PROCEEDINGS, LOS ANGELES COUNTY AND SEAOSC SYMPOSIUM ON PASSIVE ENERGY DISSIPATION SYSTEMS
FOR NEW AND EXISTING BUILDINGS, LOS ANGELES, JULY (1996)

PASSIVE ENERGY DISSIPATION - HARDWARE AND APPLICATIONS

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ABSTRACT

In the United States, the likely seismic performance of the built environment during a severe earthquake is being questioned by society at large. In particular, direct and indirect losses in excess of $50 billion dollars as a result of the 1989 Loma Prieta and 1994 Northridge earthquakes have spurred federal and state officials to fund research on the expected performance of the built environment during severe earthquakes. As part of this initiative, researchers and practitioners are identifying technologies that can be used to enhance the performance of existing and new construction.

Energy dissipation devices have been proposed as one method by which damage to the built environment can be mitigated and earthquake-related losses reduced. This paper introduces such devices in the context of an innovative class of building systems known as protective systems. The means by which the use of energy dissipation hardware reduces structural response (and thus damage and loss) is described simply by the use of energy methods and by establishing the effect of added energy dissipation or damping on the displacement response of a single-degree of freedom oscillator.

An overview of the different types of passive energy dissipation hardware available in the marketplace in the United States is provided in the paper. For a similar discussion on seismic isolation and active control devices, the reader is referred to the literature.

INTRODUCTION

The damage to buildings, transportation structures, and lifelines wrought by the 1989 Loma Prieta earthquake, the 1994 Northridge earthquake, and the 1995 Hanshin earthquake near Kobe, Japan, has forced structural engineers, disaster response agencies, building officials, building owners, lenders, and insurers to carefully consider seismic response of the built environment in terms of *performance* rather than *life-safety*.

Innovative concepts for enhancing seismic performance have been proposed; many of these concepts are in different stages of development, and some are sufficiently advanced so as to permit implementation. These innovative concepts have been categorized as *Protective Systems*. Protective systems can be considered in three main classifications [Soong and Constantinou, 1994] as shown in Table 1.

Table 1: Classification of Protective Systems

Seismic Isolation	Passive Energy Dissipation	Active Control
Elastomeric Bearings	Friction Dampers	Bracing Systems
Lead Rubber Bearings	Metallic Dampers	Mass Systems
Elastomeric Bearings with Energy Dissipation Devices	Viscoelastic Dampers	Variable Stiffness and Mass Systems
Friction Pendulum Bearings	Viscous Dampers	Pulse Systems
Flat Sliding Bearings with Restoring Force Devices	Tuned Liquid Dampers	Aerodynamic Systems
Lubricated Sliding Bearings with Energy Dissipating Devices	Tuned Mass Dampers	

Seismic isolation concepts are well-advanced, and isolation hardware has been implemented in excess of 200 buildings and 250 bridges worldwide as of March 1996. To date in the United States, three types of seismic isolators are commonly used: high-damping elastomeric bearings, lead-rubber bearings, and the Friction Pendulum bearing. Isolators are typically installed at the foundation level in a structure, and reduce the response of the superstructure by shifting the fundamental period of the superstructure and enhancing the energy dissipation characteristics of the isolation-superstructure system.

In the last ten years in the United States, much progress has been made in research, development, and implementation of passive energy dissipation hardware for civil and structural engineering applications. Impetus for the development of such hardware for seismic applications has resulted from the conversion of key defense- and nuclear energy-related technologies to civilian use. Passive energy dissipators, also known in the United States as *supplemental dampers*, play a role similar to that of seismic isolators, namely to absorb and dissipate a significant portion of the energy input to a building by earthquake shaking. However, while isolation systems employ flexible elements, at or near the foundation level, to shift the predominant structural frequency and thereby reduce the energy entering the superstructure, energy dissipators are typically distributed throughout a structure to absorb either kinetic or strain energy transmitted from the ground into the primary system. Passive energy dissipators are applicable to a broader inventory of structures than seismic isolators, although they are not always as efficient as isolators in reducing seismic response

DAMPER IMPLEMENTATION: ENERGY AND DISPLACEMENTS

It is worthwhile to view the implementation of passive energy dissipation devices from the perspectives of energy dissipation and reductions in response displacements.

The energy balance equation provides useful insight into the benefits of adding energy dissipation (or damping) per unit displacement to a building. (Note that this approach applies equally well to any structure incorporating energy dissipation hardware). This equation is generally written as follows:

$$E_I = E_K + E_S + E_\mu + E_\xi \qquad (1)$$

where E_I is the earthquake absolute input energy, E_K is the absolute kinetic energy, E_S is the elastic strain energy, E_μ is the energy dissipated by inelastic action, and E_ξ is the energy dissipated by viscous damping. Assuming for the purpose of this discussion that the introduction of energy dissipation devices does not influence the energy input to a structure by earthquake shaking (E_I is constant), an increase in the sum of E_μ and E_ξ will lead to a decrease in the sum of E_K and E_S, namely a reduction in building displacements (strain energy) and velocities (kinetic energy).

In conventional seismic design, it is anticipated that the structural frame will undergo significant inelastic deformation in the design basis earthquake to dissipate the energy input to the building. This dissipation of energy is in the form of E_μ, and the amount of energy dissipated by inelastic deformation can be related to damage in the structural frame. One objective for designers of energy dissipation systems is to minimize damage in the structural frame by dissipating energy in discrete energy dissipation devices that can be discarded after a significant earthquake if necessary. Of the passive energy dissipators identified in Table 1, the metallic-yielding and friction devices dissipate energy as E_μ, and the viscoelastic and viscous devices dissipate energy as E_ξ.

The implementation of seismic isolators beneath a stiff building can reduce the forces and displacements induced in the building by as much as a factor of 4 depending on the dynamic characteristics of the fixed-base building and the mechanical characteristics of the seismic isolators. This is achieved primarily through period shift. Similar reductions in displacements cannot be realized through the use of energy dissipation hardware unless the devices possess significant stiffness. Ignoring the contribution to reduced displacements afforded by relatively stiff energy dissipation devices, the approximate reductions in displacements that can be achieved with supplemental energy dissipation hardware, as a function of the damping provided by the energy dissipators are listed in Table 2.

Table 2: Displacement Reduction Factors

% of Critical Damping	Displacement Reduction Factor
5	1.0
10	1.2
15	1.4
20	1.6
30	1.9

It is evident from Table 2, that even if substantial levels of damping (20% to 30% of critical) are provided by the energy dissipation system, response reductions of only between 30% and 50% can be achieved through added damping. Recognizing that deformations and forces in structural members are linearly related in the elastic range, reductions in member actions of no more than about 50% should be expected by the provision of added damping devices.

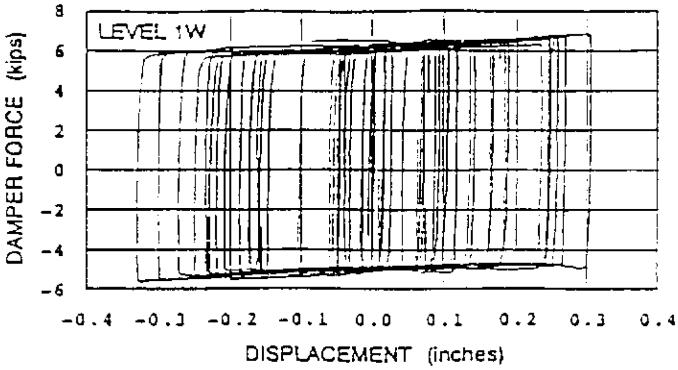
OVERVIEW OF ENERGY DISSIPATION HARDWARE

Research and development in both the academic and industrial arenas over the past decade has advanced both the concepts and the hardware of supplemental damping to the point where a number of different passive energy dissipation solutions with varying hysteretic characteristics are available. Of course, the suitability of a particular device for a given application depends on the requirements of the designer. Factors such as the allowable force to be transferred to the structural members adjacent to the device, the expected relative displacements across the device connection points, and the required amount of energy to be dissipated must all be considered. The purpose of this section is to outline the various types of devices available with particular concentration on building applications.

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 1). 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.

Figure 1: Sumitomo Friction Device Hysteresis Loops [Aiken and Kelly, 1990]



Friction dampers made by Sumitomo Metal Industries, Ltd. (Figure 2), 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 more than eight buildings in Canada, including several retrofits [Pall, et al., 1987, 1991, Vezina, et al., 1992]. The Pall device (Figure 3) 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 methodol

Figure 2: Sumitomo Friction Device Longitudinal Section [Aiken and Kelly, 1990]

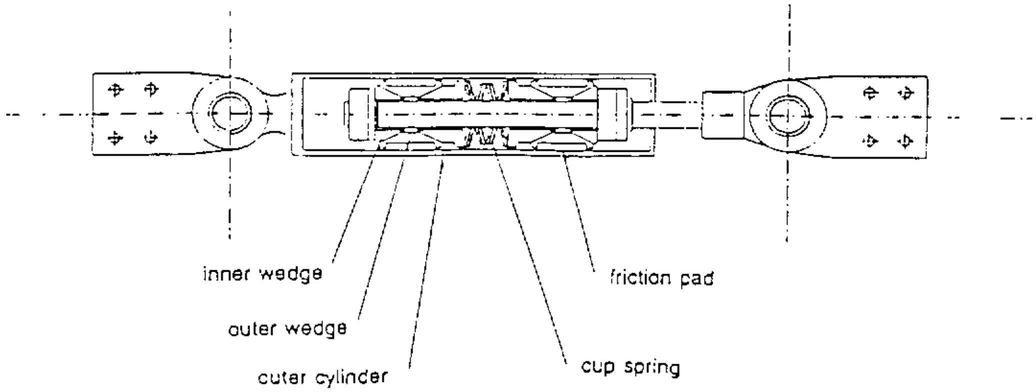
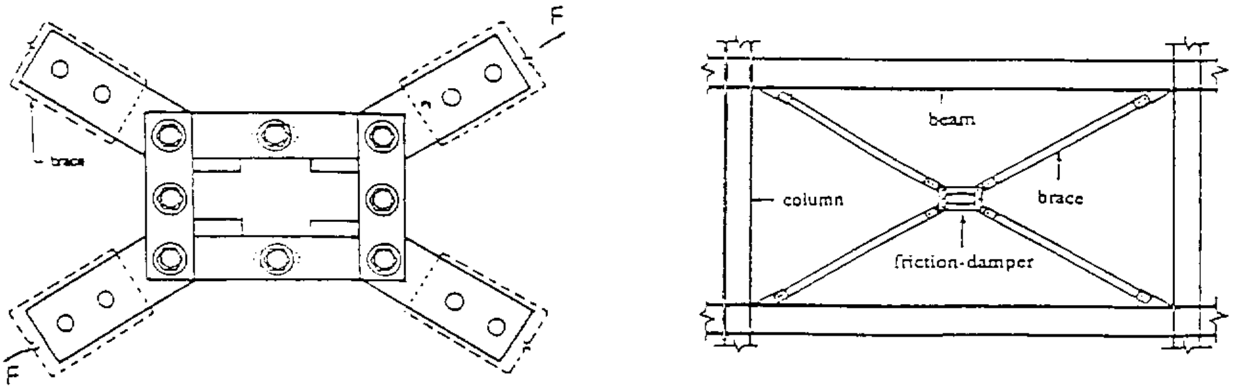


Figure 3: Pall Friction Device and Typical Installation [Vezina, et al., 1992]

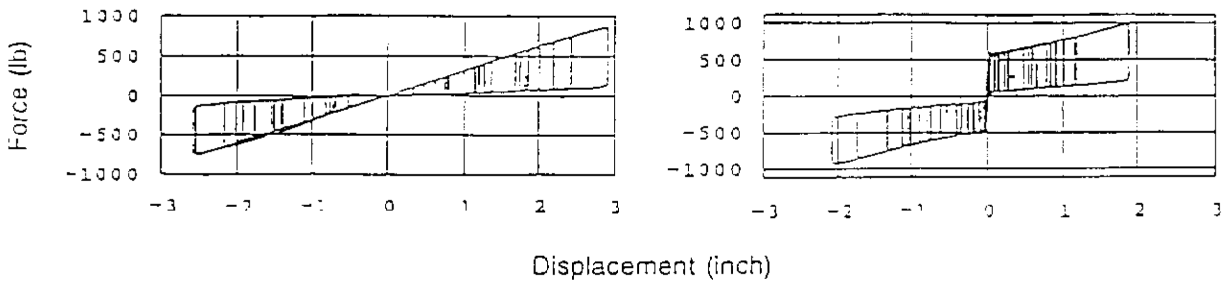


ogy has been developed for friction-damped structures [Filiatrault and Cherry, 1990]. The design of the Sumitomo devices for the two building applications was with the primary objective of reducing the response of the structures to ground-borne vibrations and small-to-moderate earthquakes. Response control 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.

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 4). 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 in [Nims, et al., 1993].

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 [Piazza and Turrini, 1988, Roik, et al., 1988, Fitzgerald, et al., 1989]. A thirteen-story hospital building in Siena, Italy incorporates such connections in X-bracing throughout the height of the building

Figure 4: Fluor-Daniel EDR Hysteresis Loops [Richter, et al., 1990]



[Piazza, et al., 1988]. 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 [Grigorian and Popov, 1994].

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 5). 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 6). 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.

Figure 5: ADAS Device Hysteresis Loops [Whittaker, et al., 1991]

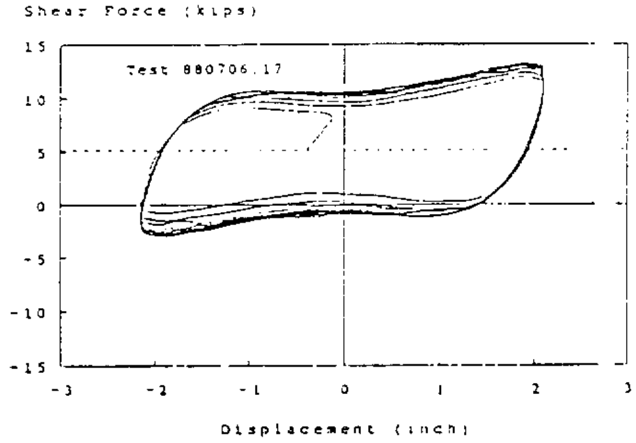
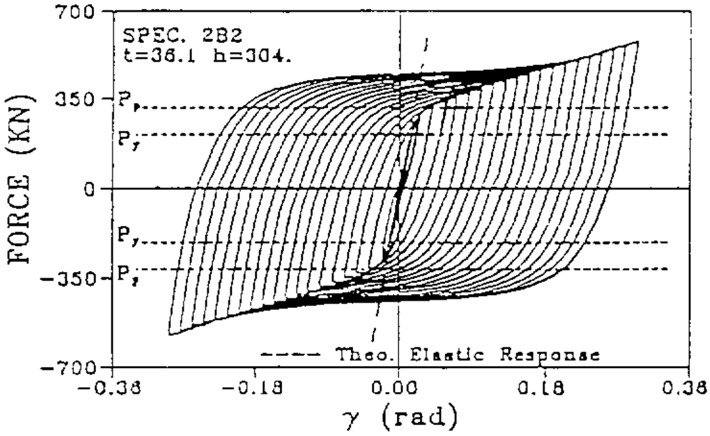


Figure 6: T-ADAS Device Hysteresis Loops [Tsai and Hong, 1992]



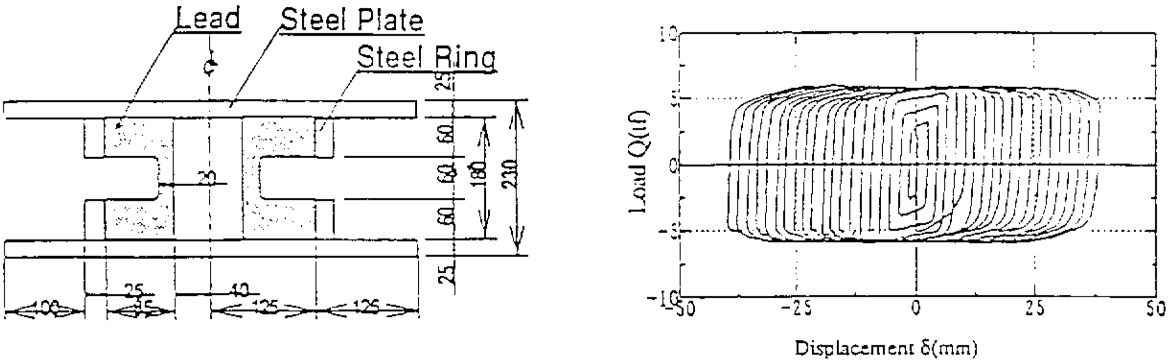
An energy dissipator for cross-braced structures, which uses mild steel round bars or flat plates as the energy absorbing element, has been developed by [Tyler, 1985]. This concept has been applied to several industrial warehouses in New Zealand. A number of variations on the steel cross-bracing dissipator 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 [Ciampi, 1993].

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 7). Experimental investigations and an analytical study have been undertaken.

Figure 7: Lead Joint Damper and Hysteresis Loops [Sakurai, et al., 1992]

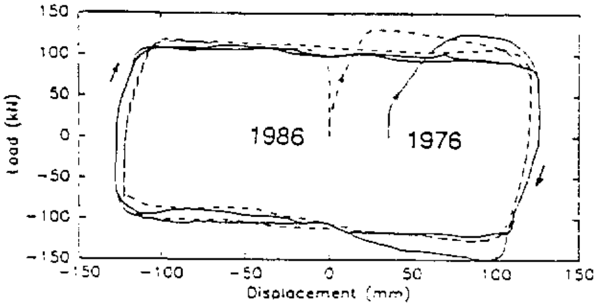


Particular issues of importance with metallic devices are the appropriate post-yield deformation range, such that a sufficient number of cycles of deformation can be sustained without premature fatigue, and the stability of the hysteretic behavior under repeated post-elastic deformations.

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 8). LEDs have been applied to a number of struc

Figure 8: LED Hysteresis Loops [Robinson and Cousins, 1987]



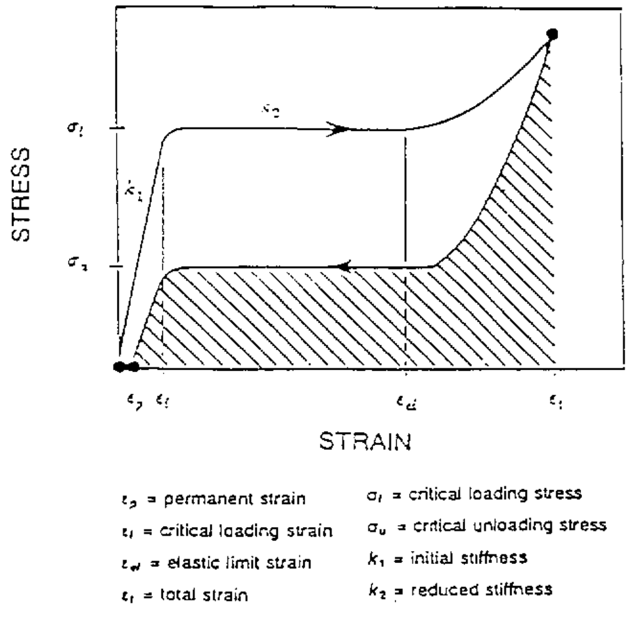
tures, for damping in seismic isolation systems, and as energy dissipators within multi-story buildings. In Wellington, New Zealand, a 10-story, cross-braced, concrete police station is base isolated, with sleeved-pile flexible elements and LED damping elements [Charleson, et al., 1987]. Several seismically-isolated 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 8).

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 9). This provides the potential for the development of simple devices which are self-centering and which perform repeatably for a large number of cycles.

Figure 9: SMA Superelastic Hysteresis Behavior [Aiken, et al., 1992]



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 Figures 10 and 11. Results showed that the SMA dissipators were effective in reducing the seismic responses of the models.

Figure 10: NiTi (Tension) Hysteresis Loops [Aiken, et al., 1992]

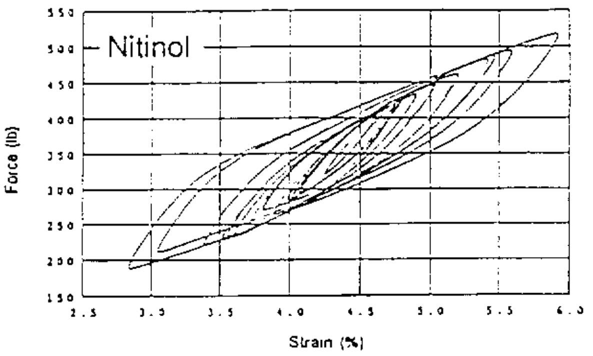
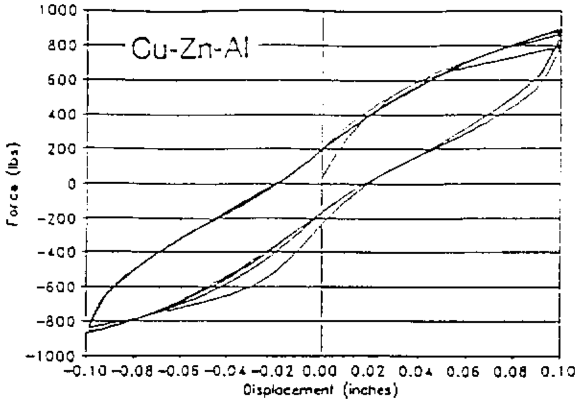


Figure 11: Cu-Zn-Al (Torsion) Hysteresis Loops [Witting and Cozzarelli, 1992]



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

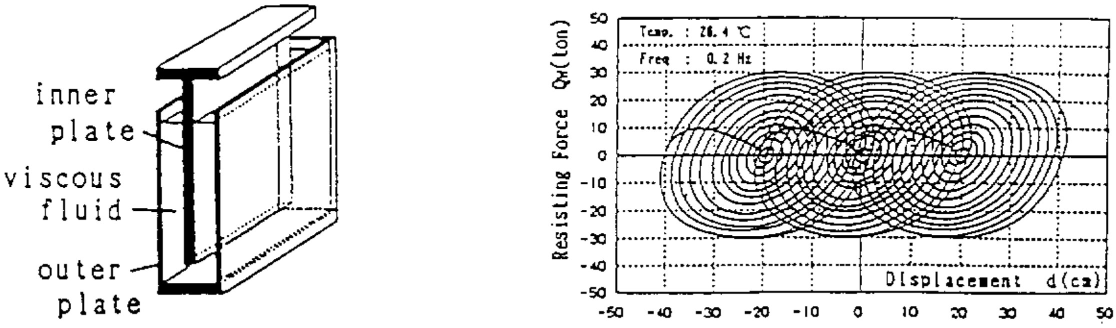
Viscoelastic materials have been in use in structural engineering for vibration control for more than 20 years. Mahmoodi described the characteristics of a double-layer, constrained-layer, viscoelastic (VE) shear damper in 1969 [Mahmoodi, 1969]. Viscoelastic copolymers developed by 3M Company have been 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]. Analytical representations of the variations in material properties due to temperature changes have also been proposed [Kasai, et al., 1993].

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 that 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 12). 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 in Shizuoka City, Japan, provides between 20 and 32 percent damping to the building, and response reductions of the order of 75 to 80 percent have been predicted [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

Figure 12: VD Wall and Hysteresis Loops [Miyazaki and Mitsusaka, 1992]



[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. More recently, shaking table tests of a 1/3-scale, 3-story, reinforced-concrete building model have also been performed [Reinhorn and Li, 1995].

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 or nonlinear viscous behavior, are relatively insensitive to temperature changes, and can be very compact in size in comparison to force capacity and stroke. A number of U.S. and European manufacturers produce fluid viscous dampers, and the devices are capable of a range of behavior. Damper force, $F = C \cdot v^{\alpha}$ is possible with α ranging from about 0.1 to 1.5 or even higher. Experimental and analytical studies of building and bridge structures incorporating fluid viscous dampers have recently been performed [Constantinou, et al., 1993] [Reinhorn, Li and Constantinou, 1995]. Large response reductions were achieved by the presence of the devices. Dampers that use a much higher viscosity material and are capable of including spring stiffness as well as a combination of viscous and hysteretic damping have been investigated in shaking table tests of a 1/3-scale, 3-story, reinforced-concrete building model [Pekan, Mander and Chen, 1995].

Fluid viscous dampers have been incorporated in several new buildings, and have been used recently in at least one building retrofit (see Appendix A). These devices have also been incorporated as part of the seismic isolation system for a new hospital in the later stages of construction in Colton, California [Asher, et al., 1994]. Several other building isolation projects currently in the design phase or soon to start construction will also used viscous dampers (see Appendix A). Nonlinear viscous dampers will be used in the seismic upgrade of the Golden Gate Bridge, and were the subject of an extensive testing program as part of the design and validation process. Appendix A lists several other bridge retrofits that will also use fluid viscous dampers.

While the different types of dampers can achieve similar force-displacement (or velocity) behavior, they do so in a number of different ways. Dampers may or may not include pressure regulators or accumulators to compensate for ambient and transient temperature changes. The damper force-velocity behavior can be obtained either by simple annular or through-piston orificing, or the use of valves (either internal or external) may be used. Damper sealing systems too can vary quite significantly from manufacturer to manufacturer. Some manufacturers also provide fluid-level or pressure indicators as a means for rapid device inspection. The highly-engineered mechanical characteristics of these types of dampers present a number of issues for the structural engineer to carefully consider, such as maintenance and inspection requirements as part of a long-term program to ensure the integrity of the devices.

SUMMARY

It is evident that while a great deal of research has been done and a wide variety of reliable devices have been developed, there are still relatively few completed applications incorporating supplemental dampers to date. However, in the wake of the loss of life, widespread damage and economic losses suffered in the recent Loma Prieta, Northridge and Hanshin earthquakes, designers, building owners, and code-writing organizations in the United States are beginning to recognize the performance limitations inherent in current building codes. This fact, combined with an enhanced awareness of the available technologies and advances in analytical capabilities, may lead to an increase over the next several years in the number of applications in which passive energy dissipation solutions are considered. What remains is to develop more straightforward design procedures that can be incorporated easily into current design guidelines, and to bring standardization to the product lines so that specification of dampers is routine.

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Appendix A: Applications of Passive Energy Dissipation Devices in North America

NAME AND TYPE OF STRUCTURE	LOCATION	TYPE AND NUMBER OF DAMPERS	DATE OF INSTALLATION	DESIGN INFORMATION
Gorgas Hospital	Panama	Friction dampers Total: 2	1970s	
McConnel Building, Concordia University library complex R.C. frames Interconnected 10- and 6-story buildings	Montreal, Canada	Friction dampers (Pall) Total: 143 Slip loads: 600-700 kN	1987	Equiv. damping ratio: > 50% for artificial 0.18g earthquake 3D nonlinear analyses for design
Ecole Polyvalente 3 precast concrete 3-story buildings	Sorel, Canada	Friction dampers (Pall) Total: 64 Slip loads: 225-355 kN	1990	Retrofit; buildings damaged in 1988 Saguernay earthquake Design for 0.18g PGA nonlinear analyses for design
Izazaga #38-40 R.C. frame with brick infill end walls 12 stories + basement 1200 m2 plan Constructed late 1970s	Mexico City, Mexico	Yielding steel (ADAS) Total: approx. 200	1990	Retrofit; damaged in 1985, 1986, 1989 earthquakes Fundamental periods (analysis): Original: 3.82, 2.33 s Upgraded: 2.24, 2.01 s 2D nonlinear analysis for final design verification Maximum interstory drift reduced by 40% Retrofit completed with building occupied
Cardiology Building R.C. frame Constructed late 1970s	Mexico City, Mexico	Yielding steel (ADAS) Total: 90	1990	Retrofit; damaged in 1985 earthquake Nonlinear analysis conducted Retrofit completed with continuous operation of hospital

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NAME AND TYPE OF STRUCTURE	LOCATION	TYPE AND NUMBER OF DAMPERS	DATE OF INSTALLATION	DESIGN INFORMATION
Reforma #476 Building Mexican Institute for Social Security 3 building complex 10-stories + basement R.C. frames Constructed in 1940s	Mexico City, Mexico	Yielding steel (ADAS) Total: approx. 400	1992	Retrofit; significant damage in 1957 earthquake National Register of Classical Buildings 2D nonlinear analysis
Wells Fargo Bank Nonductile R.C. frame 2 story, 140, 000 ft^2 Constructed 1967	San Francisco, California	Yielding steel (ADAS) Total: 7 Design yield force: 150 kips	1992	Retrofit; damaged in 1989 Loma Prieta earthquake Fundamental periods (analysis): Original: 0.84, 0.65, 0.36 s Upgraded: 0.45, 0.44, 0.23 s 3D elastic and 2D nonlinear analyses for design
School building 2 stories	Phoenix, Arizona	Viscoelastic beam-column connectors	1992	New construction
Canadian Space Agency Steel frames, 3-stories 135 m x 78 m in plar	Montreal, Canada	Friction dampers (Pall)\ Total: 58 Slip load: 500 kN	1993	Building houses sensitive equipment 40 dampers exposed to view for aesthetic purposes 3D nonlinear analyses for design
Casino de Montreal (former pavilion for Expo '67) 8-story steel frame structure	Montreal, Canada	Friction dampers (Pall) Total: 32 Slip load: 700-1800 kN	1993	Highly eccentric center of rigidity Retrofit to comply with current code standards
Santa Clara County Civic Center, East Wing Building Steel frame, 13 stories 51m x 51m plan, constructed 1976	San Jose, California	Viscoelastic dampers (3M) Total 88	1993	Retrofit; building had performed poorly in earthquakes in 1984, 1986 and 1989 Damping ratio in fundamental mode: Original: < 1% Upgrade: 17% approx.

Appendix A: Applications of Passive Energy Dissipation Devices in North America

NAME AND TYPE OF STRUCTURE	LOCATION	TYPE AND NUMBER OF DAMPERS	DATE OF INSTALLATION	DESIGN INFORMATION
Pacific Bell Center	Sacramento, California	Viscous dampers (Taylor Devices)	1995	New construction 62 x 130 kN +/- 50 mm
San Francisco Opera House	San Francisco California	Viscous dampers (Enidine)	1996	Retrofit 16 x 400 kip linear (with relief at 400 kip) +/- 3 in.
Woodland Hotel	Woodland, California	Viscous dampers (Taylor Devices)	1996	Retrofit 16 x 450 kN +/- 50 mm
Science Building II, California State University, Sacramento	Sacramento, California	Viscous dampers (Taylor Devices)	1996	New construction 40 x 220 kN +/- 50 mm
Langenbach House	Oakland, California	Viscous dampers (Taylor Devices)	1996	New construction 4 x 130 kN +/- 150 mm
The Money Store	Sacramento, California	Viscous dampers (Taylor Devices)	sched. 1997	New construction, 11-story steel frame 120 dampers (300 kip and 150 kip) +/- 2.5 in.
Civic Center Building	San Francisco California	Viscous dampers (Taylor Devices)	sched. 1997	New construction 60 x 75 kip, 112 x 175 kip, 120 x 225 kip dampers +/- 2 in.
Los Angeles Police Dept. Recruit Training Center	Los Angeles, California	Viscoelastic dampers (3M)	sched. 1997	Retrofit of steel frame building contract pending
San Mateo County Hall of Justice	Redwood City, California	Viscoelastic dampers (3M)	sched. 1997	Staged retrofit of an 8-story steel frame w/ pre-cast cladding

Appendix A: Applications of Passive Energy Dissipation Devices in North America

NAME AND TYPE OF STRUCTURE	LOCATION	TYPE AND NUMBER OF DAMPERS	DATE OF INSTALLATION	DESIGN INFORMATION
DAMPERS INCLUDED IN SEISMIC ISOLATION SYSTEMS				
San Bernardino County Medical Center	Colton, California	Viscous dampers (Taylor Devices)	1996	New construction 186 nonlinear dampers
Hayward City Hall	Hayward, California	Viscous dampers (to be det.)	sched. 1997	New construction
Kaiser Data Center	Corona, California	Viscous dampers (to be det.)		Retrofit
Los Angeles City Hall	Los Angeles, California	Viscous dampers (to be det.)	sched. 1998	Retrofit approx. 50 dampers as part of isolation system approx. 12 dampers in upper structure
BRIDGES				
Gerald Desmond Bridge	Long Beach, California	Viscous dampers (Enidine)	1996	258 x 50 kip shock absorbers 6 in. stroke
The Golden Gate Bridge	San Francisco, California	Viscous dampers (to be det.)		40 x 650 kip nonlinear dampers +/- 24 in.
Vincent Thomas Bridge	Long Beach, California	Viscous dampers (to be det.)		8 x 200 kip and 8 x 100 kip linear dampers +/- 12 in.
DAMPERS IN BUILDINGS FOR WIND VIBRATION CONTROL				
World Trade Center Tubular steel frame 2 towers, 110 stories	New York City, New York	Viscoelastic dampers (3M) Total: approx. 20,000 Evenly distributed, 10-110 floors	1969	Damping ratio with dampers: 2.5 - 3%

Appendix A: Applications of Passive Energy Dissipation Devices in North America

NAME AND TYPE OF STRUCTURE	LOCATION	TYPE AND NUMBER OF DAMPERS	DATE OF INSTALLATION	DESIGN INFORMATION
CN Tower TV antenna height: 355m	Toronto, Canada	Tuned mass damper	1973	New Construction
John Hancock Tower 58-story office building height: 244m plan: 3600 m^2	Boston, Massachusetts	Tuned mass damper (MTS) Two 300-ton lead/steel blocks	1977	Fundamental: 7.14 s Damping ratio with TMD: 4%
Citicorp Center office building height: 280m plan: 2600 m^2	New York City, New York	Tuned mass damper (MTS) 400 ton concrete block	1978	Fundamental: 6.25 s Damping ratios: No TMD: ~ 1% With TMD: 4%
Columbia SeaFirst Building 73 stories	Seattle, Washington	Viscoelastic dampers (3M) Total: 260	1982	
No. Two Union Square Building 60 stories	Seattle, Washington	Viscoelastic dampers (3M) Total: 16	1988	
Light Towers **Rich Stadium**	Buffalo, New York	Viscous dampers (Taylor Devices)	1993	12 x 50 kN +/- 460 mm
28 State Street, Boston	Boston, Massachusetts	Viscous dampers (Taylor Devices)	1996	Building renovation 40 x 670 kN +/- 25 mm