# Experimental and Analytical Investigation of Seismic Response of Structures with Supplemental Fluid Viscous Dampers

by

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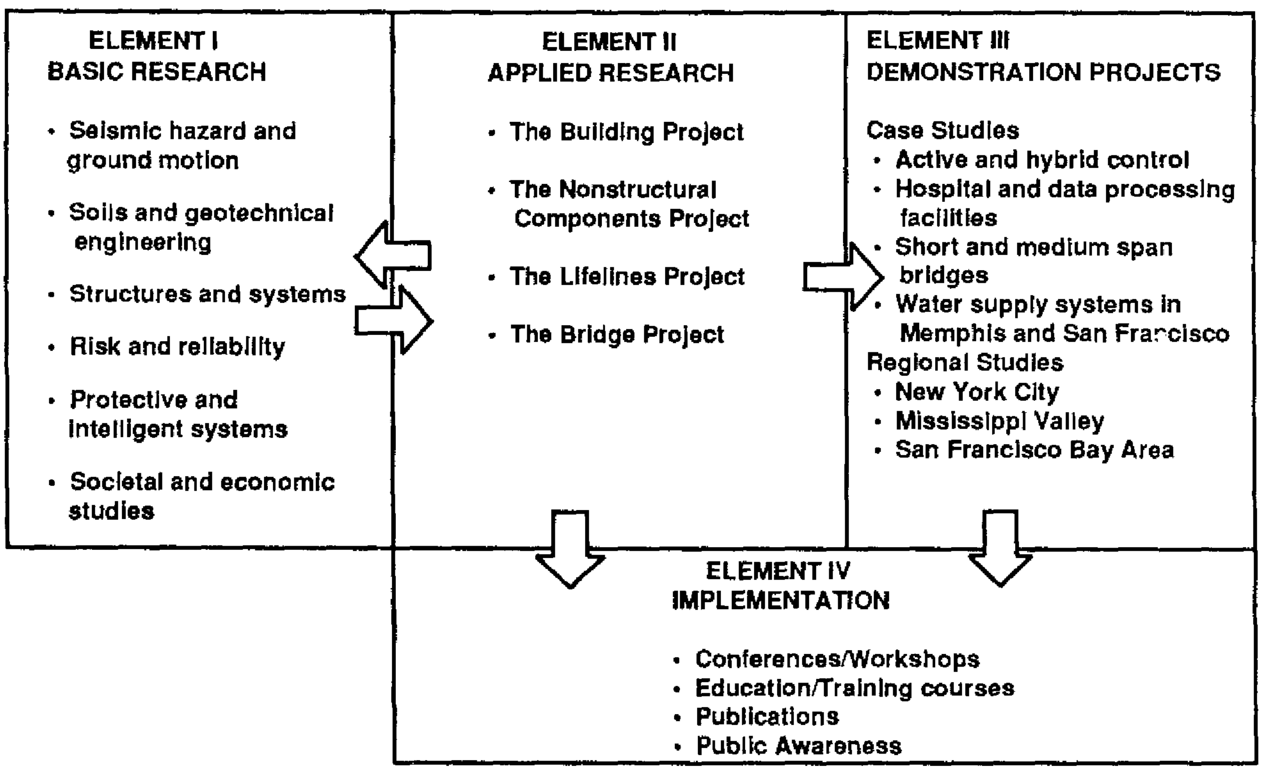
# PREFACE

The National Center for Earthquake Engineering Research (NCEER) was established to expand and disseminate knowledge about earthquakes, improve earthquake-resistant design, and implement seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures in the eastern and central United States and lifelines throughout the country that are found in zones of low, moderate, and high seismicity.

NCEER's research and implementation plan in years six through ten (1991-1996) comprises four interlocked elements, as shown in the figure below. Element I, Basic Research, is carried out to support projects in the Applied Research area. Element II, Applied Research, is the major focus of work for years six through ten. Element III, Demonstration Projects, have been planned to support Applied Research projects, and will be either case studies or regional studies. Element IV, Implementation, will result from activity in the four Applied Research projects, and from Demonstration Projects.




Research in the **Building Project** focuses on the evaluation and retrofit of buildings in regions of moderate seismicity. Emphasis is on lightly reinforced concrete buildings, steel semi-rigid frames, and masonry walls or infills. The research involves small- and medium-scale shake table tests and full-scale component tests at several institutions. In a parallel effort, analytical models and computer programs are being developed to aid in the prediction of the response of these buildings to various types of ground motion.

Two of the short-term products of the **Building Project** will be a monograph on the evaluation of lightly reinforced concrete buildings and a state-of-the-art report on unreinforced masonry.

The **protective and intelligent systems program** constitutes one of the important areas of research in the **Building Project**. Current tasks include the following:

1. Evaluate the performance of full-scale active bracing and active mass dampers already in place in terms of performance, power requirements, maintenance, reliability and cost.
2. Compare passive and active control strategies in terms of structural type, degree of effectiveness, cost and long-term reliability.
3. Perform fundamental studies of hybrid control.
4. Develop and test hybrid control systems.

*Recently, a number of innovative passive damping devices have been studied analytically and experimentally, both at NCEER and elsewhere, for structural applications in order to improve their seismic response performance. In this report, the performance of a fluid viscous damper has been investigated through component tests and earthquake simulation tests performed on one-story and three-story steel structures both with and without dampers. It is shown that the addition of supplemental dampers significantly reduces the structural response in terms of both interstory drifts and shear forces.*

## ABSTRACT

Many different supplemental energy dissipating devices have been proposed to assist in mitigating the harmful effects of earthquakes on structures. This report presents the results of a study on fluid viscous dampers.

A series of component tests with various dynamic inputs have been performed to determine the mechanical characteristics and frequency dependencies of the damper. In addition, temperature dependencies have been considered by varying the ambient temperature of the damper during component testing. Based on the component tests, a mathematical model has been developed to describe the macroscopic behavior of the damper.

Earthquake simulation tests have been performed on one-story and three-story steel structures both with and without dampers. The addition of supplemental dampers significantly reduces the response of the structure in terms of both interstory drifts and shear forces. The experimental response has been compared with the analytical response where the mathematical model of the damper is used to develop the equations of motion. The comparisons show very good agreement.

## ACKNOWLEDGEMENTS

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# SECTION 1
# INTRODUCTION

Many methods have been proposed for achieving 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 results 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 (Uang 1988)

$$E = E_k + E_s + E_h + E_d \qquad (1\text{-}1)$$

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 recently applied technique of seismic isolation (e.g., Buckle 1990, Kelly 1991, Mokha 1991, Constantinou 1991b) 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 (Constantinou 1991b).

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 (Buckle 1990, Mokha 1991).

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. These systems represent the topic of this report. A review of these systems follows.

## 1.1 Friction Devices

A frictional device located at the intersection of cross bracing has been proposed by Pall (1982, 1987) and used in a building in Canada. Figure 1-1 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

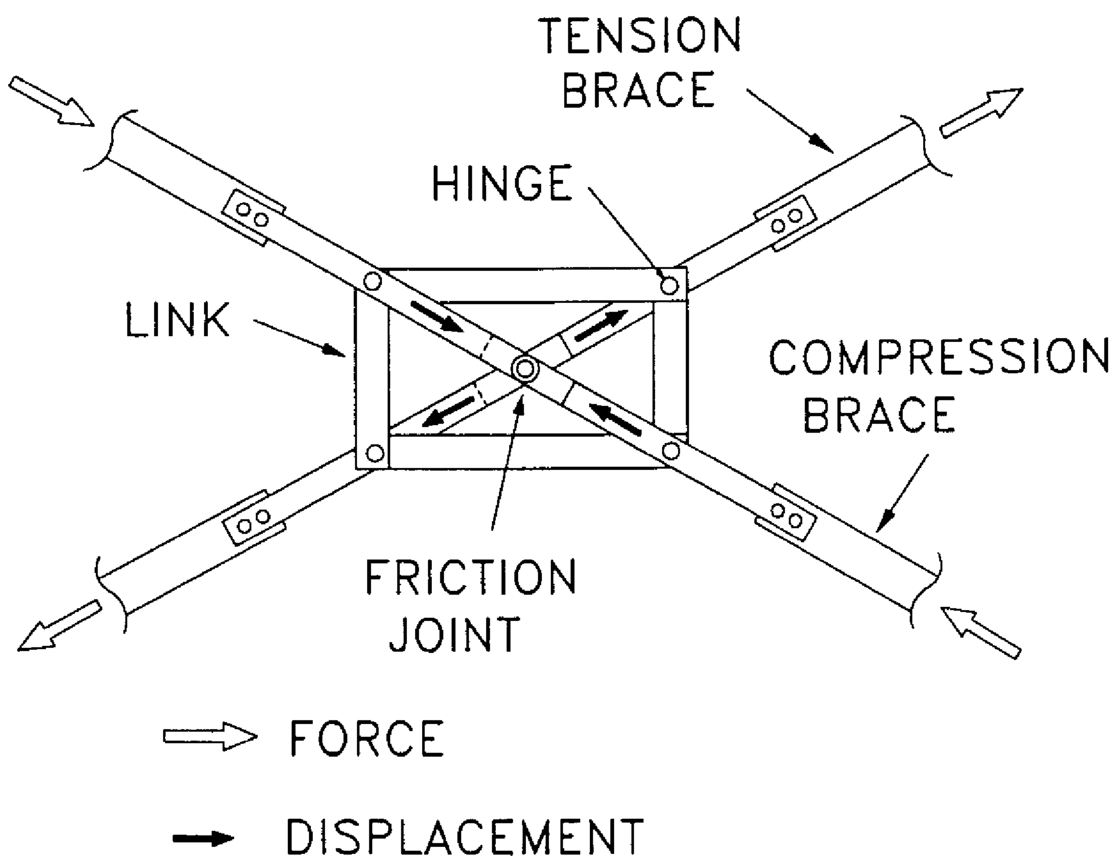


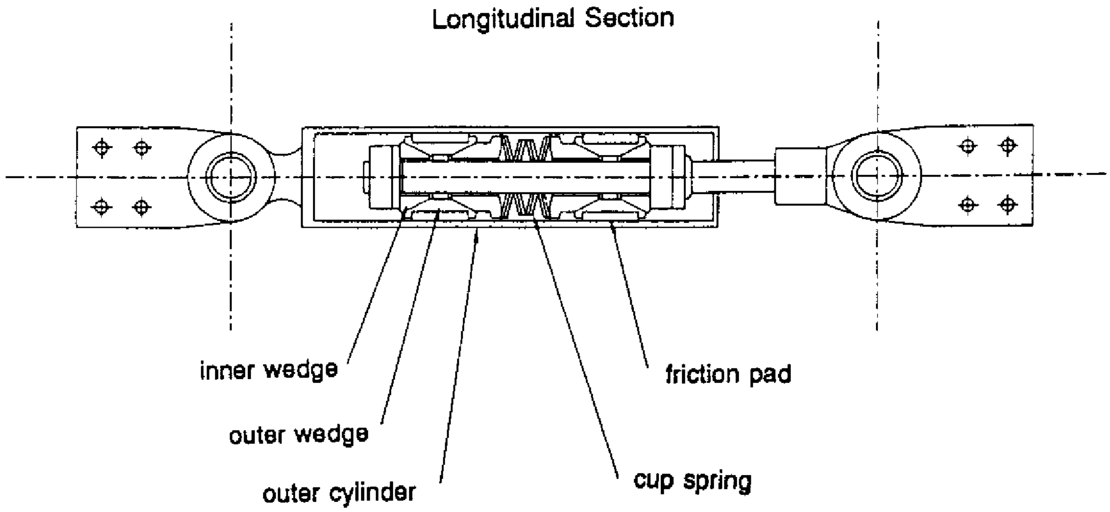

**FIGURE 1-1 Friction Damping Device of Pall (1982)**

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 Subsection 1.6.

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 1-2 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 (1991a, 1991b) 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 (BSI 1979).



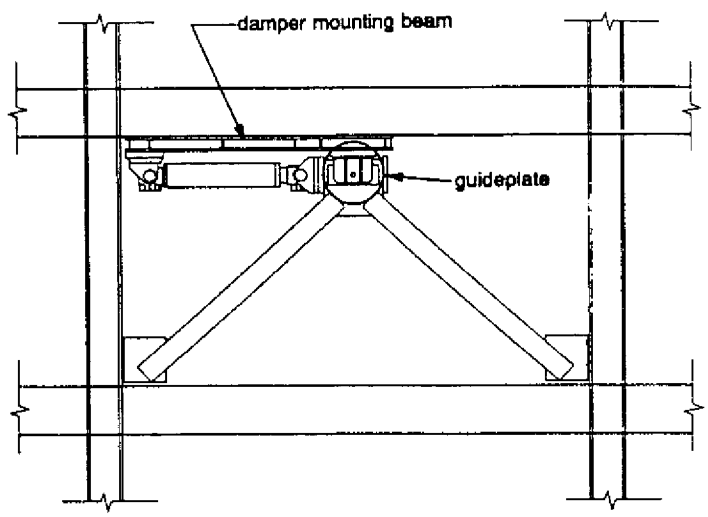




**FIGURE 1-2 Sumitomo Friction Damper and Installation Detail (from Aiken 1990)**

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 1-2 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.

## 1.2 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. 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 1-3 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 "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 1-4 and installed as illustrated in the same figure. The similarity of the device to that of Tyler (1978) and Kelly (1980) is apparent. The

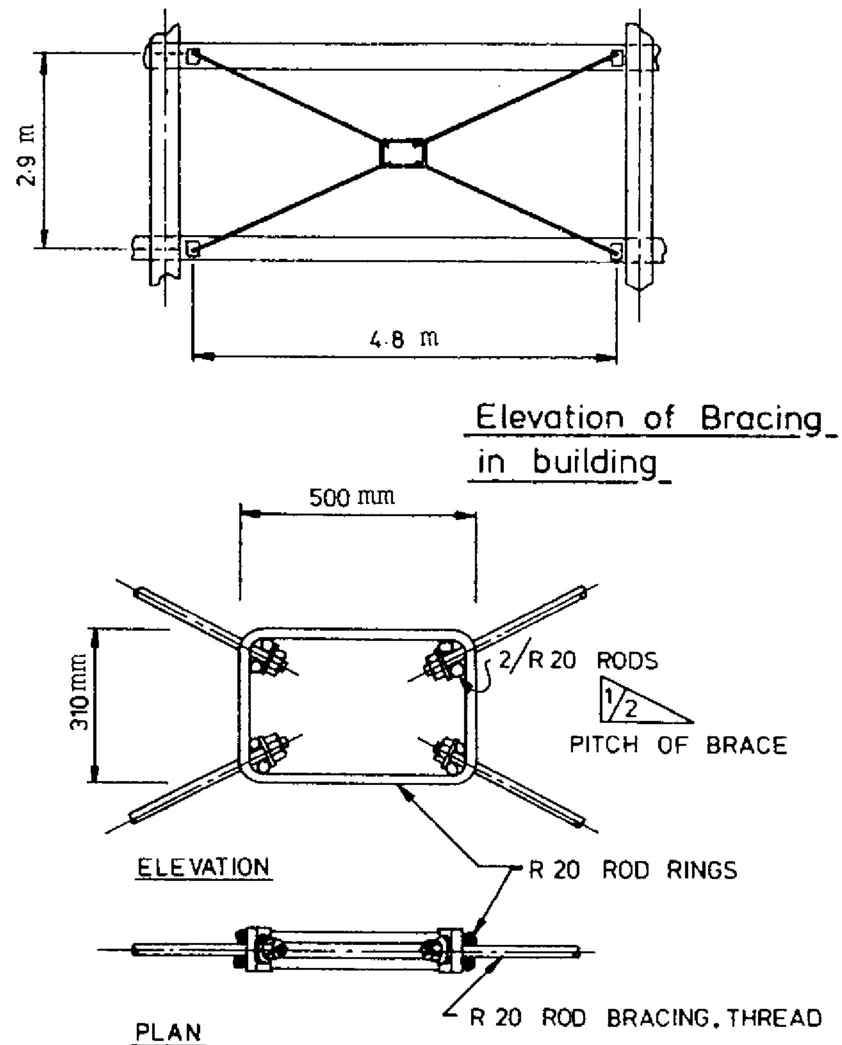
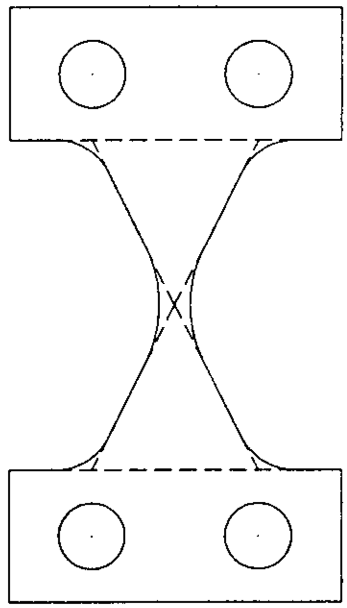



**FIGURE 1-3** **Details of a Yielding Steel Bracing System in a Building in New Zealand (from Tyler 1985)**



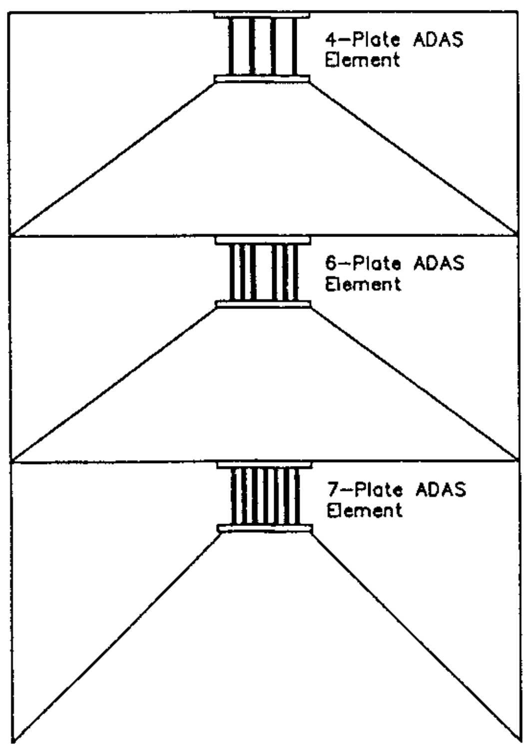



**FIGURE 1-4 ADAS X-shaped Steel Plate and Installation Detail (from Whittaker 1989)**

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 1-4). 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-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 1-4). The plate is subjected to shearing action. It has been installed in the Sumitomo Irufine Office Building, a 14-story steel structure in Tokyo.

### 1.3 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).

The suitability of the viscoelastic dampers for enhancing the earthquake resistance of structures has been experimentally studied by Lin (1988), Aiken (1990) and Chang (1991). Figure 1-5 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 (1991). At a temperature of 70°F (21°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

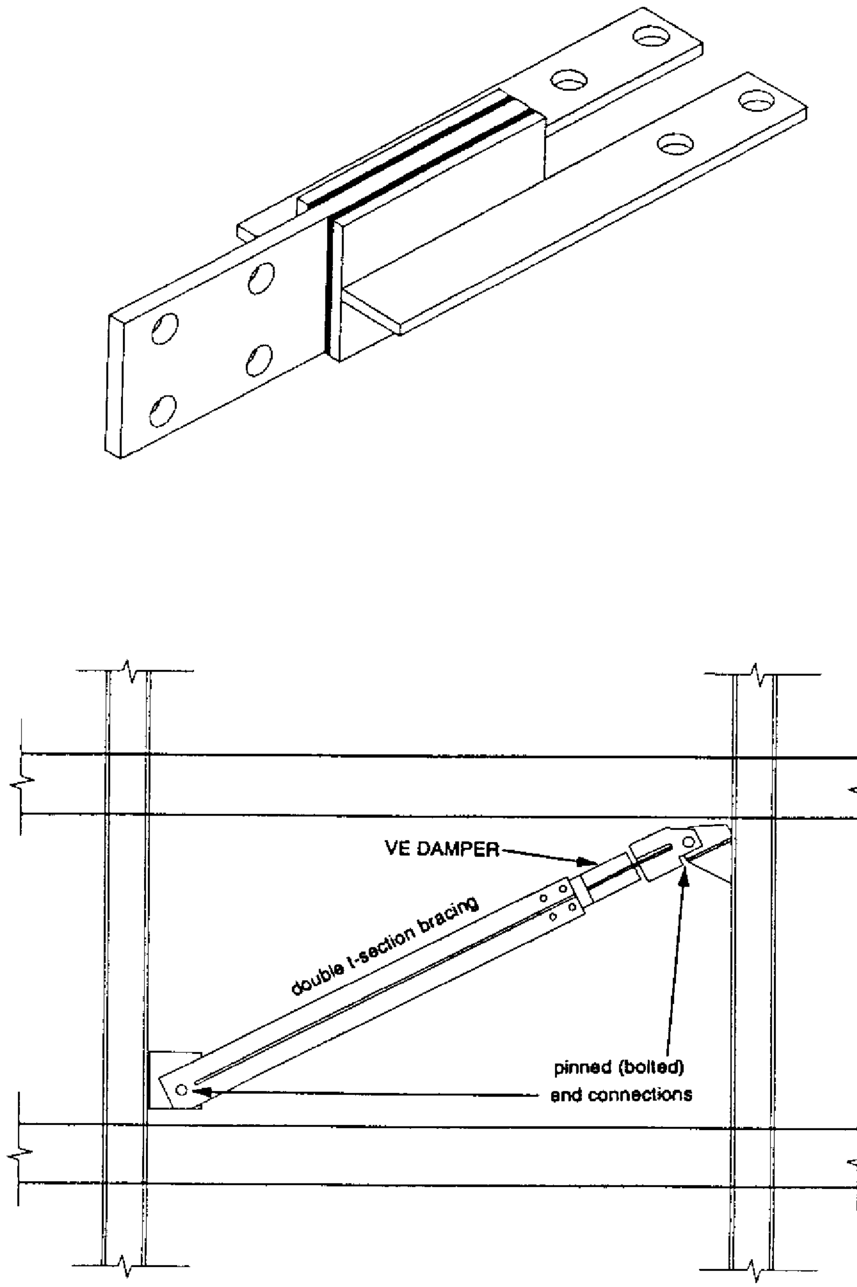



**FIGURE 1-5** **Viscoelastic Damper and Installation Detail (from Aiken 1990)**

a temperature of 90°F (32°C), the 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 percent at shear strains of 0.20.

The shake table tests of Lin (1988), Aiken (1990) and Chang (1991) demonstrated that significant benefits could be gained by the use of viscoelastic dampers. The tests of Aiken (1990) showed interstory 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 interstory drift in the viscoelastically damped structure to the interstory 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 (1991) are particularly interesting because tests were performed in a range of temperatures between 77 and 108°F (25 and 42°C). The addition of viscoelastic dampers resulted in increases of the natural frequency and corresponding damping ratio of the 5-story model structure from 3.17 Hz to 3.64 Hz and from 0.0125 to 0.15, respectively, at a temperature of 77°F (25°C). At 108°F (42°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°F (42°C) is rather small. Yet, recorded interstory drifts in the viscoelastically damped structure were typically about 60 percent 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.

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 (1990) 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 1-5, 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 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). 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 of 32 to 113°F (0 to 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.

## 1.4 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 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.

## 1.5 Fluid Viscous Dampers

Fluid viscous dampers, which operate on the principle of fluid flow through orifices, are the subject of this study. A detailed description of these devices follows in Section 2.

These devices originated in the early 1960's 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:

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 2000 Kip (8.92 MN) capacity.

d) Suppression of wind induced vibration of launching platforms such as those of the Space Shuttle and the Atlas Missile.

The particular fluid viscous damper used in this study originated in a classified application on the U.S. Air Force B-2 Stealth Bomber. Thus, the device includes performance characteristics considered as current state of the art in hydraulic technology. Two of these characteristics, which are of interest in applications of earthquake engineering, are essentially linear viscous behavior and capability to operate over a wide temperature range (typically -40°F to 160°F or -40°C to 70°C).

## 1.6 Considerations in the Design of Energy Absorbing Systems

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

Let us consider the implications of the use of energy absorbing systems in an existing moment-resisting frame building. In general, the gravity load-carrying elements of the structural system have sufficient stiffness and strength to carry the gravity loads and seismic forces in a moderate earthquake. The energy absorbing devices are installed in new bracing systems and assuming that they are capable of reducing drifts to half of those of the original system in a severe earthquake, one can immediately observe 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 1-6 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 $F\sin\theta$ ( $\theta$ = brace angle with respect to 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 devices are illustrated in Figure 1-7. We assume that the energy absorbing devices are installed in the interior columns of a reinforced concrete frame. The nominal axial force - bending

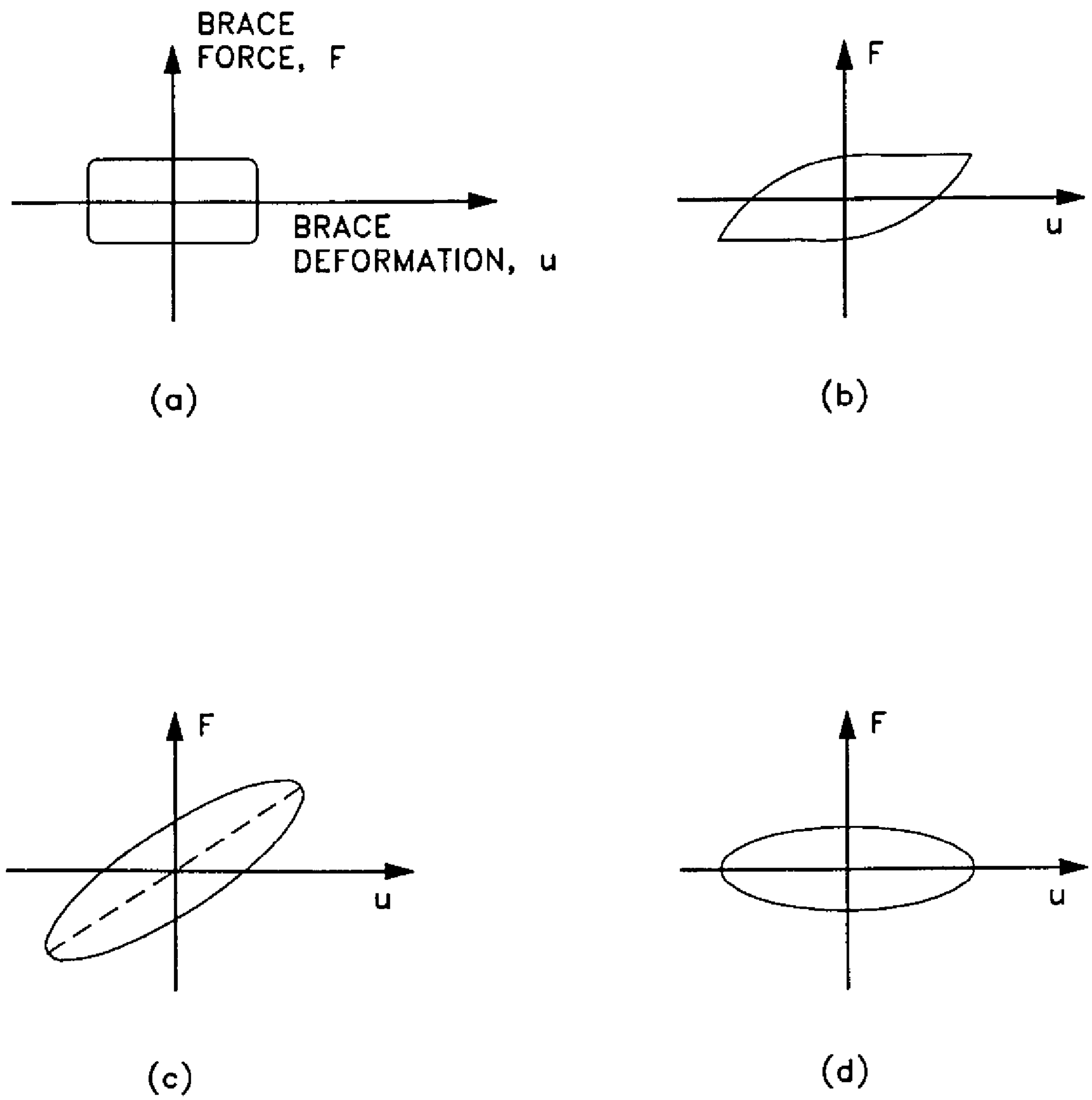



**FIGURE 1-6** **Force - Displacement Relation in (a) Friction Device, (b) Steel Yielding Device, (c) Viscoelastic Device, and (d) Viscous Device**

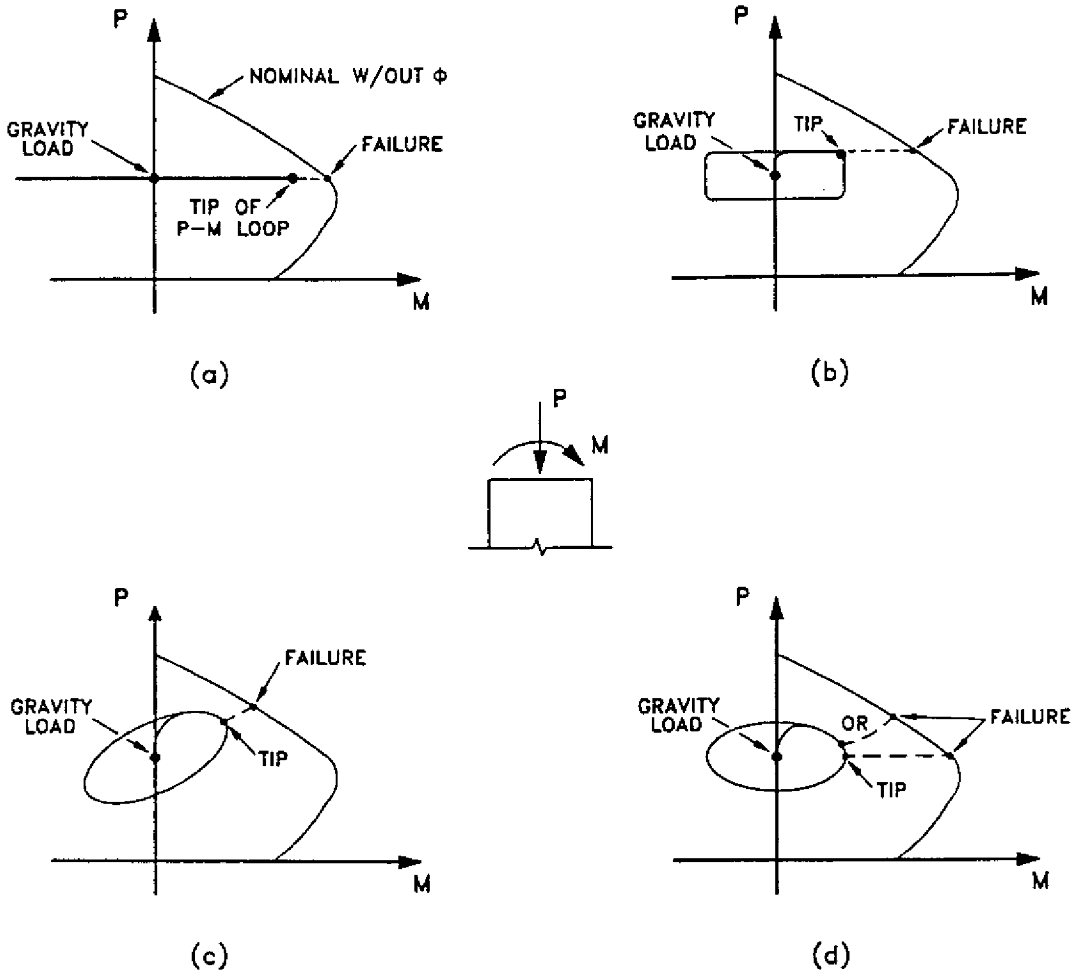



**FIGURE 1-7** Column Interaction Diagrams and Axial Force - Bending Moment Loops during Seismic Excitation for (a) Moment-resisting Frame, (b) Friction Damped Frame, (c) Visco-elastically Damped Frame, and (d) Viscously Damped Frame

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 1-7(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 1-7).

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 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.

The experimental results of Aiken (1990) on the Sumitomo friction dampers can be utilized to illustrate the significance of additional axial forces induced by energy absorbing devices. The structure tested was 9 stories tall with two identical frames as shown in Figure 1-8. The forces in the elements, braces and columns are depicted in Figure 1-8 with the assumption that all friction dampers experience sliding. The additional interior 1st

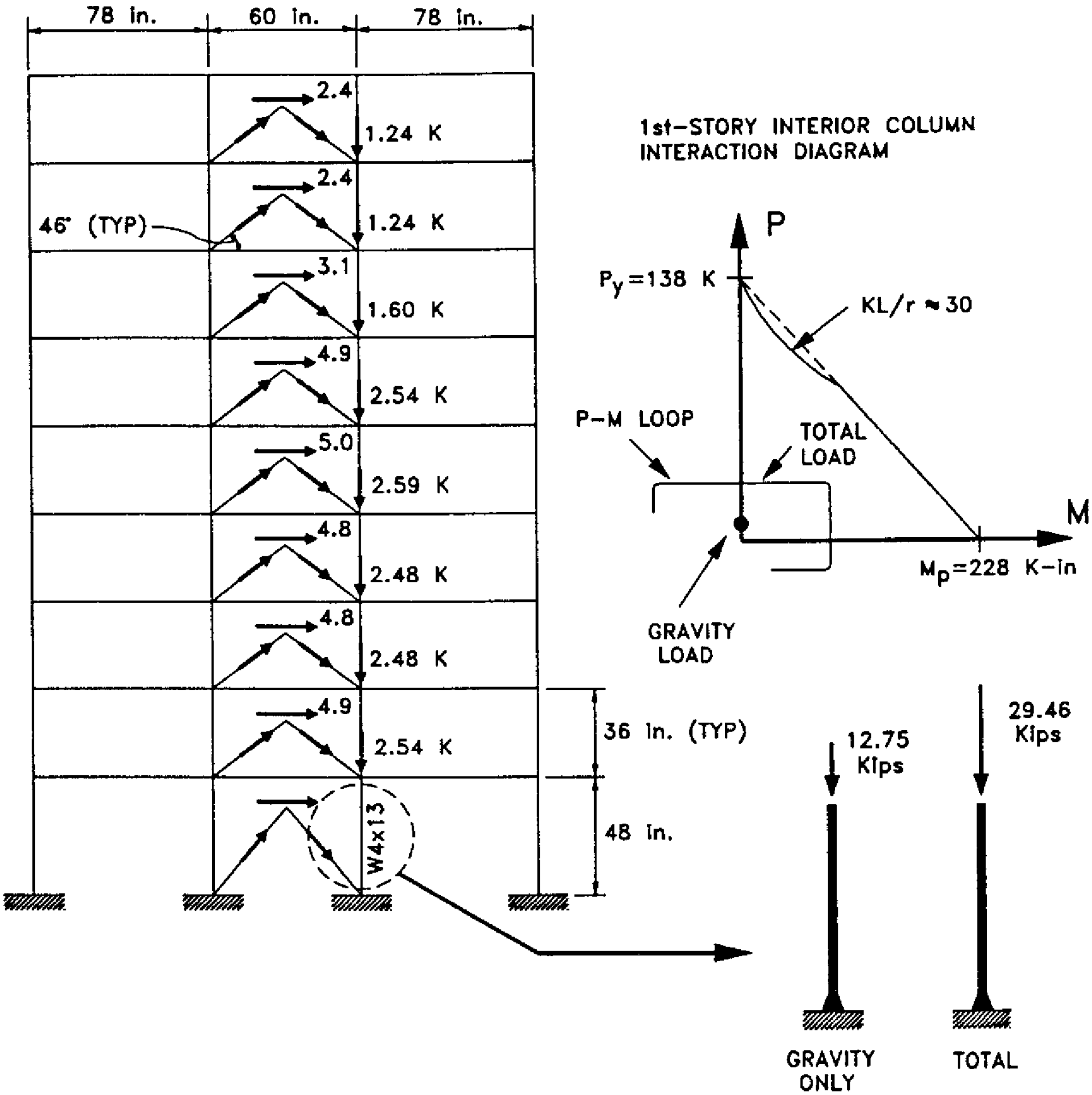



**FIGURE 1-8** Gravity and Additional Axial Load in Interior Column of 9-story Model Structure with Added Friction Dampers tested by Aiken (1990) (1 in. = 25.4 mm, 1 Kip = 4.46 KN)

story 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-story model structure with ADAS elements tested by Whittaker (1989), resulted in additional axial load of only 14 percent of the gravity load.

The relation of the gravity load and total load in the 1st story interior column of the 9-story model to the capacity of the column is illustrated in the upper right corner of Figure 1-8. It may be observed that the gravity load amounts to only 9.2 percent of the column yield force and 16.8 percent of the allowable concentric axial load ($F_a$=0.55$F_y$). Furthermore, it should be noted that the column has a very low slenderness ratio so that almost maximum column capacity is available.

## 1.7 Code Provisions for Design of Structures Incorporating Passive Energy Dissipating Devices

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 (Mayes 1990).

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 the Technical Subcommittee 12 of the Building Seismic Safety Council. When developed, these regulations are expected to eventually 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.

## 1.8 Objectives

In order to analytically predict the response of a structure containing some type of supplemental damping device, the dynamic characteristics of the damping device must be determined. In particular, the behavior of such devices is often dependent on the frequency of motion and the ambient temperature. Therefore, the initial objective is to investigate the mechanical characteristics of the damper so as to obtain a mathematical model describing the behavior of the device.

To verify the proposed mathematical model, a series of earthquake simulator tests on a model structure can be performed. From the experimental response of various structural configurations (i.e., with and without dampers), the analytical response can be verified and the benefit of supplemental dampers can be determined. In addition, the response obtained with the use of fluid viscous dampers can be compared with the response obtained from the use of other devices.

## 1.9 Scope

To achieve the objectives stated above, the following tasks were performed:

a) Selection of the devices for component testing.

b) Component testing of a single damper under a variety of dynamic inputs and under different ambient temperatures.

c) Development of a mathematical model based on mechanical properties.

d) Design of a lateral bracing system to incorporate dampers in the test structure.

e) Identification of various structural configurations (see Figures 3-2 and 3-3).

f) Earthquake simulation testing of various structural configurations using selected ground motions.

g) Comparison of experimental results and results obtained by time-history analysis.

h) Development of rigorous and approximate approaches to obtaining modal properties.

i) Perform response spectrum analysis using approximate modal properties.

j) Comparison of experimental, time-history analysis, and response spectrum results.

k) Determine effectiveness of incorporating dampers in test structure.

l) Compare performance of fluid viscous dampers with performance of other devices.