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SEISMIC DESIGN OF STRUCTURES WITH ADDED VISCOELASTIC DAMPERS

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ABSTRACT

This paper describes a simple and rational procedure on earthquake resistant design of structures with added viscoelastic (VE) dampers. Examples of a single-bay ten-story building with three different damper design alternatives are presented. Comparisons on the seismic performance among a conventionally designed special moment resisting frame and the three design alternatives with VE dampers are also carried out. It is shown that with a sufficiently large design damping ratio such as 15%, structures may remain elastic or experience only minor yielding under most current design earthquakes. The design options described in this paper can provide safe and economic solutions for designing viscoelastically damped structures under current seismic design regulations.

KEYWORDS

Viscoelastic Damper, Earthquake Resistant Design

INTRODUCTION

Earthquake resistant design and retrofit of structures using energy absorption devices has received considerable attention in recent years (ATC-17-1 1993). Among the available devices, viscoelastic (VE) dampers have shown to be capable of providing structures with considerable added damping to dissipate the seismic input energy (EERI 1993). Results from experimental studies on a 2/5 scale five story steel frame (Chang et al 1995), a 1/3 scale three story RC frame (Shen et al 1995), a full scale five story steel frame (Lai, et al 1995), and a 2/5 scale three story steel frame (Chang et al 1996a) show that VE dampers are effective in reducing the seismic response and inelastic ductility demand of structures with added VE dampers. Comparing with experimental results, analytical studies have shown that damping ratios of the viscoelastically damped structure can be accurately estimated by the modal strain energy method (Johnson 1982, Chang et al 1995). The seismic structural response with high damping can be well predicted by the conventional response spectra analyses and time history analyses (Chang et al 1996b).

This paper presents a design procedure for seismic retrofit and for design of new structures with added viscoelastic dampers. Design examples of a single-bay ten-story structure with three damper design alternatives are made to illustrate the proposed design method and to compare the safety and economy among those various design options.

DESIGN PROCEDURE

Figure 1 shows the proposed design procedure for viscoelastically damped structures. VE dampers can be applied either to retrofit existing structures or to design new structures. To design a new structure with VE dampers, member sizes of the primary frame may be proportioned by the design base shear as follows.

If the change of mode shapes due to the added dampers is neglected, the modal strain energy equation can be approximated as

$$\xi = \frac{\eta}{2}\frac{K_d}{K_s} = \frac{\eta}{2}\frac{K_d}{(K_o+K_d)} \qquad \textbf{(1)}$$

where ξ= design damping ratio, η= loss factor of the VE damper brace, K_d = lateral stiffness contribution of the VE damper braces, K_o = lateral stiffness contribution of the primary frame, and K_s= lateral stiffness of the viscoelastically frame (=K_o + K_s).

Assuming that the base shear is proportional to the structure's lateral stiffness, we have

$$V = V_d + V_o = 2\frac{\xi}{\eta - 2\xi}V_o + V_o \qquad \textbf{(2)}$$

where V = the total design base shear specified by the building code, V_d = the base shear shared by the VE damper base, and V_o = design base shear for sizing the primary frame.

From Eq. (2), the primary frame may be designed by the base shear as

$$V_o = \frac{\eta - 2\xi}{\eta}V \qquad \textbf{(3)}$$

Using Eq. (3) to size the members of the primary frame is conservative because the total design base shear was established based on 5% damping ratio. To consider the effect of added damping, the design base shear for the primary may be further reduced to (NEHRP 1995)

$$V_0' = BV_0 \qquad \textbf{(4)}$$

where B is the reduction factor for increased building damping, For ξ=15%, B=0.72.

DESIGN EXAMPLE

Description of Examples

Four design cases on a single-bay ten-story building (Fig.2) are carried out to illustrate the proposed design procedure. Case 1 represents a conventional design (UBC 1994). Case 2 applies VE dampers to the Case 1 structure to provide 15% of critical damping ratio, representing a seismic retrofit application. Case 3 designed a viscoelastically frame with 15% damping ratio by using Eq. (3) to size the structural members of the primary frame. Case 4 designs another viscoelastically damped frame by using Eq. (4) with B= 0.72 to consider the effect of added 15% damping ratio. Elastic response spectrum for Taipei area (Fig.3) is used as the design earthquake with Z=0.32, I=1.0 and C=2.4 (Tsai et al 1988). Rw=12 is used to determine the total design base shear for all the design cases. The primary structures without dampers are first designed following the equivalent static loading procedure. VE dampers are then designed for Cases 2,3,4 with 15% damping ratio at 32°C. Response spectrum and time history analyses are then carried out to compare the seismic performance of the four design cases using two artificial earthquakes (AR1, AR2) equivalent to the Taipei response spectrum and a dozen recorded ground motions on the four design cases.

Design of The Primary Frame

Following the regular equivalent static design procedure, structural members of the primary frames selected for design cases 1 (also 2), 3 and 4 are shown in Fig.2. Due to smaller design base shear, total weights of the beams and columns for Case 3 and Case 4 are 12.4% and 23.1%, respectively, less than that of the conventional frame (Case 1).

Design of The VE Dampers

Once the desired damping ratio is determined, the primary frame has been designed, and the available damper locations have been selected, the design of VE dampers are similar for design Case 2, 3 and 4 as follows.

Determine the Damper Stiffness. The damper storage stiffness, k' can be determined by constructing damper design curves using the modal strain energy method. In this example, damper design curves (Fig.4a,b) for design cases 2, 3 and 4 are first constructed with one VE damper brace at each story. For design damping ratio of 15%, the damper storage stiffness for design cases 2, 3 and 4 are 89 kN/cm, 57 kN/cm and 40 kN/cm, respectively and the associated first natural frequencies of the three viscoelastically damped structures will be 0.82 Hz, 0.69 Hz and 0.61 Hz, respectively.

Determine the Damper Thickness. The thickness of the VE material, h, can be determined based on the maximum allowable damper deformation. In this example, if the maximum damper deformation is governed by the maximum story drift ratio of 1.5%, it will be limited to 0.015 x 360 x cosθ= 4.6cm, where θ is the angle between the floor beam and the brace. If maximum damper strain of 180% is allowed at 32°C, the damper thickness, h, is then determined as 2.5 cm.

Determine the Damper Area. The area of the VE damper designed for the ith story A_i, can be determined as

$$A_i=\frac{k_i' h}{nG'} \tag{5}$$

where ki' = damper storage stiffness obtained from the damper design curves for a specified design damping ratio, h = damper thickness which depends on the maximum design drift ratio of the structure, n= number of VE slabs for each damper, G' = storage modulus of the VE material at a specified design temperature and with the design frequency obtained from the damper design curves.

In this example, if 3M ISD110 VE material is used, the storage modulus G' for design cases 2, 3 and 4 can be determined as 50.83 N/cm^2, 47.1 N/cm^2 and 43.7 N/cm^2, respectively, at 32°C and 20% strain (Chang et al 1996). If four VE slabs are used for each damper, area of the VE dampers for design cases 2, 3 and 4 can be determined to be 1095 cm^2, 756 cm^2 and 572 cm^2, respectively. The final design of the VE dampers can then be determined to be 4 x 2.5cm x 20 cm x 55 cm, 4 x 2.5cm x 20cm x 40cm, and 4 x 2.5cm x 20cm x 26cm, for Cases 2, 3 and 4, respectively, as shown in Fig. 5.

Estimate the Structural Damping Ratio: The modal strain energy method or other rational analytical methods should be used to determine if the design damping ratio has been be achieved. It should be noted that when modeling the damper braces as truss elements with their axial stiffness equal to the storage stiffness of the

VE dampers, the effective loss factor of the damper-brace assembly should be used in estimating the damping ratios of the structure unless the stiffness of the brace is much larger that of the VE damper. For a damper brace assembly, η_{v-b} can be determined as:

$$\frac{\eta_{v-b}}{\eta_v}=\frac{\frac{K_b}{K_v'}}{\eta_v^2+\frac{K_b}{K_v'}+1} \tag{6}$$

where K_b = axial stiffness of the brace with dampers, K_v'= storage stiffness of the VE damper; η_v = loss factor of the VE material. The effect of brace stiffness to the effective damper-brace loss factor is shown in Fig.6.

At this stage if the calculated damping ratio is much higher or lower than the design value, damper stiffness must be modified and another design cycle for determining the VE dampers' dimensions will begin.

Perform Dynamic Analysis: Finally, dynamic analyses of the viscoelastically damped structure under the design earthquake should be conducted to ensure that all the design parameters have been conservatively satisfied.

Following the above design procedure, the natural periods of the four design cases are calculated to be 1.44 sec., 1.23 sec., 1.44 sec. and 1.69 sec., respectively. It can be seen that statically, the conventional frame (Case 1) and the non-stiffened frame (Case 3) have almost the same lateral stiffness at the design temperature, as expected. The damping ratios calculated for Cases 2, 3 and 4 are estimated to be 15.1%, 15.4% and 15.2%, respectively. In addition, comparing design Case 4 and 3 to Case 2, total weight of the structural members is saved by 12.4% and 23.1% and the volume of VE material is reduced by 27% and 47%, respectively.

SEISMIC PERFORMANCE EVALUATION

Elastic Range

Figure 7 shows the story drift envelopes of the four design cases under the design earthquake AR1 scaled down by R_w (UBC 1994). It can be seen that all the three designs satisfy the drift requirements set by UBC (= $0.03/R_w$). In addition, VE dampers effectively reduce the story drifts as compared to the no damper case and that the lateral drift in the non-stiffened frame is only slightly larger than that in the stiffened frame.

Inelastic Range

Figure 8 shows the plastic hinge formation of the four design cases under the design earthquake AR1. It can be seen that the conventionally designed frame (Case 1) will be significantly damaged with maximum plastic hinge rotation exceeding 0.015 rad. For the stiffened frame (Case 2), only very minor yielding may occur and the structure will mostly remain elastic. For the non-stiffened frame (Case3) and the reduced stiffness frame (Case 4), more plastic hinges than the stiffened frame may form. However, the plastic hinge rotations are very small. The story drift envelopes of the four design cases are shown in Figure 9. It can be seen that the drift ratios of the structures with added VE dampers are well below the 1.5% while that of the conventionally designed structure significantly exceeds that value.

Figure 10 shows the accumulated story shear envelopes of the four structures. It can be seen that the maximum story shears experienced by these four structures are very close even though the structures with added dampers behave mostly elastic. However, the way they dissipate seismic input energy are different (Uang 1990). For the conventionally designed frame, most seismic input energy dissipated through inelastic deformation of the structural members (Fig. 11a). It is therefore expected that severe damage may occur to this structure. For the stiffened frame (Case 2), it can be seen (Fig.11b) that all the input energy has been dissipated by the VE dampers and the structure may not be damaged under this design earthquake. For the non-stiffened frame (Case 3) and the reduced stiffness frame (Case 4), it can be seen that the inelastic hysteretic energy plays only a minor role in dissipating the input energy (Fig.11c, 11d). Most of the input energy has been dissipated by the VE dampers and the structure might experience only minor yielding under this design earthquake.

From the above comparisons, it is clear that under current design regulations, the seismic resistant capacity of the viscoelastically damped structures are conservative as compared to the conventionally designed structure. Under the design earthquake, the conventionally designed frame in Case 1 may survive with severe damage to its structural and non-structural components. When VE dampers designed to add 15% damping to the conventional frame (Case 2), the frame may remain elastic under the same earthquake. The viscoelastically damped frames designed based on Eqs. 3 and 4 (Case 3 and Case 4) may experience minor yielding under this design earthquake. The viscoelastically damped structures in this design example are clearly much superior to the conventional frame in seismic response under moderate as well as strong earthquake ground motions. For economic considerations, the non-stiffened (Case 3) and the reduced-stiffness (Case 4) viscoelastically damped frames will save 12.4% and 23.1%, respectively, in structural weight and 27% and 47%, respectively, in VE material as compared to the stiffened frame.

SUMMARY AND CONCLUSION

A design procedure for seismic retrofit and for new design of structures with added viscoelastic dampers has been proposed. Examples are presented to illustrate the design procedure for viscoelastically damped structures and to compare the safety and economy among the four design alternatives. It is found that the seismic resistant capacity of the viscoelastically damped structures are better than that of the conventionally designed structure. The non-stiffened (Case 3) and the reduced-stiffness (Case 4) frame design options may provide safe and economic solutions for the design of viscoelastically damped structure under the current seismic design regulations.

Results from this study suggest that it is possible to design a structure which may remain elastic under strong earthquake ground motions if VE dampers are used to provide the structure with sufficiently large damping at a specified design temperature. Based on this study and the results from previous investigations, a design damping ratio of 15% is recommended for current design earthquakes for structures with added VE dampers.

ACKNOWLEDGEMENT

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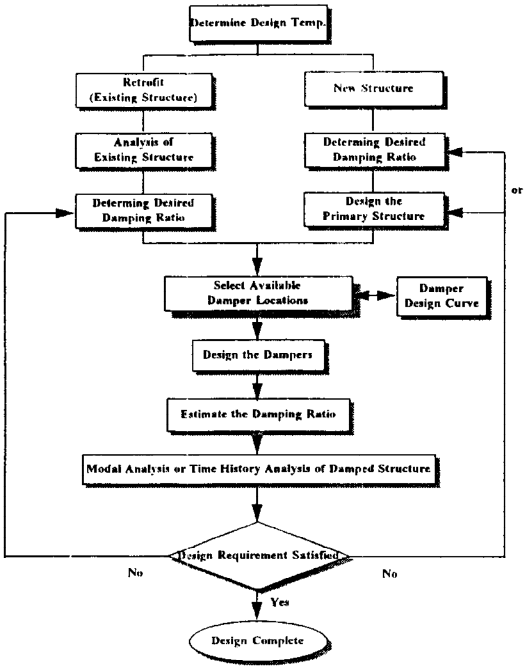
Fig1.Design Procedure



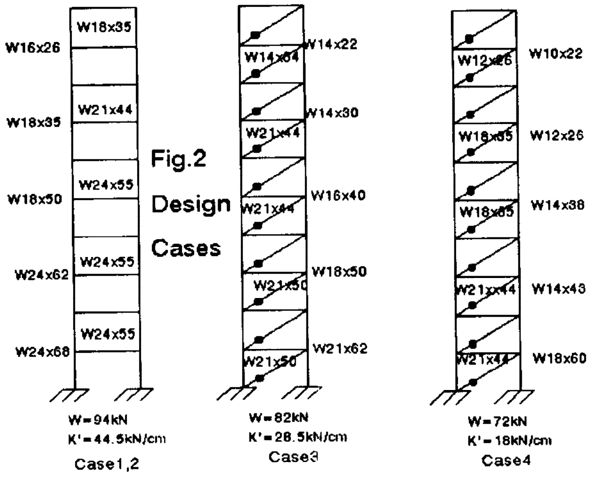


Fig.2 Design Cases

Fig.3 Design Spectrum

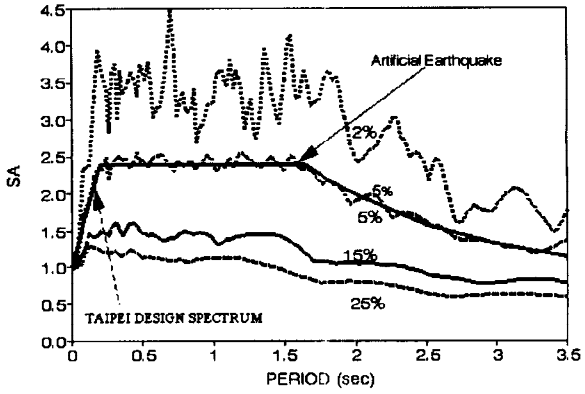


Fig.4a VE Damper Design Curve
(10-Story Frame Example)

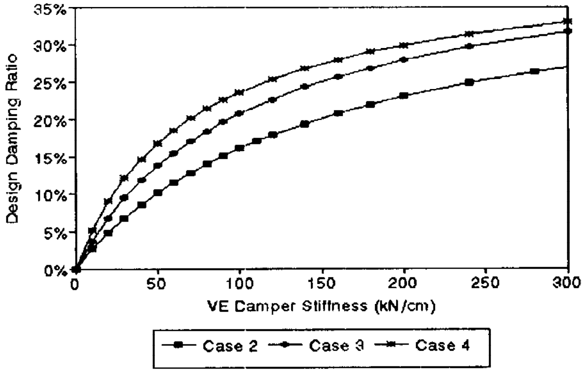


Fig.4b VE Damper Design Curve
(10-Story Frame Example)

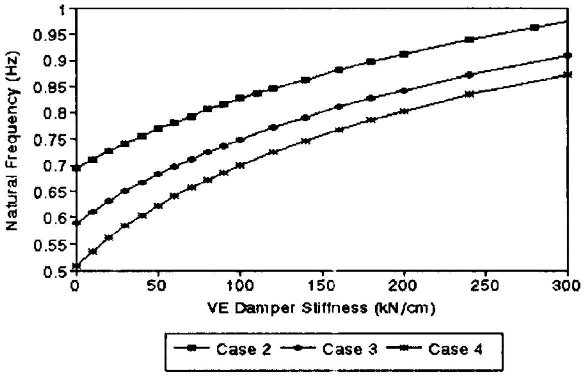


Fig.5 Layout of VE Damper

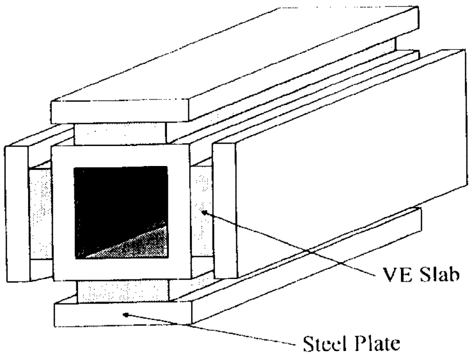


Fig.6 Effect of Bracing Stiffness on
Damper Loss Factor

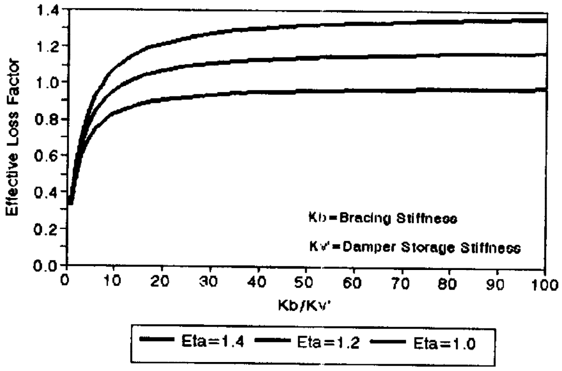


Fig7. Story Drift Envelops(26gal)
(10 Story Building Example)

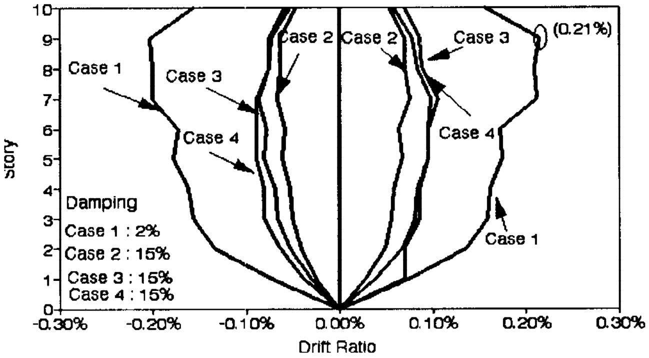


Fig8. Plastic hing formula

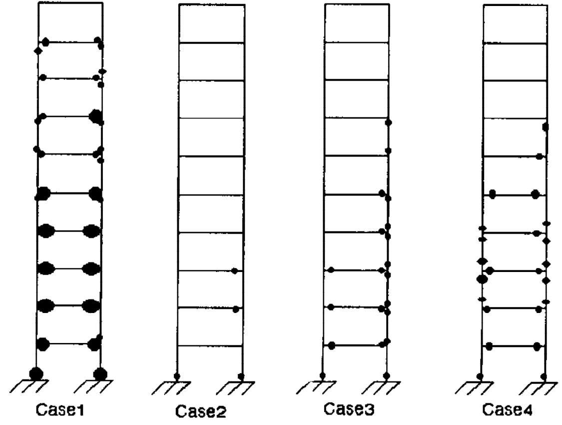


Fig.9 Story Drift Envelopes(0.32G)
(10 Story Building Example)

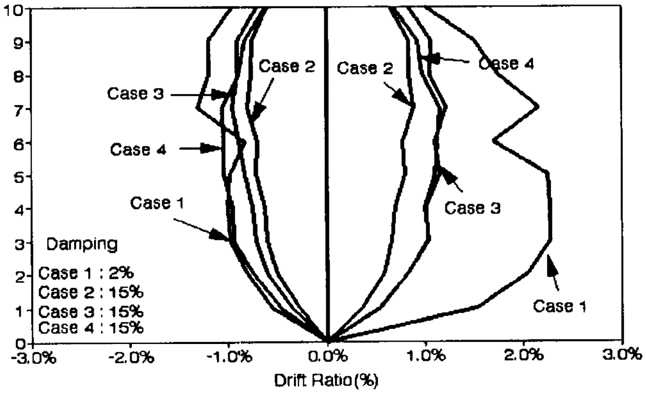


Fig.10 Story Shear Envelopes (0.32G)
(10 Story Building Example)

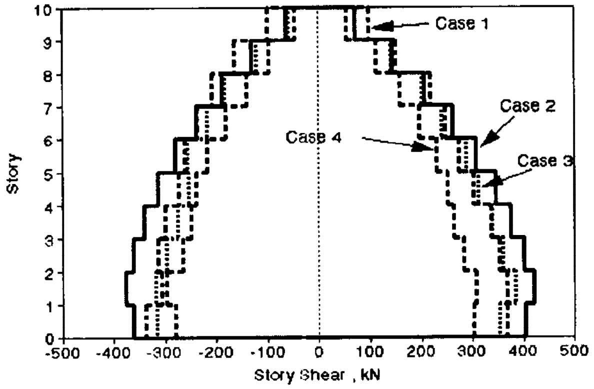


Fig.11a Input Energy Distribution
10 Story Building Example (AR1 0.32G)

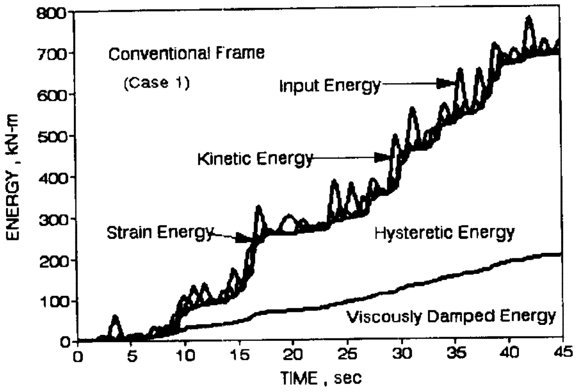


Fig.11b Input Energy Distribution
10 Story Building Example (AR1 0.32G)

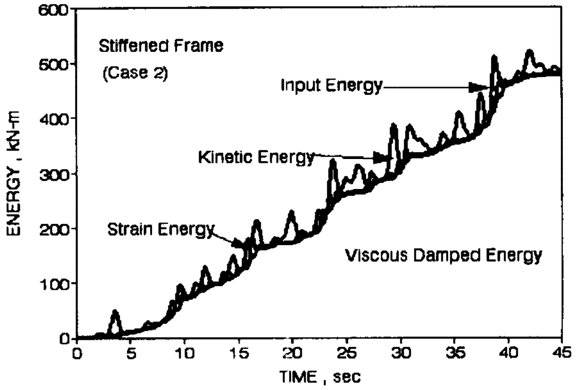


Fig.11c Input Energy Distribution
10 Story Building Example (AR1 0.32G)

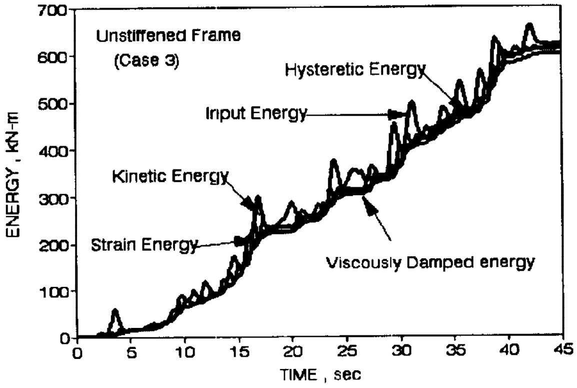


Fig.11d Input Energy Distribution
10 Story Building Example (AR1 0.32G)