PASSIVE AND ACTIVE STRUCTURAL VIBRATION CONTROL IN CIVIL ENGINEERING

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CHAPTER X

PRINCIPLES OF FRICTION, VISCOELASTIC, YIELDING STEEL AND FLUID VISCOUS DAMPERS: PROPERTIES AND DESIGN

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ABSTRACT

This section describes passive energy dissipating devices which may be used within a structural system to absorb seismic energy. These devices are capable of producing significant reductions of interstory drifts in moment-resisting frames. Furthermore, these devices may, under elastic conditions, reduce the design forces.

INTRODUCTION

The mitigation of the hazardous effects of earthquakes begins with the consideration of the distribution of energy within a structure. During a seismic event, a finite quantity of energy is input into a structure. This input energy is transformed into both kinetic and potential (strain) energy which must be either absorbed or dissipated through heat. If there were no damping, vibrations would exist for all time. However, there is always some level of inherent damping which withdraws energy from the system and therefore reduces the amplitude of vibration until the motion ceases. The structural performance can be improved if a portion of the input energy can be absorbed, not by the structure itself, but by some type of supplemental "device". This is made clear by considering the conservation of energy relationship (Uang 1988):

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

where E is the absolute energy input from the earthquake motion, E_k is the absolute kinetic energy, E_s is the recoverable elastic strain energy, E_h is the irrecoverable energy dissipated by the structural system through inelastic or other forms of action, and E_d is the energy dissipated by supplemental damping devices. The absolute energy input, E, represents the work done by the total base shear force at the foundation on the ground (foundation) displacement. It, thus, contains the effect of the inertia forces of the structure.

In the conventional design approach, acceptable structural performance is accomplished by the occurrence of inelastic deformations. This has the direct effect of increasing energy E_h. It also has an indirect effect. The occurrence of inelastic deformations results in softening of the structural system which itself modifies the absolute input energy. In effect, the increased flexibility acts as a filter which reflects a portion of the earthquake energy.

The technique of seismic isolation accomplishes the same task by the introduction, at the foundation of a structure, of a system which is characterized by flexibility and energy absorption capability. The flexibility alone, typically expressed by a period of the order of 2 seconds, is sufficient to reflect a major portion of the earthquake energy so that inelastic action does not occur. Energy dissipation in the isolation system is then useful in limiting the displacement response and in avoiding resonances. However, in earthquakes rich in long period components, it is not possible to provide sufficient flexibility for the reflection of the earthquake energy. In this case, energy absorption plays an important role.

Modern seismic isolation systems incorporate energy dissipating mechanisms. Examples are high damping elastomeric bearings, lead plugs in elastomeric bearings, mild steel dampers, fluid viscous dampers, and friction in sliding bearings (see lecture notes on Seismic Isolation Systems: Introduction and Overview).

Another approach to improved earthquake response performance and damage control is that of supplemental damping systems. In these systems, mechanical devices are incorporated in the frame of the structure and dissipate energy throughout the height of the structure. The means by which energy is dissipated is either yielding of mild steel, sliding friction, motion of a piston within a viscous fluid, orificing of fluid, or viscoelastic action in polymeric materials.

FRICTION DEVICES

A frictional device located at the intersection of cross bracing has been proposed by Pall (1982, 1987) and used in six buildings in Canada. These buildings are the Concordia University new library 10-story building in Montreal, the Canadian Space Agency building in St.-Hubert, the CCRIT building in Laval and three 3-story buildings of Ecole Polyvalante in Sorel which were damaged in the 1988 Saguenay earthquake (Pall 1993). Figure 1 illustrates the design of this device. When seismic load is applied, the compression brace buckles while the tension brace induces slippage at the friction joint. This, in turn, activates the four links which force the compression brace to slip. In this manner, energy is dissipated in both braces while they are designed to be effective in tension only.

Experimental studies by Filiatrault (1985) and Aiken (1988) confirmed that these friction devices could enhance the seismic performance of structures. The devices provided a substantial increase in energy dissipation capacity and reduced drifts in comparison to moment resisting frames. Reductions in story shear forces were moderate. However, these forces are primarily resisted by the braces in a controlled manner and only indirectly resisted by the primary structural elements. This subject is further discussed later.

Sumitomo Metal Industries of Japan developed, and for a number of years manufactured, friction dampers for railway applications. Recently, the application of these dampers was extended to structural engineering. Two tall structures in Japan, the Sonic City Office Building in Omiya City and the Asahi Beer Azumabashi Building in Tokyo, incorporate the Sumitomo friction dampers for reduction of the response to ground-borne vibrations and minor earthquakes. These structures are, respectively, 31- and 22-story steel frames. Furthermore, a 6-story seismically isolated building in Tokyo incorporates these dampers in the isolation system as energy-absorption devices.

Figure 2 shows the construction of a typical Sumitomo friction damper. The device consists of copper pads impregnated with graphite in contact with the steel casing of the device. The load on the contact surface is developed by a series of wedges which act under the compression of belleville washer springs. The graphite serves the purpose of lubricating the contact and ensuring a stable coefficient of friction and silent operation.

An experimental study of the Sumitomo damper was reported by Aiken (1990). Dampers were installed in a 9-story model structure and tested on a shake table. The dampers were not installed diagonally as braces. Rather, they were placed parallel to the floor beams, with one of their ends attached to a floor beam above and the other end attached to a chevron brace arrangement which was attached to the floor beam below. The chevron braces were designed to be very stiff. Furthermore, a special arrangement was used at the connection of each damper to the chevron brace to prevent lateral loading of the device. Figure 2 demonstrates the installation.

The experimental study resulted in conclusions which are similar to those of the study of the friction bracing devices of Pall (1982). In general, displacements were reduced in comparison to moment resisting frames. However, this reduction depended on the input motion. For example, in tests with the Japanese Miyagiken earthquake, ratios of interstory drift in the friction damped structure to interstory drift in the moment resisting structure of about 0.5 were recorded. In tests with the 1940 El Centro and 1952 Taft earthquakes, the ratio of interstory drifts was typically around 0.9. Furthermore, recorded base shear forces were, in general, of the same order as those of the moment resisting frame. However, the friction damped structure absorbed earthquake energy by mechanical means. This energy would have otherwise been absorbed by inelastic action in the frame.

An interesting outcome of the study is that, for optimum performance, the friction force at each level should be carefully selected based on the results of nonlinear dynamic analyses. The tested structure had a friction force of about 0.12W (W = model weight) at the first story and it reduced to about 0.05W at the top story.

Another friction device, proposed by Fitzgerald (1989), utilizes slotted bolted connections in concentrically braced connections. Component tests demonstrated stable frictional behavior. Figure 3 shows this friction device. It may be noted that the sliding interface is that of steel on steel.

Constantinou (1991a, 1991b) developed a friction device for application in bridge seismic isolation systems. Shown in Figure 4, this device utilizes an interface of stainless steel in contact with bronze which is impregnated with graphite. The device bears a similarity with the Sumitomo device in terms of the materials which form the sliding interface.

Very recently Grigorian (1993) tested a slotted bolted connection which was nearly identical to the one of Fitzgerard (1989) except for the sliding interface which consisted of brass in contact with steel. This interface exhibits more stable frictional characteristics than the steel on steel interface.

Frictional devices are in principle simple to construct but very difficult in maintaining their properties over prolonged time intervals. Particularly,

(a) Metal to metal interfaces typically promote additional corrosion. Specifically, common carbon and low alloy steels suffer severe additional corrosion when in contact with brass, bronze or copper in all atmospheric environments. The British Standards (BSI 1979) specifically recommend against their use. Only stainless steels with high content of chromium may be acceptable when in contact with brass or bronze under atmospheric conditions other than industrial/urban and marine (BSI 1979).

(b) The normal load on the sliding interface cannot be reliably maintained and some relaxation should be expected over the years.

YIELDING STEEL ELEMENTS

The reliable yielding properties of mild steel have been explored in a variety of ways for improving the seismic performance of structures. The eccentrically-braced frame (Roeder 1978) represents a widely accepted concept. Energy dissipation is primarily concentrated at specifically detailed shear links of eccentrically-braced frames. These links represent part of the structural system which is likely to suffer localized damage in severe earthquakes.

A number of mild steel devices have been developed in New Zealand (Tyler 1978, Skinner 1980). Some of these devices were tested at U.C. Berkeley as parts of seismic isolation systems (Kelly 1980) and similar ones were widely used in seismic isolation applications in Japan (Kelly 1988).

Tyler (1985) described tests on a steel element fabricated from round steel bar and incorporated in the bracing of frames. Figure 5 shows details of a similar bracing system which was installed in a building in New Zealand. An important characteristic of the element is that the compression brace disconnects from the rectangular steel frame so that buckling is prevented and pinched hysteretic behavior does not occur. Energy is dissipated by inelastic deformation of the rectangular steel frame in the diagonal direction of the tension brace.

Another element, called "Added Damping and Stiffness" or ADAS device has been studied by Whittaker (1989). The device consists of multiple X-steel plates of the shape shown in Figure 6 and installed as illustrated in the same figure. The similarity of the device to that of Tyler (1978) and Kelly (1980) is apparent. The shape of the device is such that yielding occurs over the entire length of the device. This is accomplished by the use of rigid boundary members so that the X-plates are deformed in double curvature.

Shake table tests of a 3-story steel model structure by Whittaker (1989) demonstrated that the ADAS elements improved the behavior of the moment-resisting frame to which they were installed by a) increasing its stiffness, b) increasing its strength and c) increasing its ability to dissipate energy. Ratios of recorded interstory drifts in the structure with ADAS elements to interstory drifts in the moment-resisting frame were typically in the range of 0.3 to 0.7. This reduction is primarily an effect of the increased stiffness of the structure by the ADAS elements.

Ratios of recorded base shears in the structure with ADAS elements to base shears in the moment-resisting frame were in the range of 0.6 to 1.25. Thus, the base shear in the ADAS frame was in some tests larger than the shear in the moment frame. However, it should be noted again that, as in the case of friction braced structures, the structure shear forces are primarily resisted by the ADAS elements and their supporting chevron braces (see Figure 6). The ADAS elements yield in a pre-determined manner and relieve the moment frame from excessive ductility demands. ADAS elements have been very recently used in the seismic retrofitting of the Wells Fargo Bank, a 2-story concrete building in San Francisco.

Various devices whose behavior is based on the yielding properties of mild steel have been implemented in Japan (Fujita 1991). Kajima Corporation developed bell-shaped steel devices which serve as added stiffness and damping elements. These dampers were installed in the connecting corridors between a 5-story and a 9-story building in Japan. The same company developed another steel device, called the Honeycomb Damper, for use as walls in buildings. They were installed in the 15-story Oujiseishi Headquarters Building in Tokyo. Obayashi Corporation developed a steel plate device which is installed in a manner similar to the ADAS elements (Figure 6). The plate is subjected to shearing action. It has been installed in the Sumitomo Irufine Office Building, a 14-story steel structure in Tokyo.

VISCOELASTIC DAMPERS

Viscoelastic dampers, made of bonded viscoelastic layers (acrylic polymers), have been developed by 3M Company and used in wind vibration control applications. Examples are the World Trade Center in New York City (110 stories), the Columbia SeaFirst Building in Seattle (73 stories) and the Number Two Union Square Building in Seattle (60 stories). Seismic applications of viscoelastic dampers have a more recent origin. For seismic applications, larger damping increases are usually required in comparison with those required for mitigation of wind-induced vibrations. Furthermore, energy input into the structure is usually spread over a wider frequency range, requiring more effective use of the viscoelastic materials. Extensive analytical and experimental studies in the seismic domain have led to the first seismic retrofit of an existing building using viscoelastic dampers in the U.S. in 1993.

Viscoelastic materials used in structural application dissipate energy when subjected to shear deformation. A typical viscoelastic (VE) damper is shown in Fig. 7 which consists of viscoelastic layers bonded to steel plates. When mounted in a structure, shear deformation and hence energy dissipation takes place when the structural vibration induces relative motion between the outer steel flanges and the center plate.

Under a sinusoidal load with frequency ω, the shear strain $\gamma(t)$ and the shear stress $\tau(t)$ oscillate at the same frequency ω but in general out-of-phase. They can be expressed by (Zhang 1989)

$$\gamma(t) = \gamma_o \sin \omega t, \quad \tau(t) = \tau_o \sin(\omega t + \delta) \tag{2}$$

where γ_o and τ_o are, respectively, the peak shear strain and peak shear stress, and δ is the lag angle. For a given γ_o, τ_o is a function of ω.

The shear stress can also be written as

$$\tau(t) = \gamma_o[G'(\omega)\sin\omega t + G''(\omega)\cos\omega t] \tag{3}$$

where $G'(\omega) = \tau_o \cos\delta/\gamma_o$ and $G''(\omega) = \tau_o \sin\delta/\gamma_o$. The stress-strain relationship can be written as

$$\tau(t) = G'(\omega)\gamma(t) \pm G''(\omega)\left[\gamma_o^2 - \gamma(t)\right]^{1/2} \tag{4}$$

which defines an ellipse as shown in Fig. 8, whose area gives the energy dissipated by the viscoelastic material per unit volume and per cycle of oscillation.

It is seen from Eq. (4) that the first term of the shear stress is the in-phase portion with $G'(\omega)$ representing the elastic stiffness, and the second term or the out-of-phase portion represents the energy dissipation component. This is seen more clearly if Eq. (3) is rewritten in the form

$$\tau(t) = G'(\omega)\gamma(t) + \frac{G''(\omega)}{\omega}\dot{\gamma}(t) \tag{5}$$

since $\dot{\gamma}(t) = \gamma_o\omega\cos\omega t$. The quantity $G''(\omega)/\omega$ is the damping coefficient of the damper material. The equivalent damping ratio is

$$\xi = \frac{G''(\omega)}{\omega}\left(\frac{\omega}{2G'(\omega)}\right) = \frac{G''(\omega)}{2G'(\omega)} \tag{6}$$

Accordingly, $G'(\omega)$ is defined as the *shear storage modulus* of the viscoelastic material, which is a measure of the energy stored and recovered per cycle; and $G''(\omega)$ is defined as the *shear loss modulus*, which gives a measure of the energy dissipated per cycle. The *loss factor*, η, defined by

$$\eta = \frac{G''(\omega)}{G'(\omega)} = \tan\delta \tag{7}$$

is also often used as a measure of energy dissipation capacity of the viscoelastic material.

The shear storage modulus and shear loss modulus of a viscoelastic material are generally functions of excitation frequency (ω), ambient temperature (T), shear strain (γ), and material temperature (θ). Their dependence on these parameters have been studied extensively both analytically and experimentally. Constitutive models that have been proposed for viscoelastic materials include the Maxwell model, the Kevin-Voight model and complex combinations of these elementary models. More recently, the concept of fractional derivatives (Tsai 1993, Kasai 1993) and constitutive modeling based on the Botzmann's superposition principle (Shen 1994) have been used in modeling VE damper properties.

In order to determine the dependence of $G'(\omega)$ and $G''(\omega)$ on the ambient temperature, the method of reduced variables can be used (Ferry 1980). This method affords a convenient simplification in separating the two principal variables, frequency and temperature, on which the VE material properties depend, and expressing these properties in terms of a single function of each, whose form can be experimentally determined.

The effect of temperature rise within the VE material when it is subjected to shear deformation can also be taken into account using the method of reduced variables. Analytically, the internal temperature, θ, within the VE material due to the mechanical work done by the damper can be calculated from the heat transfer equation (Kasai 1993)

$$s\rho\frac{\partial\theta}{\partial t} \cong K\frac{\partial^2\theta}{\partial z^2} + \tau\frac{\partial\gamma}{\partial t} \tag{8}$$

where s is the specific heat of the VE material, ρ is the mass density, and K is thermal conductivity. The spatial variation of the temperature is assumed to occur in the z-direction across the VE layer. Experimental results and finite element analyses indicate, however, this transient heat conduction term is small and Eq. (8) can be approximated by

$$\theta(t) = T + \frac{1}{s\rho}\int_0^t \tau(t)\dot{\gamma}(t)dt \tag{9}$$

where T is the ambient temperature.

In structural applications, one is interested in the temperature rise within the VE material over a loading episode. Field observations and laboratory experiments have shown that, during each wind and earthquake loading cycle, this transient temperature increase is typically less than 10°C and has a minor effect on the performance of VE dampers.

In summary, assuming VE dampers undergo moderate strain ($\leq$ 20%), the shear storage and loss moduli can be considered as functions of only the excitation frequency ω and the ambient temperature T.

Based upon the development above, it is seen from Eq. (5) that, at a given ambient temperature and under moderate strain, the stress in a VE material is linearly related to the strain and strain rate under harmonic motion. For a viscoelastic damper such as that shown in Fig. 7 with total shear area A and total thickness h, the corresponding force-displacement relationship is

$$F(t) = k'(\omega)x(t) + c'(\omega)\dot{x}(t) \tag{10}$$

where

$$k'(\omega) = \frac{AG'(\omega)}{h}, \quad c'(\omega) = \frac{AG''(\omega)}{\omega h} \tag{11}$$

Thus, unlike friction devices or yielding steel elements, a linear structure with added VE dampers remains linear with the dampers contributing to increased viscous damping as well as lateral stiffness. This feature represents a significant simplification in the analysis of viscoelastically damped structures (Zhang 1989, 1992).

In order to assess seismic applicability of viscoelastic dampers, extensive experimental programs have been designed and carried out for steel frames in the laboratory (Ashour 1987, Su 1990, Lin 1991, Fujita 1992, Kirekawa 1992, Aiken 1993, Bergman 1993, Chang 1993a), for lightly reinforced concrete frames in the laboratory (Foutch 1993, Lobo 1993, Chang 1994), and for a full-scale steel frame structure in the field (Chang 1993a). These experimental results, together with analytical modeling, have led to the development of design procedures for structures with added VE dampers.

Like many other design problems, the design of viscoelastically damped structures is in general an iterative process (Chang 1993a and 1993b). First, an analysis of the structure without added dampers should be carried out. Then the required damping ratio becomes the primary design parameter for adding VE dampers to the structure. The design will normally contain the following steps which may continue to update the structural properties after each design cycle: (a) determine structural properties of the building and perform structural analysis; (b) determine the desired damping ratio; (c) select desirable and available damper locations in the building; (d) select damper stiffness and loss factor; (e) calculate the equivalent damping ratio using the modal strain energy method; and (f) perform structural analysis using the designed damping ratio. When steps (e) and (f) satisfy the desired damping ratio and the structural performance criteria, the design is complete. Otherwise, a new design cycle will proceed which may lead to new structural properties, damper locations or damper dimensions and properties.

It can be seen that this design procedure falls into the traditional design procedure except for the determination of the required damping ratio and the selection of damper stiffness and loss factor. In general, the required damping ratio can be estimated by using the response spectra of the design earthquake with various damping ratios. The selection of damper stiffness k' and loss factor η can be a trial and error procedure. They can also be determined based on the principle that the added stiffness due to the VE dampers be proportional to the story stiffness of the structure. This is obtained from

$$k_i' = \frac{2\zeta}{\eta - 2\zeta} k_i \tag{12}$$

where ζ is the target damping ratio and k_i' and k_i are, respectively, the damper stiffness and the structural story stiffness without added dampers at the ith story. For a VE material with known G' and G'' at the design frequency and temperature, the area of the damper, A, can be determined from, as seen from the first of Eqs. (11),

$$A = \frac{k'h}{G'} \tag{13}$$

The thickness of the VE material, h, can be determined from the maximum allowable damper deformation to insure that the maximum strain in the VE material is lower than the ultimate value.

In this design procedure, the structure is assumed to be linear elastic. If inelastic deformation is allowed in the structure, the demand in VE damping can be reduced and a modified procedure has to be used. We also note that ambient temperature is an important design parameter in all cases.

Viscoelastic devices have also been developed by the Lorant Group which may be used either at beam-column connections or as parts of a bracing system. Experimental and analytical studies have been very recently reported by Hsu (1992). These devices have been installed in a 2-story steel structure in Phoenix, Arizona.

Hazama Corporation of Japan developed a viscoelastic device whose construction and installation is similar to the 3M viscoelastic device with the exception that several layers of material are used (Fujita 1991). The material used in the Hazama device also exhibits temperature dependent properties. Typical results on the storage and loss shear moduli at a frequency of 1 Hz and shear strain of 0.5 are: 355 psi (2.45 MPa) and 412 psi (2.85 MPa), respectively at 32°F (0°C) and 14 psi (0.1 MPa) and 8 psi (0.055 MPa), respectively at 113°F (45°C).

Another viscoelastic device in the form of walls has been developed by Shimizu Corporation (Fujita 1991). The device consists of sheets of thermo-plastic rubber sandwiched between steel plates. It has been installed in the Shimizu Head Office Building, a 24-story structure in Tokyo.

VISCOUS WALLS

The Building Research Institute in Japan tested and installed viscous damping walls in a test structure for earthquake response observation. The walls were developed by Sumitomo Construction Company (Arima 1988) and consist of a moving plate within a highly viscous fluid which is contained within a wall container. The device exhibits strong viscoelastic fluid behavior which is similar to that of the GERB viscodampers which have been used in applications of vibration and seismic isolation (Makris 1992).

Observations of seismic response of a 4-story prototype building with viscous damping walls demonstrated a marked improvement in the response as compared to that of the building without the walls.

FLUID VISCOUS DAMPERS

Fluid viscous dampers which operate on the principle of fluid flow through orifices were first used in the 75mm French artillery rifle of 1897. This high performance damper was adaptive, that is, its output was continuously varied depending on the angle of elevation of the weapon. It was considered a national secret of France which was shared with the U.S. and Great Britain only during World War I. Even today elements of the design are used in large artillery pieces and in most aircraft landing gears.

Fluid dampers for automotive use were invented by Ralph Peo of Buffalo, N.Y. in 1925. Since then a number of fluid damper manufacturers were established in the Buffalo area. Of these, Taylor Devices was established in 1955 and since then produced over two million devices which were used as energy absorbing buffers in steel mills, canal lock buffers, offshore oil leg suspensions and primarily in shock and vibration isolation systems of aerospace and military hardware. Some notable examples of application are launch gantry dampers for the U.S. Navy with force output of up to 2000 kips (8900 kN) and travel of over 10 feet (over 3m), seismic dampers in nuclear power plants with force output of 300 to 1000 kips (1335 to 4450 kN), payload dampers for the space shuttle, wind dampers for the Atlas and Saturn V rockets and shock isolators for most tactical and strategic missiles of the U.S. Armed Forces.

A particular fluid damper which is produced by Taylor Devices has been studied by Constantinou (1992, 1993). The construction of this device is shown in Figure 9. It consists of a stainless steel piston with a bronze orifice head and an accumulator. It is filled with silicone oil. The orifice flow is compensated by a passive bi-metallic thermostat that allows operation of the device over a temperature range of - 40°F to 160°F (-40°C to 70°C). The orifice configuration, mechanical construction, fluid and thermostat used in this device originated within a device used in a classified application on the U.S. Air Force B-2 Stealth Bomber. Thus, the device includes performance characteristics considered as state of the art in hydraulic technology.

The force that is generated by the fluid damper is due to a pressure differential across the piston head. However, the fluid volume is reduced by the product of travel and piston rod area. Since the fluid is compressible, this reduction in fluid volume is accompanied by the development of a restoring (spring like) force. This is prevented by the use of the accumulator. Tested devices showed no measurable stiffness for piston motions with frequency less than about 4 Hz. In general, this cut-off frequency depends on the design of the accumulator and may be specified in the design. The existence of the aforementioned cut-off frequency is a desirable property. The devices may provide additional viscous type damping to the fundamental mode of the structure (typically with a frequency less than the cut-off frequency) and additional damping and stiffness to the higher modes. This may, in effect, completely suppress the contribution of the higher modes of vibration. Alternatively, fluid dampers may be constructed with run-through rod. This design prevents compression of the fluid and it does not require an accumulator.

The force in the fluid damper may be expressed as

$$P = C|\dot{u}|^{\alpha} sgn(\dot{u}) \tag{14}$$

where $\dot{u}$ = velocity of piston rod, C = constant and α = coefficient in the range of approximately 0.5 to 2.0. A typical orifice design features cylindrical orifices for which the output force is proportional to the velocity squared (α=2). This performance is usually unacceptable.

To produce damping forces with coefficient α different than 2 requires specially shaped passages to alter the flow characteristics with fluid speed. This orifice design is known as fluidic control orifice. A design with coefficient α equal to 0.5 is useful in applications involving extremely high velocity shocks. They are typically used in the shock isolation of military hardware. Fluid viscous dampers with nonlinear characteristics have been recently specified in a number of projects in the U.S. The San Bernardino County Medical Center in California is a five building isolated complex utilizing 400 high damping rubber bearings and 233 nonlinear viscous dampers with α = 0.5. Construction of the complex is scheduled to begin in 1994. Furthermore, studies for the seismic retrofit of the suspended part of the Golden Gate bridge in San Francisco concluded that the use of fluid dampers with α = 0.75 produce the desired performance (Rodriquez 1994).

The suitability of fluid viscous dampers for enhancing the seismic resistance of structures has been studied by Constantinou (1992, 1993). Fluid dampers with an orifice coefficient α=1 were tested over the temperature range 32°F to 122°F (0°C to 50°C). The dampers tested exhibited variations of their damping constant from a certain value at room temperature (75°F, 24°C) to + 44% of that value at 32°F (0°C) to -25% of that value at 122°F (50°C). This rather small change in properties over a wide range of temperature is in sharp contrast to the extreme temperature dependency of viscoelastic solid dampers. Figure 10 shows experimental results on the mechanical properties of a tested fluid damper over the temperature range of 0° to 50°C ($P = C_o \dot{u}$).

The inclusion of fluid viscous dampers in the tested structures on a shake table resulted in reductions in story drifts of 30% to 70%. These reductions are comparable to those achieved by other energy dissipating systems such as viscoelastic, friction and yielding steel dampers. However, the use of fluid dampers also resulted in reductions of story shear forces by 40% to 70% while other energy absorbing devices were incapable of achieving any comparable reduction. The reason for this difference is the nearly pure viscous behavior of the fluid dampers tested.

Figure 11 shows the construction of the nonlinear viscous dampers of the San Bernardino County Medical Center. These dampers have output force of 1400 kN

315 KIPS

60 in/sec ±24"

at velocity of 1500 mm/s and a stroke of ± 610 mm. Scaled versions of these damper (scale of 1/6) have been very recently tested at the University at Buffalo. Figure 12 shows the recorded force-velocity data for one of the tested dampers. The nonlinear characteristics of the damper are evident. It may be noted in this figure that the output of the device is nearly unaffected by temperature in the range of 0 to 50° C. This temperature insensitivity has been a specific project requirement. It has been achieved entirely by passive means, that is by compensation of the changes in fluid properties with changes in the volume of the fluid and metallic parts.

DISSIPATION OF ENERGY IN SYSTEMS WITH NONLINEAR VISCOUS DAMPERS

Consider a fluid viscous damper with constitutive relation described by Equation (14). The energy dissipated in a cycle of sinusoidal motion

$$u = u_o \sin \omega_o t \tag{15}$$

is

$$W_d = \int_o^T P \dot{u} dt \tag{16}$$

where $T = 2\pi / \omega_o$, u_o = amplitude and ω_o = frequency. Integration of Equations (14) to (16) results in

$$W_d = 4 \cdot 2^\alpha \cdot \frac{\Gamma^2 (1 + \frac{\alpha}{2})}{\Gamma(2+\alpha)} \cdot C \cdot u_o^{1+\alpha} \cdot \omega_o^\alpha \tag{17}$$

where Γ is the gamma function. The dissipated energy may also be expressed in terms of the peak value of damper force $P_{max} = C u_o^\alpha \omega_o^\alpha$. That is,

$$W_d = 4 \cdot 2^\alpha \cdot \frac{\Gamma^2 (1 + \frac{\alpha}{2})}{\Gamma(2+\alpha)} \cdot P_{max} u_o \tag{18}$$

Equation (18) may be used to demonstrate the advantages of nonlinear viscous dampers with small values of parameter α. Consider two cases, one with α = 0.5 (a technologically advanced design) and one with α = 2 (a typical design with cylindrical or Bernoulian orifices). For the case of α = 0.5, W_d = 3.496 $P_{max} u_o$, whereas for the case of $\alpha = 2$, $W_d = 2.667\ P_{max}u_o$. Thus for the same level of output force and amplitude of motion, the $\alpha = 0.5$ damper dissipates 31% more energy than the $\alpha = 2$ damper.

The significance of this difference in energy dissipation capability is more conveniently demonstrated by studying the behavior of a single-degree-of-freedom system with dampers. Let the mass of the system be M and the stiffness (linear and elastic) be K. A damper with characteristics described by Equation (14) is included in the system. The damping ratio is defined by

$$\xi = \frac{W_d}{2\pi K u_o^2} \tag{19}$$

in which u_o = amplitude of harmonic motion at the undamped natural frequency $\omega_o = \sqrt{K/M}$. By virtue of Equation (17), the damping ratio is

$$\xi = \frac{2^{1+\alpha} C u_o^{\alpha-1} \omega_o^{\alpha-2}}{\pi M} \cdot \frac{\Gamma^2\left(1+\frac{\alpha}{2}\right)}{\Gamma(2+\alpha)} \tag{20}$$

Specifically, for $\alpha = 0.5$

$$\xi = 0.55641 \frac{C}{M u_o^{1/2} \omega_o^{3/2}} \tag{21}$$

for $\alpha = 1$

$$\xi = \frac{C}{2M\omega_o} \tag{22}$$

and for $\alpha = 2$

$$\xi = \frac{4Cu_o}{2\pi M} \tag{23}$$

As expected the damping ratio is dependent on the amplitude of motion. For dampers with $\alpha < 1$, the damping ratio reduces with increasing amplitude of motion. The opposite is true for dampers with $\alpha > 1$, whereas for linear dampers ($\alpha = 1$) the damping ratio is independent of amplitude of motion. To illustrate this behavior, Figure 13 shows the damping ratio of a single-degree-of-freedom system with weight

W = 7000 kN (M = 713557 Kg) and undamped frequency $\omega_o = \pi\ rad/s$. Three different cases of dampers are considered, each of which produces a peak force equal to 704 kN (or 0.1 W) at velocity of 785 mm/s. That is, damping constant C is equal to 25.13 kN $s^{1/2}/mm^{1/2}$ for $\alpha = 1/2$, 0.8967 kN s/mm for $\alpha = 1$ and 0.001142 kN s^2/mm^2 for $\alpha = 2$.

Figure 13 depicts the damping ratio of the system with $\alpha = 0.5$ approaching infinity as the amplitude of motion tends to zero. This is not realistic. Actual devices exhibit linear behavior at low levels of velocity so that the damping ratio levels off to a constant value, as shown in the figure.

The behavior of the three systems under free vibration and seismic excitation is shown in Figures 14 and 15, respectively. Figure 14 compares the time histories of displacement of the three systems when they are released from a 250 mm initial displacement. The differences in energy dissipation capability among the three systems are evident in the reduction of amplitude per cycle of motion. Figure 15 compares force-displacement loops (force is total force, that is the restoring plus damping force) of the three systems when excited by the SOOE component of the 1940 El Centro earthquake scaled to a peak ground acceleration of 0.68 g. The better performance of the nonlinear $\alpha = 0.5$ damper is apparent. Comparing the $\alpha = 0.5$ damper system to the linear viscous system ($\alpha = 1$) we observe a nearly 20% reduction in displacement and a 10% reduction in total force. This better performance of the $\alpha = 0.5$ system is actually achieved with a peak damper force lower than that of the other systems. Specifically, for $\alpha = 0.5$ the maximum damper force is 640 kN, for $\alpha = 1$ the force is 700.5 kN and for $\alpha = 2$ the force is 930.5 kN.

CONSIDERATIONS IN THE DESIGN OF ENERGY ABSORBING SYSTEMS

The presented review of energy absorbing systems demonstrates that these systems are capable of producing significant reduction of interstory drift in the moment-resisting frames in which they are installed. Accordingly, they are all suitable for seismic retrofit applications in existing buildings.

Let us consider the implications of the use of energy absorbing systems in an existing moment-resting frame building. The gravity-load-carrying elements of the structural system have sufficient stiffness and strength to carry the gravity loads and, say, seismic forces in a moderate earthquake. The energy absorbing devices are installed in new bracing systems and, say, are capable of reducing drifts to half of those of the original system in a severe earthquake. An immediate observation is that the reduction of drift will result in a proportional reduction in bending moment in the columns.provided that the behavior is elastic, which will now undergo limited rather than excessive yielding.

However, the behavior of the retrofitted structure has changed from that of a moment-resisting frame to that of a braced frame. The forces which develop in the energy absorbing elements will induce additional axial forces in the columns. Depending on the type of energy absorbing device used, this additional axial force may be in-phase with the peak drift and, thus, may affect the safety of the loaded column.

Figure 16 shows idealized force-displacement loops of various energy absorbing devices. In the friction and steel yielding devices, the peak brace force occurs at the time of peak displacement. Accordingly, the additional column force, which is equal to $F\sin\theta$ (θ is the brace angle with respect to the horizontal), is in-phase with the bending moment due to column drift. Similarly, in the viscoelastic device a major portion of the additional column force is in-phase with the bending moment. In contrast, in the viscous device the additional column force is out-of-phase with the bending moment.

The implications of this difference in behavior of energy absorbing devises are illustrated in Figure 17. We assume that the energy absorbing devices are installed in the interior columns of a reinforced concrete frame. The nominal axial force-bending moment interaction diagram of a column is shown. It is assumed that the column was designed to be in the compression controlled range of the diagram. During seismic excitation, the moment-resisting frame undergoes large drifts and column bending moments but axial load remains practically unchanged. Failure will occur when the tip of the P-M loop reaches the nominal curve as illustrated in Figure 17a. The available capacity of the column is related to the distance between the tip of the P-M loop and the nominal curve (shown as a dashed line in Figure 17).

In the frame with added energy dissipating devices, the P-M loops show less bending moment. Despite this, the available capacity of the column may not have increased since the distance between the tip of the P-M loop and the nominal curve may have remained about the same. An exception to this behavior can be found in the viscous device.

The conclusion of the preceding discussion is that drift is not the only concern in design. Energy absorbing devices may reduce drift and thus reduce inelastic action. However, depending on their force-displacement characteristics, they may induce significant axial column forces which may lead to significant column compression or even column tension. This concern is particularly important in the seismic retrofitting of structures which suffered damage in previous earthquakes. After all, it may not always be possible to upgrade the seismic resistance of such structures by the addition of energy absorbing devices alone. It may also be necessary to strengthen the columns.

Constantinou (1992) utilized the experimental results of Aiken (1993) to demonstrate that the addition of friction dampers (Sumitomo type) to a tested 9-story structure resulted in significant additional axial load to the interior columns. Specifically, this additional axial load was 130% of the axial load due to gravity (gravity load = 12.8 kips, total axial load = 29.5 kips). Furthermore, similar calculations for a 3-story structure with ADAS elements tested by Whittaker (1989), resulted in additional axial load of only 14% of the gravity load.

CONCLUSIONS

Supplemental damping devices are capable of producing significant reductions of interstory drifts in the moment-resisting frames in which they are installed. They are suitable for applications of seismic retrofit of existing structures.

The behavior of structures retrofitted with supplemental damping devices changes from that of a moment-resisting frame to that of a braced frame. The forces which develop in the devices induce additional axial forces in the columns. For frictional, steel yielding and viscoelastic devices this additional axial force occurs in-phase with the peak drift and, thus, affects the safety of the loaded columns. This represents an important consideration in design and may impose limitations on the use of these devices in tall buildings. Exemption to this behavior can be found in a certain type of fluid damper which exhibits essentially viscous behavior.

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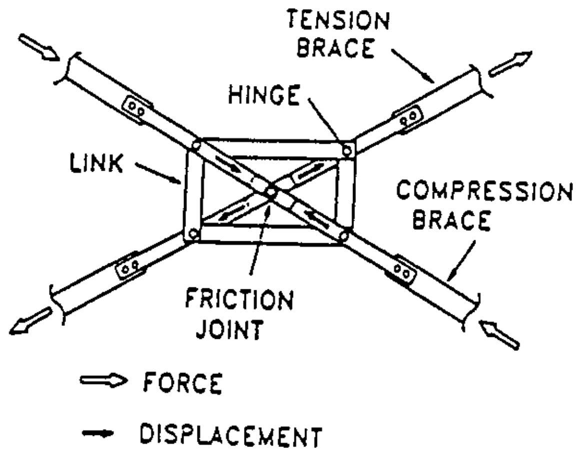

Figure 1 Friction Damper of Pall (1982).

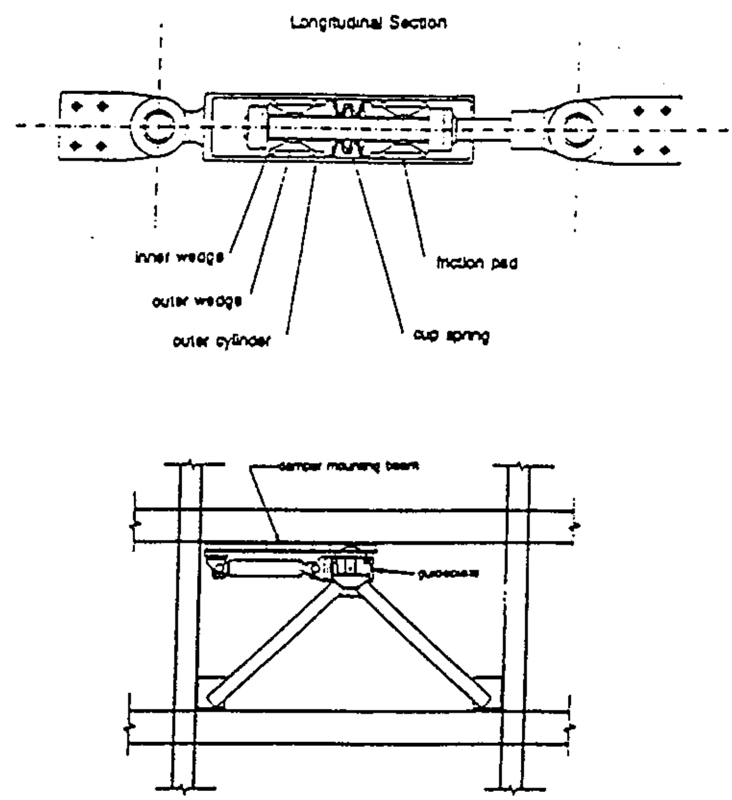

Figure 2 Sumitomo Friction Damper and Installation Detail (from Aiken 1990).

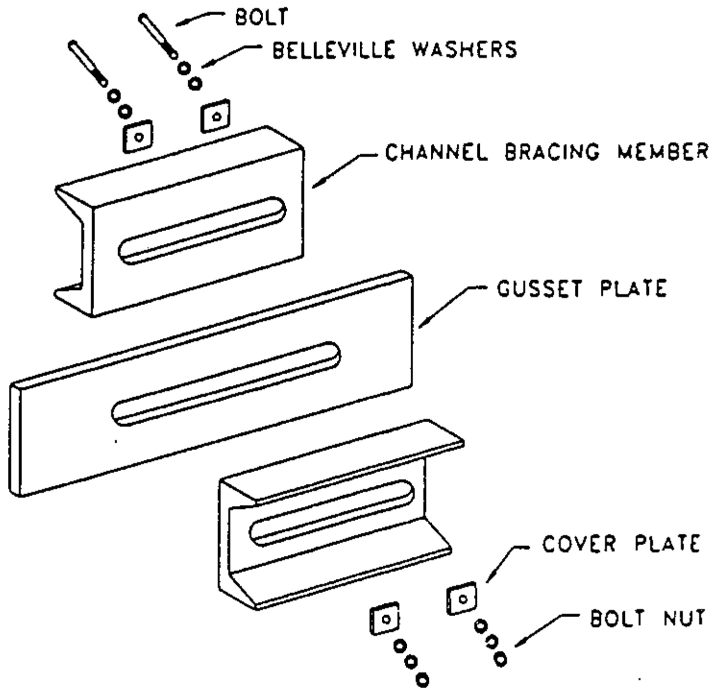

Figure 3 Slotted Bolted Connection of Fitzgerald (1989).

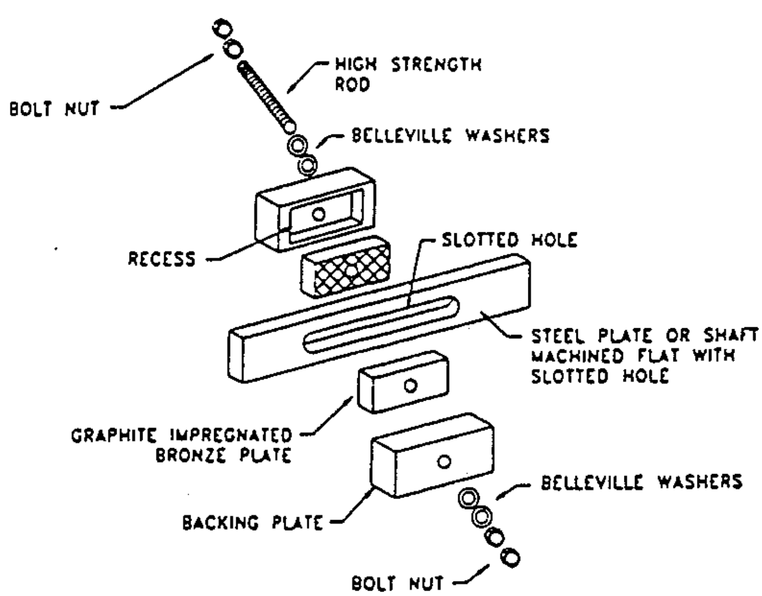

Figure 4 Friction Assembly in Displacement Control Device of Constantinou (1991a).

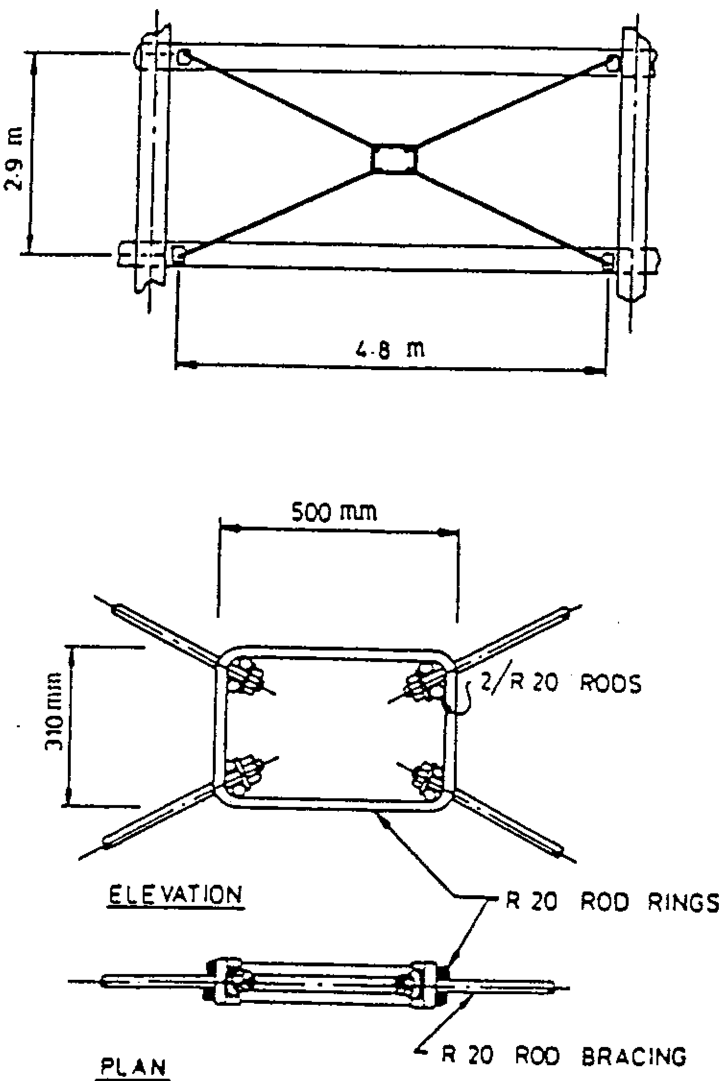

Figure 5 Yielding Steel Bracing System (from Tyler 1985).

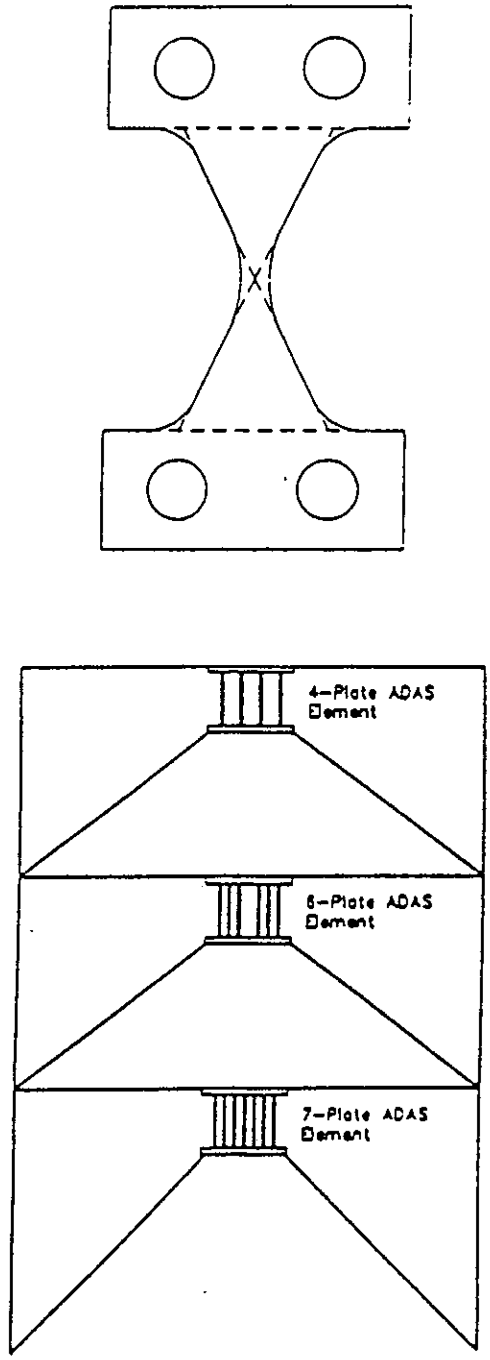

Figure 6 ADAS Element and Installation Detail (from Whittaker 1989).

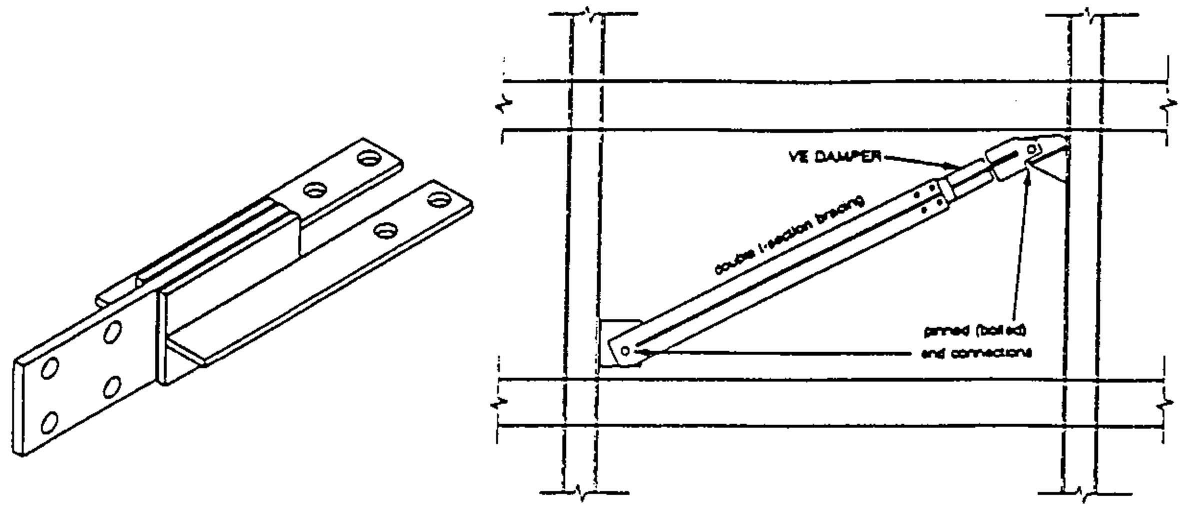

Figure 7 Viscoelastic Damper and Installation Detail (from Aiken 1990).

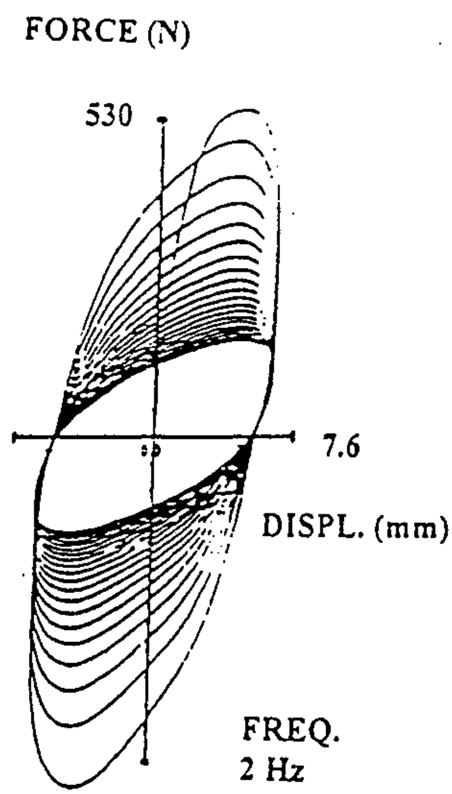

Figure 8 Force-displacements Loops of Viscoelastic Damper under Cyclic Loading (from Kasai 1993).

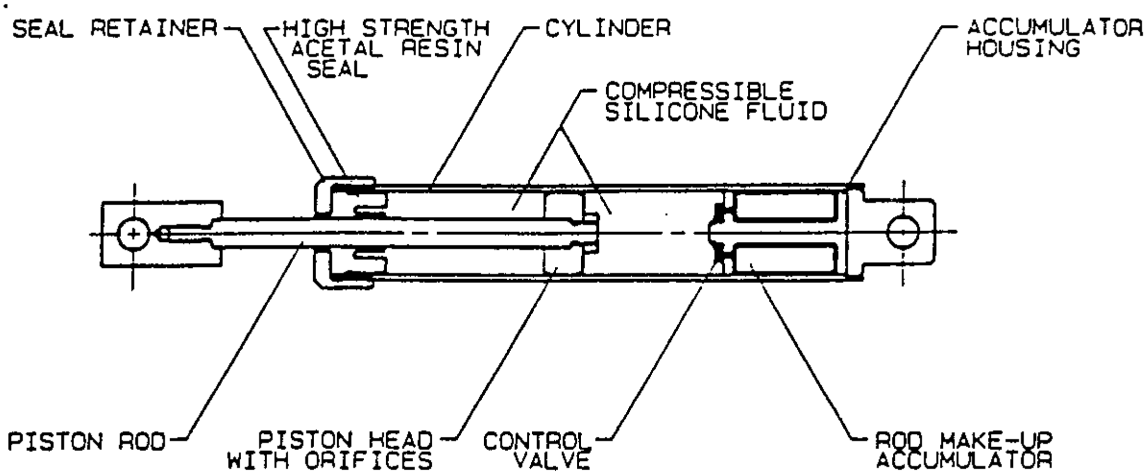

Figure 9 Construction of Fluid Viscous Damper with Accumulator.

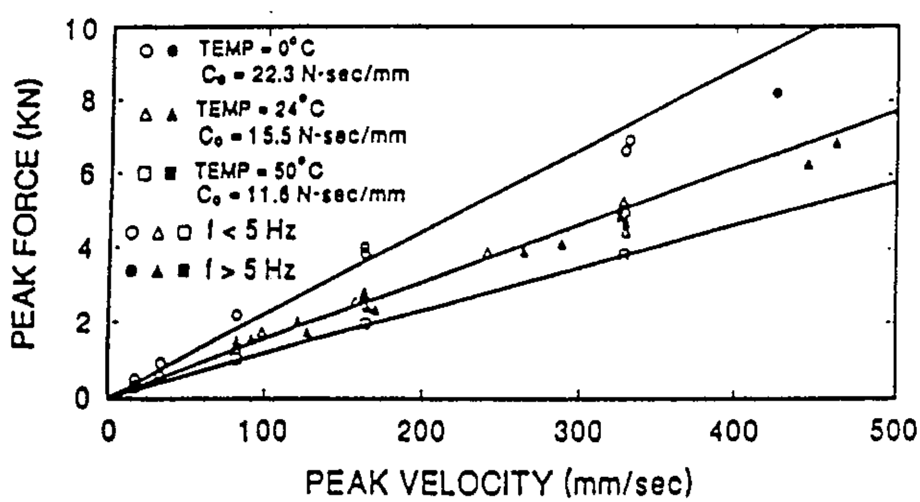

Figure 10 Effect of Temperature on Mechanical Properties of Linear Fluid Viscous Damper.

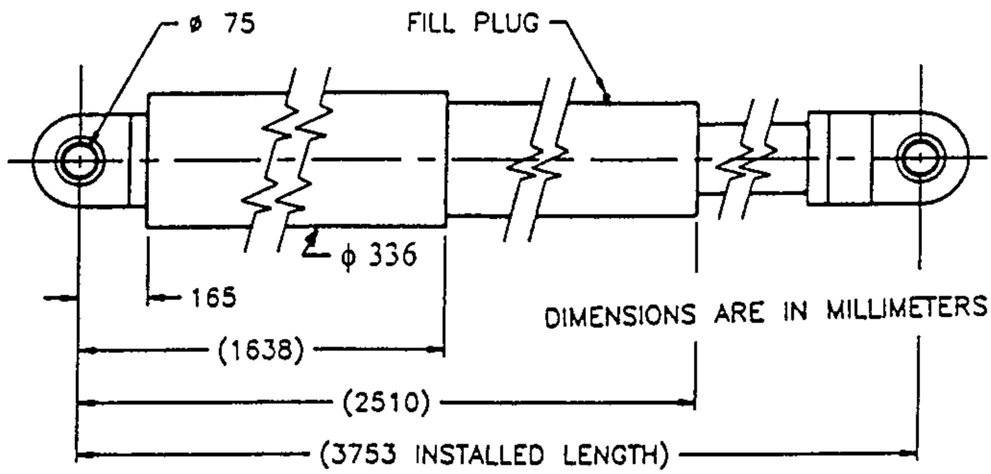

Figure 11 Construction of Nonlinear Fluid Viscous Damper for the San Bernardino County Medical Center, CA.

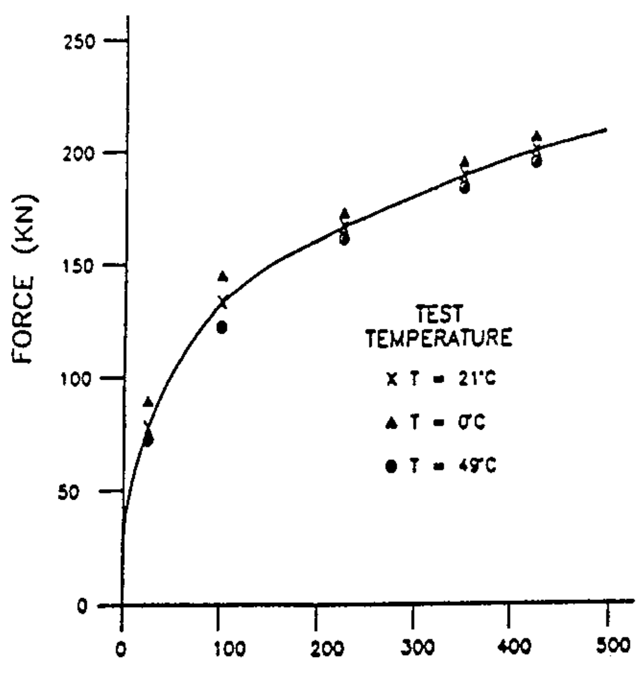

Figure 12 Force-Velocity Relation of 1/6 Scale Prototype Fluid Damper of San Bernardino County Medical Center.

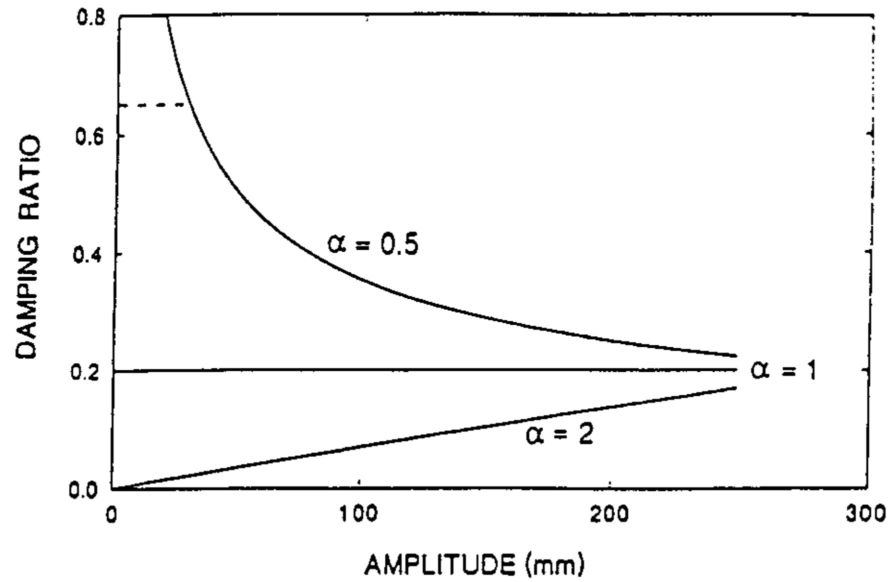

Figure 13 Damping Ratio of Systems with Nonlinear Fluid Dampers as Function of Amplitude of Motion.

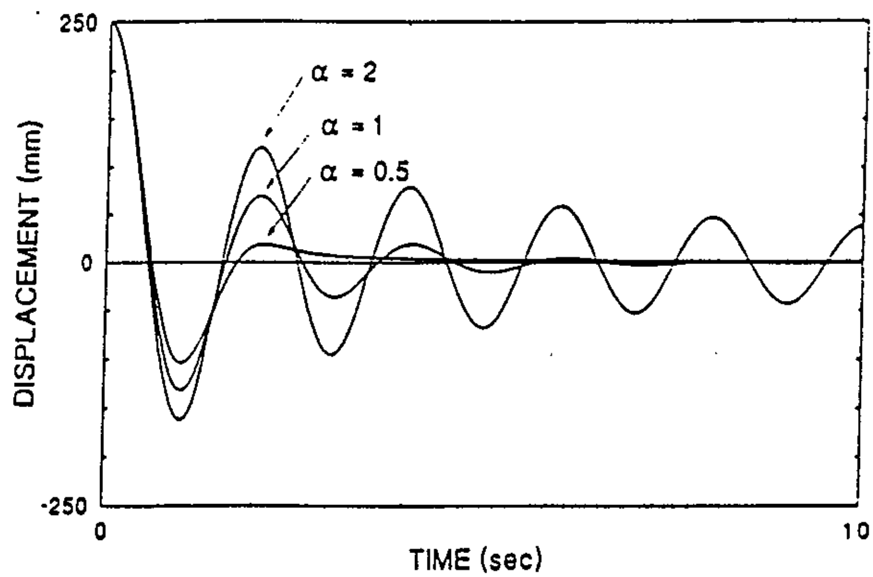

Figure 14 Time Histories of Motion of Systems with Nonlinear Fluid Dampers when Released from an Initial Displacement.

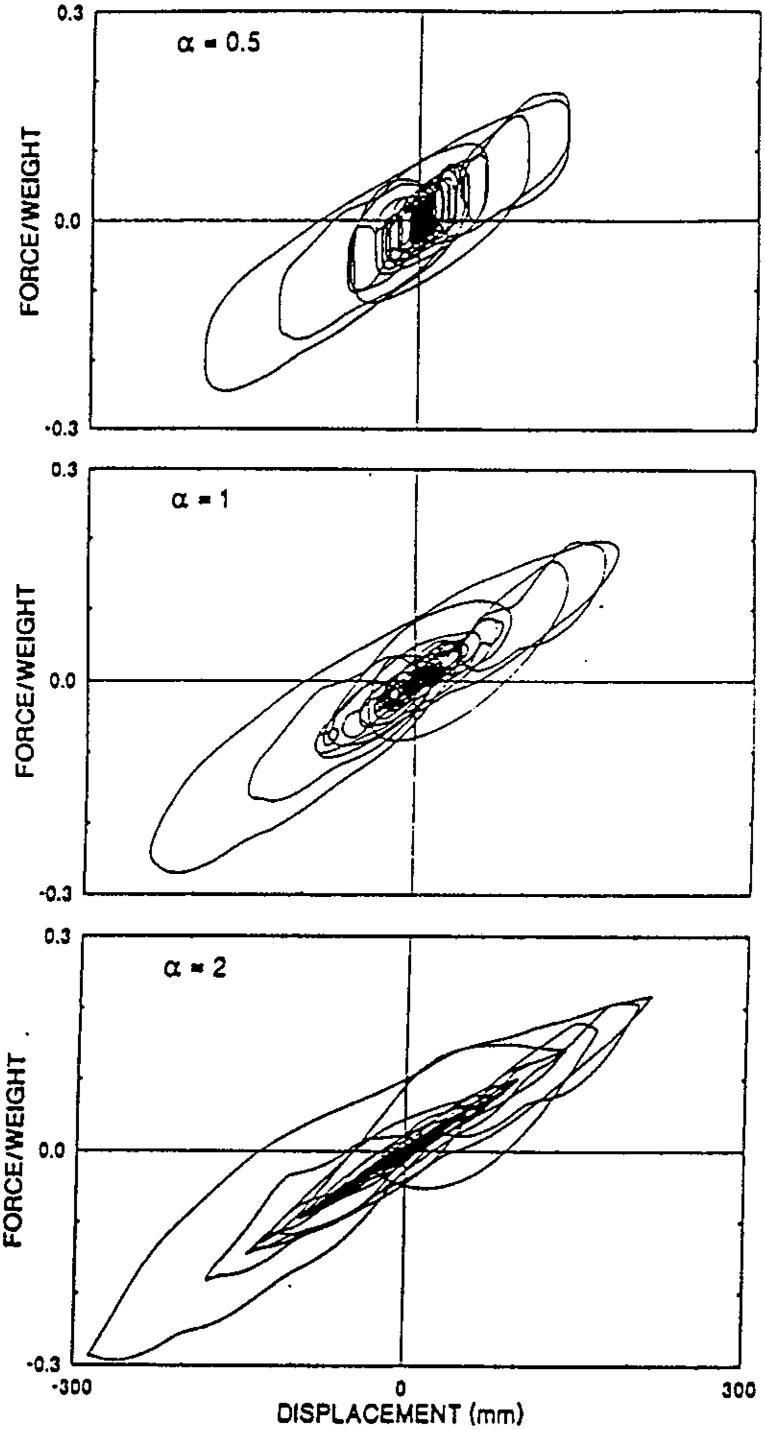

Figure 15 Force-displacement Loops of Response of Systems with Nonlinear Viscous Dampers when Subjected to the 1940 El Centro, Component S00E Earthquake, Scaled to 0.68g.

200%

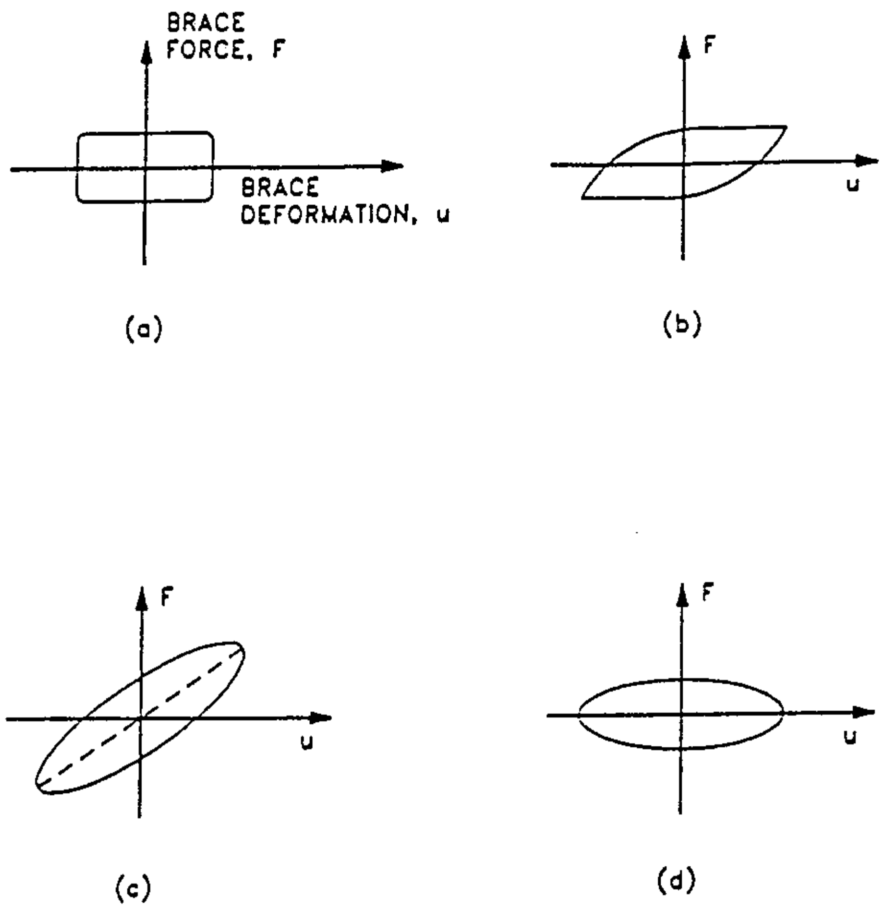

Figure 16 Force-displacement Loops of (a) Friction Device, (b) Steel Yielding Device, (c) Viscoelastic Device, (d) Viscous Device.

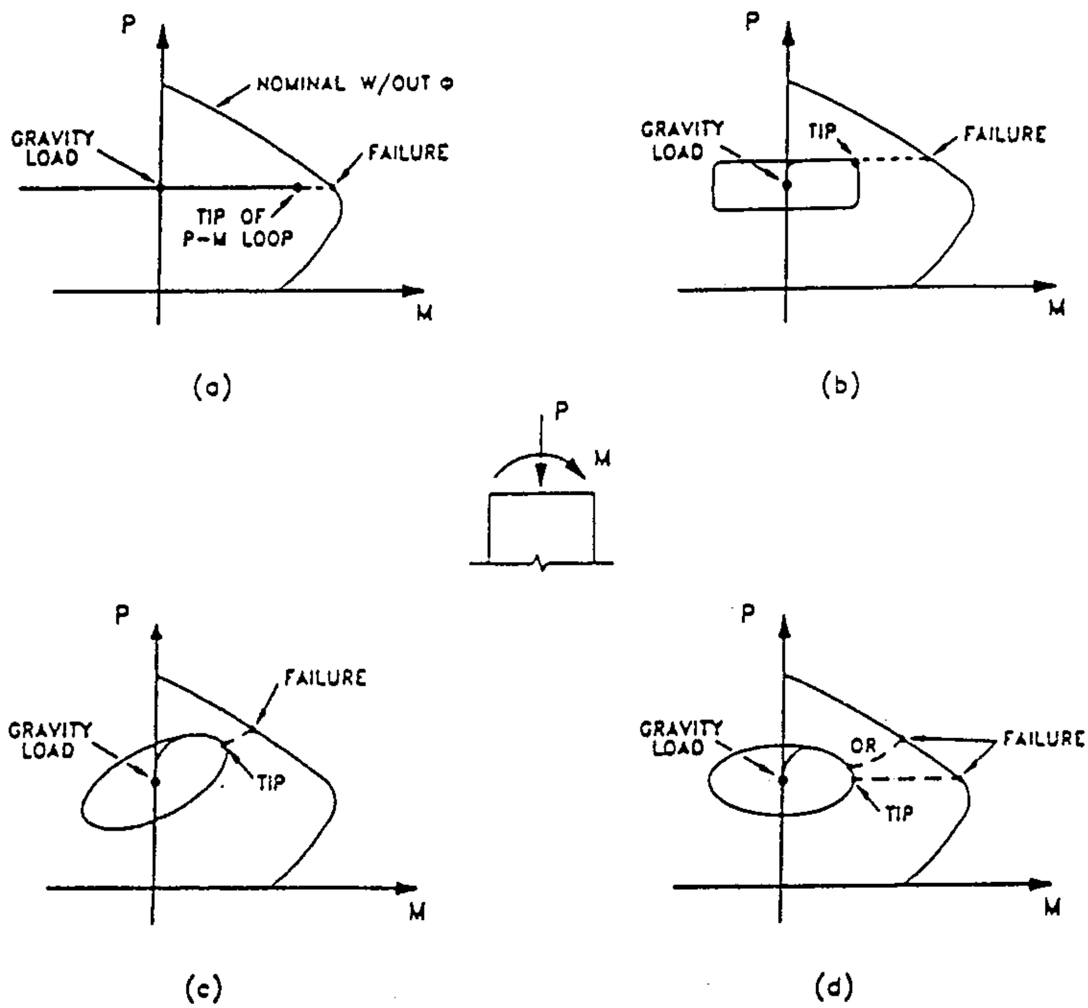

Figure 17 Column Interaction Diagrams and Axial Force- Bending Moment Loops during Seismic Excitation for (a) Moment-resisting Frame, (b) Friction Damped Frame, (c) Visco-elastically Damped Frame, and (d) Viscously Damped Frame.

CHAPTER XII

PASSIVE ENERGY DISSIPATION DEVELOPMENT IN U.S.

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ABSTRACT

Passive energy dissipation systems were developed in the United Stated either specifically for civil engineering applications or they evolved from devices and materials used in industrial, automotive, military and aerospace applications. Yielding steel and frictional devices were specifically developed for structural applications, whereas viscoelastic dampers and fluid viscous devices were developed for other applications and adapted for structural applications.

FRICTION DAMPERS

The earliest work on the development of friction dampers for reducing seismic motions in buildings appears to have been that of Keightley (1977,1979) at Montana State University. The friction dampers of Keightley consisted of steel plates clamped together with bolts and belleville washers. Various forms of lubricants were used to prevent locking of the interfaces. Of these only powdered oil shale was found to be satisfactory. Keightley's work was concluded with a number of unanswered questions and suggestions for future research. The questions on the possible relaxation of the clamping assembly, the long-term stability of the lubricant and corrosion of the steel to steel sliding interface could have prevented the use of this device today.

In the late 1970's the firm of Severud, Perrone, Sturn and Bendel of New York has installed two large friction dampers between the existing structure of the Gorgas hospital in the Panama Canal Zone and two exterior massive concrete pylons.

Experimental studies of slotted bolted connections started at San Jose State University and proceeded approximately concurrently with the research of Keightley. Fitzgerald (1989) reported on the results of this study. This slotted bolted connection consisted of a gusset plate, two back-to-back channels sections, cover plates and bolts with belleville washers as shown in Figure 1. The figure shows also typical force-displacement loops obtained in tests of the device. Recently, Grigorian (1993) conducted tests of a similar slotted bolted connection which consisted of a brass to steel sliding interface. Figure 2 shows a schematic of this device together with a representative force-displacement loop.

Constantinou (1991) described another friction device of which the interface consisted of graphite impregnated bronze in contact with stainless steel. Figure 3 shows the device and representative force-displacement loops. One should note the exceptional stability of the properties of the device over 200 cycles of testing (total travel = 20.3 m at peak velocity of 25 mm/s). This was the result of proper selection of the materials forming the interface and the use of graphite as solid lubricant.

Fluor Daniel developed a frictional device called Energy Dissipating Restraint (EDR). Shown in Figure 4, this device is characterized by self-centering capability as demonstrated in the loops of Figure 4 (Nims 1993).

The described devices utilize sliding interfaces consisting of steel on steel, brass on steel and graphite impregnated bronze on stainless steel. The composition of the interface is of paramount importance for ensuring the longevity of the device. Carbon and low allow steels (common steel) will corrode and thus the frictional properties of steel to steel interfaces will change with time. However, brass and bronze when in contact with common steel promote severe additional corrosion of steel and such interfaces should be avoided. Only stainless steels with high content of chromium do not suffer additional corrosion when in contact with brass or bronze (BSI 1979).

VISCOELASTIC DEVICES

Viscoelastic materials (acrylic polymers) have been originally developed for surface damping treatments (Nashif 1985). Devices made of bonded viscoelastic layers were developed by the 3 M Company and used in wind vibration control applications. The devices have been extensively studied for applications of seismic energy dissipation (Lin 1991, Aiken, 1993, Chang 1993, Lobo 1993).

Viscoelastic dampers exhibit viscoelastic solid behavior with strong dependencies on temperature, frequency and amplitude of motion. Particularly, the temperature dependency of these devices is an important design consideration and needs to be explicitly modeled for the dynamic analysis of viscoelastically damped structures. Kasai (1993) presented a fractional derivative formulation with temperature effects of the constitutive relation of the 3M viscoelastic material. The formulation is capable of capturing the viscoelastic and temperature effects with very good accuracy. Figure 5 demonstrates the accuracy of the model.

The 3M viscoelastic devices are for use as energy dissipating braces (see lecture notes on "Principles of Friction, Viscoelastic, Yielding Steel and Fluid Viscous Dampers: Properties and Design". A different approach to the use of viscoelastic materials has been proposed by the Lorant Group in Phoenix, Arizona and studied by Hsu (1992). Figure 6 shows a detail of a beam to column connection which incorporates viscoelastic materials. It has been used at a 2-story building in Phoenix, Arizona.

METALLIC DEVICES

A number of yielding steel devices has been tested at U.C. Berkeley in the late 1970's for use in seismic isolation systems and as damping supports for piping systems (Kelly 1980). While none of these devices was used in seismic isolation systems in the U.S., modifications of these devices have been recently studied for applications of energy dissipation. The ADAS devices are X-shaped double-clamped steel devices which have been tested as energy dissipation devices in buildings (Bergman 1987, Whittaker 1989). Figure 7 shows a hysteretic loop of a tested ADAS device (Whittaker 1989). The device exhibits stable hysteretic behavior for a large number of cycles. Repeated yielding of the device leads to fatigue failure.

Shape memory alloys have been studied at the University of California and the University at Buffalo (Whitting 1992). Materials such as Nitinol (nickel-titanium) and Cu-Zn-Al (copper-zinc-aluminum) undergo reversible phase transformation when deformed, so that they exhibit hysteretic behavior without yielding. The behavior of these materials is very desirable (hysteresis without yielding), however they are currently prohibitively expensive.

FLUID VISCOUS DAMPERS

Fluid dampers which operate by fluid flow through orifices were invented by Ralph Peo of Buffalo, N.Y. in 1925 and used in automotive applications. Taylor Devices of New York have been manufacturing such devices since 1955 with over two million units produced since then. These devices have been used in shock and vibration isolation systems of military and aerospace hardware, as wind dampers, as crane buffers and recently have been studied as energy dissipating devices in buildings and bridges (Constantinou 1992, 1993, Tsopelas 1994).

A variety of designs of fluid dampers has been developed in the United States. Figure 8 illustrates the four basic design characteristics. The fluidic device uses specially shaped orifices to achieve a force output

$$F = C|\dot{u}|^{\alpha} sgn(\dot{u}) \tag{1}$$

where F = force, C = damping constant, $\dot{u}$ = velocity and α = coefficient in the range of 0.5 to 2. The value α = 2 is achieved with cylindrical orifices, a performance which is typically unacceptable. A value α = 0.5 is particularly effective in attenuating high velocity pulses, as those expected in near fault earthquake excitations. A value of α = 1 results in linear viscous behavior which is usually desirable in applications of seismic energy dissipation. Figure 9 shows recorded force-displacement loops of a device with α = 0.5 from tests conducted at the University at Buffalo. This device was a scaled prototype of the dampers of the San Bernardino County Medical Center, an isolated five-building complex in California (see Section on Principles of Friction, Viscoelastic, Yielding Steel and Fluid Viscous Dampers: Properties and Design). The test consisted of three cycles of sinusoidal displacement at frequency of 1.082 Hz and amplitude of 63 mm (peak velocity = 432 mm/s). The temperature of testing was 0, 21 and 49°C. It may be seen that the behavior of the device is nearly unaffected by temperature.

The metering tube and metering pin designs can produce force output of the type

$$F = C|\dot{u}|^{2} f(u) sgn(\dot{u}) \tag{2}$$

where f(u) is a function of displacement. The design can be effective when tuned for a specific displacement signature. The pressure responsive valve design uses multiple spring loaded poppet valves to achieve a force output of the type of Equation (1). However, it has limited life due to the several moving parts in its design.

APPLICATION OF PASSIVE ENERGY DISSIPATION SYSTEMS

Passive energy dissipation systems for seismic motion reduction have been applied at the Wells Fargo Bank in San Francisco. This two-story structure suffered damage during the 1989 Loma Prieta earthquake and in 1992 it was retrofitted by the use of ADAS elements (Fierro 1993).

A two-story new school building in Phoenix, Arizona has been constructed in 1992 with is beam to column connections incorporating viscoelastic materials as shown in Figure 6. Furthermore, retrofit of the Santa Clara County Building in San Jose, California started in 1993. This 14-story steel building with exterior concrete core will have viscoelastic dampers as braces in its steel part. The Travelers Hotel, a landmark hotel built in the 1920's in Sacramento, California has been designed with fluid viscous dampers as part of its seismic retrofit scheme. Construction has not yet started.

While growth and development in this field continues, energy dissipating systems are considered for retrofit and new building and. bridge applications in California and elsewhere. Currently design specifications for structures incorporating passive energy dissipating devices exist. Specifically, the Structural Engineers Association of Northern California developed "Tentative Seismic Design Requirements for Passive Energy Dissipation Systems. These requirements will eventually become part of the Uniform Building Code. The Technical Subcommittee 12 of the Building Seismic Safety Council developed provisions for "Passive Energy Dissipation Systems", which have been approved for incorporation into the 1994 NEHRP (National Earthquake Hazards Reduction Program) Recommended Provisions for the Development of Seismic Regulations for New Buildings. Furthermore, the New Technologies team of the Applied Technology Council (ATC) project No. 33 is currently developing guidelines for the design of energy dissipation systems, which will become part of the "NEHRP Recommended Guidelines for the Seismic Rehabilitation of Existing Buildings".

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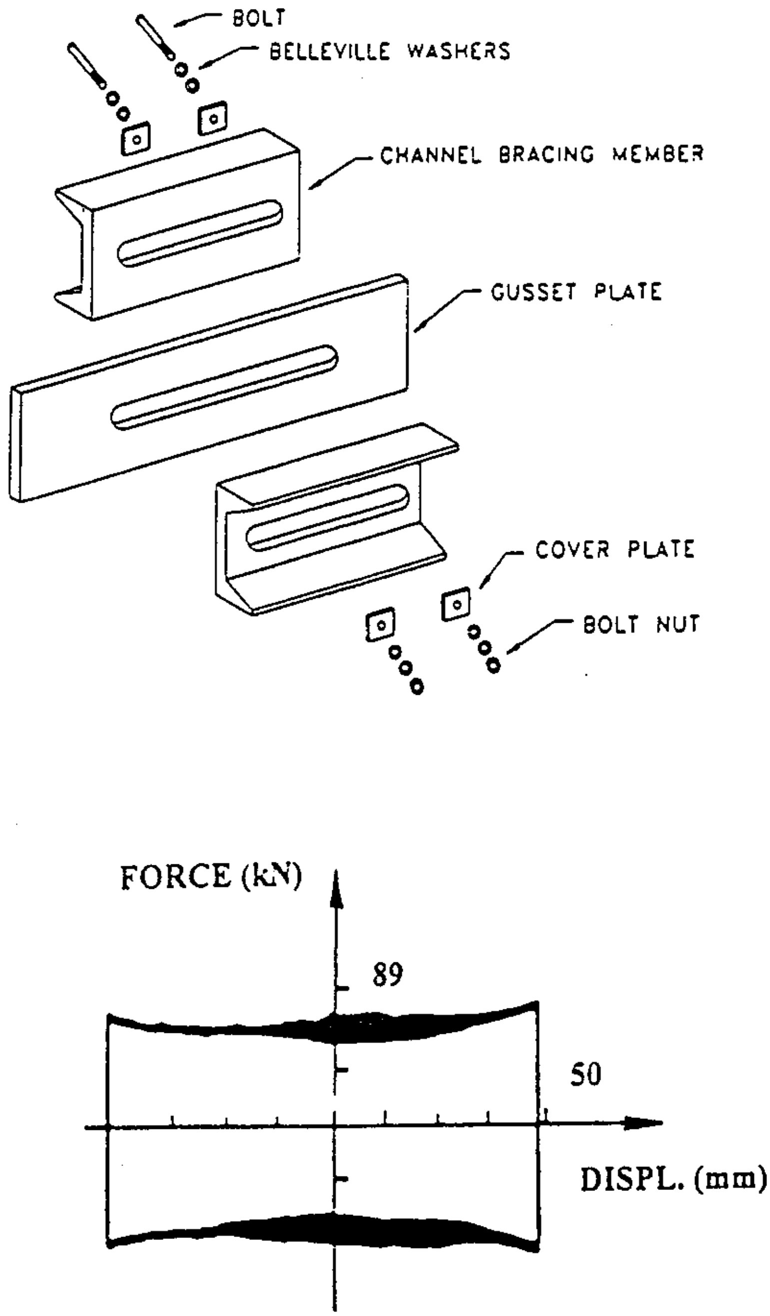
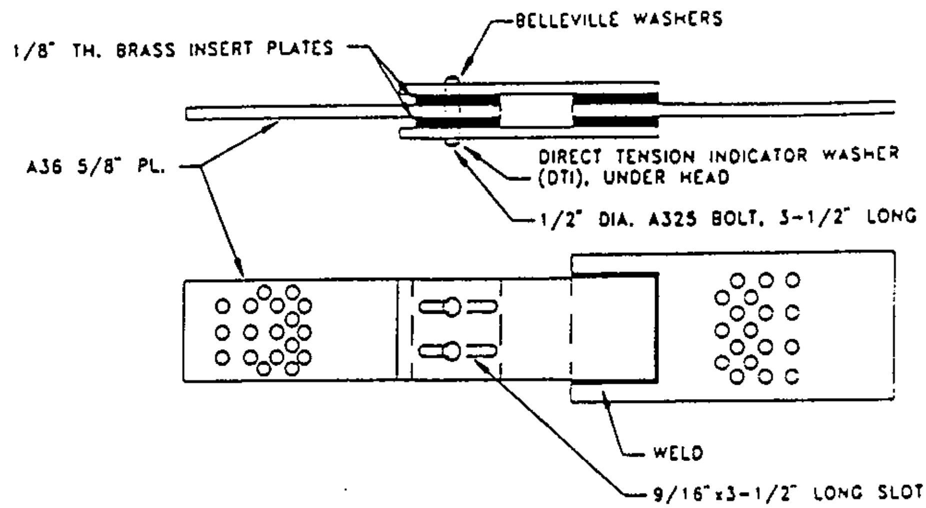


Figure 1 Slotted Bolted Connection of Fitzgerald (1989) and Typical Force-Displacement Loop.



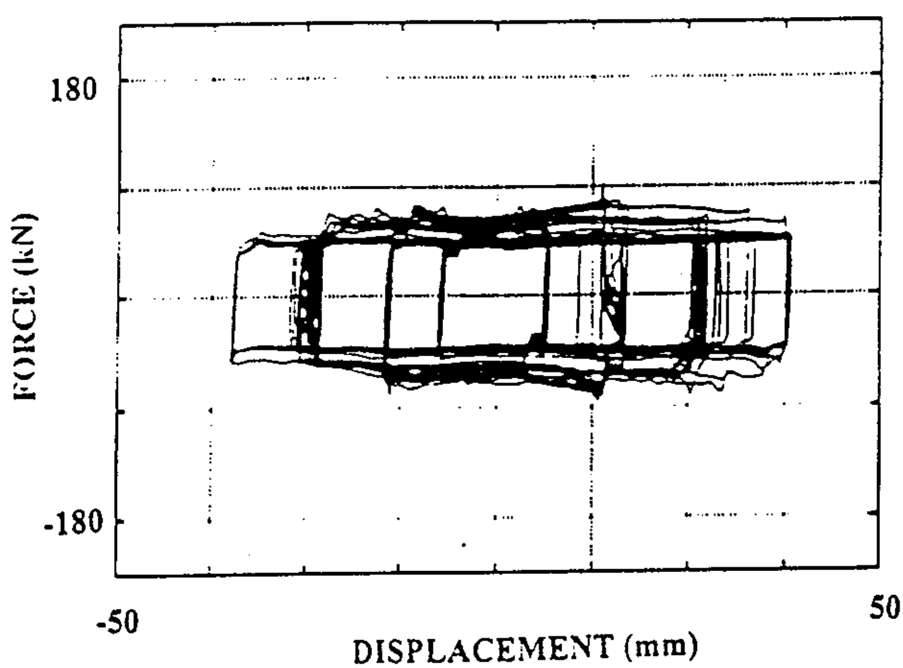


Figure 2 Slotted Bolted Connection of Grigorian (1993) and Typical Force-Displacement Loop.

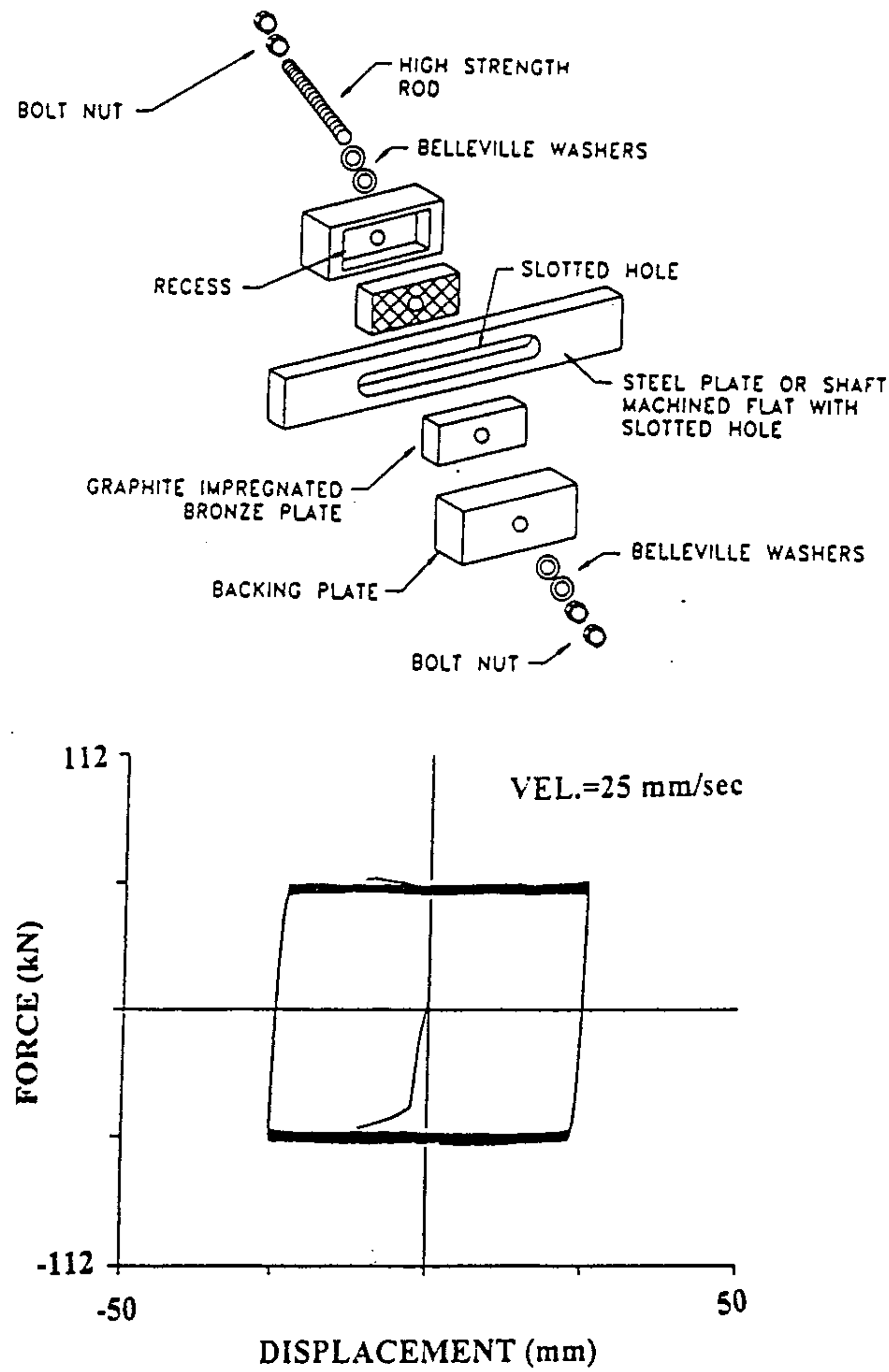


Figure 3 Friction Device of Constantinou (1991) and Force-Displacement Loop in 200-cycle Test.

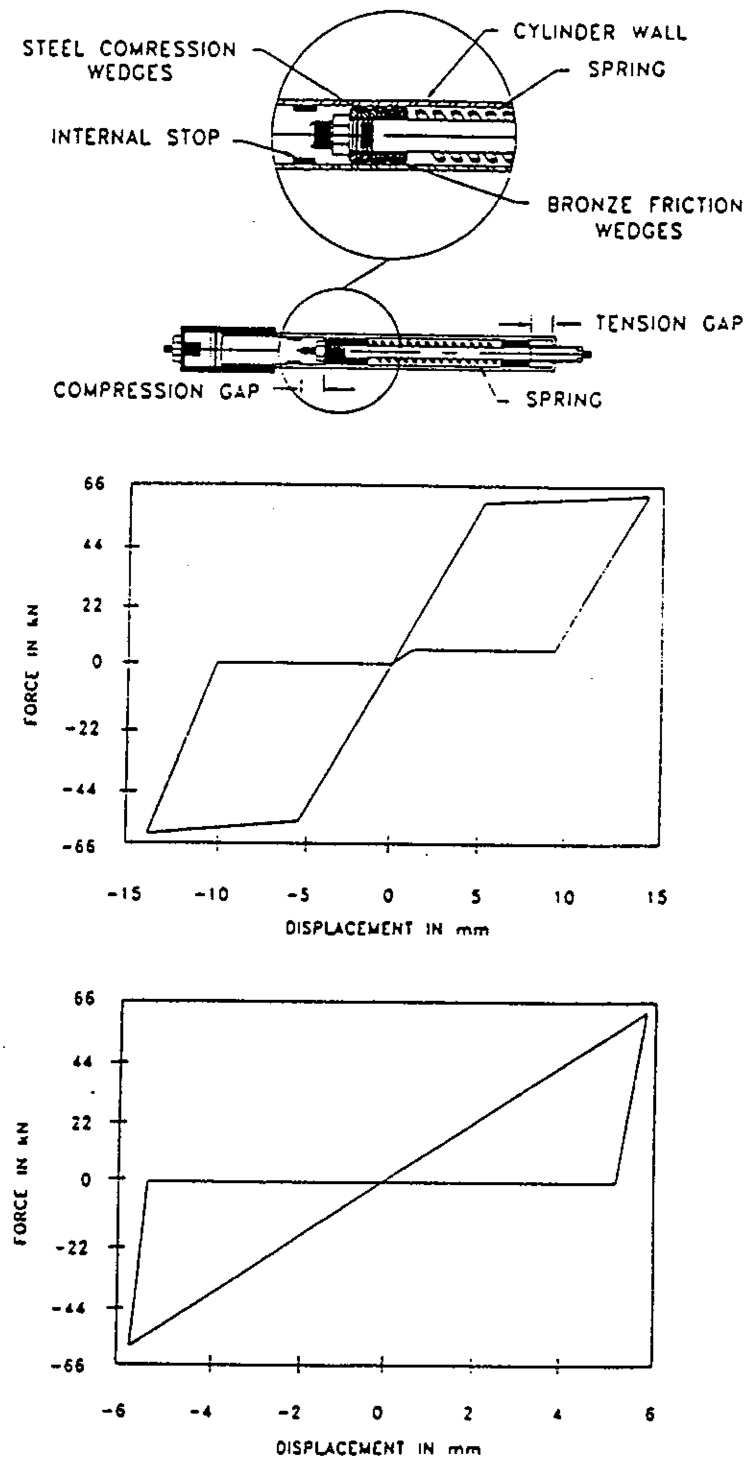


Figure 4 Energy Dissipating Restraint and Representative Force-Displacement Loops (from Nims 1993).

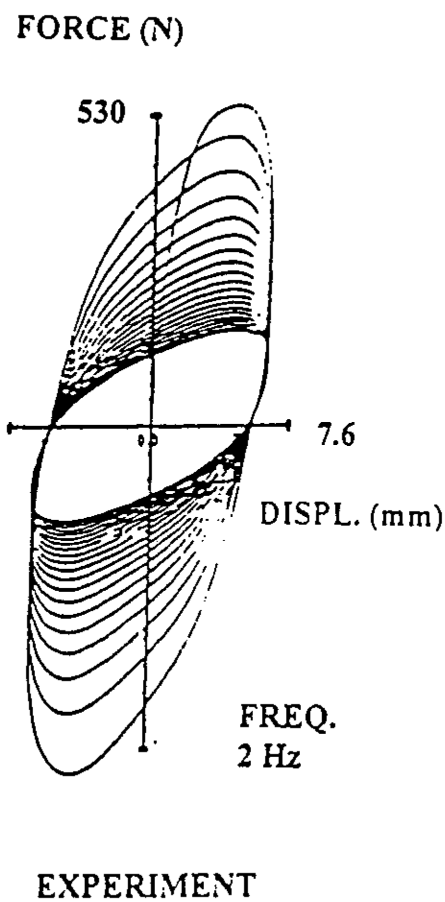


Figure 5 Analytical and Experimental Force-Displacement Loops of Viscoelastic Damper at Temperature of 24°C (from Kasai 1993).

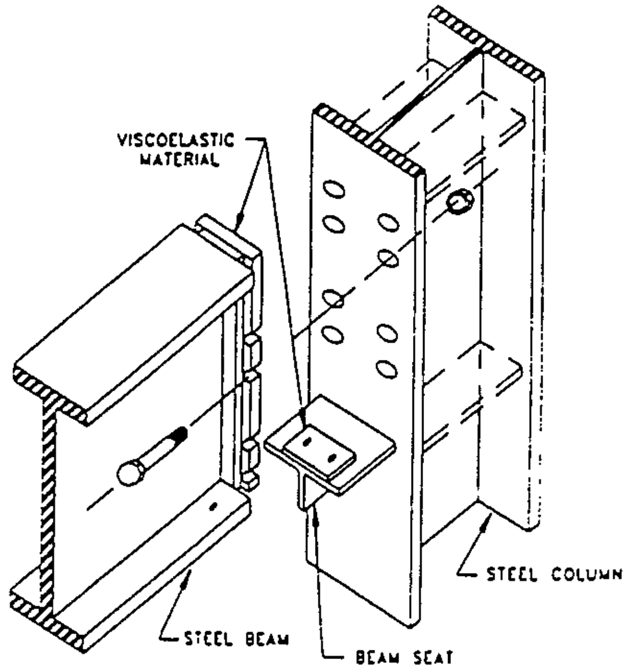


Figure 6 Detail of Beam to Column Connection with Viscoelastic Material.

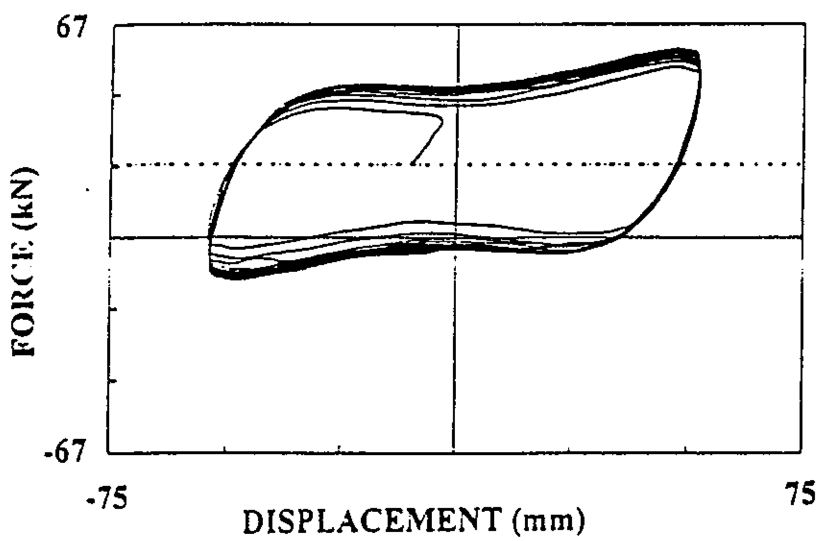


Figure 7 Force-Displacement Loop of ADAS Element (from Whittaker 1989).

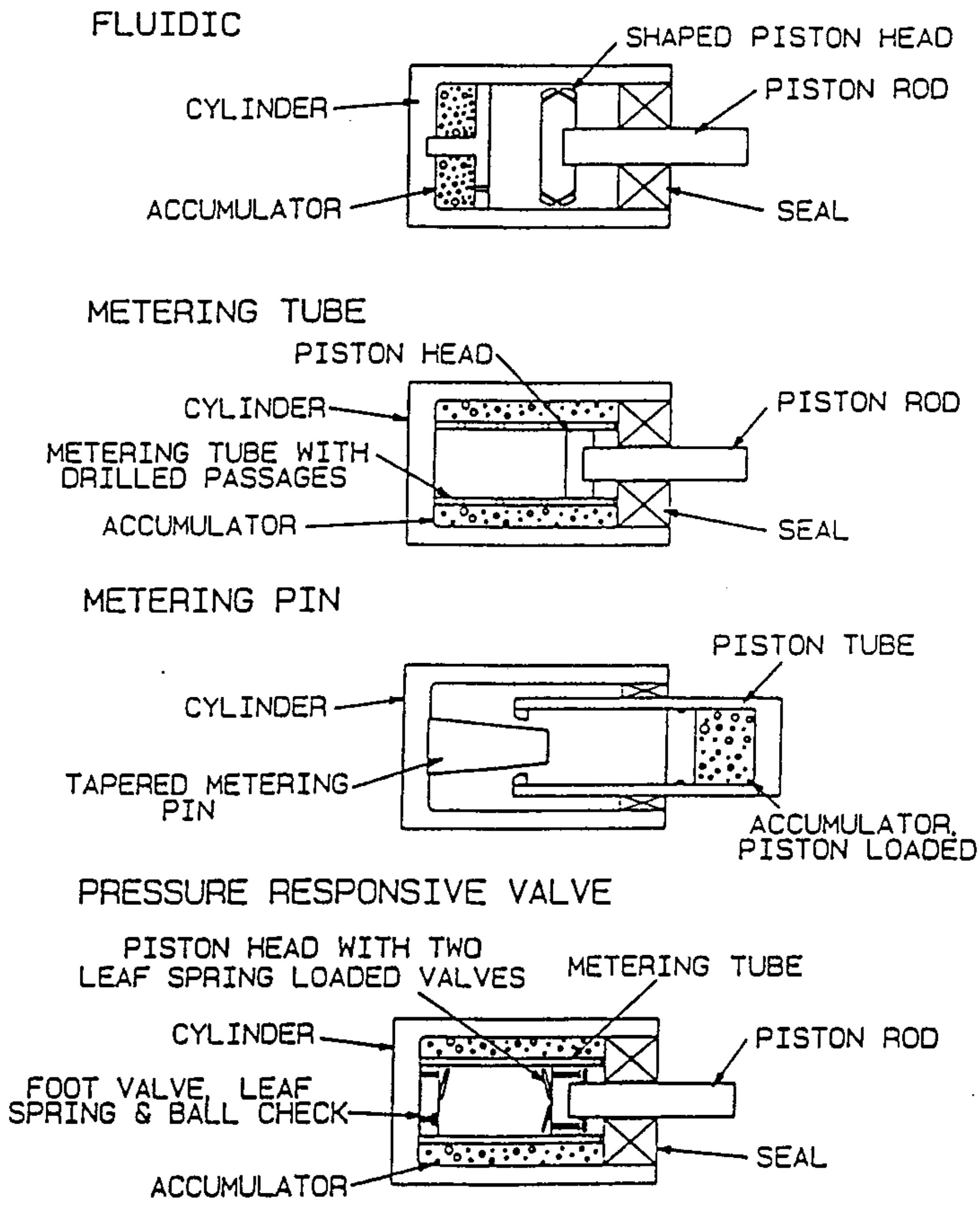


Figure 8 Design Characteristics of Fluid Dampers.

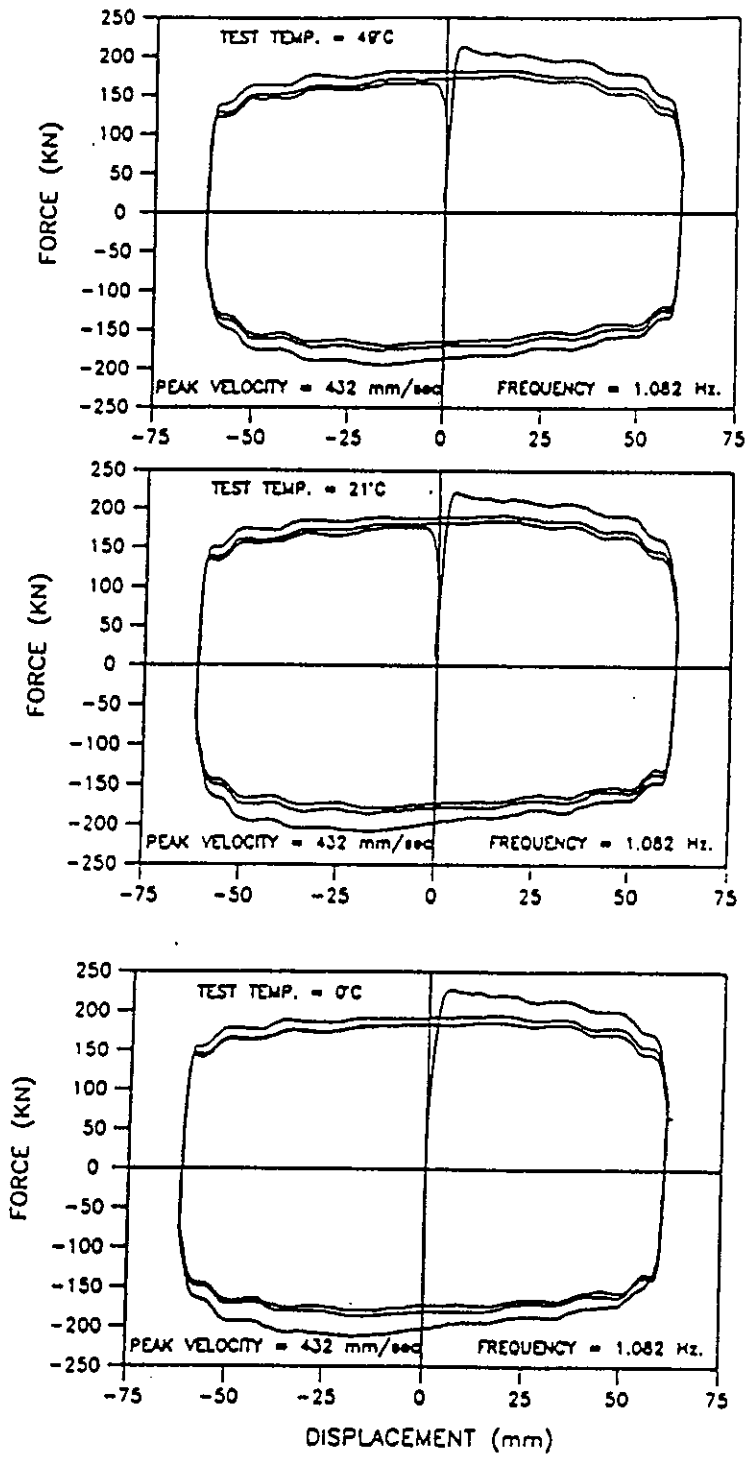


Figure 9 Force-Displacement Loops of Nonlinear Viscous Fluid Damper (α = 0.5).