SEISMIC RESPONSE OF STRUCTURES WITH SUPPLEMENTAL DAMPING

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SUMMARY

This paper presents a review of supplemental damping devices used for the control of the seismic response of structures. The mechanical properties of these devices are discussed and considerations in the design of energy absorbing systems are presented.

1. INTRODUCTION

Many methods have been proposed for achieving the optimum performance of structures subjected to earthquake excitation. The conventional approach requires that structures passively resist earthquakes through a combination of strength, deformability, and energy absorption. The level of damping in these structures is typically very low and therefore the amount of energy dissipated during elastic behavior is very low. During strong earthquakes, these structures deform well beyond the elastic limit and remain intact only due to their ability to deform inelastically. The inelastic deformation takes the form of localized plastic hinges which result in increased flexibility and energy dissipation. Therefore, much of the earthquake energy is absorbed by the structure through localized damage of the lateral force resisting system. This is somewhat of a paradox in that the effects of earthquakes (i.e. structural damage) are counteracted by allowing structural damage.

An alternative approach to mitigating 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:

$$E = E_k + E_s + E_h + E_d \quad (1)$$

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 the 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 recently applied technique of seismic isolation [2-5] 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 two 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 [5].

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 [2, 4].

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 rubber-like materials.

2. ENERGY ABSORBING SYSTEM

This section presents a review of energy absorbing systems.

2.1. Friction Devices

A frictional device located at the intersection of cross bracing has been proposed by Pal [6, 7] and used in a building in Canada. 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.

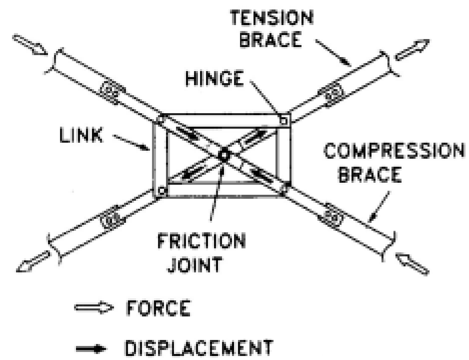

FIGURE 1
FRICTION DAMPING DEVICE (PALL 1982)

Experimental studies by Filiatrault [8] and Aiken [9] 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 storey 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 in Section 3.

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-storey steel frames. Furthermore, a 6-storey 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.

The Sumitomo friction device bears a similarity to a displacement control device described by Constantinou [10] for applications in bridge seismic isolation. These devices utilize a frictional interface consisting of graphite impregnated copper in contact with steel (Sumitomo device) or in contact with stainless steel (displacement control device). A difference exists in the use of stainless steel which is known not to suffer any additional corrosion when in contact with copper. In contrast, carbon and low alloy steels will suffer moderate to severe corrosion [11].

An experimental study of the Sumitomo damper was reported by Aiken [l2]. Dampers were installed in a 9-storey 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 [6]. 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 inter-story drift in the friction damped structure to inter-story 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 inter-story 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.

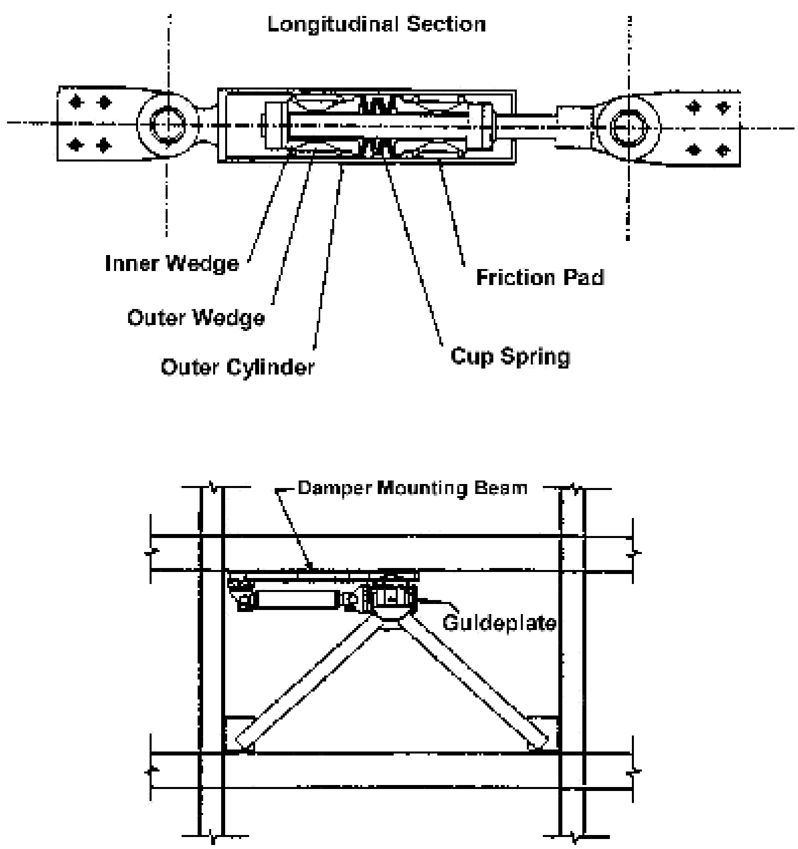

FIGURE 2
SUMITOMO FRICTION DAMPER AND INSTALLATION DETAIL
(AIKEN AND KELLY 1990)

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 $0{\cdot}12W$ (W = model weight) at the first storey and it reduced to about $0{\cdot}\,05W$ at the top storey.

Another friction device, proposed by Fitzgerald [l3], utilizes slotted bolted connections in concentrically braced connections. Component tests demonstrated stable frictional behavior.

2.2. 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. This eccentrically-braced frame [14] 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 [15, l6]. Some of these devices were tested at U.C. Berkeley as parts of seismic isolation systems17 and similar ones were widely used in seismic isolation applications in Japan [18].

Tyler [l9] described tests on a steel element fabricated from round steel bar and incorporated in the bracing of frames. Figure 3 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 an “added damping and stiffness” (ADAS) device has been studied by Whittaker [20]. The device consists of multiple x-steel plates of the shape shown in Figure 4 and installed as illustrated in the same Figure. The similarity of the device to that of Tyler [15] and Kelly [l7] 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-storey steel model structure by Whittaker [20] 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 inter-story drifts in the structure with ADAS elements to inter-story 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.

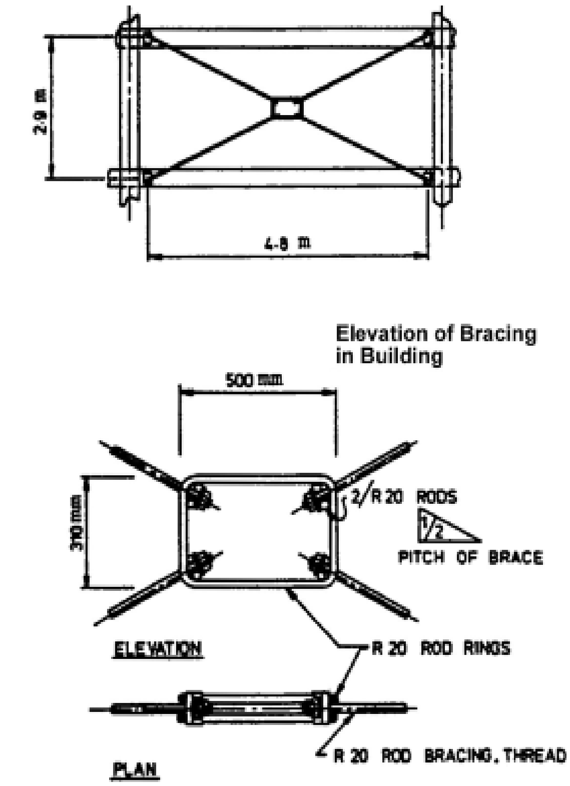

FIGURE 3
DETAILS OF A YIELDING STEEL BRACING SYSTEM IN A BUILDING IN NEW ZEALAND (TYLER 1985)

Ratios of recorded base shears in the structure with ADAS elements to base shears in the moment-resisting frame were in the range 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 4). 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-storey concrete building in San Francisco.

Various devices whose behavior is based on the yielding properties of mild steel have been implemented in Japan [21].

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-storey and a 9-storey 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-storey Agastache Headquarters Building in Tokyo.

Obayashi Corporation developed a steel plate device which is installed in a manner similar to the ADAS elements (Figure 4). The plate is subjected to shearing action. It has been installed in the Sumitomo Irufine Office Building, a 14-storey steel structure in Tokyo.

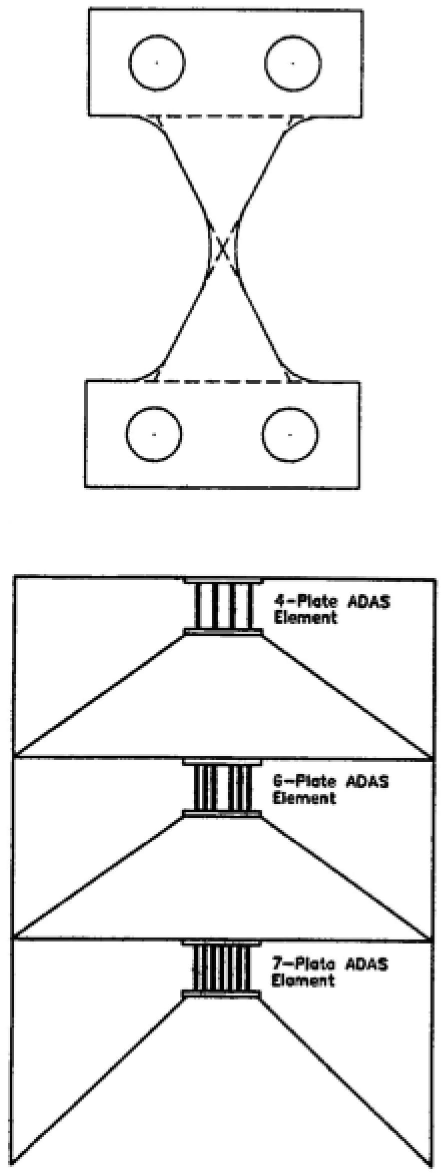

FIGURE 4
ADAS X-SHAPED STEEL PLATE AND INSTALLATION DETAIL
(WHITTAKER, ET AL. 1989)

2.3. Viscoelastic Dampers

Viscoelastic dampers, made of bonded viscoelastic layers (acrylic polymers), have been developed by the 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).

The suitability of viscoelastic dampers for enhancing the earthquake resistance of structures has been experimentally studied by Lin [22] Aiken [12] and Chang [23]. Figure 5 illustrates a viscoelastic damper and its installation as part of the bracing system in a structure.

The behavior of viscoelastic dampers is controlled by the behavior in shear of the viscoelastic layers. In general, this material exhibits viscoelastic solid behavior with both its storage and loss moduli being dependent on frequency and temperature.

Typical viscoelastic material properties were reported by Chang [23]. At a temperature of 70 degrees F (21 degrees C) and shear strain of 0·05, the properties of storage and loss shear moduli were both approximately equal to 55 psi (0·38 MPa) at a frequency of 0·1 Hz and equal to about 450 psi (3·11 MPa) at a frequency of 4 Hz. At a temperature of 90 degrees F (32 degrees C), these values reduced to about 30 psi (0·21 MPa) at a frequency of 0 1 Hz and 185 psi (1·28 MPa) at a frequency of 4 Hz. Furthermore, these values reduced by an additional 10% to 20% at shear strains of 0·20.

The shake table tests of Lin [22] Aiken [l2] and Chang [23] demonstrated that significant benefits could be gained by the use of viscoelastic dampers. The tests of Aiken [12] showed inter-storey drift reductions in comparison to those of the moment resisting frame which were slightly better than those of the friction (Sumitomo damper) damped structure. The ratio of inter-story drift in the viscoelastically damped structure to the inter-story drift in the moment resisting frame was between 0·5 and 0·9. Base shear forces in the viscoelastically damped structure were about the same as in the moment resisting frame.

The results of Chang [23] are particularly interesting because tests were performed in a range of temperatures between 77 degrees F and 108 degrees F (25 degrees C and 42 degrees C). The addition of viscoelastic dampers resulted in increases of the natural frequency and corresponding damping ratio of the 5-storey model structure from 3·17 Hz to 3·64 Hz and from 0·0125 to 0·15, respectively, at a temperature of 77 degrees F (25 degrees C). At 108 degrees F (42 degrees C) temperature, the increases were from 3·17 Hz to 3·26 Hz and from 0·0125 to 0·053, respectively.

The modification of the structural damping at the temperature of 108 degrees F (42 degrees C) is rather small. Yet, recorded inter-storey drifts in the viscoelastically damped structure were typically about 60% of those in the moment resisting frame. However, this substantial reduction is merely a result of the very low damping capacity of the moment resisting frame. If the moment resisting frame had a realistic damping ratio, the reduction would have been less dramatic.

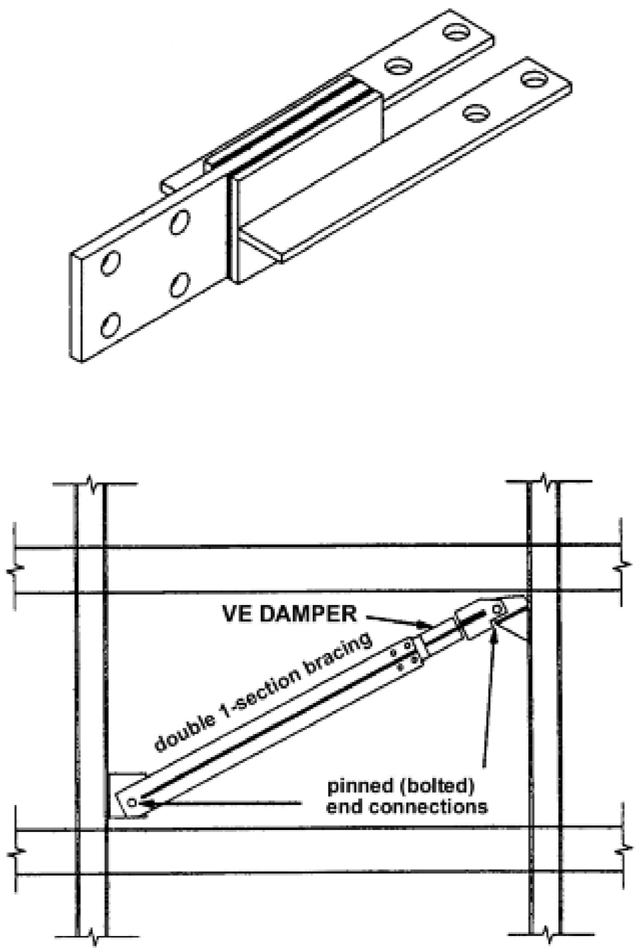

FIGURE 5
VISCOELASTIC DAMPER AND INSTALLATION DETAIL
(AIKEN AND KELLY 1990)

The temperature dependency of viscoelastic dampers appears to be a major concern which needs to be addressed at the design stage. An interesting problem may arise in a symmetric viscoelastically damped structure in which either the dampers on one face of the structure or the dampers in the upper floors are at a higher temperature. In effect, the viscoelastically damped structure now exhibits either asymmetry in plan or vertical irregularity.

Aiken [l2] reported several delamination failures of viscoelastic dampers during testing. The failures were attributed to the development of tensile stresses. It was recommended that the dampers should not be constructed as shown in Figure 5, but rather be fitted with a bolt directly through the damper, which prevents spreading of the steel plates.

Viscoelastic devices have 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 reported very recently by Hsu [24]. These devices have been installed in a 2-storey steel structure in Phoenix, Arizona.

The Hazuma 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.21 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 degrees F (0 degrees C) and 14 psi (0·1 MPa) and 8 psi (0·055 MPa), respectively at 113 degrees F (45 degrees C). Thus, the ability of the device to dissipate energy (expressed by the loss shear modulus) reduces by a factor of 50 in the temperature range 32 degrees F to 113 degrees F (0 degrees C to 45 degrees C).

Another viscoelastic device in the form of walls has been developed by the Shimizu Corporation [21]. 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-storey structure in Tokyo.

2.4. 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 the Sumitomo Construction Company [25] 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 similar to that of the GERB viscodampers used in applications of vibration and seismic isolation [26].

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

2.5. Fluid Viscous Dampers

Fluid viscous dampers which operate on the principle of fluid flow through orifices originated in the late 1950s for use in steel mills as energy absorbing buffers on overhead cranes. Variations of these devices were used as canal lock buffers, offshore oil rig leg suspensions, and mostly in shock isolation systems of aerospace and military hardware. Some large-scale applications of these devices include the following.

(a) *The West Seattle Swing Bridge:* Fluid dampers with a built-in hydraulic logic system could provide damping at two pre-determined levels. The logic system can determine if the bridge condition is normal or faulted. Under normal conditions, damping is very low. When a fault occurs, due to motor runaway, excessive current or wave loadings, or earthquakes, the device senses the higher than normal velocity and absorbs significant energy.

(b) *The New York Power Indian Point 3 Nuclear Power Plant:* Each nuclear generator is connected to the containment building walls by eight 300 kip (1·34 MN) capacity fluid dampers. The dampers are specifically designed for seismic pulse attenuation.

(c) *The Virginia Power North Ana Nuclear Station:* This is an application similar to that of the Indian Point 3 Plant, except that the dampers have 1000 kip (4·46 MN) capacity.

(d) Suppression of wind induces vibration of launching platforms: Such as those of the Space Shuttle and the Atlas and Saturn 5 missiles.

A particular fluid damper has been studied by the authors [27] The construction of this device is shown in Figure 6. 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 degrees F to 160 degrees (-40 degrees C to 70 degrees 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.

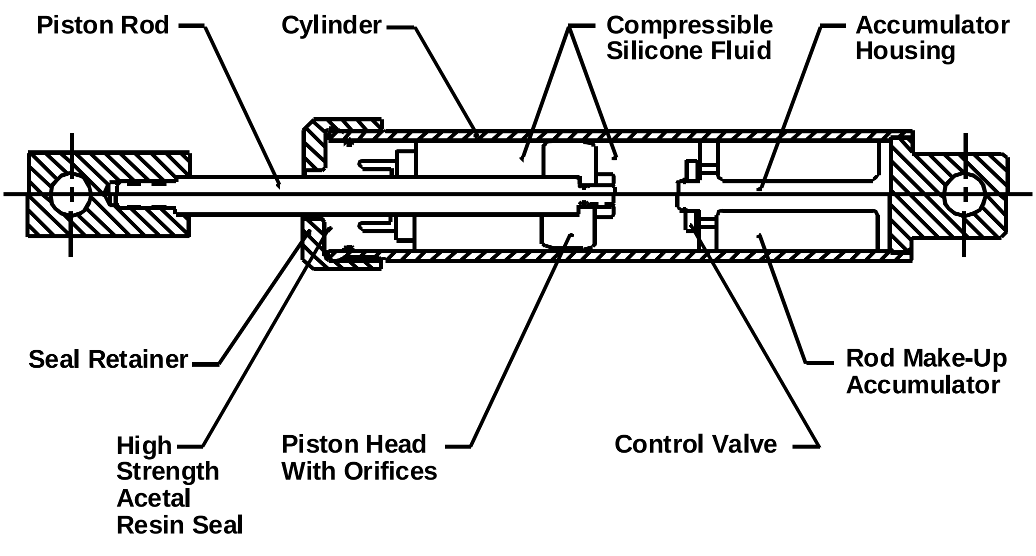

FIGURE 6
CONSTRUCTION OF FLUID VISCOUS DAMPER

The force that is generated by the fluid damper is due to a pressure differential across the piston head. Consider that the piston moves from left to right in Figure 6 (device subjected to compression force). Fluid flows from chamber 2 towards chamber 1. Accordingly, the damping force is proportional to the pressure differential in these two chambers. 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 [27] 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.

The force in the fluid damper may be expressed as

$$P = bp_{12}$$

where p_{12} is the pressure differential in chambers 1 and 2. Constant b is a function of the piston head area, A_p, piston rod area, A_r, area of orifice, A_1, number of orifices, n, area of control valves, A_2, and the discharge coefficient of the orifice, C_{d1}, and control valve, C_{d2}.

The pressure differential across the piston for cylindrical orifices is given by

$$\rho_{12} = \frac{\rho}{2n^2 C_{d1}^2} \left(\frac{A\,\rho}{A_1} \right)^2 \dot{u}^2 \operatorname{sgn}(\dot{u})$$

where ρ is the fluid density and $\dot{u}$ is the velocity of the piston with respect to the housing.

In cylindrically-shaped orifices, the pressure differential is proportional to the piston velocity squared. Such orifices are termed “square law” or “Bernoullian” orifices since (3) is predicted by Bernoulli’s equation. Bernoullian orifices produce damper forces which are proportional to velocity squared, a usually unacceptable performance.

The orifice design in the fluid damper tested by the authors [27] produces a force that is not proportional to velocity squared. The orifice utilizes a series of specially shaped passages to alter flow characteristics with fluid speed. It is known as “fluidic control orifice.” It provides forces which are proportional to $|\dot{u}|^{\alpha}$, where α is a predetermined coefficient in the range 0·5 to 2·0. 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. In earthquake engineering applications, a design with $\alpha = 1$ appears to be the most desirable. It results in essentially linear viscous behavior.

The suitability of fluid viscous dampers for enhancing the seismic resistance of structures has been studied by the authors [27]. Fluid dampers with an orifice coefficient = 1 were tested over the temperature range 32 degrees F to 122 degrees F (0 degrees C to 50 degrees C). The dampers tested exhibited variations of their damping constant from a certain value at room temperature (75 degrees F, 24 degrees C) to + 44% of that value at 32 degrees F (0 degrees C) to -25% of that value at 122 degrees F (50 degrees C). This rather small change in properties over a wide range of temperature is in sharp contrast to the extreme temperature of viscoelastic dampers.

The inclusion of fluid viscous dampers in the tested structures on a shake table resulted in reductions in storey 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 storey 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 linear viscous behavior of the fluid dampers tested.

3. CONSIDERATIONS IN THE DESIGN OF ENERGY ABSORBING SYSTEMS

The preceding review of energy absorbing systems demonstrates that these systems are capable of producing significant reduction of inter-story 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-resisting 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, 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 7 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 (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.

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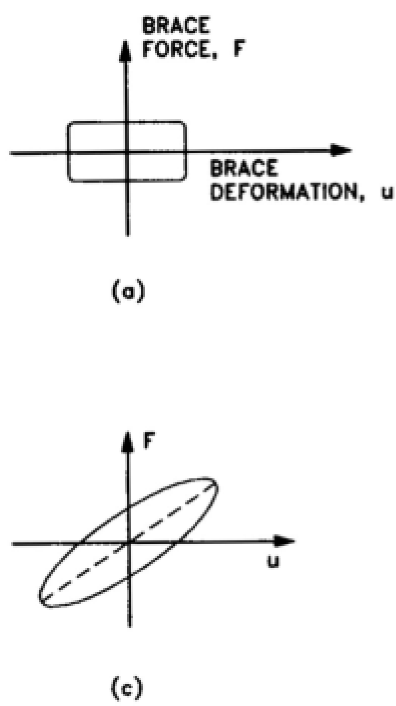

FIGURE 7
FORCE-DISPLACEMENT RELATION IN:

(a) FRICTION DEVICE **(b) STEEL YIELDING DEVICE**
(c) VISCOELASTIC DEVICE **(d) VISCOUS DEVICE**

The implications of this difference in behavior of energy absorbing devices are illustrated in Figure 8. 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 8 a. 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 8).

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.

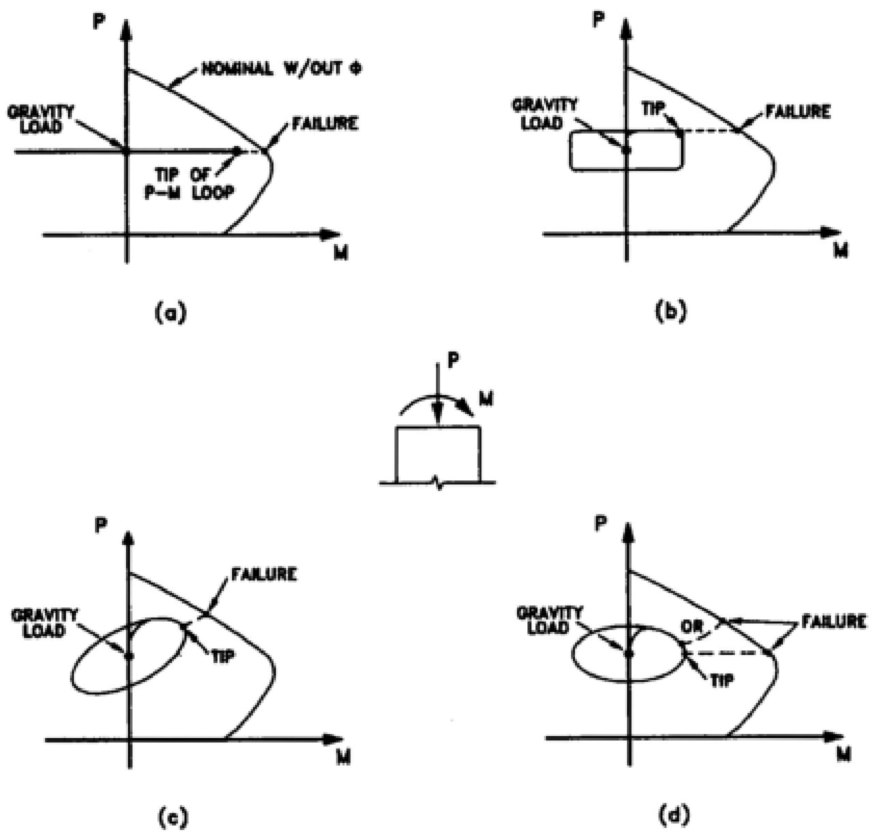

FIGURE 8
COLUMN INTERACTION DIAGRAMS AND AXIAL FORCE-BENDING MOMENT LOOPS DURING SEISMIC EXCITATION FOR:
(a) MOMENT-RESISTING FRAME **(b) FRICTION DAMPED FRAME**
(c) VISCOELASTICALLY DAMPED FRAME **(d) VISCOUSLY DAMPED FRAME**

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 column compression failure. 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.

To illustrate that the additional axial forces induced by energy absorbing devices are significant, we utilize the experimental results of Aiken [12] on the Sumitomo friction dampers. The structure tested was nine stories tall with two identical frames as shown in Figure 9. Let us assume that all friction dampers experience sliding. The forces in the elements, braces and columns are depicted in Figure 9. The additional interior 1st storey column axial force adds up to 16·71 kips (74·5 kN). The force in the column due to the weight of the structure is 12·75 kips (56·9 kN). The substantial additional axial load may be regarded as a result of the height of the structure (9-stories). Similar calculations with the 3-storey model structure with ADAS elements tested by Whittaker [20], resulted in additional axial load of only 14% of the gravity load.

The relation of the gravity load and total load in the 1st storey interior column of the 9-storey model to the capacity of the column is illustrated in the upper right corner of Figure 9. It may be observed that the gravity load amounts to only 9·2% of the column yield force and 16·8% of the allowable concentric axial load ($F_a = 0{\cdot}55F_y$). Furthermore, it should be noted that the column has a very low slenderness ratio so that almost maximum column capacity is available.

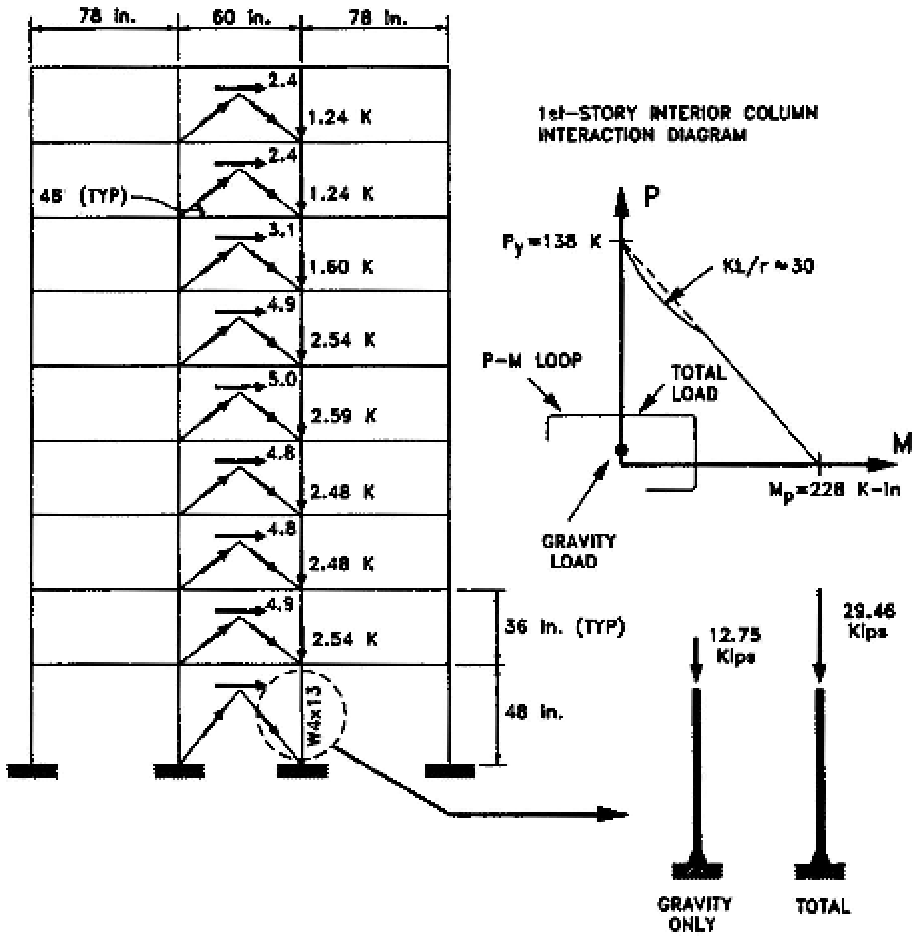

FIGURE 9
GRAVITY AND ADDITIONAL AXIAL LOAD IN INTERIOR COLUMN OF 9-STOREY MODEL STRUCTURE WITH ADDED FRICTION DAMPERS TESTED BY AIKEN AND KELLY 1990 (1 in. = 25·4 mm 1 kip = 4·5 kN)

The existence of design specifications is significant in the implementation of the technology of energy dissipating devices. Currently, such specifications do not exist. The absence of such specifications, while not a deterrent to the use of the technology, may prevent widespread use of the technology. This is equivalent to the experience in the United States with the use of the technology of seismic isolation [28].

Efforts for the development of regulations for the design and construction of structures incorporating passive energy dissipating devices are currently in progress by the Structural Engineers Association of California and by Technical Subcommittee 12 of the Building Seismic Safety Council. When developed, these regulations are expected eventually to become part of the Uniform Building Code and the NEHRP (National Earthquake Hazards Reduction Program) Recommended Provisions for the Development of Seismic Regulations for New Buildings, respectively.

4. CONCLUSIONS

Supplemental damping devices are capable of producing significant reductions of inter-story 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 linear viscous behavior.

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