Fişa suspiciunii de plagiat / Sheet of plagiarism's suspicion	Indexat la: 0137/06

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OS	CHEŞCA, Alexandru Basarab, VĂCĂREANU, Radu; GHICA, Raluca. Seismic Retrofitting Using Fluid Viscous Dampers. Case Study. *Scientific Bulletin of the Technical University of Civil Engineering, Bucureşti*, Series: Mathematical Modelling in Civil Engineering. No.1. March 2006. p.12-20.
OA	HWANG, Jenn-Shin. Seismic design of structures with viscous dampers. *International Training Programs for Seismic Design of Building Structures.* 2002. p.123-138. Disponibil la: http :// www . ncree . org . tw / itp2002 / 08_SeismicDesignOfStructuresWithViscousDampers.pdf. Accesat la: 21 ianuarie 2015.

Incidenţa minimă a suspiciunii / Minimum incidence of suspicion	
p.14:01-p.16:13	p.127:07-p.130:05
Fişa întocmită pentru includerea suspiciunii în Indexul Operelor Plagiate în România de la Sheet drawn up for including the suspicion in the Index of Plagiarized Works in Romania at www.plagiate.ro	

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Seismic Design of Structures with Viscous Dampers

Jenn-Shin Hwang[1]

1、Introduction

In addition to the loads due to the effects of gravity, earthquake loading must be considered when designing structures located in seismically active areas. The philosophy in the conventional seismic design is that a structure is designed to resist the lateral loads corresponding to wind and small earthquakes by its elastic action only, and the structure is permitted to damage but not collapse while it is subjected to a lateral load associated with moderate or severe seismic events. As a consequence, plastic hinges in structures must be developed in order to dissipate the seismic energy when the structure is under strong shakings. The design methods based on this philosophy are acceptable to account for the needs for both economic consideration and life safety. However, the development of the plastic hinges relies on the large deformation and high ductility of a structure. The more ductility a structure sustains, the more damage it suffers. Besides, some important structures such as hospitals and fire stations have to remain their functions after a major earthquake, the aforementioned design philosophy (life-safety based) may not be appropriate. These structures should be strong enough to prevent from large displacement and acceleration so that they can maintain their functions when excited by a severe ground motion.

Structural passive control systems have been developed with a design philosophy different than that of the traditional seismic design method. These control systems primarily include seismic isolation systems and energy dissipation systems. A variety of energy dissipation systems have been developed in the past two decades, such as friction dampers, metallic dampers, visco-elastic dampers and viscous dampers. A structure installed with these dampers does not rely on plastic hinging to dissipate the seismic energy. On the contrary, the dissipation of energy is concentrated on some added dampers so that the damage of the main structure is reduced and the functions of the structure can then be possibly preserved.

This article will focus on the seismic design of structure with supplemental "viscous dampers". The effect of the supplemental viscous dampers to a structure in resisting seismic force can be clearly illustrated from energy consideration. The event of a structure responding to an earthquake ground motion is described using an energy concept in the follows. The absolute energy equation (Uang and Bertero, 1988) is given by:

$$E_I = E_k + E_s + E_h + E_d \tag{1}$$

where E_I is the earthquake input energy, E_k is the kinetic energy, E_s is the recoverable elastic strain energy, E_h is the irrecoverable hysteretic energy, and E_d is the energy dissipated by the inherent structural damping capability and/or the supplemental viscous dampers. The

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Figure 2-3(a) shows the hysteresis loop of a pure linear viscous behavior. The loop is a perfect ellipse under this circumstance. The absence of storage stiffness makes the natural frequency of a structure incorporated with the damper remain the same. This advantage will simplify the design procedure for a structure with supplemental viscous devices. However, if the damper develops restoring force, the loop will be changed from Figure 2-3(a) to Figure 2-3(b). In other words, it turns from a viscous behavior to a viscoelastic behavior.

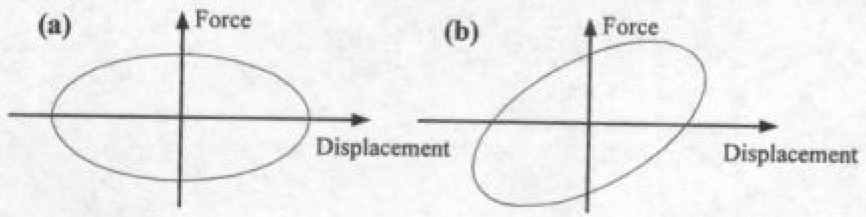

Figure 2-3 Hysteresis Loops of Dampers with Pure Viscous and Viscoelastic Behavior

3、The effective damping ratio of structures with linear viscous dampers

Considering a single degree of freedom system equipped with a linear viscous damper under an imposed sinusoidal displacement time history

$$u = u_0 \sin \omega t \tag{3}$$

where u is the displacement of the system and the damper; u_0 is amplitude of the displacement; and the ω is the excitation frequency. The measured force response is

$$P = P_0 \sin(\omega t + \delta) \tag{4}$$

where P is the force response of the system; P_0 is amplitude of the force; and the δ is the phase angle. The energy dissipated by the damper, W_D, is

$$W_D = \oint F_D du \tag{5}$$

where F_D is the damper force which equals to $C\dot{u}$; C is the damping coefficient of the damper; and $\dot{u}$ is the velocity of the system and the damper. Therefore,

$$\begin{aligned} W_D &= \oint C\dot{u}du = \int_0^{2\pi/\omega} C\dot{u}^2\, dt \\ &= C u_0^2\, \omega^2 \int_0^{2\pi} \cos^2 \omega t \;\; d(\omega t) \\ &= \pi C u_0^2\, \omega \end{aligned} \tag{6}$$

Recognizing that the damping ratio contributed by the damper can be expressed as $\xi_d = C / C_{cr}$, it is obtained

$$\begin{aligned} W_D &= \pi C u_0^2 \omega = \pi \xi_d C_{cr} u_0^2 \omega = 2\pi \xi_d \sqrt{Km} u_0^2 \omega \\ &= 2\pi \xi_d K u_0^2 \frac{\omega}{\omega_0} = 2\pi \xi_d W_s \frac{\omega}{\omega_0} \end{aligned} \tag{7}$$

where C_{cr}, K, m, ω_0 and W_s are respectively the critical damping coefficient, stiffness, mass, nature frequency and elastic strain energy of the system. The damping ratio attributed to the damper can then be expressed as

$$\xi_d = \frac{W_D}{2\pi W_s}\frac{\omega_0}{\omega} \tag{8}$$

W_D and W_s are illustrated in Figure 3-1. Under earthquake excitations, ω is essentially equal to ω_0, and Eq. (8) is reduced to

$$\xi_d = \frac{W_D}{2\pi W_s} \tag{9}$$

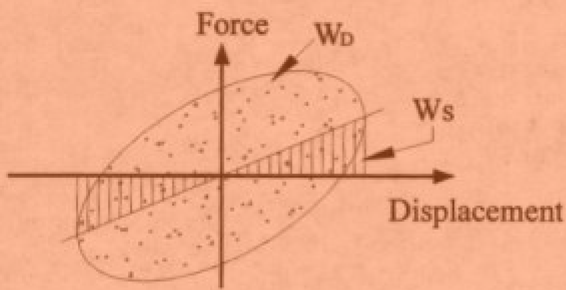

Figure 3-1 Definition of Energy Dissipated W_D in A Cycle of Harmonic Motion and Maximum Strain Energy W_s of A SDOF System with Viscous Damping Devices

Considering a MDOF system shown in Figure 3-2, the total effective damping ratio of the system, ξ_{eff}, is defined as

$$\xi_{eff} = \xi_0 + \xi_d \tag{10}$$

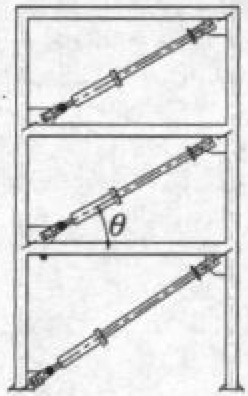

Figure 3-2 A MDOF Model of A Structure with Viscous Dampers

where ξ_0 is the inherent damping ratio of the MDOF system without dampers, and ξ_d is the viscous damping ratio attributed to added dampers. Extended from the concept of a SDOF system, the equation shown below is used by FEMA273 to represent ξ_d

$$\xi_d = \frac{\sum W_j}{2\pi W_K} \tag{11}$$

where $\sum W_j$ is the sum of the energy dissipated by the j-th damper of the system in one cycle; and W_K is the elastic strain energy of the frame. W_K is equal to $\sum F_i \Delta_i$ where F_i is the story shear and Δ_i is the story drift of the i-th floor. Now, the energy dissipated by the viscous dampers can be expressed as

$$\sum_j W_j = \sum_j \pi C_j u_j^2 \omega_0 = \frac{2\pi^2}{T} \sum_j C_j u_j^2 \tag{12}$$

where u_j is the relative axial displacement of damper j between the two ends.

Experimental evidence has shown that if the damping ratio of a structure is increased the higher mode responses of the structure will be suppressed. As a consequence, only the first mode of a MDOF system is usually considered in the simplified procedure of practical applications. Using the modal strain energy method, the energy dissipated by the dampers and the elastic strain energy provided by the primary frame can be rewritten as

$$\sum_j W_j = \frac{2\pi^2}{T} \sum_j C_j \phi_{rj}^2 \cos^2 \theta_j \tag{13}$$

and

$$\begin{aligned} W_K &= \Phi_1^T [K] \Phi_1 = \Phi_1^T \omega^2 [m] \Phi_1 \\ &= \sum_i \omega^2 m_i \phi_i^2 = \frac{4\pi^2}{T^2} \sum_i m_i \phi_i^2 \end{aligned} \tag{14}$$

where $[K]$, $[m]$, Φ_1 are respectively the stiffness matrix, the lumped mass matrix and the first mode shape of the system; ϕ_{rj} is the relative horizontal displacement of damper j corresponding to the first mode shape; ϕ_i is the first mode displacement at floor i; m_i is the mass of floor i; and θ_j is the inclined angle of damper j. Substituting Eqs. (11), (13) and (14) into Eq. (10), the effective damping ratio of a structure with linear viscous dampers given by

$$\xi_{eff} = \xi_0 + \frac{\frac{2\pi^2}{T} \sum_j C_j \phi_{rj}^2 \cos^2 \theta_j}{2\pi \frac{4\pi^2}{T^2} \sum_i m_i \phi_i^2} = \xi_0 + \frac{T \sum_j C_j \phi_{rj}^2 \cos^2 \theta_j}{4\pi \sum_i m_i \phi_i^2} \tag{15}$$

Corresponding to a desired added damping ratio, there is no substantial procedure suggested by design codes for distributing C values over the whole building. When designing the dampers, it may be convenient to distribute the C values equally in each floor. However, many experimental results have shown that the efficiency of dampers on the upper stories is smaller than that in the lower stories (Pekcan et al., 1999). Hence an efficient distribution of the C values of the dampers may be to size the horizontal damper forces in proportion to the story shear forces of the primary frame.

4、The effective damping ratio of structures with nonlinear viscous dampers

Considering a SDOF system with a nonlinear viscous damper under sinusoidal motions, the velocity of the system is given by

$$\dot{u} = \omega u_0 \sin\omega t \tag{16}$$

Recognizing $F_D = C\dot{u}^{\alpha}$ and substituting Eqs. (2) and (16) into Eq. (5), the energy dissipated by the nonlinear damper in a cycle of sinusoidal motion can be acquired.

$$\begin{aligned} W_D &= \oint F_D du = \int_0^{2\pi/\omega} F_D \dot{u} dt \\ &= \int_0^{2\pi/\omega} \left| C\dot{u}^{1+\alpha} \right| dt \\ &= C(\omega u_0)^{1+\alpha} \int_0^{2\pi/\omega} \left| \sin^{1+\alpha} \omega t \right| dt \end{aligned} \tag{17}$$

Let $\omega t = 2\theta$ and $dt = \frac{2}{\omega} d\theta$, Eq. (17) is rewritten as

$$\begin{aligned} W_D &= C(\omega u_0)^{1+\alpha} \frac{2}{\omega} \int_0^{\pi} \left| \sin^{1+\alpha} 2\theta \right| d\theta \\ &= 2^{2+\alpha} C\omega^{\alpha} u_0^{\;1+\alpha} \int_0^{\pi/2} 2\sin^{1+\alpha}\theta \cos^{1+\alpha}\theta d\theta \\ &= 2^{2+\alpha} C\omega^{\alpha} u_0^{\;1+\alpha} \frac{\Gamma^2(1+\alpha/2)}{\Gamma(2+\alpha)} \end{aligned} \tag{18}$$

where Γ is the gamma function.

Following a similar procedure to that of the SDOF with linear viscous dampers, equivalent damping ratio of the SDOF system contributed by nonlinear dampers can be obtained

$$\xi_d = \frac{\lambda C \omega^{\alpha-2} u_0^{\;\alpha-1}}{2\pi m} \tag{19}$$

in which

$$\lambda = 2^{2+\alpha} \frac{\Gamma^2(1+\alpha/2)}{\Gamma(2+\alpha)} \tag{20}$$

For the convenience of practical applications, the values of λ are tabulated in FEMA 273 based on Eq. (20). It is worthy of noting that the damping ratio determined by Eq. (19) is

- *Maximum story shear,* $V_{\max,i1}$

$$V_{\max,i1} = CF_1 \cdot V_{i1}\,|_{Max.\ Disp.} + CF_2 \cdot V_{di1}\,|_{Max.\ Vel.}$$

$$V_{\max,i1} = 0.93\begin{Bmatrix} 54.4 \\ 104.8 \\ 135.7 \end{Bmatrix} + 0.37\begin{Bmatrix} 21.8 \\ 34.5 \\ 50.1 \end{Bmatrix} = \begin{Bmatrix} 58.7 \\ 110.2 \\ 144.7 \end{Bmatrix}\ (kN)$$

Higher mode responses may be calculated through the same procedure. Design forces thus could be obtained by combining results of all modes with SRSS or CQC rules.

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