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Seismic response of viscoelastically damped structure under strong earthquake ground motions

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ABSTRACT: This paper summarizes an experimental and analytical study on the application of VE dampers as energy dissipation devices in structural applications. It can be concluded that VE dampers are effective in reducing excessive vibrations of structures under strong earthquake ground motions. It is also found that the modal strain energy method can be used to reliably predict the equivalent structural damping and the seismic response of a viscoelastically damped structure can be accurately estimated by conventional modal analysis techniques. Based on the above studies, a design procedure for viscoelastically damped structures is presented. This design procedure fits naturally into the conventional structural design flow chart by including damping ratio as an additional design parameter.

1 INTRODUCTION

Viscoelastic (VE) dampers have been successfully applied in tall buildings to reduce wind-sway for over twenty years (Mahmoodi et al. 1987). The application of VE dampers to reduce seismic response of buildings, however, has been investigated only in the last few years or so. Analytical investigations on the use of VE dampers in civil engineering structures have been carried out at the University of Michigan, Ann Arbor (Ashour 1987) and at the State University of New York at Buffalo (Zhang et at. 1989). Results from these studies showed that the response of buildings due to strong earthquakes can be reduced significantly. Experimental studies using shaking tables have also been conducted on a three-story (Lin et al. 1991) and a nine-story (Aiken and Kelly 1990) steel frame at Buffalo and Berkeley, respectively. Their results showed significant increase in structural damping. The corresponding structural responses under seismic loading also decreased accordingly. However, reliable analytical models which can accurately predict the equivalent structural damping and response due to addition of VE dampers were not available. Therefore, a rational design procedure for viscoelastically damped structures could not be established.

Recently, an analytical and experimental study on dynamic response of VE dampers and on seismic response of viscoelastically damped structures has been carried out at the State University of New York at Buffalo. The experimental program was conducted on a 2/5 scale five-story steel frame under a variety of recorded ground motions and intensities. Based on the test results, it can be shown that the equivalent structural damping of the viscoelastically damped structures can be accurately predicted using the modal strain energy method. The seismic response can then be estimated using conventional dynamic linear analysis routines.

In this paper, experimental and analytical results on seismic behavior of the 2/5 scaled steel frame with and without added viscoelastic dampers under strong earthquake motions will be first presented and discussed. Then, a simple design procedure to implement VE dampers in seismic resistant structures will be proposed and discussed.

2 VE DAMPER PROPERTY

Figure 1 shows a typical design of a VE damper. The energy dissipation capacity of VE dampers are characterized by shear storage modulus, G', and shear loss modulus G''. G' determines the stiffness of the damper, k', while the ratio of G'' to G' determines the damper loss factor, η, as

$$k' = \frac{G'A}{h} \tag{1}$$

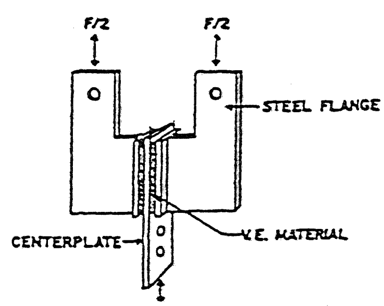

Figure 1. Viscoelastic Damper.

$$\eta = \frac{G''}{G'} \qquad (2)$$

where A is the total shear area of VE material and h is the thickness of each VE slab. k' and η will later be used to calculate modal damping of the structure.

The above VE dampers properties are dependent on the vibrational frequency and environmental temperature. In general, as the vibrational frequency goes higher, the values of G' and G" also become larger. The opposite is true for the effect of ambient temperature. The energy dissipation capacity of the VE damper also decreases with increasing ambient temperature. The loss factors, however, remain somewhat constant regardless of the frequencies and ambient temperatures. Test results with the average of the first twenty cycles showing the above effects from a typical VE damper are listed in Table 1. It can be seen that the damper properties remain somewhat constant for each temperature and frequency for strains up to 20%.

Table 1. Typical VEM and damper properties.

Temp· °C	Freq., Hz	Strain, %	k', lb/in	G', psi	G'', psi	η
24	1.0	5	2124	142	193	1.36
24	1.0	20	2082	139	192	1.38
24	3.0	5	4084	272	324	1.19
24	3.0	20	3840	256	306	1.2
36	1.0	5	880	59	67	1.13
36	1.0	20	873	58	65	1.12
36	3.0	5	1626	108	119	1.1
36	3.0	20	1542	103	112	1.09

The damper properties are also, to a certain degree, dependent on the number of loading cycles and the range of deformation; especially under large strain excitations because of the temperature increase within the damper material. However, these effects have been shown to be insignificant in seismic applications (Chang et al. 1992). This is because in an earthquake ground motion, it is typical that the peak accelerations occur in only a few cycles of excitation. The average excitation is normally far less severe than the peaks. Therefore, it is possible to analyze the seismic response of viscoelastically damped structures accurately based on the properties of the VE dampers corresponding to 20% strain.

In general, damper properties can be obtained through constitutive modeling to include the effect of frequency, temperature and deformation. For practical applications, they can also be obtained from regression analysis on the test data to include the effect of frequency and ambient temperature (Chang et al. 1992).

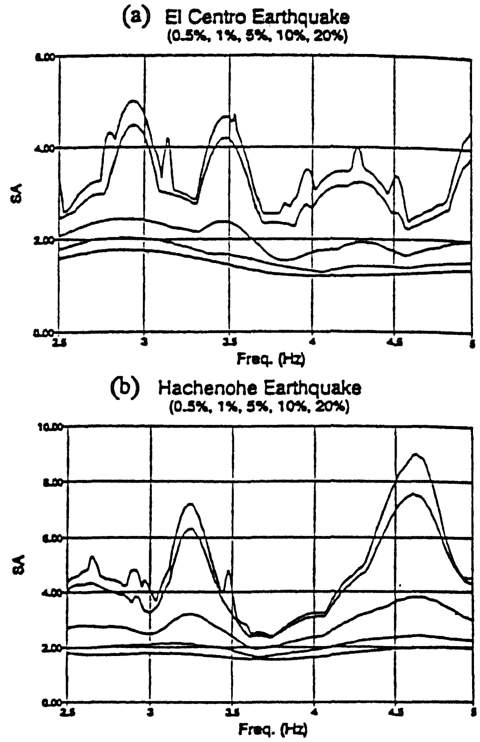

Figure 2. Time scaled response spectra with different damping ratios.

3 EXPERIMENTAL OBSERVATION

Response of a 2/5 scale model steel structure with and without added VE dampers was studied experimentally under strong earthquake ground motions with a peak acceleration of 0.6g. Tests were conducted using a shaking table at the State University of New York at Buffalo.

The natural frequency of the model structure without added dampers is 3.1 Hz while the natural frequency of the viscoelastically damped model structure lies between 3.5 Hz and 3.7 Hz, depending on the intensities of input ground motions. The VE dampers were designed to have 15% damping ratio for the first mode of the model structure at room temperature without significantly changing the natural frequency of the structure. Figures 2a and 2b show the scaled response spectra with damping ratios of the two earthquake ground motions used in the experimental study. It can be seen that while there are ups and downs in response spectra, they are nearly constant for 15% damping. This indicates that providing extra damping to the structure will reduce not only the seismic response but also dependency on frequency contents of earthquake motions.

Shaking table tests were carried out on the viscoelastically damped structure at room temperature (25 °C) under time scaled El Centro of 1940 and Hachinohe of 1968 earthquakes with scaled peak accelerations of 0.6g. Numerical studies using an inelastic analysis program DRAIN-2D (Kanaan and Powell 1973) showed that without added VE

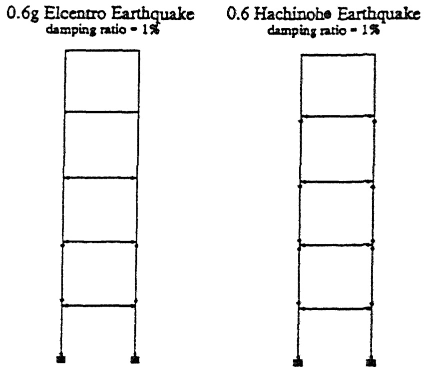

Figure 3. Distribution of plastic hinges in the model structure with
(a) El Centro earthquake.
(b) Hachinohe Earthquake.

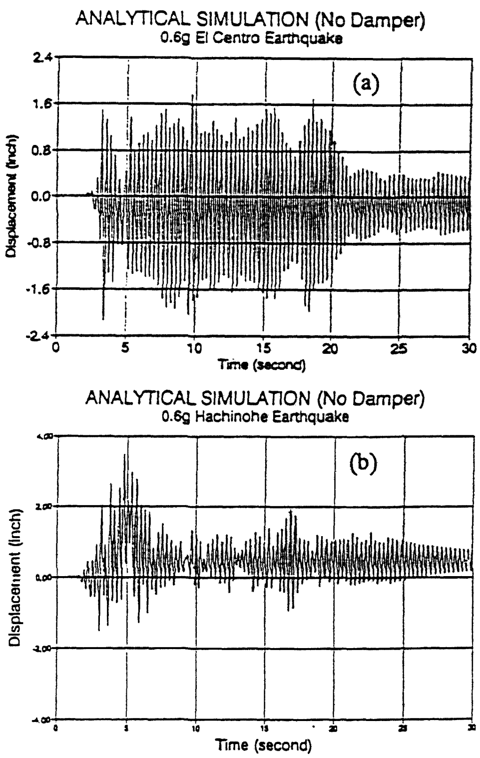

Figure 4. Calculated displacements without dampers added.
(a) El Centro earthquake.
(b) Hachinohe Earthquake.

dampers, the model structure would experience inelastic deformation under these ground motions (Figures 3a and 3b). In this case only analytical studies were conducted. The inelastic analysis results are used to access the efficiency of VE dampers under strong earthquake ground motions.

Figures 4a and 4b show the calculated displacement time histories at the roof of the model structure without added VE dampers under 0.6g El Centro and Hachinohe earthquake ground motions, respectively. Figures 5a and 5b show the displacements with added dampers. It can be seen that VE dampers provide significant extra damping to the structure so that the structure behaved elastically and the seismic response greatly reduced. Similar observation were attained for story drifts and floor accelerations at all floor levels.

Figures 6a-6d show the envelop curves of the lateral displacement, inter-story drift, accumulated story shear, and overturning moment of the model structure with and without added dampers under 0.6g El Centro earthquake. It can be seen that adding VE dampers to the structure reduces not only the deformation but also the base shear and overturning moment even when the structure without the added dampers is allowed to have inelastic deformation. Therefore, the VE dampers dissipate a significant amount of seismic input energy to prevent the structure from inelastic deformation. Similar results were obtained for 0.6g Hachinohe earthquake.

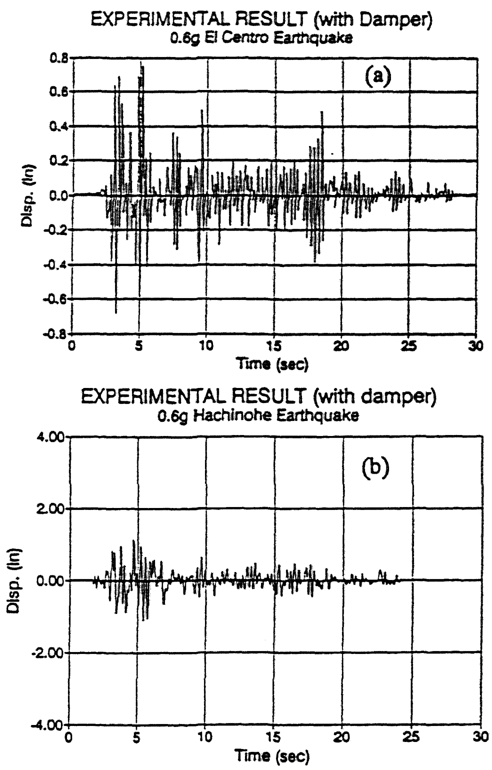

Figure 5. Measured displacements with dampers added.
(a) El Centro earthquake.
(b) Hachinohe Earthquake.

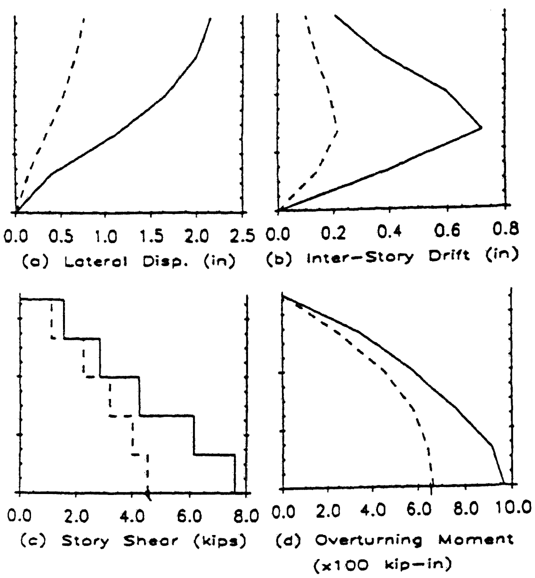

Figure 6. Envelop curves: - - - with dampers, —— without dampers.

4 NUMERICAL SIMULATION

As can be observed from Table 1, the damper properties are nearly constant for damper strains up to 20% under a given frequency and temperature. Using damper stiffness and loss factors given in Table 1 at 25 °C, the modal damping ratio of the model structure with added VE dampers is calculated to be 14.5% from the modal strain energy method (Soong and Lai 1991; Chang, et al. 1992)

$$\zeta = \frac{\eta}{2}\left(1 - \frac{\phi_s K_o \phi_s}{\phi_s K_s \phi_s}\right) \tag{3}$$

where K_s is the stiffness matrix of the structure including added damper stiffness, ϕ_s is the associated mode shape and K_o is the stiffness matrix of the original structure without adding dampers.

If the added damper stiffness is small compared to the structural stiffness or the mode shape of the structure does not change noticeably with dampers added. Using Rayleigh quotient, Equation 3 can be simplified to

$$\zeta \approx \frac{\eta}{2}\left(1 - \frac{\omega_o^2}{\omega_s^2}\right) \tag{4}$$

where ω_s and ω_o are the natural frequencies of the structure with and without dampers, respectively. The modal damping ratio becomes a function of the natural frequency increase due to added dampers. For a desired damping ratio, the required frequency increase depends on the VE material loss factor. The larger the loss factor, the smaller will be the frequency increase.

However, Equation 4 must be used with care since it can over-estimate the damping if the mode shape changes noticeably after dampers are added. For instance if one of the added dampers is very stiff and the deformation becomes very small compared to other part of the structure, the energy dissipated by the damper and the structural modal damping become smaller. In this case, the frequency does not increase with further increase in damper stiffness.

Figure 7 shows the numerical prediction for the model structure at the roof under 0.6g El Centro earthquake. The prediction correlates quite well with the experimental results as shown in Fig. 5a. Similar correlation was obtained for other numerical simulations of the test results (Chang et al. 1992).

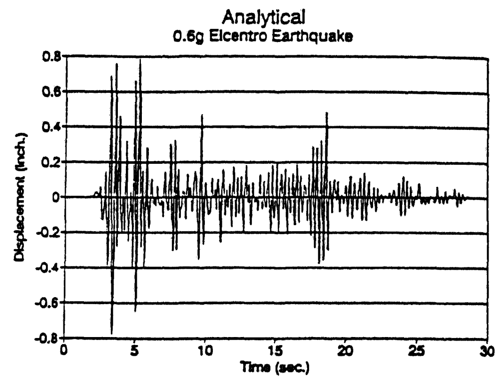

Figure 7. Estimated displacements with dampers added; El Centro earthquake.

5 DESIGN PROCEDURE

One of the fundamental requirements in a structural design is to reliably predict the designed structure under specified loading condition. Current state-of-practice enables the engineers to correctly analyze the structures they design, provided all the design parameters are properly given. In designing structures with added VE dampers, the most important design parameter is the damping ratio. By properly incorporating the modal strain energy method into the design flow chart, design of structures with added VE dampers can be accomplished with minimum modifications on the current design practice.

Like many other design problems, design of viscoelastically damped structures is in general an iterative process. First, an analysis of the structure without added dampers should be carried out. Then the required damping ratio becomes the primary design parameter by adding VE dampers to the structure. The design will normally contain the following steps which may continuously be updated to determine the structural properties after each design cycle: (a) determine structural properties of the buildings and perform structural analysis; (b) determine the desired damping ratio; (c) select available damper locations in the building; (d) select damper stiffness and loss factor; (e) calculate the equivalent damping ratio using the modal strain energy method; (f) perform structural analysis using the designed damping ratio. When steps (e) and (f) satisfy the desired damping ratio and structural performance criteria, the design is completed. Otherwise, a new design cycle will proceed which may lead to new structural properties, damper locations or damper dimensions and properties. A general flow chart of the design procedure is shown in Figure 8.

It can be seen that this design procedure falls into the traditional design procedure by including the required damping ratio and the selection of damper stiffness and loss factor. In general, the required damping ratio can be estimated by using the response spectra of the design earthquake with various damping ratios. The selection of damper stiffness and loss factor can be a trial and error procedure or based on the principal that the added stiffness from the VE dampers be proportional to the distribution of the total structural stiffness in each floor. This can be obtained by modifying the modal strain energy method for each story as:

$$k_i' = \frac{2\zeta}{\eta - 2\zeta} k_i \quad (5)$$

where k_i is the structural stiffness without added dampers at the ith story, k'_i is the effective damper stiffness contribution to the ith story, and ζ is the desired damping ratio. Once a VE material with known G' and G'' at the designed frequency and temperature is selected, the thickness, h, of the VE material can be chosen to be large enough to ensure the expected maximum strain in the VE material is smaller than the ultimate strain. The total area, A, of the damper can be calculated as

$$A = \frac{k'h}{G'} \quad (6)$$

Since the damper shown in Figure 1 has two VE slabs, the area of each slab will be one half of the value calculated from Equation 6.

6 SUMMARY AND CONCLUSION

This paper summarizes an experimental and analytical study on the application of VE dampers as energy dissipation devices in structural applications. It can be concluded that VE dampers are effective in reducing excessive vibrations of structures due to earthquake ground motions. It is also found that the modal strain energy method can be used to reliably predict the equivalent structural damping. The seismic response of viscoelastically damped structures can be accurately predicted using conventional modal analysis techniques.

Based on the experimental and analytical studies, a design procedure for viscoelastically damped structures is presented. This design procedure fits easily into the conventional structural design flow chart by including the damping ratio as a additional design parameter.

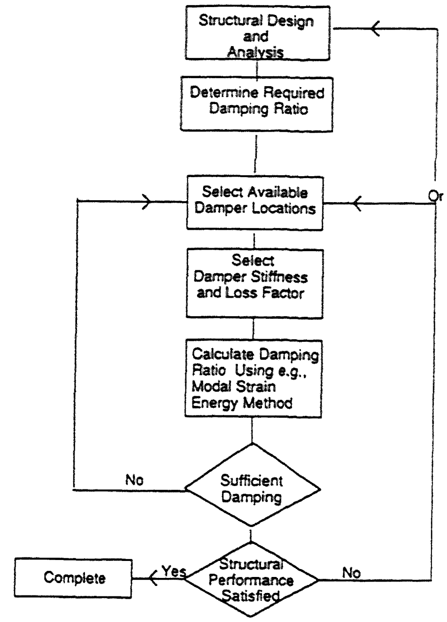

Figure 8. VE damper design flow chart.

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