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Energy Dissipation Systems for Vibration Control of Framed Buildings: A Review

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Abstract* — In conventional structural design, the stiffness and energy absorption mechanisms are combined in a single system, and the structure is allowed to deform inelastically. Experience with recent earthquakes has shown that the economical penalty associated with repairing conventionally designed structures can be significant. Situations also exist in which the conventional design approach is not appropriate. When a structure must remain functional after an earthquake, as is the case of important lifeline buildings (such as hospitals) the conventional design approach focusing on only life safety is inappropriate. For such cases, the structure must be designed with sufficient strength so that inelastic action is either prevented or minimised. But this approach is very costly. Moreover, in such structures, special precautions need to be taken to safeguarding against damage or failure of important occupational and functional systems, which are needed for continuing serviceability. Use of supplemental energy dissipation devices that can dissipate a large proportion of the vibration energy can be a viable option to safeguard the occupational and functional systems. An examination of the behavior and effects of these systems considers the distribution of energy within a structure. During a seismic event, 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. There is always some level of inherent damping, which dissipates energy from the system and therefore reduces the amplitude of vibration until the motion ceases. The structural performance can be improved if a larger portion of the input energy can be absorbed, not by structure itself, but by some type of supplemental energy-dissipating devices. This paper presents a review on energy dissipation system for vibration control of framed buildings.

Keywords-Earthquake Resistant Structures; Dampers; Vibration Control; Energy Dissipation

I. INTRODUCTION

In-structure damping, or energy dissipation, encompasses any component to reduce the movement of structures under lateral loads such as wind and earthquakes. Usual structural engineering processes attempt to achieve more capacity than demand by increasing the capacity of the structure. Passive control takes the opposite approach and attempts to reduce the demand on the structure. In recent years serious efforts have been taken to develop the concept of energy dissipation or supplemental damping into a workable technology, and a number of these devices have been installed in structures throughout the world. This strategy attempts to reduce the demand on a structure, rather than more usual approach of adding capacity. This paper provides an overview of the basic principles, mathematical model and concepts of structural control as applied to civil engineering structures. Various means of controlling structural vibrations produced by earthquakes or wind have been investigated by the structural community. The focus of vibration control of structures in this study is on building applications only, although the basic working principles are the same for bridges and other structures.

II. APPROACHES IN VIBRATION REDUCTION

The vibration reduction techniques can be divided into four main classes. Each class of technique is fundamentally different and achieves the objective of reduced response in a different way. These techniques can be categorised as [1]:

A. Modification of excitation source.
B. Modification of structural properties.
C. Dissipation of excitation energy.
D. Modification of characteristics of transmitted excitation.

Each of these techniques has their advantages and disadvantages. The most effective technique for vibration control in complex systems may require the use of a combination of these techniques. In other cases, more than one option may be available for vibration control. In such situations, it is important to understand the fundamental differences in the different techniques in order to make effective decisions. Some of the common techniques under each category stated above will be discussed in this section.

A. Modification of Excitation Source

Modification of source can be carried out only where the source of energy leading to excessive vibration is properly identified. This is usually possible only when the vibrations in machinery or equipment are under consideration. In such cases, excessive vibration is mainly caused due to design or fabrication error or due to damage in machinery during operation. Since improper operation of machinery due to defects may severely affect its performance, these are required to be corrected as soon as the problem is identified. It should also be realised that modification of source of excessive vibration to make a machinery operate as per allowable specification is the most effective technique of vibration control. This should be the first technique attempted whenever possible.

For machinery with design or fabrication errors, the techniques to eliminate excessive vibrations are well known. For example, turbines may exhibit excessive vibration due to fabrication defects in the blade. These can be corrected by regrinding and repolishing the blades. Similarly, turbines and other rotating machines may exhibit excessive bearing vibrations due to misalignment or due to sag in the axle. These may be corrected by rebalancing the machinery to correct the axis of vibration or by modal balancing which modifies the dominant modes of vibrations by adding masses along the length of the machine shaft. All these techniques are relatively well understood and can be carried out in field without much difficulty.

B. Modification of Structural Properties

Certain situations requiring vibration control, the structural properties of the system can be changed in such a manner that the response to excitation is reduced. These changes in structural properties are achieved through the introduction of additional sub-structure (or auxiliary mass) to the main structure, and not through modifications to the main structure itself. As a result, this technique is conceptually different from techniques requiring modification of source that has been discussed above. The sub-structures those are added act as vibration absorbers, which reduces the proportion of total energy that acts on the main structure. Typically, the vibration absorber consists of a single oscillator or a series of oscillators, which are attached at various points of the main structure.

Several different types of vibration absorbers have been proposed for control of excessive vibration. The configuration that is chosen for a given situation depends on the characteristics of input excitation as well as the modal properties of the structure. A common requirement in most of these vibration absorbers is that their fundamental natural frequency should be very close to that frequency of excitation that causes excessive vibration. As a result, vibration control using this technique is also referred to as vibration control using tuned mass dampers (TMDs).

In most cases of equipment or machine vibrations, the input excitation is very well defined and its dominant frequencies are well known. In such cases, separate tuned mass dampers can be designed for each dominant excitation frequency, and the analysis procedure can be limited to TMD with sinusoidal excitation. When the excitation is not well characterised, the analysis must be carried out using random vibrations theory and the design of tuned mass dampers is considerably more difficult.

C. Dissipation of Excitation Energy

Vibration control through the dissipation of excitation energy has emerged as a practical technique only recently. Due to the rapid advancement in development of new vibration absorbing materials, this technique is fast emerging as the most effective means for vibration control. Since the energy dissipaters can be designed relatively independently of the properties of the main system and are also found to be effective for wide variation in excitation characteristics, this is the best technique for control when the input excitation is not well defined and when fail-safe design is required. Modern vibration control techniques now invariably use energy dissipaters in conjunction with any other technique that may have been chosen.

Vibration control using this technique requires the introduction of special structural elements in the structure that dissipate energy under excitation. These structural elements may be individual elements that are introduced between different locations of the structure. In some cases, energy dissipation is carried out through the application of a high-damping layer on the main structure, as is usually done in aerospace structures.

D. Modification of Characteristics of Transmitted Excitation

The last group of vibration control techniques that will be discussed are commonly referred to as vibration isolation or base isolation techniques. In this class of technique, reduction in vibration is effected through the introduction of a resilient member between the structure and its support. The function of this isolator is to modify the characteristics of transmitted excitation so as to reduce the magnitude of motion transmitted from a vibrating support to the equipment or structure, or to reduce the magnitude of force transmitted from the equipment to its foundation.

Vibration isolation has emerged as a practical technique for vibration control of a large variety of structures and equipments. It is very commonly used for vibration control in relatively simple equipments. Its popularity is mainly due to the simple analytical tools that are required for design calculations and the simple (and relatively inexpensive) test procedure that is commonly required for design of base isolation system.

In general, base isolation works well only on structures or equipments whose natural frequency is reasonably high. If the natural frequency is already low, it may not be possible to make it much lower through the introduction of an isolator, as this may lead to unacceptable amplitudes of displacement. Due to this reason, base isolation is used for moderately rigid equipments and for building structures, which are no more than 6-8, stories high.

II. VARIOUS PROTECTION SYSTEMS

Mechanical devices are incorporated into the frame of the structure and dissipate energy throughout the height of the structure as supplementary devices. The means by which energy is dissipated is yielding of mild steel, sliding friction, motion of a piston or a plate within a viscous fluid, orificing of fluid, or visco-elastic action in polymeric materials. In addition to increasing the energy dissipation capacity per unit drift of a structure, some energy dissipation systems also increase the strength and stiffness. Such systems include the following types of energy dissipation devices: metallic yielding, friction, and visco-elastic. Energy dissipation systems utilising fluid viscous dampers will not generally increase the strength or stiffness of a structure unless the excitation frequency is high [2]. In general, the addition of an energy dissipation system will result in a reduction in drift and, therefore, reduction of damage (due to energy dissipation) and an increase in the total lateral force exerted on the structure (due to increased strength and or stiffness).

Modern structural protective systems can be divided into three major groups: [2]

A. Seismic isolation.

B. Semi-active and active systems.

C. Passive energy dissipation systems.

A. Seismic Isolation

A seismic isolation system is typically placed at the foundation of a structure. By means of its flexibility and energy absorption capability the isolation system partially reflects and partially absorbs some of the earthquake input energy before this energy can be transmitted to the structure. The net effect is a reduction of energy-dissipated demand on the structural system, resulting in an increase in its survivability. Despite wide variation in detail, base isolation techniques follow two basic approaches with certain common features [3]. In past few years many base isolation systems have been proposed and used. The following text describes important aspects of few commonly used base isolators;

1. Elastomeric Bearings.
2. Lead Rubber Bearings.
3. Combined Electrometric and Sliding Bearings.
4. Sliding Friction Pendulum Systems.
5. Sliding Bearings with Restoring Force.
6. Variable Frequency Pendulum Isolation.

In the first approach the isolation system introduces a layer of low lateral stiffness between the structure and the foundation. This layer gives the structure a fundamental frequency that is much lower than both its fixed-base frequency and the predominant frequencies of the ground motion. So the structure has a natural period that is much longer than its fixed-base natural period. The first dynamic mode of the isolated structure involves deformation only in the isolation system, the structure above being to all intents and purposes rigid. The higher modes do not participate in the motion. The lengthening of natural period can reduce the pseudo-acceleration and hence the earthquake-induced forces in the structure, but the deformation is increased; this deformation is concentrated in the isolation system, however, accompanied by only small deformations in the structure. This type of isolation system is effective even if the system is linear and undamped. Damping is beneficial, however, in further reducing the forces in the structure and the deformation in the isolation system. The most common system of this type uses short, cylindrical bearings with one or more holes and alternating layers of steel plates and hard rubber. Interposed between the base of the structure and the foundation, these laminated bearings are strong and stiff under vertical loads, yet very flexible under lateral forces. Because the natural damping of the rubber is low, some form of mechanical damper usually provides additional damping. These have included lead plugs inserted into the holes, hydraulic dampers, steel bars, or steel coils.

The second most common type of isolation system uses sliding elements between the foundation and the base of the structure. The shear force transmitted to the structure across the isolation interface is limited by keeping the coefficients of friction as low as practical. However, the friction must be sufficiently high to sustain strong winds and small earthquakes without sliding, a requirement that reduces the isolation effect. In this type of isolation system, the sliding displacements are controlled by high-tension springs or laminated rubber bearings, or by making the sliding surface curved; these mechanisms provide a restoring force, otherwise unavailable in this type of system, to return the structure to its equilibrium position. The friction pendulum system (FPS) is a sliding isolation system wherein the weight of the structure is supported on spherical sliding surfaces that slide relative to each other when the ground motion exceeds a threshold level. Raising the building slightly when sliding occurs on the spherical surface causes the restoring action. The dynamics of structures on slider type of isolation systems is complicated because the slip process is intrinsically non-linear [3]. VFPI is a kind of new isolation. In this isolator, the shape of the sliding surface is non-spherical. This isolation system retains the advantage of both pure friction (PF) isolation system and FPS, due to amplitude dependent time-period and softening mechanism of isolator restoring force [4]. In this kind of sliding surface geometry the performance is similar to that of FPS for low levels of excitation and similar to that of pure friction for high level of excitations. This is achieved by making the oscillation frequency of the isolator response dependent. The isolator geometry is such that its frequency decreases with increase in sliding displacement and asymptotically approaches zero (PF system) at very large displacement. This result in continuous variation of oscillation frequency even for high level of excitation and the isolation always remain effective. This system thus differs from conventional PF and FPS systems in two fundamental properties: (1) VFPI provides for progressive period lengthening mechanism that is dependent on sliding displacement, (2) It also permits softening of restoring force at large displacement so that energy dissipation characteristics of the isolator are superior to that of other available isolators.

B. Semi-Active and Active Systems

Semi-active and active structural control is an area of structural protection in which the motion of a structure is controlled or modified by means of the action of a control system through some external energy supply. However, semi-active systems require only nominal amounts of energy to adjust their mechanical properties and, unlike fully active systems; they cannot add energy to the structure.

1. Active Bracing Systems
2. Active Mass Dampers
3. Variable Stiffness and Damping Systems
4. Smart Materials.

C. Passive Energy Dissipation Systems

Passive energy dissipation systems are classified herein as hysteretic, visco-elastic and others. Examples of hysteretic systems include device based on yielding of metals or through sliding friction. Fig. 1 shows typical force-displacement loops of hysteretic energy dissipation systems. The simplest models of hysteretic behaviour involve algebraic relations between force and displacement. Hence, hysteretic systems are often called displacement-dependent. Visco-elastic energy dissipation systems include devices consisting of visco-elastic solid materials, devices operating on the principle of fluid orificing and devices operating by deformation of visco-elastic fluids. Fig. 2 shows force-displacement loops of these devices. Typically, these devices exhibit stiffness and damping coefficients, which are frequency dependent. Moreover the damping force in these devices is proportional to velocity. Unlike seismic isolation, passive energy dissipation devices can be effect against wind-induced motions as well as due to earthquakes. Contrary to active control systems, there is no need for an external supply of power. Following are various categories of passive control systems.

1. Visco-elastic Solid Dampers
2, Metallic Dampers
3. Friction Dampers
4. Viscous Fluid Dampers
5. Tuned Mass Dampers
6. Tuned Liquid Dampers

1) Visco – Elastic Solid Damper

Materials at which some of the energy input is stored and recovered in each cycle of loading, and some is dissipated as heat are called visco-elastic. As its name implies, viscoelasticity is a generalisation of elasticity and viscosity. The elastic element can be modelled by a linear spring and the viscous element by a dashpot. So it considers both the stiffness and dissipation property. In this viscosity is responsible for dissipation. The viscous damping force is a function of the velocity of vibration, and is due to fluid resistance during oscillation. Therefore the passive systems that dissipate energy in a rate dependent mean velocity dependent are in VE systems. In VE system, response is dependent upon frequency of vibration, the level of strain, and the ambient temperature. But VE solid materials can be used to dissipate energy at all deformation levels. Therefore, VE dampers can find applications in both wind and seismic protection. The VE dampers were chosen primarily because they provide the structure with significantly increased damping for frequent low-level ground shaking, as well as for large seismic events. Thus, unlike metallic or frictional dampers, a linear structural system with added visco-elastic 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 VE damped systems [5; 6]. Energy dissipation system utilising fluid viscous dampers will not generally increase the strength or stiffness of a structure unless the excitation frequency is high. The application of VE dampers to civil engineering structures appears to have begun in 1969 when 10,000 VE dampers were installed in each of the twin towers of the World Trade Centre in New York to help resist wind loads [7]. Visco-elastic solid materials used in civil engineering structural applications are usually copolymers or glassy substances that dissipate energy when subjected to shear deformation. Dampers are designed so that part of the mechanical energy of building motion is converted to heat, which results in a reduction of the amplitude of vibration motion. A typical VE solid damper configuration has shown in Fig. 3.

a) Visco - Elastic (VE) models

There are several different kinds of modelling for VE dampers from constitutive relation have come out stage by stage. So far, popular models for this damper have been proposed include the Maxwell model, the Kelvin-Voigt model, and complex combinations of these elementary models. In general VE is combination of elastic element and viscous element. If the two elements are combined in series, it is known as a Maxwell model or if combined in parallel it is known as Kelvin-Voigt model. The combination of Maxwell model and a linear spring connected in parallel is a standard linear model. This model gives the following relationship between σ and ε :

$$\sigma + \alpha_1 \frac{d\sigma}{dt} = E\varepsilon + \beta_1 E \frac{d\varepsilon}{dt} \qquad (1)$$

where α_1 and β_1 are the constants [8].

The above is the basic model to describe the material behaviour of most VE materials. In addition the generalized Maxwell model is the combination of number of Maxwell models in parallel and generalized Voigt model is the combination of Voigt models in series. The most attractive features of these models are, perhaps, their simplicity. Fortunately, not many constants are needed when they are applied to solid materials whose properties do not show significant variation with respect to temperature and frequency but in reality which is not so. The standard linear model gives variation of storage and loss modulii with frequency is much more rapid than is usually observed in real polymeric materials. The limitations of the simple form of the standard model can be reduced by introducing additional derivatives of and in Eq. (1) to give

$$\sigma + \sum_{n=1}^{\infty} \alpha_{1,n} \frac{d^n\sigma}{dt^n} = E\varepsilon + E\sum_{n=1}^{\infty} \beta_{1,n} \frac{d^n\varepsilon}{dt^n} \qquad (2)$$

The major drawback, however is that the evaluation of a large number of derivative terms acting on stress and strain is required in order to characterize the frequency and temperature-dependent storage and loss moduli for most VE materials [9]. Another disadvantage of the models is that substantial number of terms (values of α_n and β_n) are needed to model adequately a real material over a wide frequency range [8]. To represent a wider range of frequency, a model with more elements is necessary.

Kirekawa et al. [10] has proposed acrylic VE material has a large damping capacity through experiment result. In this proposed material, properties are significantly influenced by temperature and excitation frequency. But the shear strain amplitude has little influence on the dynamic characteristics comparing to other material.

In order to reduce the number of terms required by the generalized standard model to take adequate account of the slower rate of change of properties with frequency seen in real materials, the integral derivatives can be replaced by fractional derivatives. The concept of fractional; derivatives was first used by Gemant [11] to describe such VE material moduli. In the last few years, fractional calculus has been used in the modelling development of VE dampers by many researchers. The constants used in the fractional derivative used by Bagley [12] cannot be found through the tests in the time domain, such as stress relaxation tests. In fact, the constants in the constitutive relation based on the concept of fractional derivatives are usually found by curve fitting the data in the frequency domain, since the formation of frequency dependent moduli is straightforward. It is seen that curve fitting require data over wide frequency band in order to obtain the constants used in constitutive relation with certain degree of confidence. Therefore, if only limited data over a small frequency range is available due to the capacity limitation of test facilities, some arbitrariness of these constants is inevitable [13]. Lee and Tsai [14] used fractional derivative for analytical model of VE dampers through time domain analysis. They have considered application of this model directly without transformation and inverse transformation to frequency domain, saving from the computational difficulties. From the experimental and analytical study of VE damper, Lee and Tsai [14] has proposed that mechanical properties of the VE material is dependent upon strain rate instead of frequency which is opposite to material tested by Kirekawa et al. [10]. The unknown parameters used in the constitutive equations give the idea of mechanical properties. The effect of strain rate is due to energy accumulation in faster rate during a loading with higher strain rate, and the heat transformed from the strain energy thus softens the material and reduces its energy absorbing capacity. Tsai and Lee [15; 16] have used the constitutive relation in time domain dynamic analysis. To solve that, they have proposed finite element method. The frequency dependency of moduli of VE material brings about some difficulties in the nonlinear response analysis of a structural system with VE dampers since a frequency domain approach, such as Discrete Fourier Transformation (DFT), is not generally applicable for nonlinear systems. It needs to be pointed out that the VE material is linear over a wide range of strain provided the temperature is constant. At large strains, there is a considerable self-heating due to large amount of energy dissipated. The heat generated changes the mechanical properties of the material, and the overall behaviour is nonlinear. The heating-softening effect is present even if the stress-strain response of the material is linear. This means that a linear analysis can only be for approximation of the response, and the frequency domain approach is not suitable for seismic applications when large strains are most likely experienced [17].

Shen and Soong [13] have presented more consistent model based on the Boltzmann superposition principal. They have showed the temperature and frequency dependent properties of the VE material quite well. The temperature effect has taken into account by the method of variables. Based on analytical and experimental results, the proposed model is shown to be capable of describing, with resonance accuracy, the mechanical behaviour of VE dampers under various loading conditions. Moreover, all the constants in the constitutive relation have physical meaning and can be determined from simple time domain and frequency domain tests. The hysteresis loops are stable and these moduli are approximately independent of strain if it is within 20% and the excitation frequency is below 3.0Hz. These findings were consistent with results obtained from previous investigations by Chang et al. [18].

2) *Metallic Dampers*

The effect of the ground motion is to feed energy into the structure. Some of the energy is dissipated through the damping and the remainder is stored in the structure in the form of kinetic energy of motion of mass and in the form of strain energy of deformation of the structural members. If the energy input is sufficiently large, the structure cannot absorb it in elastic strain energy, exceed the elastic limit with consequent permanent deformations, or some part of the structure will fail. In either event, the effect is to dissipate energy. If the structure is designed so that permanent deformation can occur without failure of members, then at any instant the sum of the kinetic energy plus strain energy plus energy dissipated through normal damping plus energy dissipated through permanent deformation will be equal to the total energy input. In traditional frame structures, aseismic design relies upon the post-yield ductility of structural members to provide the required dissipation.

Metallic dampers are usually made from steel or lead. If mild steels are designed to deform so much when building vibrates during an earthquake then they cannot return to their original shape. This permanent deformation is called inelastic deformation, and it uses some of the earthquake energy, which goes into building. But in case of soft metal like lead the energy dissipates due to its hysteretic force displacement relationship behaviour and no permanent deformation exist. The simplest models of hysteretic behaviour of these kinds of devices involve algebraic relations between force and displacement. Hence these devices are often called displacement dependent and velocity independent. However, the ideas of utilising separate metallic hysteretic dampers within a structure to absorb a large portion of the seismic energy began with the conceptual and experiment work by Skinner et al. [19; 20]. In order to effectively include these devices in the design of an actual structure, one must be able to characterize their expected nonlinear force-displacement behaviour under arbitrary cyclic loads.

During the ensuing years, considerable progress has been made in the development of metallic dampers. Many devices have been proposed, including the X-shaped and triangular plate dampers [21; 22; 15; and 16] displayed in Fig. 4. Alternative material such as lead and shape memory alloys [23; 24 and 25] have been proposed. Though their characteristics do not involve yielding, its force-displacement resembles to hysteresis loops.

Among several metallic dampers, steel plate added damping and stiffness (ADAS) device has been more popular in building structures. It is an assemblage of steel plates that is designed for installation in a building frame such that the relative storey drift causes the top of the device to move horizontally relative to the bottom. By yielding a large volume of steel, The ADAS device can dissipate substantial energy during an earthquake. There are a number of benefits of dissipating energy through the yielding of ADAS devices: (1) Energy dissipation is concentrated at locations that have been designed for this purpose; (2) Energy dissipation demands on other structural members can be substantially reduced; and (3) Yielding of ADAS devices will not affect the gravity load service capacity of the structural systems, because the devices are part of lateral load resisting system only.

a) *Mathematical Modelling*

A force-displacement relationship can be developed from a constitutive model of the metal, along with a geometry description of the device, by employing the laws of mechanics. Some typical models that have been used to represent the nonlinear force-displacement relationships are the simple elasto-plastic model, the bilinear model, and the polynomial model (Fig. 5). The area contained within one cycle of the hysteretic curve is the energy dissipated per cycle. The equivalent viscous damping may be obtained by setting the area within the hysteretic loop equal to the area within a viscous damper cycle. It is important that the equivalent viscous damping for each model should be established. Metallic devices could be small relative to the structural framing member sizes. In this case, devices can be extremely effective and can be evaluated as equivalent viscous damping until the structure yields. However, numerical complications may arise when performing time history analysis of a structural system incorporating the elasto-plastic or bilinear model due to sharp transition from the inelastic to elastic states during the loading and reloading cycles. The presence of such abrupt changes in stiffness needs to locate these transition points in order to avoid erroneous results. As the number of devices installed in a building structure increases and the different phase or stiffness transitions conditions for each device have to be taken into account in the numerical calculations. So these elasto-plastic or bilinear model of the metallic device becomes computationally inefficient. In any case, the assumed model is an idealisation and not the true representation. So a continuous Boun-Wen's model may be used to characterise the hysteretic force displacement behaviour of the metallic yielding device [26].

3) Friction Dampers

In recent years, there have been some structural applications of friction devices aimed to provide an extra protection to new and retrofitted buildings. Dry friction is enhancing system performances due to damping and isolation properties. Whenever the friction device slips, a large portion of the vibration energy is dissipated mechanically in friction rather than inelastic yielding of the main structural components during severe earthquake excitations. The following will describe most of the proposed types of friction devices and their basic mechanism.

a. Limited Slip Bolt Joints [27]

b. X Braced Friction Dampers [28]

c. Slotted Bolted Connection Element [29]

d. Energy Dissipating Restraint (EDR) Device [30]

e. Adjustable Slippage Elements / Spring-Friction Dampers [31]

a) Limited Slip Bolt Joints

Pall et al. [27] began their development of friction dampers by conducting static and dynamic tests on a variety of simple sliding elements having different surface treatments. The goal was not necessarily to obtain maximum energy dissipation, but rather to identify a system that possesses a consistent, predictable response. For these tests, contact was maintained between faying surfaces by pre tensioning 12.7mm diameter high-tension bolts. The resulting hysteretic behaviour under constant amplitude displacement controlled cyclic loading is shown in Fig. 6. Metalized surfaces show the maximum static slip load among the various surface treatments. However, the cyclic response was quite erratic, with considerable stick-slip associated with the transition from static to kinetic frictional response. Similar cyclic behaviour was obtained for contact between steel plates with mill scale or sand blasted surfaces. Zinc-rich painted surfaces and polyethylene coatings produced a smoother cyclic response; however degradation of slip load occurred. On the other hand, the systems containing brake lining pads inserted between steel plates did provide a consistent, predictable response. Brake lining pad materials have been developed over a large number of years in the automotive industry specifically to provide reliable frictional response. It has been seen that the characterisation of simple brake lining frictional system in terms of an elastic-perfectly-plastic model is quite appropriate. The macroscopic hysteretic model employed to simulate the behaviour of the Limited Slip Bolted (LSB) joint is shown in Fig. 7. In this the parameters and Δ_b represent the slip load and the total displacement at first contact with the bearing surface, respectively. Additionally, K_0 is the elastic stiffness and the stiffness in bearing is K_2. The model, which assumes zero stiffness during slippage, is specified in rate form in order to properly address arbitrary loading-unloading histories. The superposed dot represents differentiation with respect to time.

b) X Braced Friction Dampers

By providing sliding friction devices in the bracing system of the frame buildings, their earthquake resistance and damage control potential can be considerably enhanced. The device may also be conveniently incorporated in existing frame buildings to upgrade their earthquake resistance. Pall and Marsh [28] proposed a system in which the braces in a moment resisting frame incorporated frictional devices. These devices utilise the similar heavy-duty brake lining pads discussed above. The typical X braced friction damper has been shown in Fig. 8.

P_s A friction joint with slotted holes can be used to slip in tension and compression provided the brace is designed not to buckle in compression up to the slip load value. Hysteretic behaviour of such a joint is shown in Fig. 9a. Friction joints, which slip at a high load in tension and at a low load in compression, before the brace buckles, are also possible. More often, the braces are quite slender and are designed to be effective in tension only, in which case the friction joint slips in tension but will not slip back during reversal of load. In subsequent cycle, the brace will not slip again until it is stretched beyond the previous elongated length, thus offering very little energy dissipation. Hysteretic behaviour of such a friction joint is shown in Fig. 9b. When tension in one of the braces forces the joint to slip, it activates the four links, which force the joint in the other brace to slip simultaneously. In this manner, energy is dissipated in both the braces in each half cycle. Moreover, in each cycle, the mechanism brings the connection back and is ready to participate in future excursions. Hysteretic behaviour of this joint is shown in Fig. 9c.

The assumed hysteresis behaviour is accurate only if the device slips at every cycle, which is not the case in an actual earthquake. In times the tension brace will not slip but the compression brace will buckle. Under such conditions, Pall and Marsh's assumed hysteresis behaviour will no longer be valid, since the mechanism will not activate the links to pull back the buckled brace. Therefore, this simple model overestimates the energy absorption of the friction device. To overcome this situation, a more accurate or refined model has been developed by Filiatrault and Cherry [32]. Superposing truss and beam-column elements for the diagonal braces can develop a refined model, which accurately reflects the true behaviour of the friction device. A schematic of model is shown in Fig. 10. Initially all the members are modelled by truss elements with their own stress - strain curves. The four outside diagonal braces are allowed to buckle elastically in compression and the two diagonal pads of the device slip in tension and compression. The device links are permitted to yield in both tension and compression. For the diagonal braces we superimpose beam-column elements with zero cross – sectional area such that they can carry bending moment only, which is required to ensure stability. To represent the pinned connections at the four corners of the frame zero plastic moment capacity for the beam column elements are specified.

The energy dissipation in the brace is proportional to the product of slip load and the slip travel during each excursion. For very high slip loads, the energy dissipation in friction will be zero, as there will be no slippage. If the slip load is very low, the amount of energy dissipation again will be negligible. Between these extremes, there is an intermediate value to give the maximum energy dissipation. Softening of the structure due to slipping of the braces can mean an invitation to higher or lower seismic forces, depending on its relation to the frequency content of the ground motion. By the proper selection of the slip load, it is therefore possible to adjust the response of the structure to an optimal value.

Wu et al. [33] have studied hysteretic behaviour of improved pall friction damper (IPFD) experimentally and numerically. They have considered the numerical analysis based on geometric nonlinearity of a four-link mechanism model of the device. Where as, in ordinary pall friction damper geometric nonlinearity has not been considered. The influence of device parameters on brace force cannot be realistically predicted without consideration of the geometric non-linearity.

(c) Slotted Bolted Connection Element

FitzGerald et al. [29] and Grigorian et al. [34] introduced frictional resistance through slotted bolted connections, which eliminates inelastic member buckling. Slotted Bolted Connection (SBC) is concentric bracing member connections where slip displacement can occur at a designated friction resistance in long slotted bolt holes. The required level of bolt tension for Belleville spring washer provides the design normal force assembles in the slotted-bolted gusset plate connection. In comparison with the traditional concentric braced system under repeated cycles of reversed loading, the SBC system produces rectangular hysteresis loop.

The SBC system is analogous to a very stiff elastic and perfectly plastic yield member. This member would have very small elastic deformation up to tension yield, and then flat plastic yield in tension. The complete SBC assembly consists of a gusset plate, two back-to back channel sections, cover plates, and bolts with Belleville washers (Fig. 11). At initial installation, the bolts are located at the center of the slots and both gusset and channel slots are at the same longitudinal position. The same friction factor has been assumed for gusset and cover plate faying surfaces. The coefficient of friction on the faying surface has been assumed as 0.4, and also correlated with the experimental and theoretical behaviour. SBC systems have proved to be very efficient in dissipating energy, which is shown through numerous numerical investigations [35; 36].

(d) Energy Dissipating Restraint (EDR) Device

The unique characteristics of these devices are that is strongly self-centering and is passive device whose frictional force is proportional to displacement. Both these characteristics are not found in other friction devices for energy dissipation.

A detailed presentation of the design and its performance is provided in Nims et al. [30]. As indicated in Fig. 12, the EDR utilizes steel compression wedges and bronze friction wedges to transform the axial spring force into normal pressure acting outward on the cylindrical wall. Thus, the frictional surface has been formed by the interface between the bronze wedges and the steel cylinder. Internal stops have been provided within the cylinder in order to create the tension and compression gaps. The length of internal spring can be altered during operation, providing a variable frictional slip force. Typical experiment hysteretic behaviour is displayed in Fig. 13 for three different configurations. Fig. 13a represents the response obtained with zero gaps and zero spring preload. Triangular shaped hysteresis loops result indicating slip force proportional to the device displacement. With non-zero spring preload and very large gaps, the device acts as a standard Coulomb damper as indicated in Fig. 13b. Finally, with non-zero preload, but no initial gaps, the flag-shaped hysteresis loops of Fig. 13c have been obtained. So the response characteristics of the EDR are quite different from those of the other friction dampers.

c) Adjustable Slippage Element (ASE)

Tritchkov et al. [31] have proposed an adjustable slippage element (ASE) to control vibration. The main characteristics of an ASE are that its response is nonlinear elastic and that its force-displacement curve consists of an initial steep and subsequent smooth. The transition from the steep to the smooth has been viewed as slipping of the device. The transition point, or the slippage threshold, can be adjusted within the structure to obtain an enhanced dynamic performance based on a redistribution of elastic deformations which leads to decreased force transmissibility, and improved ability to escape resonance. The application of ASE in conjunction with damping devices can improve the performance of the dampers by making it possible to control the structure's stiffness. For example when applied with friction dampers this can provide better control of the yield-slip ratio in order to avoid the stick-slip phenomenon and can also provide for better maintenance and control of the friction surfaces.

a) Mathematical Modelling

The dynamic behaviour of friction devices is closely related to the contact theory since there are friction forces generated by sliding surfaces. In general, the systems involving friction has been idealised as Coulomb's friction in frame structures. In Coulomb's friction model the magnitude of friction is constant at both stick and sliding mode which is proportional to the force normal to direction of sliding, and its direction is opposite to that of the sliding velocity. The effectiveness of these systems mostly relies on the modelling of devices and their implementation in numerical solution process because of its highly non-linear behaviour. To linearize the system Coulomb friction has been approximately represented by an equivalent viscous damping [37]. For friction-based systems elasto-plastic model is quite adequate. It has been characterised without a sharp yield point with the use of Bouc and Wen [38] model by a number of researchers. Some investigators used different equations of motion for each of stick and sliding phase [4; 39; and 40]. But it has been found that stick and sliding phase can easily modelled and formulate for single degree of freedom structure but becomes complicated in cases where many vibrating parts of the structure are connected by friction devices for example of multi-storey structures. Dimova et al. [35] has simplified the solution process through the special approximation to the Coulomb's friction model. By this approximation they have simplified the mathematical model from non-linear differential equation to the linear differential equation. Levy et al. [36] have developed design methodology for these systems using bilinear hysteretic behaviour. They have presented an algorithm for displacement reversal in the transition from slip to stick.

There are certain numbers of numerical simulations of structures with friction devices. In order to carry out the numerical solutions, some developed computer program for specific problem while others use commercial software packages [2] such as DRAIN 2D, DRAIN-2DX, DRAIN-3DX, DRAIN-TABS, DRAIN-BUILDING, SAP2000, ETAB, IDARC 2D, ADINA. Basically the existing models used in commercial software packages fall into one of these following two categories:

- Models where the dynamic behaviour of the friction devices is described by the contact analysis theory. This approach can be accurate but costly in terms of computational effort.
- Simpler models where elasto-plastic laws for the friction devices are implemented in finite element models of the whole structures.

4) Viscous Fluid dampers

Fluids can also be effectively employed to dissipate energy and numerous device configurations and materials have been proposed. One class involves the use of a cylindrical piston immersed in a viscoelastic fluid [41]. Another proposed device involves the concept of a viscous damping wall; these walls dissipate energy through shearing action of the fluid in containers [42]. These dampers, widely used in aerospace and military applications, have recently been adapted for building applications. Characteristics of these device which are of primary interest in building applications are the linear viscous response achieved over a broad frequency range, insensitivity to temperature, and compactness in comparison to stroke and output force. The viscous nature of the device is obtained through the use of specially configured orifices, and is responsible for generating damper forces that are out of phase with displacement. A typical damper of this type is shown in Fig. 14.

5) Tuned Mass Dampers (TMDs) and Tuned Liquid Dampers (TLDs)

This consists of a secondary mass with properly tuned spring and damping elements, providing a frequency – dependent hysteresis that increases damping in the primary structure. It can be an effective and practical means for reducing resonant vibration in structures. It is a modular device composed of spring, mass and dashpot. The principle of tuned mass dampers (TMDs) is shown in Fig. 15. These three components can each be implemented in a number of different ways. The stiffness and mass of the TMD are chosen to put the TMD natural frequency just below the frequency of the target mode of the base structure, i.e. the mode to be damped. This causes a strong dynamic interaction between the TMD and the target mode. The target mode is replaced by the two modes, one slightly above and one slightly below the original frequency. Most important, both of these split modes will be damped by the dashpot of the TMD. The success of such system in reducing wind-excited structural vibrations is well established. Numerical and experimental studies have been carried out on the effectiveness of the TMDs in reducing seismic response of structures [43]. These results show that the effectiveness of TMDs on reducing the response of the same structure during different earthquakes or different structures during the same earthquake is significantly different. This implies that there is dependency on the attained reduction in response on the characteristics of the ground motion that excites the structure. Also, TMDs are of limited effectiveness under pulse-like seismic loading. To overcome the frequency-related limitations of TMDs, more than one TMD in a given structure, each tuned to a different dominant frequency, can be used.

Similar in concept to a TMD, the tuned liquid damper (TLD) and tuned liquid column damper (TLCD) impart indirect damping to the system and thus improve structural performance [44]. A tuned liquid damper absorbs structural energy by means of viscous actions of the fluid and wave breaking. TLD operate on the same basic principles as TMD. However, some of drawbacks of TMD systems are not present in TLD due to the simple physical concepts on which the restoring force is provided in TLD, no activation mechanism is required. Therefore, maintenance cost is minimized. The mechanism activating a TMD must be set to a certain threshold level of excitation, while TLD systems are at all times active, avoiding problems due to an inadequate activation system. Although the mathematical theory involved in accurately describing motion of fluid in the container may be quite complicated, the hardware requirements are sufficiently simple that a minimum of installation is required.

IV. Comparative Study of Dampers

1. Visco - elastic (VE) dampers have no threshold or activation force level, and they dissipate energy at all levels of earthquake excitations. With this the structures have been found effective against wind induced motion and earthquake excitation.
2. The addition of VE damper result in a significant increase in modal damping ratios in all modes considered.
3. It is also that though VE dampers increase the structural stiffness, which does not improve the structure's seismic performance.
4. As the temperature increases the VE material softens and the effectiveness of damper decreases. It's also sensitive to excitation frequency of ground motion.
6. Hysteretic devices are more relevant since performance is not sensitive to frequency of ground motion.
7. Steel, lead and shape memory alloys are extensively used in metallic dampers. The hard metal like steel dissipates energy through its inelastic deformation and lead dissipates through extrusion.
8. Friction dampers dissipate energy mechanically throughout the height of the structure rather than by localised inelastic action of the main structural members. It introduces dissipation by metal to metal or non-metal contact. The resonance of the structure is difficult to establish, as the device acts like an automatic gear in limiting the input energy. As there is no yielding of material involved in the process of energy dissipation, thus no damage is caused and the structure is ready to face the future earthquakes with the same efficiency.
9. The major difference between velocity dependent and displacement dependent devices is the maximum force that each device will develop during an earthquake. The maximum displacement and velocities determine the maximum earthquake forces developed in the velocity dependent devices. The maximum earthquake forces in the displacement dependent devices equal the design friction force or design yield force plus strain hardening. Thus, the maximum earthquake forces are more easily controlled in displacement dependent devices.

V. Concluding Remarks

Each type of energy dissipation device acts primarily to dissipate energy, its mechanism for doing so leads to distinctly different hysteretic behavior, and thus performance of structure to which it is attached. The basic characteristics of the device in terms of its displacement or velocity dependence must be considered in the analysis and design procedure. The introduction of energy dissipation devices within the structural framing of a building introduces a number of analysis and design issues that must be considered by the structural engineer but which are not directly addressed in code based documents.

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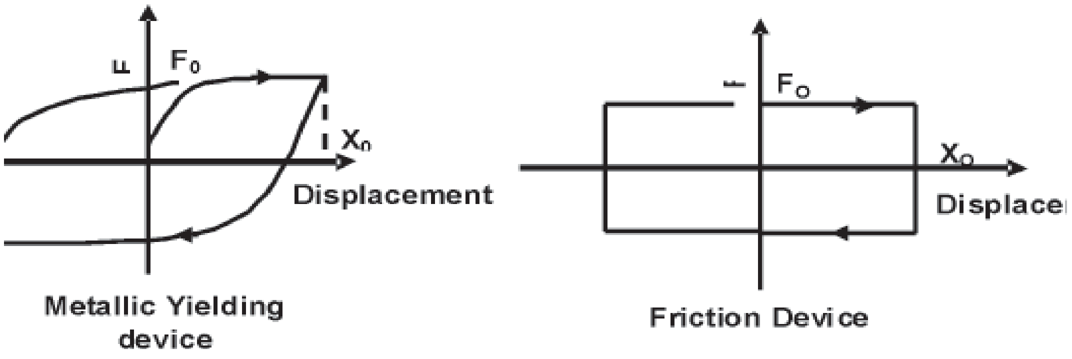


Figure 1. Idealized force-displacement loops of hysteretic energy dissipation devices [2].

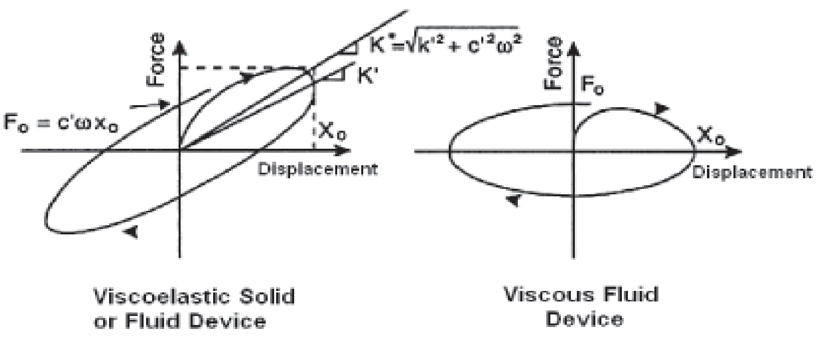


Figure 2. Idealized force-displacement loops of visco-elastic energy dissipation devices [2].

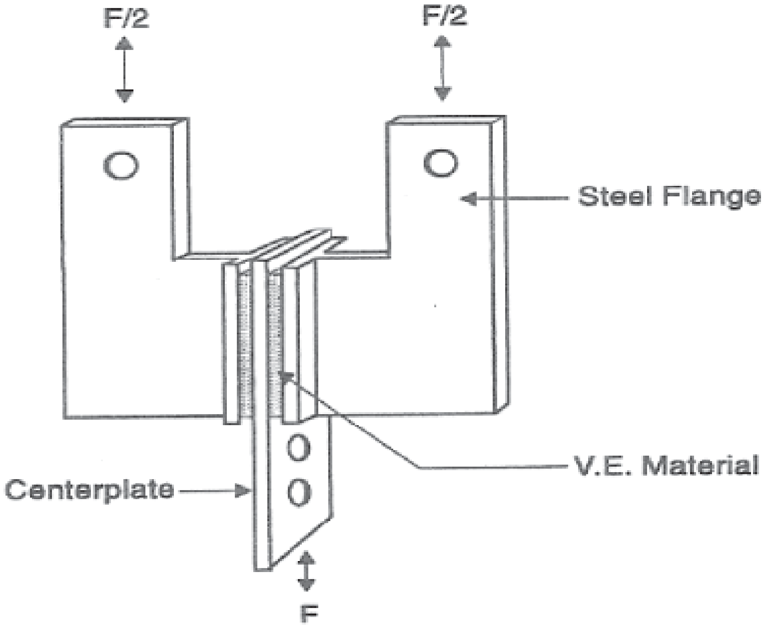
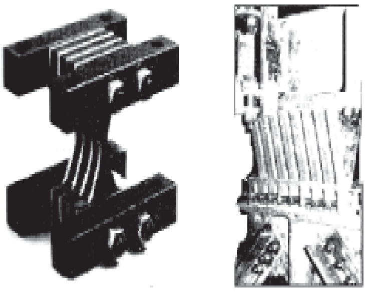
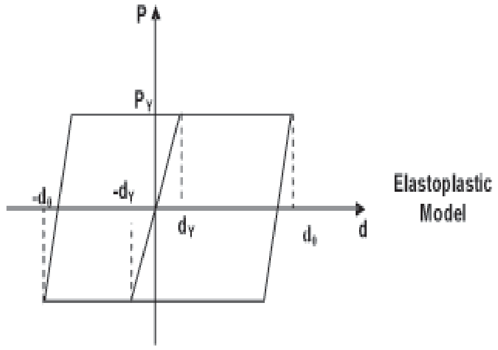


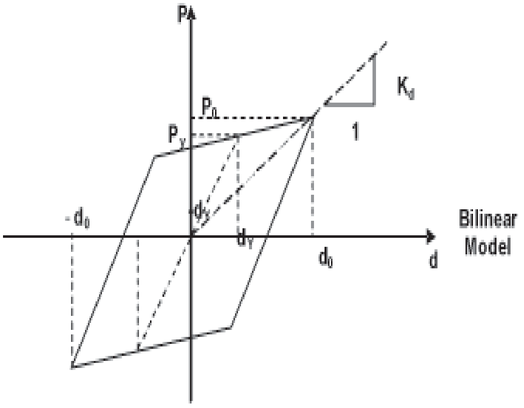
Figure 1. Typical visco-elastic solid damper configurations [5].



(a) X-shaped Plate Damper (b) Triangular Plate Damper

Metallic dampers: (a) X-shaped damper (b) Triangular damper [45].





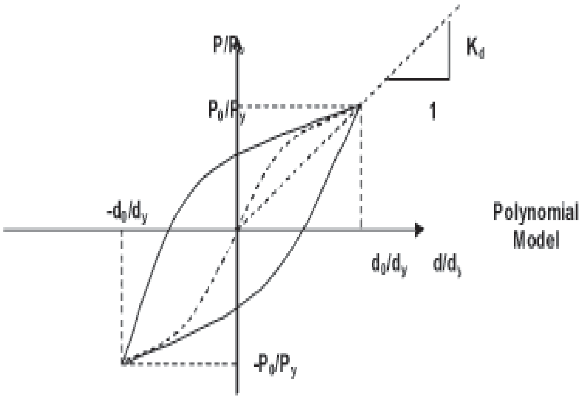
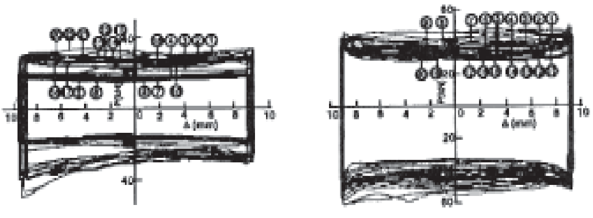
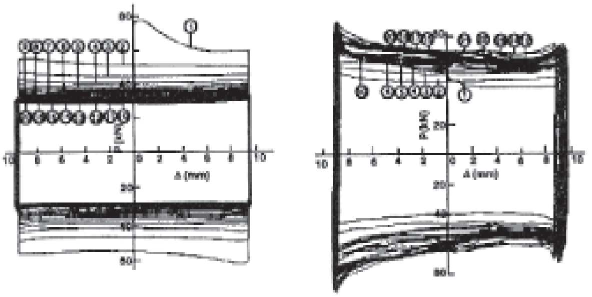


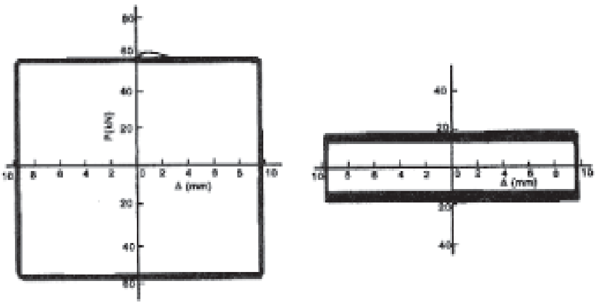
Figure 1. Non-linear force-displacement models [46]



(a) Mill scale (b) Sand blasted



(c) Inorganic Zinc-Rich paint (d) Metalized



(e) Brake Lining Pads (f) Polyethylene Coating

Figure 6. Hysteresis loops of limited slip bolted joints [27].

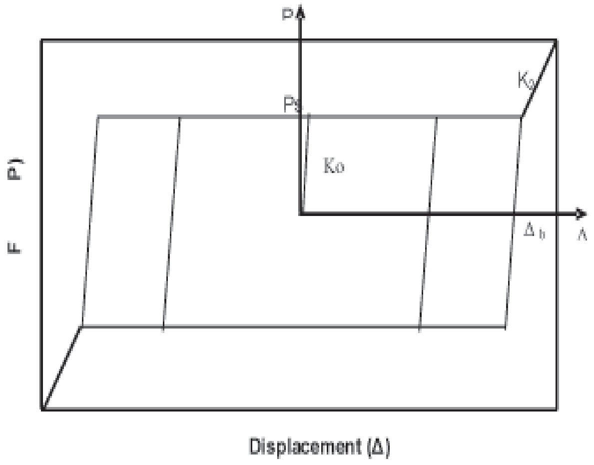


Figure 7. Macroscopic model for limited slip bolted joints [27].

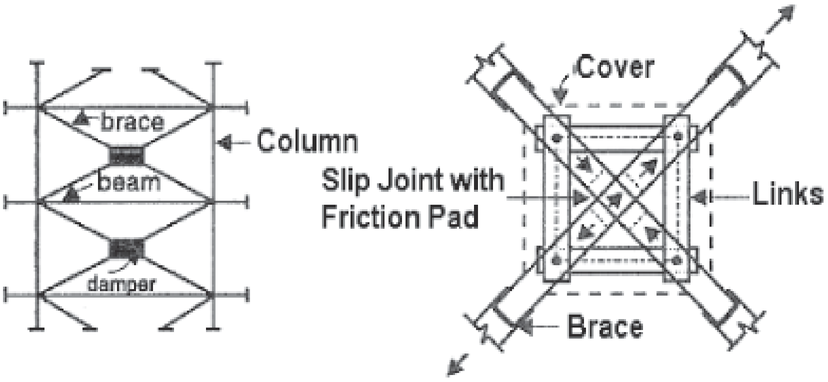
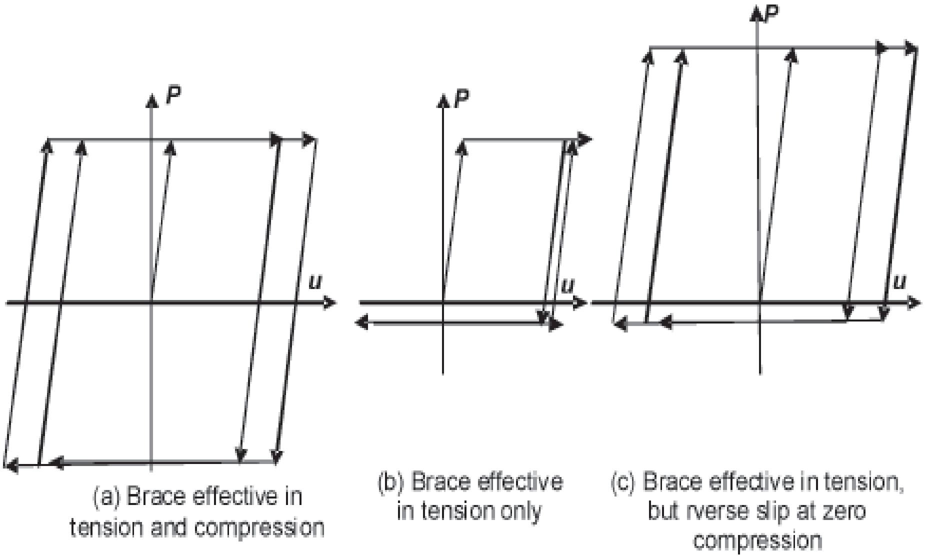


Figure 1. X Braced friction damper [28].



(a) Brace effective in tension and compression

(b) Brace effective in tension only

(c) Brace effective in tension, but rverse slip at zero compression

Figure 9. Idealised hysteretic behaviour of friction jointed brace [28].

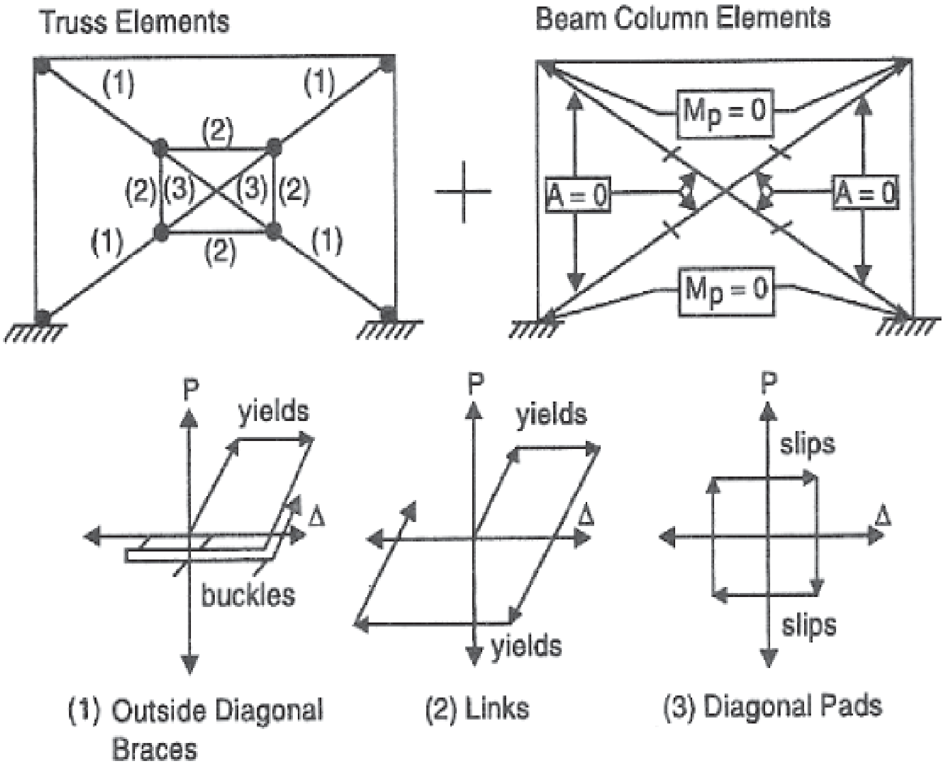


Figure 1. Refined model for X-braced friction damper [32].

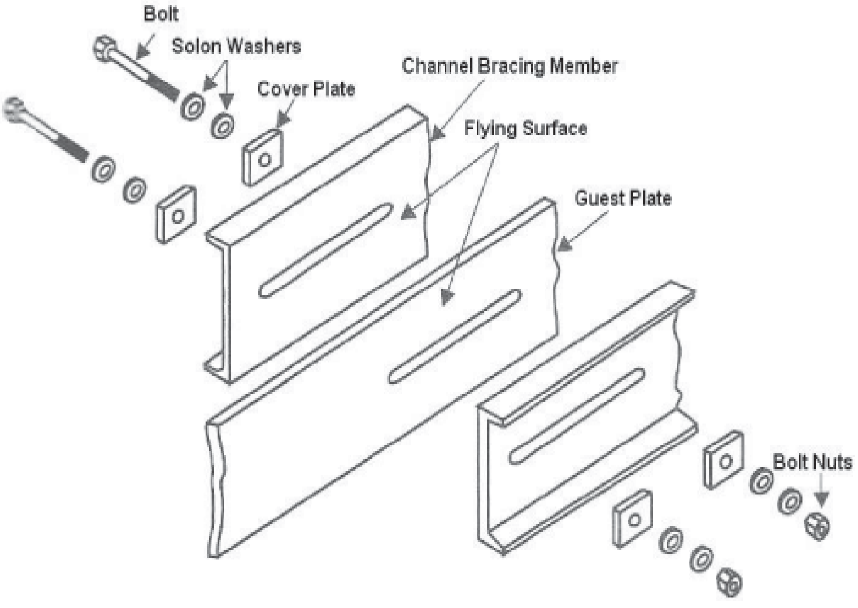


Figure 11. Slotted-bolted connections [29].

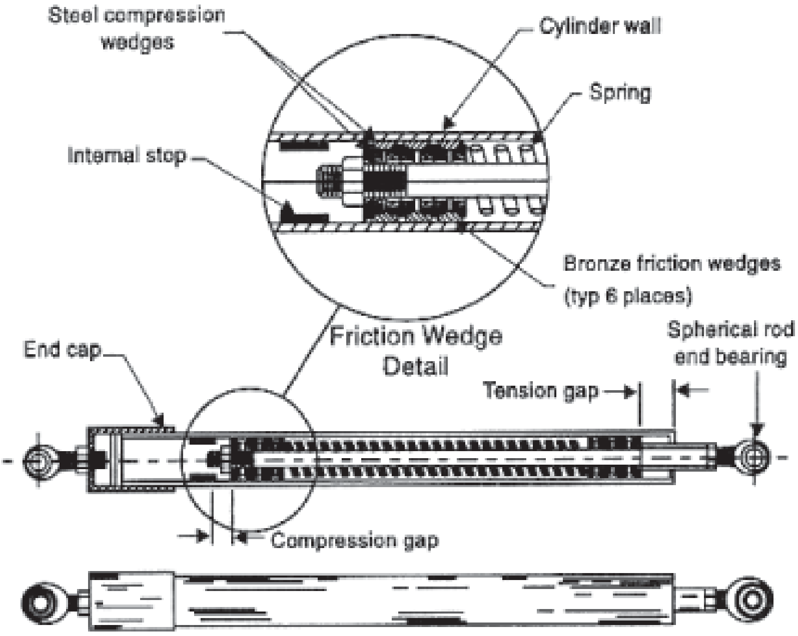
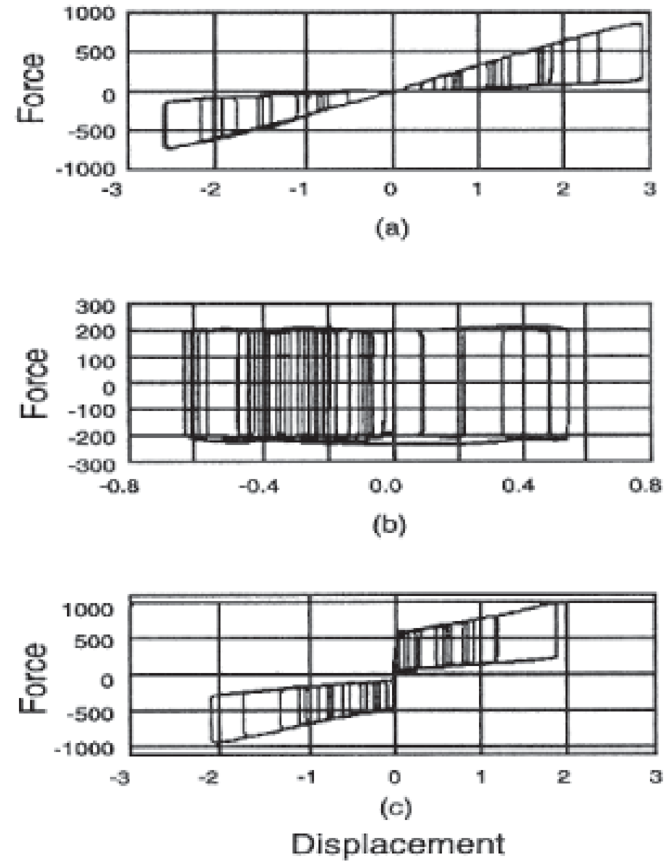


Figure 12. Energy dissipating restraint [30].



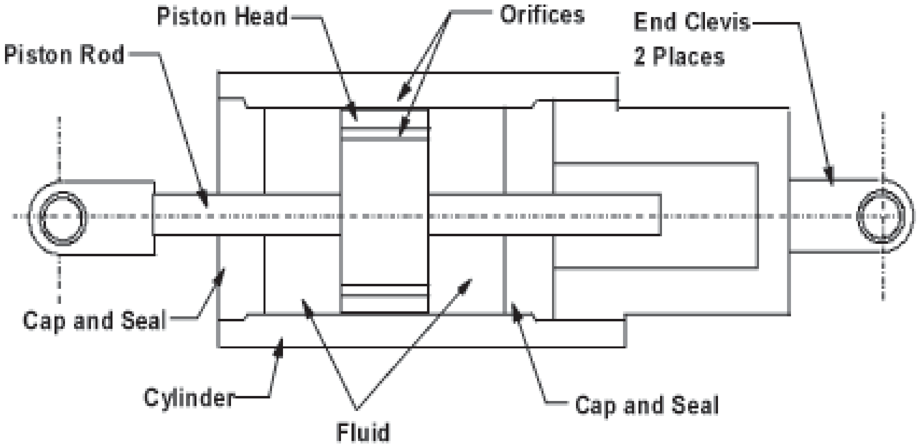


Figure 14. Orificed viscous fluid device, run-through rod design: Taylor devices [46].

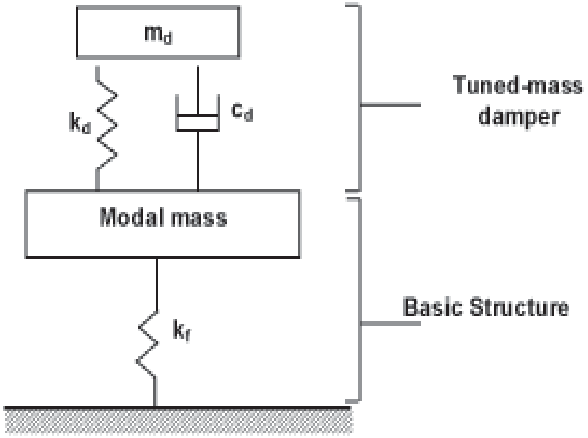


Figure 15. Principle of tuned mass dampers (TMDs).