PROCEEDINGS, ATC-17-1 SEMINAR ON SEISMIC ISOLATION, PASSIVE ENERGY DISSIPATION, AND ACTIVE CONTROL, APPLIED TECHNOLOGY COUNCIL, SAN FRANCISCO, CALIFORNIA, MARCH (1993)

STATE-OF-THE-ART AND STATE-OF-THE-PRACTICE IN SEISMIC ENERGY DISSIPATION

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ABSTRACT

The results of several studies on the effects of supplemental viscous damping on the response of elastic and elasto-plastic single-degree-of-freedom systems are used to provide insight to the effects of energy dissipation devices on the earthquake response of buildings and to assist interpretation of studies reporting the damping and stiffness characteristics of specific types of energy dissipation devices. Extension to multi-story buildings is discussed. The hysteretic characteristics of energy dissipation devices utilizing friction, metallic hysteresis, and viscous and viscoelastic materials which have been tested (and some used in construction) are presented. While it is now possible to design and construct buildings with improved seismic performance with energy dissipation devices, new devices and design developments will continue to be made.

INTRODUCTION

This paper provides a background to response modification improvements which can be expected from the addition of mechanical damping devices to a structural system and descriptions of a large number of energy dissipation devices that have been studied experimentally or implemented as part of an earthquake-resistant structural system. The devices are described in three main classes - friction, metallic, and viscous and viscoelastic - and within each class, a number of specific types are presented. Actual building applications are also described. The descriptions focus on building applications for seismic control, although many of these devices were actually developed, or show good potential, for bridges. An extensive reference list provides more in-depth information on the various devices and applications described. Specific comparisons of performance or design attributes between the various devices or classes of devices are beyond the scope of this paper.

Conventional seismic design practice permits design for forces lower than those expected from elastic response on the premise that inelastic action in a suitably designed structure will provide that structure with significant energy dissipation potential and enable it to survive a severe earthquake without collapse. This inelastic action is typically intended to occur in specially detailed critical regions of the structure, usually in the beams near or adjacent to the beam-column joints. Inelastic behavior in these regions, while able to dissipate substantial energy, also often result in significant damage to the structural member, and although the regions may be well detailed, their hysteretic behavior will degrade with repeated inelastic cycling. Further, the large interstory drifts required to achieve significant hysteretic energy dissipation in critical regions usually result in substantial damage to non-structural elements such as in-fill walls, partitions, doorways, and ceilings.

The objective of using energy dissipation devices is to preferentially dissipate earthquake-induced energy in a structure in devices designed especially for this purpose, and to minimize (or even eliminate in the ideal case) the energy dissipation demand on, and thus inelastic action in, primary structural members such as beams, columns, or walls. By controlling response in this way, interstory drifts may be reduced, thus reducing nonstructural damage. Lower accelerations and hence shear forces lead to lower demands on the primary structural system and on equipment and other building contents. Current damping systems are capable of providing a structural system with the drift performance of a braced structure and the acceleration performance of a moment-resisting frame. Some systems can achieve even greater levels of response reduction.

Many analogous applications exist in other areas of structural vibration control. Some of these include shock absorbers for vehicles, equipment vibration isolators, pipe restraints and snubbers, shock isolation devices to mitigate blast effects, and mass damping systems to control wind-induced vibrations in buildings. Relatively few devices, however, have been applied specifically to reduce seismic effects. Many of the devices that have emerged for passive seismic control were first developed as damping components for seismic isolation systems, and a number of the early applications are for isolation. Yielding steel and lead extrusion systems were developed in New Zealand in the 1970s [Kelly, et al, 1972; Robinson and Greenbank, 1976], and have since been adopted for passive energy dissipation applications. A variety of energy dissipation devices were developed in Italy in the 1980s as damping components for bridge seismic isolation [Medeot,1991].

First, the response of simple single mass dynamic systems with supplemental viscous damping will be reviewed for steady state and earthquake inputs. Some considerations which need to be made when extending these results to multi-degree of freedom systems are discussed. From this review it will be possible to select energy dissipation system characteristics that have the potential to provide significant performance advantages for the earthquake resistant design of new buildings and seismic retrofit upgrading of existing buildings.

Next, energy dissipation devices utilizing friction, metallic hysteresis and viscous and viscoelastic materials will be discussed. Friction and yielding metallic damping devices whose characteristics depend upon nonlinear behavior result in equivalent viscous damping values which are amplitude dependent. Thus, the expected level of earthquake response must be known when selecting the appropriate equivalent viscous damping values. A major difference between viscous / viscoelastic and friction / yielding devices is the maximum force that each device will develop during an earthquake. The maximum earthquake forces developed in the viscous/viscoelastic devices are determined by the maximum displacements and velocities in the devices. The maximum earthquake forces in the friction or yielding devices equals the design friction force or the design yield force plus strain hardening. Thus, the maximum earthquake forces are more easily controlled in the friction or yielding devices.

In some cases it may be necessary to evaluate the final building designs using these devices by inelastic dynamic response calculations to verify the reliability of the damping assumptions because the devices can have frequency and temperature dependencies.

EFFECT OF VISCOUS DAMPING ON SEISMIC RESPONSE

The presence of some damping (energy dissipation) in conventional buildings has long been recognized and accepted by structural engineers. Although the nature of the energy dissipation inherent in buildings has not been explicitly identified, inherent equivalent viscous damping in the range of two percent to five percent of critical has become accepted in practice for linear response analysis of typical buildings. In fact, most design spectra are developed assuming about five percent of critical viscous damping in the system. The following is presented to give the designer an appreciation for different views of damping.

When a single-degree-of-freedom system with less than critical viscous damping which is initially at rest is released from a displaced position, it will vibrate with decreasing amplitudes as shown in Figure 1 for 2, 5, 10 and 20 percent of critical damping. If the earthquake response of a building is thought of as a series of responses to individual earthquake pulses, it is concluded that the response of higher damped systems is less because the individual responses decay quickly and cannot accumulate.

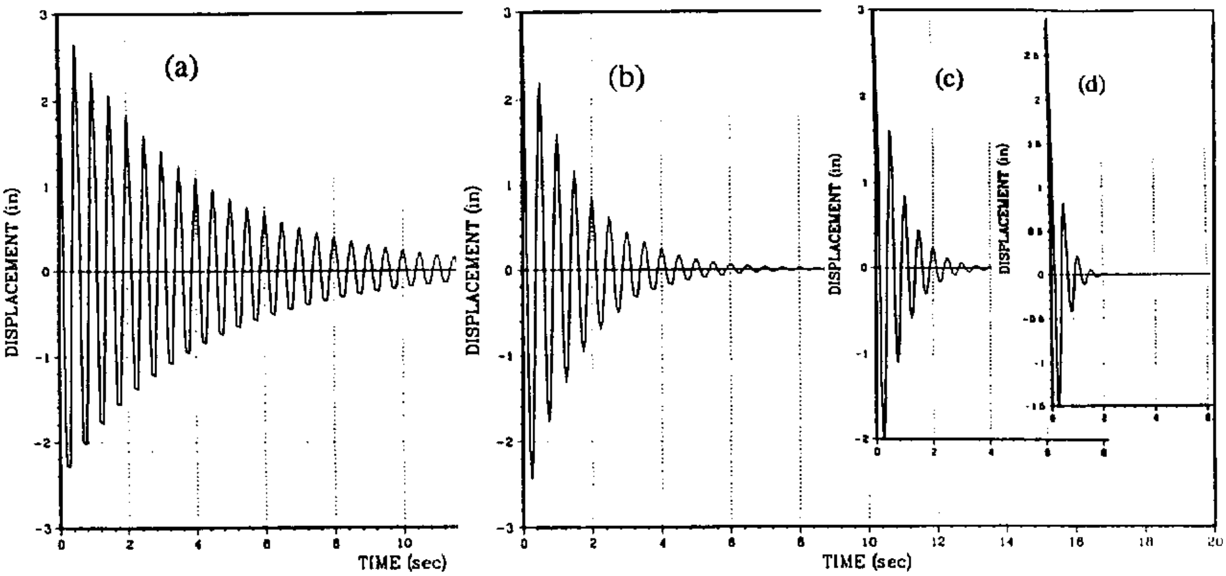


Figure 1. Free Vibration with Various Fractions of Critical Viscous Damping.
(a) 0.02, (b) 0.05, (c) 0.10, and (d) 0.20

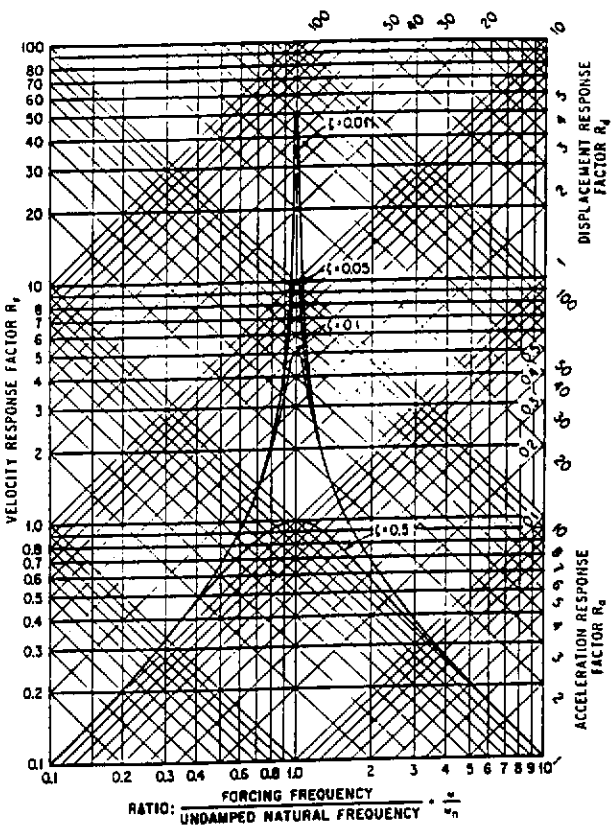


Figure 2. Dynamic Amplification Factors for Force Applied to the Mass [Blake, 1961]

The classic steady-state response of this system to a sinusoidal forcing function is shown in Figure 2. The dynamic amplification factor provides a basis for determining the maximum displacement response of the mass for different ratios of excitation frequency to natural frequency and for different ratios of viscous damping to critical viscous damping. It should be observed that increasing damping has a significant effect on the dynamic response of the system only when the excitation frequency is nearly the same as the natural frequency of the system (within about plus or minus 20 percent). Thus, if the frequencies of the system are not close to the expected frequencies of the excitations, added viscous damping will not have a significant impact on the response.

For earthquake ground motion inputs, the displacement response spectra, SD, is a key parameter in estimating the maximum displacement responses of the building. Ashour [1987] developed a relationship which described the decrease in SD for elastic systems with changes in viscous damping and correlated this relationship with results obtained from existing earthquake accelerogram records. Natural periods, Tn, of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 seconds were used to cover a representative range. Damping values used were 0, 2, 5, 10, 20, 30, 50, 75, 100, 125 and 150 percent of critical. Three real (1940 El Centro NS, 1952 Taft N69W, and 1957 Alameda Park) and twelve artificial (B1, B2, C1, C2 and D1 generated at Caltech [Jennings, et al 1968], one generated by a San Francisco consultant to represent a bay mud site, and six generated at Michigan using the Ruiz and Penzien [1969] procedure) earthquake accelerogram records were used as excitation inputs.

The calculated values of SD for a selected T_n and damping ratio were normalized with respect to the SD at T_n for zero damping for each earthquake record and were averaged over the 15 records to obtain a mean value for each period and ratio of critical damping. Because many design spectra are developed on the basis of an assumed five percent of critical damping, a second normalization was made on the basis of the SD at T_n for five percent of critical damping. The results for the mean SD values for both zero and five percent normalizations are given in Figure 3. These curves can be represented by simple decaying functions,

$$rf = [\{ 1 - e^{-\beta B} \} / \{ \beta B \}]^{1/2} \qquad (1)$$

where ß is the selected fraction of critical damping and B is a coefficient which was evaluated to be 24 for the upper bound and 140 for the lower bound, Figure 4(a), for zero initial damping normalization . For an initial elastic spectral normalization with damping of α, the simple decaying function can be expressed by

$$rf = [\alpha \{ 1 - e^{-\beta B} \} / \beta \{ 1 - e^{-\alpha B} \}]^{1/2} \qquad (2)$$

The system damping, β, must be greater than or equal to the initial elastic spectral normalization damping, α, to use this equation. For five percent damped spectra normalization, $\alpha = 0.05$. Ashour found the upper bound B = 18 and the lower bound B = 65 for this case, Figure 4(b).

If more than the sample of twelve earthquake records is required to determine the appropriate SD reduction factors, rf, for design code use, it is a simple matter to include any selected earthquake records for this determination. Because earthquake resistant design codes use earthquake spectral reduction factors to account for building inelastic response capabilities (R_W in the Uniform Building Code; R in the National Building Code and the Standard Building Code), it is important to consider the consequences of including the effects of increased viscous damping on the inelastic response of structural systems so that appropriate supplemental damping reductions can be included in these code design procedures. The following presents the results of a study by Wu [1987] which included supplemental viscous damping to elastic-plastic single-degree-of-freedom systems.

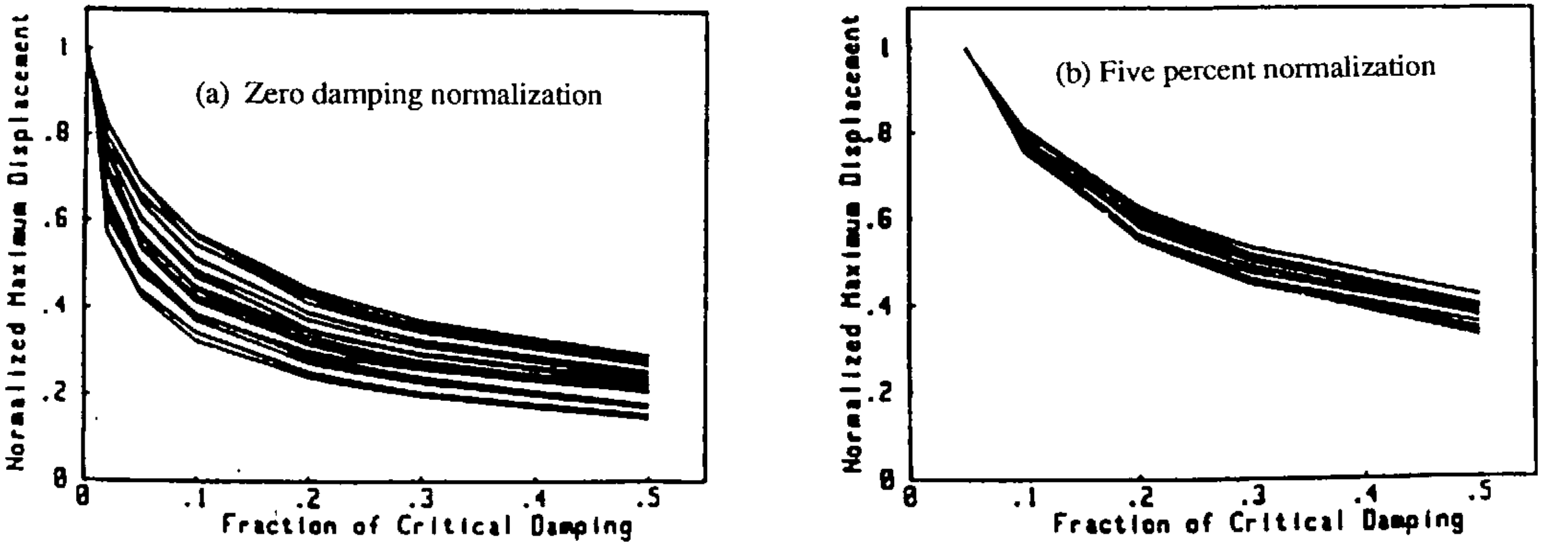


Figure 3. Normalized Mean Displacement for 15 Earthquake Accelerogram Records
from Ashour (1987)

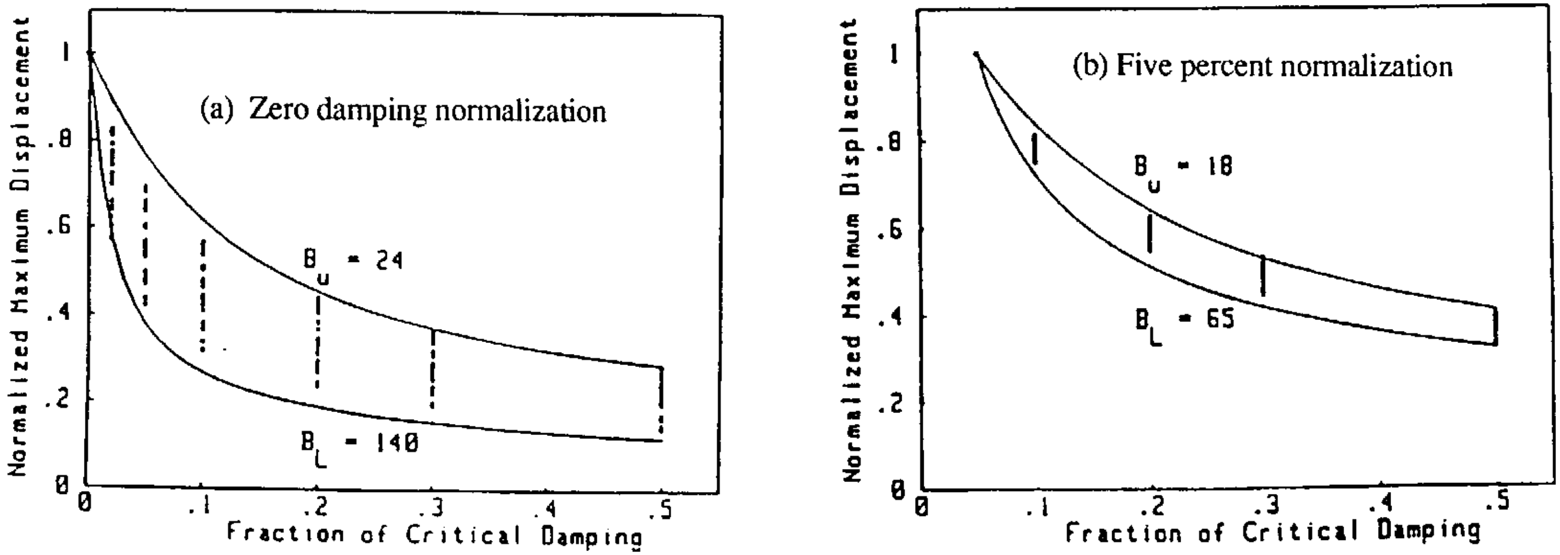


Figure 4. Envelope of Normalized Mean Displacement Response
from Ashour (1987)

It is more difficult to establish a comparative basis for inelastic response evaluations than for elastic responses. One form for presentation uses peak ground motion parameters to derive inelastic response spectra. Two periods in the spectral acceleration region ($T_n = 0.1$ and 0.5 seconds), one in the pseudo-spectral velocity region, and two in the displacement region ($T_n = 3.0$ and 10.0 seconds)were selected. One artificial and nine real earthquake records were used in this study [Wu and Hanson, 1989]. Results for the three spectral regions are shown in Figures 5, 6 and 7 and equations for these amplification factors are

$$\psi = -\,0.349 \ln (0.0959\,\beta)\ \ (2.89\,\mu - 1.89)^{-0.244} \qquad \text{for } T_n = 0.1 \text{ second} \qquad (3)$$

$$\psi = -\,0.547 \ln (0.417\,\beta)\ \ (1.82\,\mu - 0.82)^{-0.562} \qquad \text{for } T_n = 0.5 \text{ second} \qquad (4)$$

$$\psi = -\,0.471 \ln (0.524\,\beta)\ \ (1.53\,\mu - 0.53)^{-0.706} \qquad \text{for the velocity region} \qquad (5)$$

$$\psi = -\,0.478 \ln (0.475\,\beta)\ \ \mu^{-1.06} \qquad \text{for } T_n = 3.0 \text{ seconds} \qquad (6)$$

$$\psi = -\,0.291 \ln (0.0473\,\beta)\ \mu^{-1.06} \qquad \text{for } T_n = 10.0 \text{ seconds} \qquad (7)$$

where ψ is the spectral amplification factor, β is the fraction of critical damping and μ is the structural ductility factor. It should be noted that the structural ductility factor μ does not have a direct relationship with either R_W or R as used in the design codes.

These amplification factors can be divided into terms which include the viscous damping of the system and terms which include the structural inelastic yielding. The relatively small scatter of the data with changes in damping (from 10 to 50 percent) shows that spectral modifications for high damping and for inelastic response can be considered separately. Thus, code design procedures which acknowledge spectral reductions due to inelastic deformations and other factors can be retained while incorporating a separate reduction factor for energy dissipation devices.

By setting the ductility factor equal to 1.0 in the equations for the amplification factor, ψ, given in equations 3, 4, 5, 6 and 7 the effect of damping only can be determined for each of the regions. The ratio of ψ at specific damping values divided by ψ calculated at five percent damping is given in Table 1. It can be seen that the values at periods of 0.1 and 10.0 seconds are similar, and that the values at periods of 0.5 seconds, the velocity region, and 3.0 seconds are similar. By comparing these values with equation 2 using $\alpha = 0.05$ and Figure 4(b) it is seen that the Table 1 values are nearly on the B = 18 line.

Table 1. Amplification Ratio as a Function of Viscous Damping [Wu, 1987]

T_n, sec	0.1	0.5	Velocity	3.0	10.0
Damping Ratio	(equation 3)	(equation 4)	(equation 5)	(equation 6)	(equation 7)
0.05	1.0	1.0	1.0	1.0	1.0
0.10	0.87	0.82	0.81	0.81	0.88
0.20	0.74	0.64	0.62	0.63	0.77
0.30	0.67	0.53	0.51	0.52	0.70
0.50	0.57	0.41	0.37	0.38	0.61

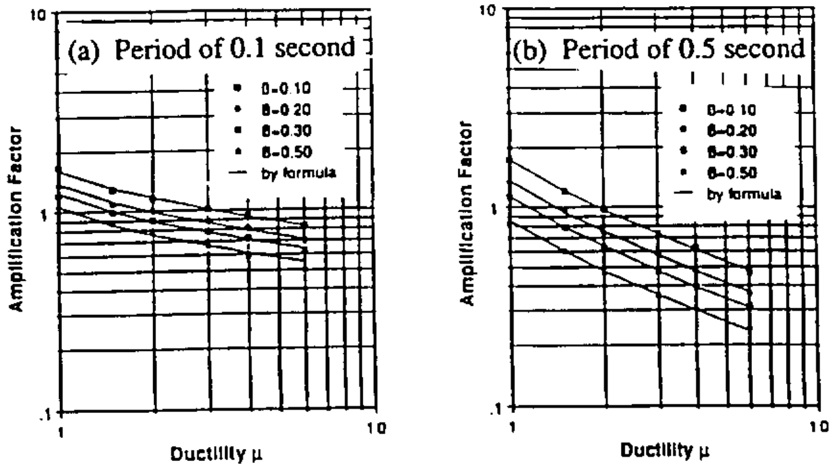


Figure 5. Amplification Factors for Acceleration Spectra in the Acceleration Region

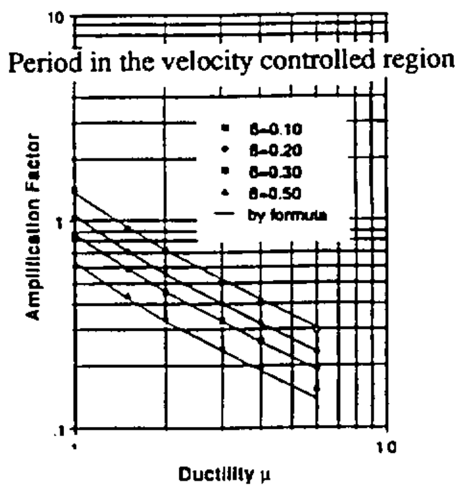


Figure 6. Amplification Factors for Pseudo-Velocity Spectra in the Velocity Region

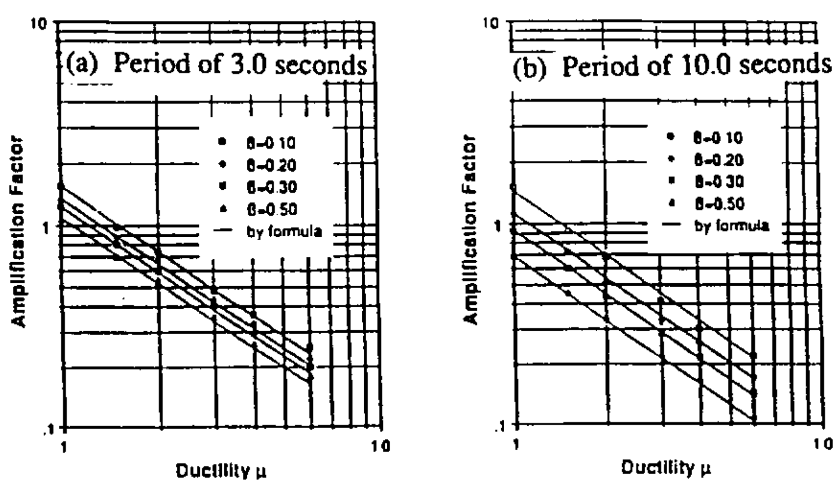


Figure 7. Amplification Factors for Displacement Spectra in the Displacement Region

A similar comparison can be made using the spectral amplification coefficients developed by Newmark and Hall [1982]. Taking their amplification coefficients for median response in the three spectral regions, acceleration (A), velocity (V) and displacement (D) the values for 10 and 20 percent damping were divided by the corresponding values for five percent damping to give the amplification ratios shown in Table 2. Although the values in Table 2 are not identical to those in Table 1 they provide additional substantiation for the use of equation 2 with B = 18 for $\alpha = 0.05$.

These three independent studies (Newmark and Hall [1982], Ashour [1987], and Wu [1987]) using different philosophies and different sets of earthquake accelerograms have reached the same general conclusions regarding the reduction of earthquake spectral response due to increases in viscous damping.

Table 2. Amplification Ratio as a Function of Viscous Damping [Newmark and Hall, 1982]

Region	A	V	D
Damping Ratio			
0.05	1.0	1.0	1.0
0.10	0.77	0.83	0.86
0.20	0.55	0.65	0.73

Equivalent Viscous Damping

A convenient way to visualized viscous damping is by combining the stiffness and damping terms, $(c\dot{x} + kx)$, of the single-degree-of-freedom equation of motion

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{z} \tag{8}$$

as shown in Figure 8. The damping ratio is usually given in the form

$$\beta = c / 2\sqrt{k\ m} \tag{9}$$

Although the terms in these equations express the properties of the entire structure, this is the same form used for individual devices. Therefore, care must be taken to include both the stiffness of the damping device and the stiffness of the structure in determining the total k for these equations.

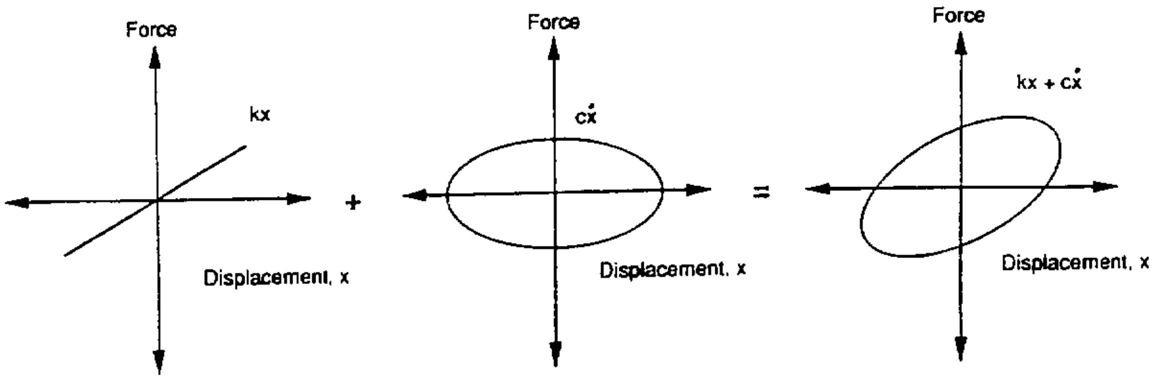


Figure 8. Steady-State Force-Displacement Characteristics for Stiffness, Viscous Damping, and Combined Stiffness and Viscous Damping

The equivalent viscous damping coefficient is selected so that the energy dissipated per cycle for the device and for the equivalent viscous damper are equal. This is accomplished by setting the area within the device hysteresis loop equal to the area of the viscous damper hysteresis (Figure 8).

$$c_{eq} = W_D / (\pi \omega (x_{max})^2) \tag{10}$$

where W_D is the cyclic energy dissipated, ω is the frequency of response in radians per second and x_{max} is the maximum cyclic displacement under consideration.

As early as 1930, Jacobsen [1930] recognized the relationship between energy dissipation and maximum strain energy as a means for approximating the equivalent viscous damping for structures responding nonlinearly. With slight modification in definition of terms this relationship is now commonly defined as:

$$W_D = 4 \pi \beta \; W_S \tag{11}$$

in which the peak cyclic strain energy, W_S , can be calculated as

$$W_S = 1/2 \, k \, (SD)^2 \tag{12}$$

where SD is the maximum spectral displacement of the system. The W_S for earthquake excitation of structures was defined by Hudson [1956] as:

$$W_S = 1/2 \, m \, (SV)^2 \tag{13}$$

in which SV is the pseudo response spectral velocity. This relationship assumes that the maximum strain energy in the system equals the maximum kinetic energy in the system. It appears that this relationship is valid for earthquakes with at least several pulses and for damping ratios up to about 20 percent of critical.

Knowing W_S and W_D for a particular structural system, equation 11 can be used to calculate the equivalent viscous damping of the system, β. Note that W_S is not directly related to the input ground motion, but rather is determined from structural response to the motion and includes the damping in the structure.

In the 1960s and 1970s several researchers extensively studied the equivalent viscous damping possible from inelastic response of structures, Jennings [1964 and 1968], Hudson [1965], and Ray [1968]. The structural systems analyzed involved initial elastic behavior with no energy dissipation and subsequent inelastic behavior with accompanying energy dissipation. This idealized system is entirely consistent with the ductile response behavior concept that is prevalent today for conventional earthquake resistant structural design. It is important to note that the elastic and inelastic response portions of this system act in series. The conclusion of these investigators established that equivalent viscous damping for ductile buildings could range between a low of about ten percent to a high of about 55 percent, depending on the assumed effective vibration period of the structure [Rosenblueth, 1965].

Energy dissipation devices that have recently become commercially available involve the addition of a supplemental damping system to the primary structural system, and indeed, the design philosophy behind some of these devices is to keep the response of the structural system elastic during severe earthquake motion. Thus the supplemental system acts in parallel with the basic system to provide the desired damping. Although the basic parameters for evaluating equivalent viscous damping for series systems and parallel systems, namely strain energy demand and energy dissipation, are the same, care must be taken to account for both the stiffness and strain energy contributions from both the basic structural system and the energy dissipation devices.

Multi-Story Buildings

The distribution of damping devices throughout the height of the building is a major consideration. Most of the papers discussing the application of devices for new buildings recommend a distribution throughout the height similar to the distribution of story stiffnesses (without abrupt changes). This has the mathematical advantage that the damping does not produce dynamic modal coupling. However, from a number of studies weak dynamic modal coupling does not alter the overall characteristics of the response of buildings with supplemental damping. It is recommended that the damping coefficient, c_{eq}, be established for each story and the modal damping in the first mode be established from those values to be used for design. The reason for selecting the first mode is that this is the dominant mode for earthquake responses, except in exceptional cases.

For nonlinear devices it has been recommended that the distribution of slip force/yield force be similar to the story stiffnesses (slowly varying values). It should be noted that the relationships expressed in equations 11, 12, and 13 are also valid for each mode for multi-story buildings.

Equivalent viscous damping for each mode can be determined using the appropriate higher mode periods and appropriate stiffnesses for the devices. Modal superposition can be applied to obtain appropriate member forces. Care must be taken, however, to account for the device forces when designing supporting members.

OVERVIEW OF ENERGY DISSIPATION DEVICES

Friction Systems

There are a variety of friction devices which have been proposed for structural energy dissipation. All of the friction systems, except one (the Fluor-Daniel EDR), generate rectangular hysteresis loops characteristic of Coulomb friction. (Figure 9). Typically these devices have very good performance characteristics, and their behavior is not significantly affected by load amplitude, frequency, or the number of applied load cycles. The devices differ in their mechanical complexity and in the materials used for the sliding surfaces.

Friction dampers made by Sumitomo Metal Industries, Ltd. (Figure 10), have been used in two buildings in Japan [Aiken and Kelly, 1990], and a friction device manufactured by Pall Dynamics, Ltd., has been used in three buildings in Canada, one retrofit and two new buildings [Pall, et al., 1987, 1991, Vezina, et al., 1992]. The Pall device (Figure 11) is intended to be mounted in X-bracing. Several earthquake simulator studies of multi-story steel frames incorporating Pall devices have been performed [Filiatrault and Cherry, 1987, Aiken, et al., 1988], and a design methodology has been developed for friction-damped structures [Filiatrault and Cherry, 1990]. The design of the Sumitomo devices for the two building applications was with the primary objective of reducing the response of the structures to ground-borne vibrations and small-to-moderate earthquakes. Response control under large earthquake shaking was not a primary design consideration. The Sumitomo device is an evolution of a friction damper used for railway cars, and the frictional resistance is generated by copper alloy pads with graphite plug inserts sliding against the inner surface of the steel barrel of the device.

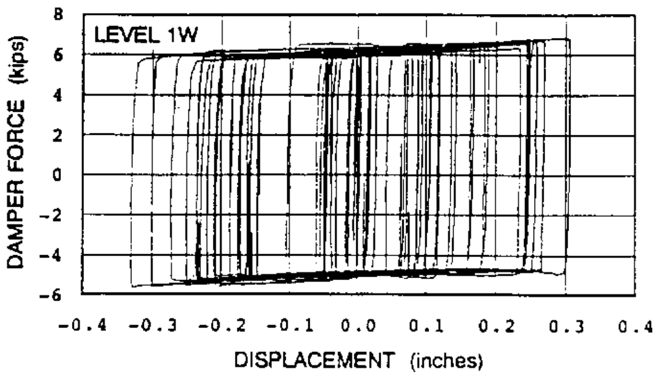


Figure 9. Sumitomo Friction Device Hysteresis Loops
[Aiken, 1990]

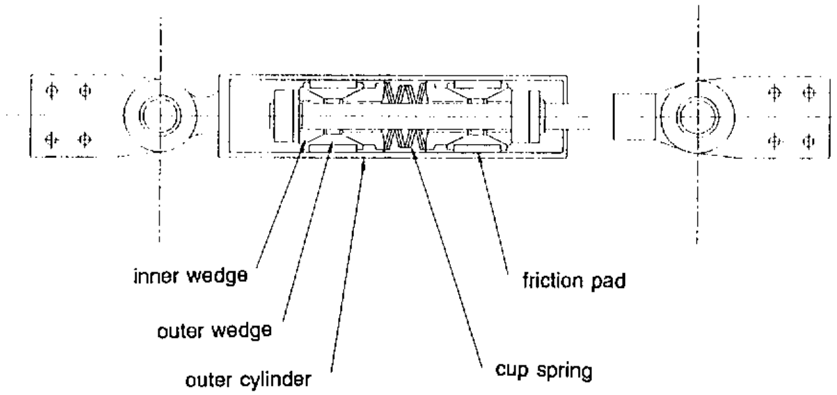


Figure 10. Sumitomo Friction Device Longitudinal Section
[Aiken, 1990]

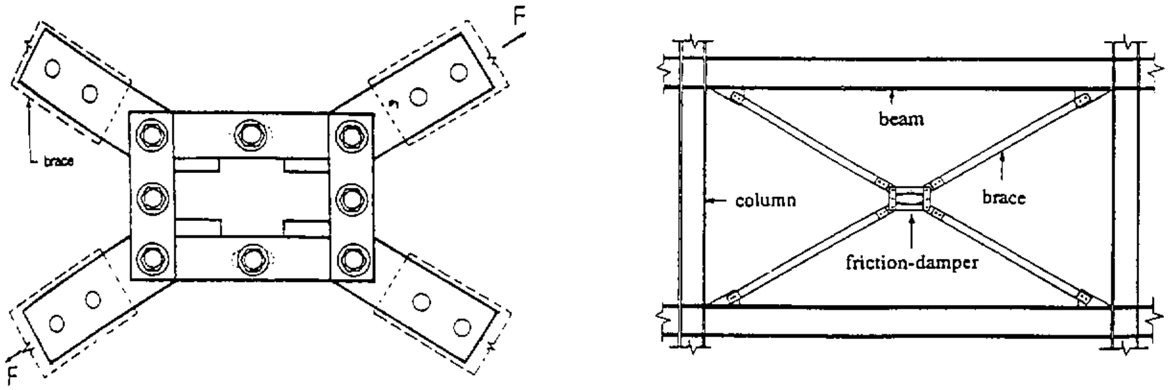


Figure 11. Pall Friction Device and Typical Installation
[Vezina, 1992]

Fluor Daniel, Inc., has developed and tested a unique type of friction device, called the Energy Dissipating Restraint (EDR) [Richter, et al., 1990]. The EDR has self-centering capabilities, and the slip load is proportional to the displacement. Several hysteresis behaviors are possible (Figure 12). The friction surfaces in this device are bronze wedges sliding on a steel barrel. A detailed description of the EDR and its behavior is provided elsewhere in these proceedings [Nims, et al., 1993].

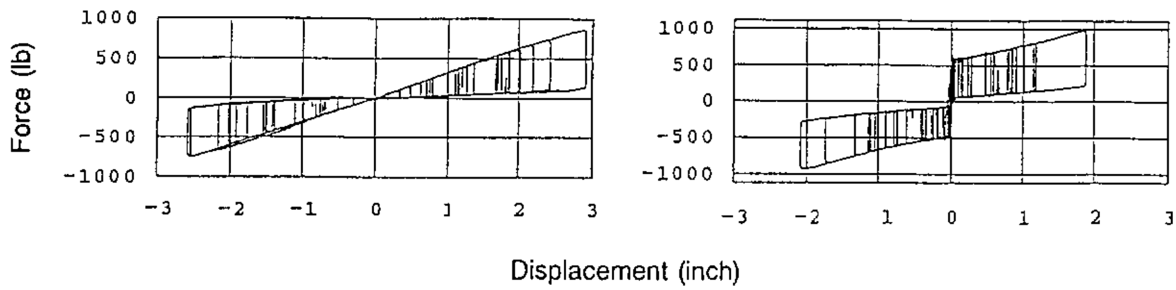


Figure 12. Fluor-Daniel EDR Hysteresis Loops [Richter, 1990]

Simpler devices with Coulomb behavior include those which use a brake pad material on steel friction interface [Giacchetti, et al., 1989, Tyler, 1985]. Other friction schemes that involve no special devices, but rather allow slip in bolted connections, have also been developed [Roik, et al., 1988, Fitzgerald, et al., 1989]. A promising refinement of the slotted bolted concept has recently been made using a brass on steel friction couple [Grigorian, et al., 1992]. Earthquake simulator tests of a three-story steel building model with these slotted bolted connection (SBC) energy dissipators have recently been completed.

Issues of importance with friction devices are long-term reliability and maintenance; the potential for introduction of higher frequencies as the devices undergo stick-slip behavior; and possible permanent offsets after an earthquake. The maintenance and protection from deterioration of a device in which the sliding surfaces are required to slip at a specific load during an earthquake, even after decades of nonuse, is essential.

Metallic Systems

These energy dissipation systems take advantage of the hysteretic behavior of metals when deformed into their post-elastic range. A wide variety of different types of devices have been developed that utilize flexural, shear, or extensional deformation modes into the plastic range. A particularly desirable feature of these systems is their stable behavior, long-term reliability, and generally good resistance to environmental and temperature factors.

Yielding Steel Systems

The ability of mild steel to sustain many cycles of stable yielding behavior has led to the development of a wide variety of devices which utilize this behavior to dissipate seismic energy [Kelly, et al., 1972, Skinner, et al., 1980]. Many of these devices use mild steel plates with triangular or hourglass shapes [Tyler, 1978, Stiemer, et al., 1981] so that the yielding is spread almost uniformly throughout the material. The result is a device which is able to sustain repeated inelastic deformations in a stable manner, avoiding concentrations of yielding and premature failure.

One such device that uses X-shaped steel plates is the Bechtel Added Damping and Stiffness (ADAS) device. ADAS elements are an evolution of an earlier use of X-plates, as damping supports for piping systems [Stiemer, et al., 1981]. Extensive experimental studies have investigated the behavior of individual ADAS elements and structural systems incorporating ADAS elements [Bergman and Goel, 1987, Whittaker, et al., 1991]. The tests showed stable hysteretic performance (Figure 13). ADAS devices have been installed in a two-story, non-ductile reinforced-concrete building in San Francisco as a part of a seismic retrofit [Fiero, et al., 1993], and in two buildings in Mexico City. The principal characteristics which affect the behavior of an ADAS device are its elastic stiffness, yield strength, and yield displacement. ADAS devices are usually mounted as part of a bracing system, which must be substantially stiffer than the surrounding structure. The introduction of such a heavy bracing system into a structure may be prohibitive.

Triangular-plate energy dissipators were originally developed and used as the damping elements in several base isolation applications [Boardman, et al., 1983]. The triangular plate concept has been extended to building dampers in the form of the triangular ADAS, or T-ADAS, element [Tsai and Hong, 1992]. Component tests of T-ADAS elements and pseudodynamic tests of a two-story steel frame have shown very good results (Figure 14). The T-ADAS device embodies a number of desirable features; no rotational restraint is required at the top of the brace connection assemblage, and there is no potential for instability of the triangular plate due to excessive axial load in the device.

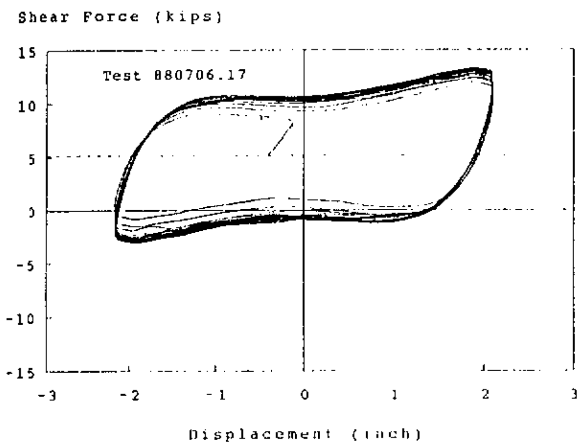


Fig. 13. ADAS Device Hysteresis Loops [Whittaker, 1991]

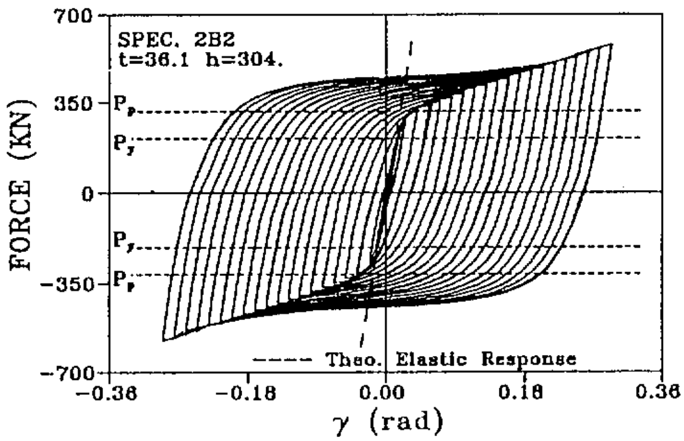


Fig. 14. T-ADAS Device Hysteresis Loops [Tsai, 1992]

An energy dissipator for cross-braced structures, which uses mild steel round bars or flat plates as the energy absorbing element, has been developed by [Tyler, 1985]. This concept has been applied to several industrial warehouses in New Zealand. A number of variations on the steel cross-bracing dissipator concept have been developed in Italy [Ciampi, 1991]. A 29-story steel suspension building (with floors "hung" from the central tower) in Naples, Italy, utilizes tapered steel devices as dissipators between the core and the suspended floors.

A six-story government building in Wanganui, New Zealand, uses steel-tube energy-absorbing devices in precast concrete cross-braced panels [Matthewson and Davey, 1979]. The devices were designed to yield axially at a given force level. Recent studies have experimentally and analytically investigated a number of different cladding connection concepts [Craig, et al., 1992]

Several types of mild steel energy dissipators have been developed in Japan [Kajima Corp., 1991, Kobori, et al., 1988]. So-called honeycomb dampers have been incorporated in 15-story and 29-story buildings in Tokyo. Honeycomb dampers are X-plates (either single plates, or multiple plates connected side by side) that are loaded in the plane of the X. (This is orthogonal to the loading direction for triangular or ADAS X-plates). Kajima Corporation has also developed two types of omni-directional steel dampers, called "Bell" dampers and "Tsudumi" dampers [Kobori, et al., 1988]. The Bell damper is a single-tapered steel tube, and the Tsudumi damper is a double-tapered tube intended to deform in the same manner as an ADAS X-plate but in multiple directions. Bell dampers have been used as part of an atrium roof system connecting a 5-story and a 9-story building, and Tsudumi dampers have been used in a massive 1600-ft long ski-slope structure to permit differential movement between four dissimilar parts of the structure under seismic loading while dissipating energy. Both of these applications are located in the Tokyo area.

Another type of joint damper for application between two buildings has been developed [Sakurai, et al., 1992]. The device is a short lead tube that is loaded to deform in shear (Figure 15). Experimental investigations and an analytical study have been undertaken.

Particular issues of importance with metallic devices are the appropriate post-yield deformation range, such that a sufficient number of cycles of deformation can be sustained without premature fatigue, and the stability of the hysteretic behavior under repeated post-elastic deformations.

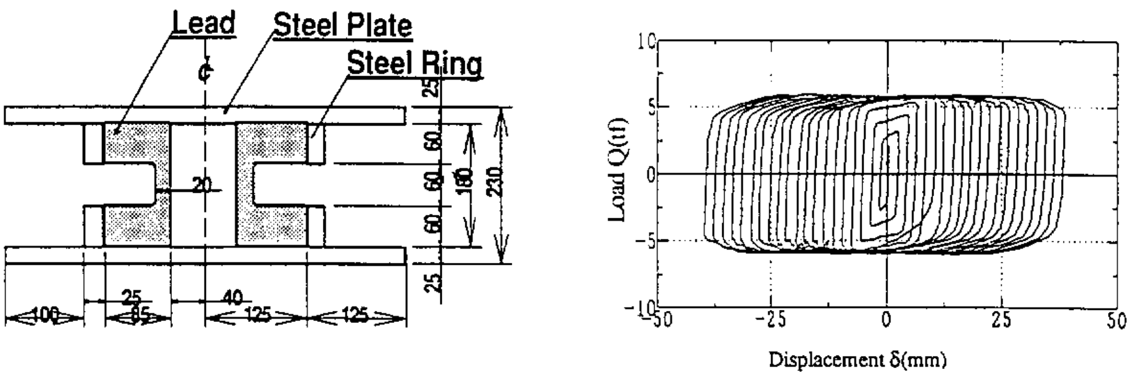


Figure 15. Lead Joint Damper and Hysteresis Loops
[Sakurai, 1992]

Lead Extrusion Devices (LEDs)

The extrusion of lead was identified as an effective mechanism for energy dissipation in the 1970s [Robinson and Greenbank, 1976]. LED hysteretic behavior is very similar to that of many friction devices, being essentially rectangular (Figure 16). LEDs have been applied to a number of structures, for damping in seismic isolation systems, and as energy dissipators within multi-story buildings. In Wellington, New Zealand, a 10-story, cross-braced, concrete police station is base isolated, with sleeved-pile flexible elements and LED damping elements [Charleson, et al., 1987]. Several seismically-isolated bridges in New Zealand also utilize LEDs [Skinner, et al., 1980]. In Japan, LEDs have been incorporated in 17-story and 8-story steel frame buildings [Oiles Corp., 1991]. The devices are connected between precast concrete wall panels and the surrounding structural frame.

LEDs have a number of particularly desirable features: their load-deformation relationship is stable and repeatable, being largely unaffected by the number of loading cycles; they are insensitive to environmental factors; and tests have demonstrated insignificant aging effects [Robinson and Cousins, 1987] (Figure 16).

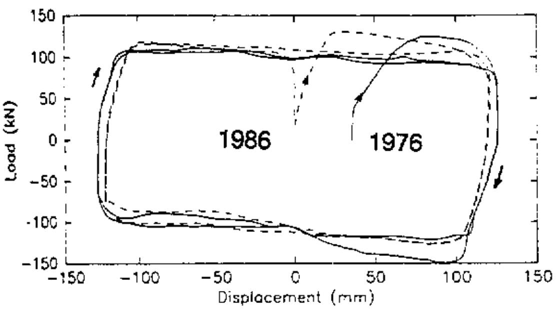


Fig. 16. LED Hysteresis Loops
[Robinson, 1987]

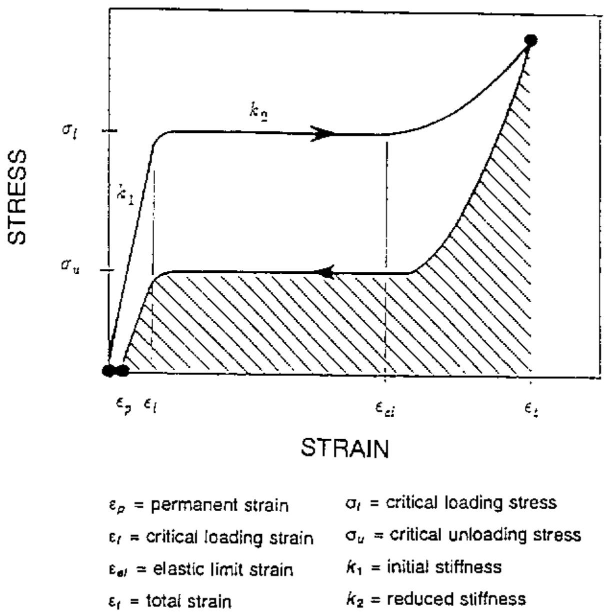


Fig. 17. SMA Superelastic Hysteresis Behavior
[Aiken, 1992]

Shape Memory Alloys (SMAs)

Shape memory alloys have the ability to "yield" repeatedly without sustaining any permanent deformation. This is because the material undergoes a reversible phase transformation as it deforms rather than intergranular dislocation, which is typical of steel. Thus, the applied load induces a crystal phase transformation, which is reversed when the load is removed (Figure 17). This provides the potential for the development of simple devices which are self-centering and which perform repeatably for a large number of cycles.

Several earthquake simulator studies of structures with SMA energy dissipators have been carried out. At the Earthquake Engineering Research Center of the University of California [Aiken, et al., 1992] a 3-story steel model was tested with Nitinol (nickel-titanium) tension devices as part of a cross-bracing system, and at the National Center for Earthquake Engineering Research [Witting and Cozzarelli, 1992] a 5-story steel model was tested with copper-zinc-aluminum SMA devices. In this second study, devices with torsion, bending, and axial deformation modes were investigated. Typical hysteresis loops from these tests are shown in Figure 18. Results showed that the SMA dissipators were effective in reducing the seismic responses of the models.

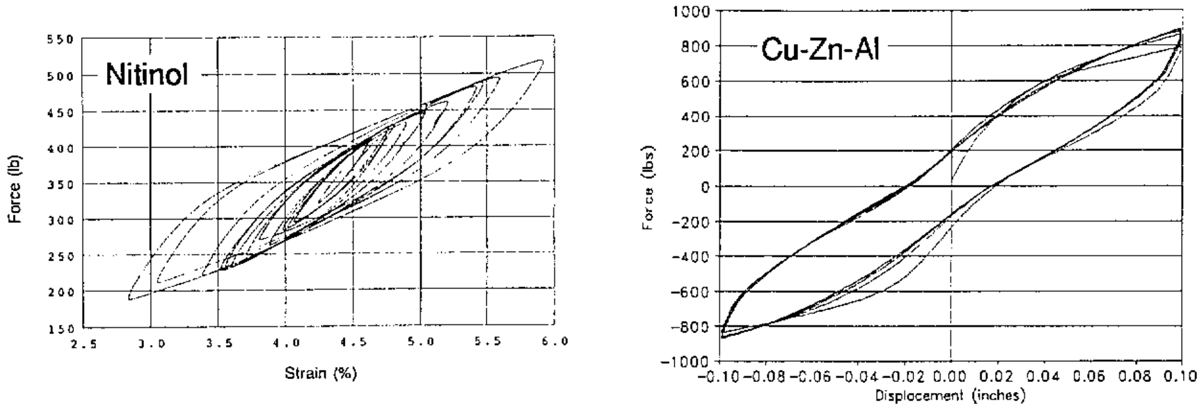


Figure 18. NiTi (Tension) and Cu-Zn-Al (Torsion) Hysteresis Loops
[Aiken, 1992, Witting, 1992]

Shape memory devices must be designed such that the device deformations do not occur beyond the elastic limit strain (into the plastic range), resulting in permanent yield in the material. The elastic limit strain varies by SMA, but is typically of the order of 5 percent. Some members of the SMA family also exhibit excellent fatigue resistance. Nitinol, among the family of SMAs, has outstanding corrosion resistance, superior even to that of stainless steels and other corrosion-resistant alloys.

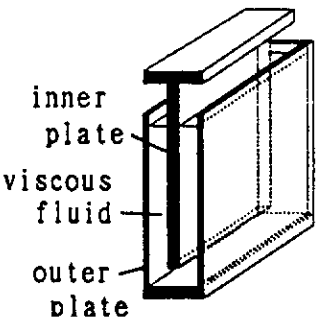
Viscous and Viscoelastic Systems

Viscoelastic materials have been in use in structural engineering for vibration control for more than 20 years. Mahmoodi described the characteristics of a double-layer, constrained-layer, viscoelastic (VE) shear damper in 1969 [Mahmoodi, 1969]. Viscoelastic copolymers developed by 3M Company have been used in a number of structural applications. Double-layer shear dampers using a 3M material were used in the 110-story, twin towers of the World Trade Center in New York City, where a total of 10,000 dampers were installed in each tower to damp wind-induced dynamic response [Mahmoodi, et al., 1987]. VE damping systems have since been adopted in several other tall buildings for the same purpose [Keel and Mahmoodi, 1986, Mahmoodi and Keel, 1989].

The extension of VE shear dampers to the seismic domain has occurred more recently. Wind vibration control applications have typically involved providing the building with only about 2 percent of critical damping. The level of damping required for a feasible seismic energy dissipation system is significantly higher than this; in experimental studies that have been undertaken, damping ratios of the order of 10 to 20 percent have been targeted. To obtain a feasible design for a VE damper system, a number for factors that affect material properties must be taken into account. The stiffness and damping properties of VE polymers are influenced by the level of shear deformation in the material, temperature, and frequency of loading. Practical materials have been fully characterized for a wide range of these factors. Several earthquake simulator studies of large-scale, steel frame models with VE dampers have been conducted [Lin, et al., 1988, Aiken and Kelly, 1990]. In each study, the VE dampers were found to significantly improve the response of the test models, reducing drifts and story shears (compared to those of the models without VE dampers). More recently, tests of VE dampers applied to a 1/3-scale, non-ductile reinforced-concrete model have been performed, and a full-sized steel frame has been constructed in China as a test structure for VE dampers. One study subjected a VE-damped model to earthquake shaking under different levels of ambient temperature [Lin, et al., 1988], and several experiments have monitored the internal temperature in the VE layers of a shear damper during earthquake shaking. Observed transient temperature increases have not been very significant (typically less than 10 °F). A number of analytical studies have also been undertaken, and an effective modal design method developed [Chang, et al., 1992].

Several companies in Japan have developed damping systems based on different VE materials. Shimizu Corporation has developed a bitumen rubber compound (BRC) VE damper which has been used in a one 24-story steel building of a twin-tower complex. Both buildings are instrumented to provide seismic response data for comparison between VE-damped and undamped responses [Yokota, et al., 1992]. Bridgestone Corporation has developed a visco-plastic rubber shear damper and this has been shake table tested in a 5-story steel frame model [Fujita, et al., 1991].

A viscous-damping (VD) wall system has been developed by Oiles and Sumitomo Construction (Figure 19). Earthquake simulator tests of a full-scale, 4-story steel frame with and without VD walls showed very large response reductions — up to 60 to 75 percent — achieved by the walls [Arima, et al., 1988]. A 4-story, reinforced-concrete test building with VD walls was constructed in Tsukuba, Japan, in 1987. It has since been monitored for earthquake response; observed accelerations are 25 to 70 percent lower than those of the building without VD walls [Arima, et al., 1988]. A VD wall system in a 15-story building now under construction in Shizuoka City, Japan, will provide between 20 and 32 percent damping to the building, and achieve response reductions of the order of 75 to 80 percent [Miyazaki and Mitsusaka, 1992]. Another type of wall damping system has been developed and tested by Kumagai-Gumi Corporation. It is a super-plastic and silicone rubber VE shear damper that is included at the top connection of a wall panel to the surrounding frame [Uehara, et al., 1991]. Earthquake simulator tests of a 1/2-scale, 3-story steel frame showed significant response reductions in the VE damped model; as large as 50 percent in story accelerations and 60 percent in story displacements.



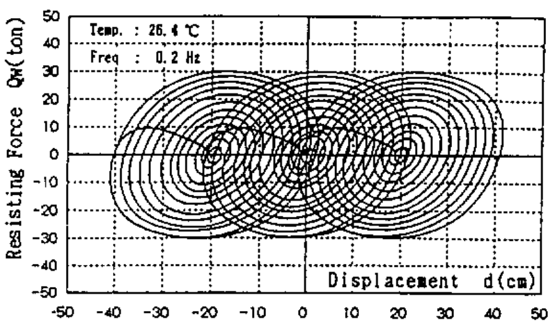


Figure 19. VD Wall and Hysteresis Loops [Miyazaki, 1992]

Fluid viscous dampers, which for many years have been used in the military and aerospace fields, are beginning to emerge in structural engineering. These dampers possess linear viscous behavior, are relatively insensitive to temperature changes, and can be very compact in size in comparison to force capacity and stroke. Experimental and analytical studies of building and bridge structures incorporating fluid viscous dampers made by Taylor Devices, Inc., have recently been performed [Constantinou, et al., 1993]. Very large response reductions were achieved by the presence of the devices. The feature of a pure viscous damper that the damping force is out-of-phase with the displacement can be a particularly desirable attribute for passive damping applications to buildings. If dampers are included in the structure in such a way that there is a column axial force component to the damper force (i.e., with a diagonal brace), then the out-of-phase peak damper force means that the peak induced column moments are less than if the peak damper force occurred at peak displacement.

SUMMARY AND CONCLUSIONS

Significant advances in the field of passive energy dissipation for improved structural seismic resistance have been made in recent years. Developments in the research and analysis arena have been paralleled by significant improvements and refinement of available device hardware. Most, if not all, of these systems are now sufficiently well understood for their use in new or retrofit design of buildings.

A wide range of behavioral characteristics are possible. Of particular importance for all energy dissipation devices is that they have repeatable and stable force-deformation behavior under repeated cyclic loading, and reliable behavior in the long term. Seismic damping devices typically possess nonlinear force-displacement behavior, and thus nonlinear time-history analysis methods are usually necessary to verify design performance, at least until the confidence level of designers increases.

As the number of viable energy dissipation systems increases, it is becoming increasingly necessary to find a common basis for evaluation and comparison of these systems and their use in established reasonable design standards. There have been few test programs which have included more than two or three systems, and those have not attempted comparisons beyond evaluation of general performance characteristics. The following conclusions are presented on the basis of the foregoing information.

1 The effects of supplemental viscous damping on the earthquake response of buildings can be considered separately from other effects, including structural ductilities, and are complementary to the current code procedures when using R or R_W factors.

2 The design coefficient for added damping building systems can be selected using the reduction factor, rf, given in equation (2). This requires that both the fraction of critical damping assumed for the design spectra and the equivalent viscous damping provided by the energy dissipation system be known.

3. The relative effectiveness of damping decreases as the amount provided increases. The cost effective limit for an energy dissipation approach will depend upon the structural system and the type of damping device selected.

4. There is a need to consolidate the basis for subsequent developments and applications of seismic energy dissipation systems. Some of the current general and specific issues related to these future applications are:

   (a) Stable and repeatable performance characteristics under dynamic loading.
   (b) Variable performance characteristics as a function of loading, e.g. temperature, amplitude and frequency dependence
   (c) Practical design methodologies and criteria
   (d) Long term reliability, e.g. deterioration, corrosion, design life
   (e) Maintenance requirements and in situ performance evaluation
   (f) Standards for device assessment and comparison

We are on the verge of significant growth and development in this field. The potential for improved seismic safety and cost effectiveness is enormous.

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