random vibration method [22] under the initial setting location and parameters of VE dampers firstly. Then in accordance with the objective function and constraint conditions, the new parameters can be searched by the simplex method. Under the new parameters, the seismic responses of the structure can be calculated and the objective function value can be obtained. Iterative process is carried until the minimum objective function value is found. Some programs for this method are developed in Matlab language by authors.

4. Numerical and test verification

4.1. Numerical example

Consider an eight-story shear building with a mass of 8.8×10^5 kg, a stiffness of 7.2×10^8 N/m, story height of 4.5 m for the first floor and a mass of 8.0×10^5 kg, a stiffness of 9.0×10^8 N/m, story height of 3.3 m for the others. The ordinary VE damper as shown in Fig. 1 is adopted, whose storage modulus G_1 is 1.0×10^7 N/m^2 and loss modulus G_2 is 1.4×10^7 N/m^2. The working temperature is 25 °C, the initial location of VE dampers is [12, 10, 8, 4, 2, 1, 1, 1], and the initial area and thickness of VE layer are $A_\mathrm{v} = 8 \times 10^{-3}$ m^2 and $h_\mathrm{v} = 12 \times 10^{-3}$ m, respectively.

For wide suitability of optimization analysis results, the stationary white noise random excitation is adopted

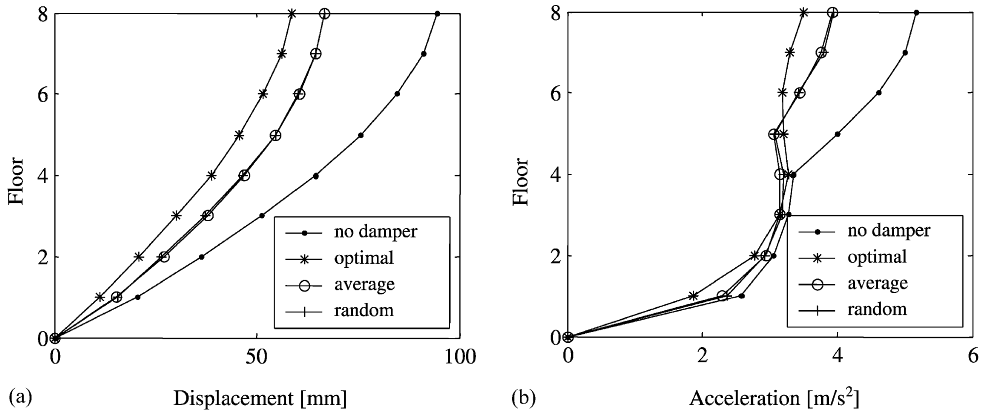

Fig. 3. Comparison of the maximum seismic responses of the four locations under 200 gal El Centro wave: (a) displacement; (b) acceleration.

as earthquake input. The power-spectral density $S_0 = 180\ \mathrm{cm^2/s^2}$ is equivalent to the earthquake wave with 200 gal acceleration amplitude [22]. The optimal location [16, 12, 7, 1, 0, 0, 0, 0], the area of VE layer $A_v = 4.9 \times 10^{-3}\ \mathrm{m^2}$ and the thickness of VE layer $h_v = 8.2 \times 10^{-3}$ m can be obtained by the simplex method. To verify the accuracy of the optimal location of dampers, the calculating results of the time-history analysis method are compared with those of the simplex method. In optimization analysis of the time history analysis method, the area of VE layer $A_v = 4.9 \times 10^{-3}\ \mathrm{m^2}$ and the thickness of VE layer $h_v = 8.2 \times 10^{-3}$ m are predetermined, the optimal location of dampers can be got by cycle calculation [22]. When the structure is subjected to the 200 gal El Centro earthquake wave, the optimal location of dampers is [18, 13, 8, 2, 0, 0, 0, 0]. At the same time, the optimal location of dampers [17, 12, 8, 1, 0, 0, 0, 0] can be obtained under the 200 gal Taft earthquake wave. Different earthquake excitations will lead to different optimal locations, but the difference is very slight and can be accepted. It can be shown that the optimal results under the stationary white noise random excitation can represent the optimal results under the same intensity earthquake excitation.

In order to confirm the efficiency of the optimal location of dampers, seismic responses of structures with different locations are compared. The first location is the optimal location [16, 12, 7, 1, 0, 0, 0, 0] calculated by the simplex method; the second location is [5, 5, 5, 5, 4, 4, 4, 4], which represents dampers' average distribution; the third location is [5, 9, 3, 4, 2, 5, 2, 6], which represents dampers' random location. Sum of VE dampers in the three locations is all 36. Under the 200 gal El Centro earthquake excitation, responses of the structure with VE dampers of the three locations and without dampers are calculated. Fig. 3(a) and (b) shows comparison about the maximum displacement and the maximum acceleration of the four structures, respectively. Fig. 4(a) and (b) shows comparison about the maximum displacement and the maximum acceleration of the four structures under the 400 gal El Centro earthquake excitation, respectively.

It can be seen from Figs. 3 and 4 that VE dampers can reduce the displacement and acceleration responses effectively. The displacement responses of the structure under the optimal location are smaller than those under the other locations. The acceleration responses of most floors under the optimal location are smaller than those under the other locations. Rational location of VE dampers can make the stiffness and the damping of the structure uniform, and avoid abrupt change in the stiffness and the damping of the structure, thus the seismic responses can be reduced more effectively. It can be shown from consistency between Figs. 3 and 4 that the optimal results obtained under

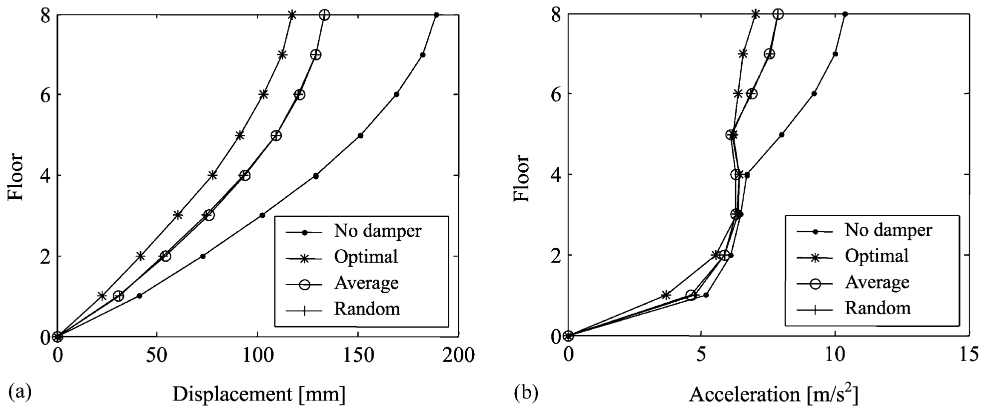

Fig. 4. Comparison of the maximum seismic responses of the four locations under 400 gal El Centro wave: (a) displacement; (b) acceleration.

the minor earthquake adapt to the larger earthquake. It can be concluded from analysis that VE dampers' location is not average distribution and random location, but optimal location in accordance with the dynamic characters of the designed structure. When VE dampers' location is optimal, the seismic responses of the structure are reduced more effectively, and the damage degree of the structure is alleviated more effectively.

4.2. Shaking table test

The test frame models are two identical 1/5-scale three-story plain reinforced concrete frames, i.e. length similarity ratio $S_l = 0.2$. In order to strengthen the stability of the frame and be convenient to add weight, two identical frames are adopted. Overall dimensions of each test frame are 1200 mm in plan, story height of 800 mm for the first story and 660 mm for the other two, as shown in Fig. 5. For one test frame model, mass of each floor is $m\,(\mathrm{kg}) = [576.9, 586.4, 548.1]$ and stiffness of each floor is $k = [2.868, 3.766, 3.766] \times 10^6$ N/m.

The ordinary VE damper as shown in Fig. 1 is adopted. Fig. 6 shows the joint construction of the VE brace, both ends of dampers are connected with braces by bolts. 9050A material, whose storage modulus G_1, loss modulus G_2 and loss factor η are 0.510 MPa, 0.09 MPa and 0.18, respectively, when the temperature is 16.7 °C, frequency is 0.2 Hz and the strain amplitude is 100%, is used as VE material. The shear area $A_v = 2.42 \times 10^{-3}$ m^2, the thickness $h_v = 3.67 \times 10^{-3}$ m and the optimal location of VE dampers [2, 0, 0] can be acquired by the simplex method. According to the calculating results and actual manufacturing devices,

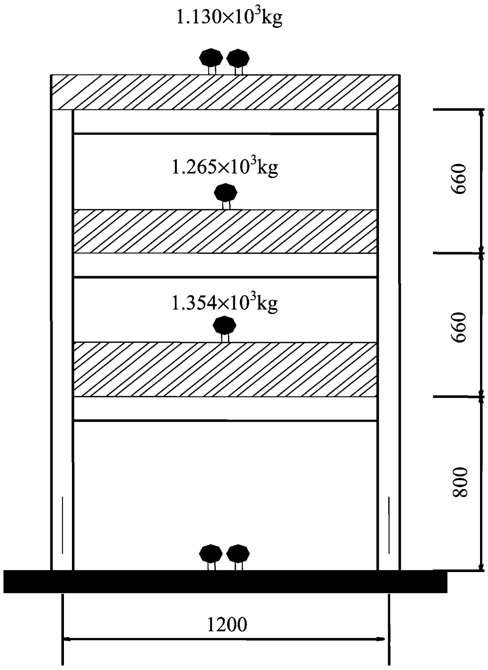

Fig. 5. The test frame model.

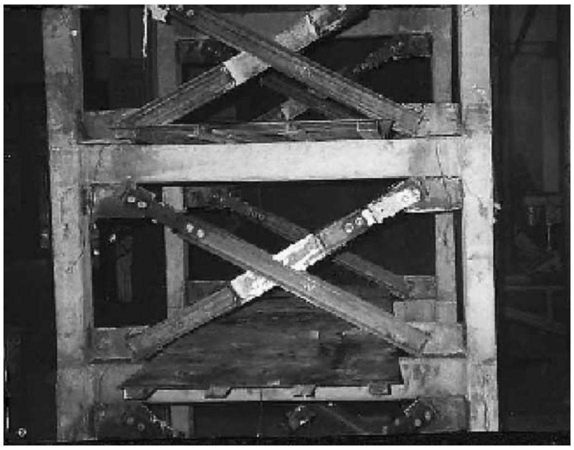

Fig. 6. The experimental viscoelastic braces.

the shear area A_v and the thickness h_v of VE layer are chosen as 60 mm × 50 mm and 5 mm, respectively.

Six seismograph apparatuses fixed in the structure are used to measure the displacements and accelerations of each floor and base slab, as shown in Fig. 5. The time-scaled El Centro wave record is used as the seismic inputs for the shaking table tests. The optimization test of the structure with VE dampers is carried out by installing or removing the bolts between dampers and braces. This test is performed in the Structure Laboratory of Xian Architecture and Technology University in China in 2000.

4.3. Test results and analysis

When the locations of dampers are [0, 0, 0], [0, 0, 2], [2, 0, 0], [2, 0, 2] and [2, 2, 2], the test results are analyzed under 200 gal El Centro wave. Fig. 7(a) and (b) shows the comparison about the displacement responses and the acceleration responses of the top floor between the locations of dampers [0, 0, 0] and [2, 0, 0], respectively. It can be seen clearly from Fig. 7 that the displacement and acceleration responses of the structure with VE dampers are smaller than those of the structure without dampers. The maximum displacement and acceleration responses of the top floor of the structure without dampers are 4.56 mm and 4.89 m/s^2, respectively, while those of the top floor of the structure with VE dampers are 3.16 mm and 3.20 m/s^2, respectively. The displacement response is reduced by 30.7%, and the acceleration response is reduced by 34.6%, which shows that VE dampers can reduce seismic responses of the structure effectively.

Fig. 8 shows comparison about the maximum displacement of each floor under the different locations of VE dampers. It can be seen from Fig. 8 that under 200 gal El Centro wave the maximum displacement responses of the first floor and the second floor in the structure with optimal location dampers are smaller than those in the structure with dampers' location [2, 2, 2]. The maximum displacement responses of the first floor and the second floor in

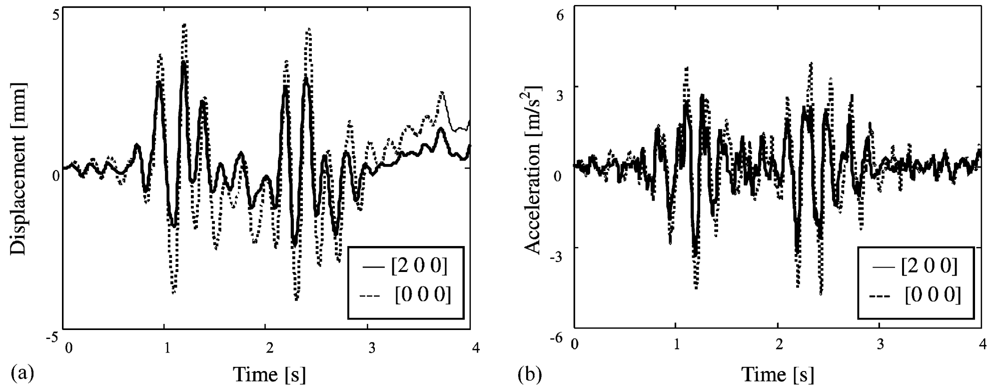

Fig. 7. Comparison about seismic responses of structures with dampers and without dampers: (a) the top floor displacement; (b) the top floor acceleration.

the structure under the optimal location are 89.8 and 87.2% of those under the location [2, 2, 2], while the maximum displacement response of the top floor under the optimal location is larger than that under the location [2, 2, 2] slightly, which is 100.9% of that under the location [2, 2, 2]. It can also be seen from Fig. 8 that the maximum displacement responses under the optimal location are smaller than those under the other three locations. For the displacement response of the top floor, when the location of dampers is [2, 0, 2], the number of used dampers is two more than the number under the optimal location, while the maximum displacement response is increased by 23.4% compared with that under the optimal location. At the same time, the maximum displacement responses under the location [0, 0, 2] and the location [0, 0, 0] are increased by 38.9 and 44.3%, respectively, compared with that under the optimal location.

The maximum acceleration responses of the top floor in the structure under the [2, 2, 2], [2, 0, 2], [0, 0, 2] and [0, 0, 0] are 3.80, 3.81, 4.02 and 4.89 m/s^2. Compared with the maximum acceleration response 3.20 m/s^2 of the top floor of the structure under the optimal location, which are increased by 18.8, 19.1, 25.6 and 52.8%, respectively. It is shown that,

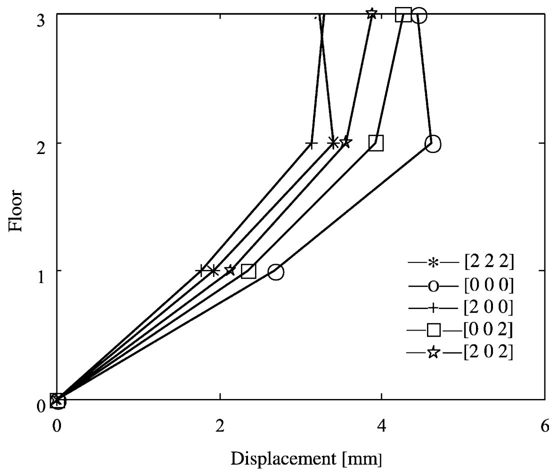

Fig. 8. Comparison about the experimental maximum displacement of each floor.

rational location of VE dampers can make the stiffness and the damping of the structure be distributed well and reduce seismic responses of the structure effectively, in contrary, if the dampers are installed irrationally, the stiffness and the damping are not distributed well, seismic response cannot be reduced effectively, even may be increased, and the more viscoelastic dampers do not mean the better shock absorption effect.

5. Conclusions

- VE dampers can increase the stiffness and the damping of structures, and reduce the seismic responses of structures effectively.
- The optimization design of the structure with VE dampers can be finished by the simplex method, i.e. the parameters and the location of VE dampers can be design optimally under the fixed objective function and constrained conditions.
- Rational location of VE dampers can make the stiffness and the damping of structures well-distributed, and reduce seismic responses of structures effectively, in contrary, if the dampers are installed irrationally, the stiffness and the damping are not distributed well, seismic responses cannot be reduced effectively, even may be increased.
- The more VE dampers do not mean the better shock absorption effect, the shock absorption effect of VE dampers is best when the location of VE dampers is optimal.

Acknowledgements

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