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State of the art in the pounding mitigation techniques

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Summary

Pounding introduces impact loads that have to be superimposed on those caused by the ground acceleration itself. When these impact loads from pounding are too high, the structural system has to be modified to reduce the response.

Several methods have been proposed to avoid pounding induced collapse of buildings. The methods may be classified according to their approach to the problem of pounding: methods to avoid pounding, methods to strengthen structures to withstand pounding, and techniques to reduce pounding effects in the structures.

KEYWORDS: pounding, seismic gap, damping, energy dissipation, impact

1. POUNDING MITIGATION TECHNIQUES

Pounding introduces impact loads that have to be superimposed on those caused by the ground acceleration itself. When these impact loads from pounding are too high, the structural system has to be modified to reduce the response.

Several methods have been proposed to avoid pounding induced collapse of buildings. The methods may be classified according to their approach to the problem of pounding: methods to avoid pounding, methods to strengthen structures to withstand pounding, and techniques to reduce pounding effects in the structures.

1.1. Seismic gap

The first work for pounding prevention was to establish a good and reliable estimate of the minimum gap required for the design earthquake so that pounding between the structures will not occur.

Providing a sufficient gap has been the commonly accepted strategy adopted by building codes throughout the world. The value of the separation distance between two structures which is sufficiently large to prevent pounding is known as the seismic gap.

1.1.1 Building Code Requirements

Building codes in zones of active seismicity around the world have recognized the destructive effects that pounding may induce in constructions. The approach commonly adopted in building codes has been to avoid contact interactions between the structures by providing sufficient separation between them.

The criterion has been defined by Valles (1997) using four different expressions:

gap ≥ factor (sum of individual displacements D_1 and D_2 of buildings) (1)
gap ≥ coefficient (height) (2)
gap ≥ fixed distance (3)
gap ≥ SRSS (of the displacements D_1 and D_2) (4)

where D_1 and D_2 are the maximum displacement of the individual buildings (Figure 1).

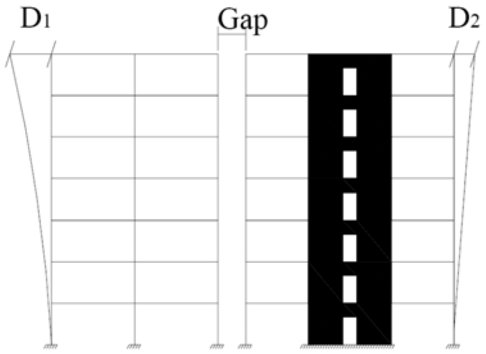

Figure 1 – Definition of the notations

The first criterion may be considered as equivalent to the absolute sum of maximum, multiplied by an amplification factor. The amplification factor in most cases comes from the increase in displacements due to the inelastic response of the structures. This criterion does not take into account that the maximum displacements in the structures, in general, will not occur at the same time.

The second condition may be easily justified, since; in general, building codes specify a maximum inelastic drift related to structures (story height). Using this approach, the dynamic characteristics of the structures are not relevant to the gap computation, since the lateral deformations are always checked. This approach is the easiest. Nevertheless, this form of specifying the gap, by not considering the dynamic properties of the adjacent structures, may be overly conservative for buildings that tend to respond in phase; for example, buildings with high percentages of critical damping, or inelastic buildings for some ratios of frequencies to the characteristic earthquake frequencies.

The third one is specified for construction considerations, that is, to allow for adequate space to place the formwork for beams and columns, to build masonry walls, or place elements of the facade.

The last one takes into account the fact that the maximum displacements in the structures will not occur at the same times. It uses the SRSS (Square Root of the Sum of the Squares) modal combination rule that is assuming that the input motion is stationary, and the response of each structure is uncorrelated with the others. It refers to the theory of probability which indicates that the SRSS combination provides the most probable value of the maximum of [D_1 (t) + D_2 (t)].

Therefore, it yields conservative results when the response of the structures is somewhat too perfectly correlated.

First example of code requirements. In the Eurocode 8, the specification against pounding phenomenon is:

Building pounding is a phenomenon that occurs when adjacent structures are separated at distances less than the differential lateral displacements that occurs in each structure as a result of their earthquake response. Buildings shall be protected from earthquake-induced pounding from adjacent structures or between structurally independent units of the same building. This principle is considered to be satisfied if:

1. For buildings, or structurally independent units, that do not belong to the same property, if the distance from the property line to the potential of impact is not less than the maximum horizontal displacement D_s of the building at the corresponding level (Recall: displacements D_s in Eurocode 8 are q times the elastic displacements De computer under the design earthquake, the latter being on earthquake "reduced" by the behaviour factor q: D_s=q.D_e);

2. For buildings, or structurally independent units, belonging to the same property, if the distance between them is not less than the square root of the sum of the squares (SRSS) of the two maximum horizontal displacement of the building or units at the corresponding level.

A specification is however made: if the floor elevations of the building or independent unit under design are the same as those of the adjacent building or unit, the above referred minimum distance may be reduced by a factor of 0,7.

Second example of code requirements. The Uniform Building Code (UBC) specifies that the separation distance between two buildings shall be at least (0.375xRw) times the displacement due to seismic forces, where R_w is the US equivalent to the behaviour factor q. Pantelides and Ma (1998) have found that the UBC code values for the seismic separation distance to avoid pounding seems to be conservative.

Anagnostopoulos and Spiliopoulos in 1992 obtained that the Eurocode requires more conservative gap sizes than the Uniform Building Code (UBC) one.

Only one building code was found that allowed some level of pounding if the effects do not jeopardize the integrity of either construction (Valles and Reinhorn, 1997). However, no procedure was outlined to indicate how the collision effects are to be calculated.

1.1.2 Double Difference Combination rule

Series of dynamic time history analyses can estimate the seismic gap by obtaining the maximum relative distance of the adjacent structures. However, an alternative, called the "spectral difference (SPD) method," based on a spectrum approach has been proposed by various authors. The method accounts for phasing associated with vibration of adjacent structures, defined as "vibration phase." They also propose simplified rules to predict the inelastic vibration phase, and demonstrate the accuracy of the SPD method for a variety of adjacent building pairs and earthquakes. Unlike the time history analysis method, the SPD method clarifies the effects of various parameters on the relative displacement through a closed-form solution. The SPD method is also useful for various relative displacement problems between adjacent structures, such as bridges. It is more accurate than the current code calculation method that ignores the vibration phase.

An estimate of the required separation, based on random vibration considerations, has been proposed by Jeng, Kasai and Maison (1996). They proposed a spectral difference method to calculate the minimum gap to avoid pounding for linear structures. The method was named Double Difference Combination rule (DDC):

$$u_{rel} = \sqrt{u_A^2 + u_B^2 - 2\rho_{AB} u_A u_B} \qquad (5)$$

Where u_A, u_B = design peak displacements of buildings A and B.

The correlation coefficient (ρ_{AB}) is calculated according to the simplified formulas for white noise input:

$$\rho_{AB} = \frac{8\left(\xi_A + \xi_B \frac{T_B}{T_A}\right)\left(\frac{T_B}{T_A}\right)^{3/2}\sqrt{\xi_A \xi_B}}{\left(1-\left(\frac{T_B}{T_A}\right)^2\right)^2 + 4\xi_A \xi_B \left(1+\frac{T_B}{T_A}\right)^2 \frac{T_B}{T_A} + 4\left(\xi_A^2+\xi_B^2\right)\left(\frac{T_B}{T_A}\right)^2} \qquad (6)$$

ξ = damping ratio and T_B/T_A = ratio of the fundamental periods of the two buildings.

Good results are obtained, at least for elastic systems.

Garcia (2004) evaluates four different methods to calculate critical separation distances. All methods use Double Difference combination rule, but follow different approaches to calculate the correlation coefficient ρ. Then he proposes a new one which consists of using values of parameter ρ derived from empirical estimates obtained through numerical simulations.

1.2 Increasing the stiffness of one or both buildings

Since the gap between two buildings usually cannot be increased, increasing the stiffness of one or both buildings may reduce the seismic deformations to the point where impact is precluded with the existing gap. Increasing the stiffness of the building, reduce the period of this one and lead to a decrease of its displacement.

1.3 Supplemental energy dissipation

Another method to avoid pounding is the use of supplemental energy dissipation devices in the buildings.

Using supplemental energy dissipation devices reduces the maximum lateral deflections of the building. Even if the reduction in the maximum energy levels provided may not be sufficient to avoid pounding, the amplification effects of impacts in the structures will be smaller.

1.4 Alternative load paths

If increasing the stiffness is not feasible (ex. stiff shear wall buildings) FEMA-172 proposes to provide alternative load paths for the vertical load-resisting members that may be damaged or destroyed by the impact. These alternative load paths would include supplementary columns or vertical shoring to support the floor or roof systems. These supplementary supports would be installed at sufficient distance from the vulnerable exterior walls or columns to be protected when the existing elements are damaged.

1.5 Impact absorbing materials

A measure for reducing the effects of pounding, while maintaining small separation distances, would be to fill the gap with a special, shock absorbing material (bumper dampers). Bumper damper elements must be dissipative to reduce pounding accelerations and forces during contact. Under bumper damper elements, all energy dissipation devices available that can be placed between the structures, but connected only to one of them, are considered. Bumper dampers are therefore energy dissipation links that are activated when the gap is closed. The presence of the bumper damper element will reduce the impulsive forces transmitted from one structure to the other.

If the element provides only stiffness the impulse loads will still be reduced since the impacting bodies will encounter a spring element reducing the kinetic energies of the structure before the stroke of the element is reached, at which point the full pounding of the masses will take place, but the impacting velocities will be smaller. Although the velocities at the onset of pounding are smaller, the linear spring will increase the velocities after pounding, but the high frequency accelerations observed will be reduced.

Anagnostopoulos (1988) showed that a soft viscoelastic material filling gap between two adjacent structures can reduce the effects of pounding significantly. This solution, however, did not reduce the building response below the values reached without pounding. Another inconvenient of this solution is that it does not solve the problem for the last building in a row. This building will behave like a pendulum.

Wolf and Skrikerud (1980) also studied a tuning device which completely occupies the existing gap size. It is assumed that this tuning device consists of a visco-elastic material which is modelled as an elastic spring with a stiffness coefficient k_t and a viscous damper (working in parallel) with a coefficient c_t. They found that introducing a tuning device between the two involved structures reduces the maximum impact force and thus local response somewhat.

1.6 Connecting buildings together

As an alternative to seismic separation, permanent connections of the adjacent buildings have been investigated. A permanent linkage would provide a continuous force to the structures which is proportional to the stiffnesses and thus more in-line with the dynamic behaviour of the unlinked frames.

Linking adjacent buildings has a number of disadvantages, including possible high forces in the link, the fact that the dynamic characteristics and the design failure mechanisms are changed, and the uncertainties inherent when the two structures of different characteristics must become one.

Nevertheless if those problems are solved, linking two structures will reduce the possibility or the influence of pounding interactions (Plumier et al. (2005)). If an energy dissipation device is used between the two structures, pounding will occur if the stroke of the element is not sufficient.

2. CLASSIFICATION OF DEVICES USED TO CONTROL THE SEISMIC MOVES OF STRUCTURES

2.1. Introduction

A great number of protective systems for structures built on seismic areas have been developed since the years 1970's. These developments have been made to mitigate action effect in individual structure, without special consideration on pounding problem.

After a brief summary of these energy dissipaters, the next chapter will be on studies on pounding mitigation using these devices.

Modern structural protective systems can be divided into three groups as shown in Table 1.

Table 1 - Modern Structural Protective Systems

Seismic Isolation	**Passive Energy Dissipation**	**Semi-active and Active Control**
Elastomeric	Metallic Dampers	Active Bracing Systems
	Friction Dampers	Active Mass Dampers
Lead Rubber Bearings	Viscoelastic Dampers	Variable Stiffness or Damping Systems
	Viscous Fluid Dampers	Smart Materials
Sliding Friction Pendulum	Tuned Mass Dampers	
	Tuned Liquid Dampers	

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. As it cannot be used either to reduce the individual displacement of one structure or to connect two neighbouring structures, the seismic isolation system will not be presented in this section.

Passive energy dissipation devices for structural applications are similar to seismic isolation technology. Their basic function is to absorb or consume a portion of the input energy, thereby reducing energy dissipation demand on primary structural members and minimizing possible structural damage. Contrary to semi-active or active systems, there is no need for an external supply of power.

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

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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.

2.2. Passive control devices

Passive control techniques are based on the artificial increase of the dissipation capacity, obtained by means of the insertion, in proper positions, of special devices of the which both the stiffness and strength have to be defined in order to achieve:

- a limitation of the relative move of buildings one toward the other;
- energy dissipation.

Recentering of the system after the earthquake is another identified goal, for practical use of the structure after the earthquake.

Devices with force-displacement response characteristics that are primarily a function of the displacement amplitude are classified as rate (in fact strain rate) independent devices. The behaviour of these devices is generally independent of the relative velocity or the frequency of motion. They include friction and metallic devices.

2.2.1 Metallic dampers

In recent years, a variety of mechanical devices that incorporate the yielding deformation of mild steel to provide supplemental damping have been implemented in earthquake-resistant designs of buildings and other structures. Some particularly desirable features of these devices are their stable hysteretic behaviour, low-cycle fatigue property, long term reliability, and relative insensitivity to environmental temperature.

They typically exhibit hysteretic force-displacement behaviour, which can be approximated as bilinear or trilinear. These devices tend to be inexpensive to produce and their properties will remain stable over the long lives of buildings. Unfortunately, they often have a limited number of working cycles, which may require them to be replaced after large seismic events.

The yield strength of the connector is difficult to decide because if the yield strength is too high, the connector may not function properly but if the yield strength is too low, the energy absorbing capacity may be too small during a strong earthquake. However, some possibility to tune the device exist by the fact that stiffness, which is related to section, and yield strength, which is mater of section and yield stress, can be decided independently, to some extend.

Several of the devices considered included torsional beam, flexural beam, and U-strip dampers are shown schematically in Figure 2.

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Many new designs have been proposed, including the X-shaped and triangular plate dampers displayed in Figure 3. With this shape yielding is spread almost uniformly throughout the material.

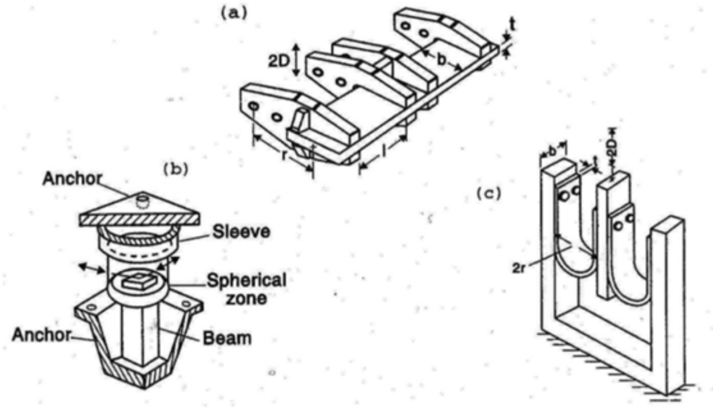

Figure 2 - a) Torsional Beam, b) Flexural Beam, c) U-strip (Soong and Dargush 1997)

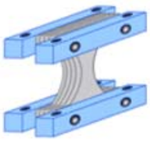

Figure 3 - X-plate Metallic damper (Soong and Dargush 1997)

An inconvenient is that they are designed to deform so much when building vibrates during an earthquake that they cannot return to their original shape and have permanent deformation.

2.2.2 Friction dampers

Friction dampers utilize the mechanism of solid friction to provide the desired energy dissipation. The friction develops between two solid bodies sliding relative to one another. When the parts slide over each other, they create friction, which uses some of the energy from the earthquake that goes into the building. Friction between dry surfaces produces a constant force independent of velocity, always opposed to the direction of motion that is proportional to the contact forces between the sliding surfaces and the coefficient of friction of the materials. The behaviour of the devices are nearly unaffected by amplitude, frequency, temperature, or the number of applied loading cycles.

Friction devices generally exhibit rigid-plastic behaviour so the force-displacement curves of the devices are rectangular loops as shown in Figure 4. These devices can be characterized by their displacement amplitude and slip-load. The friction force in the damper can be adjusted through appropriate torque of the bolts that control the pressure on the friction surfaces.

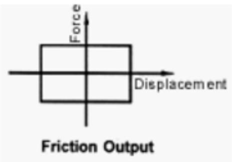

Figure 4
Force displacement relation for friction device

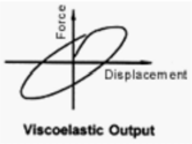

Figure 5
Force-displacement for a viscoelastic damper

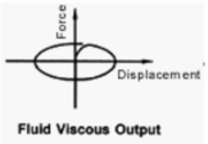

Figure 6
Force-displacement for a fluid viscous damper

Practical engineer must pay attention that frictional devices must be loaded beyond the slip threshold, and thus are likely to be ineffective under small to moderate shaking.

Several types of friction dampers have been developed for the purpose of improving seismic response of structures. They are illustrated in Figure 7.

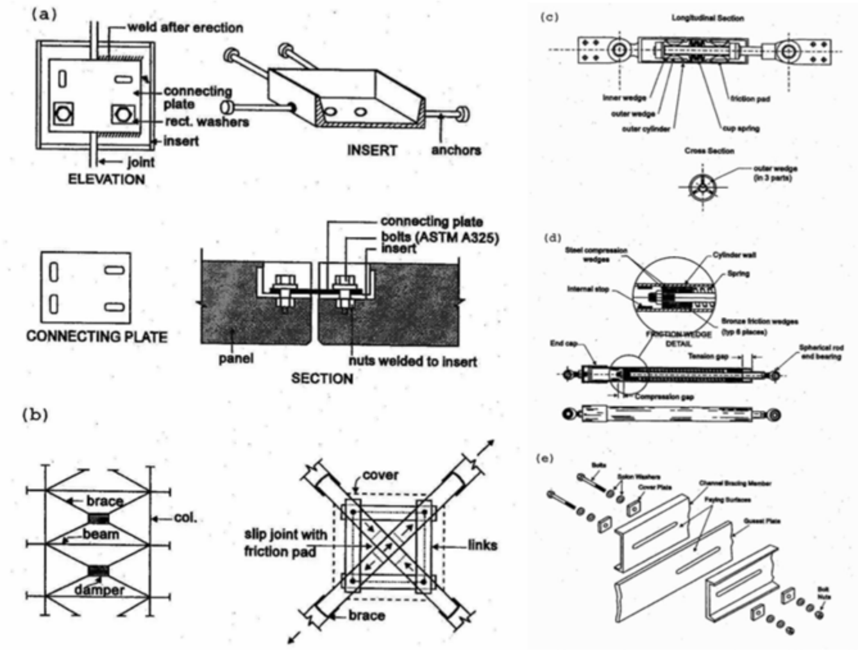

Figure 7 - a) Limited Slip Bolt Joint, b) X-braced Friction Damper c) Sumitomo Friction Damper d) Energy Dissipation Restraint e) Slotted Bolted Connection (Soong and Dargush 1997)

In recent years, there have been a number of structural applications of friction dampers aimed at providing enhanced seismic protection of new and retrofitted structures. For example, the applications of friction dampers to the McConnel Library of the Concordia is shown in Figure 8.

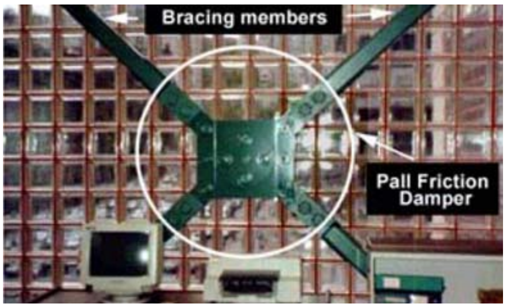

Figure 8 - Pall Friction Damper installed in the Webster Library of Concordia University in Montreal, Canada.

One important thing is to ensure that the contact forces between the sliding surfaces and the coefficient of friction do not change with the long-term periods. Another inconvenient is that friction dampers restrict a structure from restoring itself to its original position after seismic events. They need to be supplemented by a restoring force mechanism.

2.2.3 Viscoelastic dampers

Viscoelastic materials used in structural application are typically copolymers or glassy substances which dissipate energy when subjected to shear deformation. A typical viscoelastic damper is shown in Figure 9 which consists of viscoelastic layers bonded with steel plates. When mounted in a structure, shear deformation and hence energy dissipation take place when the structural vibration induces relative motion between the outer steel flanges and the centre plate.

They provide extra damping, alleviate mechanical vibration, and thus improve overall system dynamic responses.

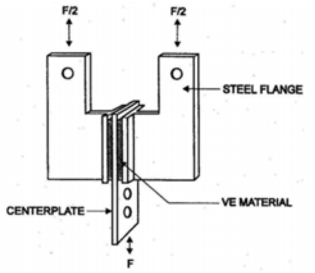

Figure 9 - Viscoelastic Damper

Viscoelastic devices have an output that is somewhere between that of a damper and a spring. Under high-level seismic inputs, the spring response dominates, producing a response that increases stresses of adjacent columns at any given deflection. Viscoelastic dampers are quite linear in their response and are able to dissipate energy under low levels of shaking.

The designer has to take into account the effect of ambient temperature and excitation frequency for an effective design of viscoelastic dampers in structural applications. These devices can be modelled with Maxwell model, which consists of a spring and dashpot in series. The force-displacement curves of the devices are shown in Figure 5.

2.2.4 Fluid viscous dampers

Viscous damping involves taking advantage of the high flow resistance of viscous fluids. The forces developed in a viscous damper are proportional to the velocity of its deformation. Fluid viscous dampers put out virtually zero force at the low velocities associated with thermal motion. The force-displacement curves of the devices are shown in Figure 6.

Viscous fluid dampers are similar to shock absorbers in a car. They consist of a closed cylinder containing a viscous fluid like oil. A piston rod is connected to a piston head with small holes in it. First, the piston moves in the cylinder, then the oil is forced to flow through holes in the piston head, causing friction. When the damper is installed in a building, the friction converts some of the earthquake energy going into the moving building into heat energy. The force depends on the size and shape of the orifices and the viscosity of oil.

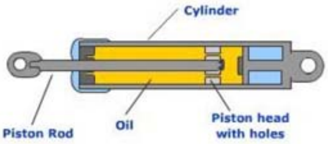

Figure 10 - Example of fluid viscous damper

The restoring force in an elastic structure damped by viscous dampers is proportional to the velocity at which the material is strained, so that energy is dissipated via viscous damping.

$$F_{damper} = CV^{\alpha} \tag{7}$$

where C = damping constant, V = velocity and α = velocity exponent

with (0,3 ≤ α ≤ 1,0).

When α is equal to unity, the damper is a linear viscous damper. The fluid damper commercially available consists of a cylinder and a stainless-steel piston with a bronze orifice head and accumulator. The orifice utilizes a series of specially shaped passages to alter flow characteristics with fluid speed.

Fluid viscous damping reduces stress and deflection because the force from the dampers is completely out of phase with stresses due to flexing of the columns. This is only true with fluid viscous damping, where damping force varies with stroking velocities. Consider a building shaking laterally back and forth during a seismic event. Column stress is at a maximum when the building has flexed a maximum amount from its normal position. This is also the point at which the flexed columns reverse direction to move back in the opposite direction. If we add a Fluid Viscous Damper to the building, damping force will drop to zero at this point of maximum deflection. This is because the damper stroking velocity goes to zero as the columns reverse direction. As the building flexes back in the opposite direction, maximum damper force occurs at maximum velocity, which occurs when the column flexes through its normal, upright position. This is also the point where column stresses are at a minimum. It is this out of phase response that is the most desirable design aspect of fluid viscous damping.

Fluid inertial dampers have several inherent and significant advantages: linear viscous behaviour, insensitivity to stroke and output force; easy installation; almost free maintenance; reliability and longevity. Fluid viscous dampers allow the structure to re-center itself perfectly at all times.

2.2.5 Tuned mass dampers

The objectives of incorporating a tuned mass damper into a structure is basically the same as those associated with metallic dampers and other energy dissipation devices, namely to reduce energy dissipation demand on the primary structural members under the action of external forces.

This reduction, in this case, is accomplished by transferring some of the structural vibrational energy to the tuned mass damper which, in its simplest form, consists of an auxiliary mass-springdashpot system anchored or attached to the main structure.

In tuned mass dampers, typically a solid concrete or metal block acts as the secondary mass. Additional spring and dampers are used to attach this secondary mass to the primary structure, and to provide the restoring and dissipate mechanisms needed to tune the system for near-optimal response under various types of dynamic excitations.

It is noted that a passive Tune Mass Dampers (TMD) can only be tuned to a single structural frequency. While the first-mode response of a MDOF structure with TMD can be substantially reduced, the higher mode response may in fact increase as the number of stories increases. For earthquake-type excitations, the response reduction is large for resonant ground motions and diminishes as the dominant frequency of the ground motions gets further away from the structure's natural frequency to which the TMD is tuned.

2.2.6 Tuned liquid dampers

Tuned Liquid Dampers work according to the same principle as Tuned Mass Dampers; a tank filled with water replaces the mass and the sloshing of the liquid creates the mass-springdashpot system, due to grids with holes that slow down the liquid moves.

2.3 Active control devices

The term "active" is used to indicate that the operation of these systems requires a significant amount of external power. Active control devices utilize the feed back from sensors measuring the response of a structure to control the behaviour of structural elements through mechanical actuators. Records from the sensors are then fed into a controller (computer) that activates devices for modifying the structure's response continuously during its excitation. There are several different types of active control devices presently in use, some of which are as follows: active mass damper, active base isolator and active tendons.

Active tendons are devices wherein tension in the prestressed tendons is varied during the earthquake excitation in a way to reduce the structure's response.

The active mass damper is a combination of a passive Tuned Mass Damper and an active control actuator. The ability of this device relies mainly on the natural motion of the TMD. The forces from the control actuator are employed to increase the efficiency of the device.

One of the problem with this devices is that since active control systems depend on power supply, it has to be ensured that this supply will not be interrupted during a strong earthquake, otherwise the whole system will remain idle exactly at the time that it will required to function.

2.4 Semi-active connectors

Nestled between passive and active structural control technologies is an emerging area of research addressing the possible use of innovative or "smart" materials for sensing and control purposes. This class of smart materials can be incorporated into structural elements, capable of modifying structural behaviour in response to external stimuli. Semi-active control systems have been developed to take advantage of the best features of both passive and active control systems.

The term "semi-active" is used to indicate that the operation of these systems requires a very small amount of external power. As in an active control system, the mechanical properties are typically adjusted based on feedback from the structural system to which they are attached. As in a passive control system, semi-active control systems utilize the motion of the structure to develop control forces. The control forces are developed through appropriate adjustment of damping or stiffness characteristics of the semi-active control system. Semi-active are fail-safe because they can be designed to exhibit either prescribed damping or prescribed stiffness characteristics in the event of a complete loss of power.

The most predominant materials that have been examined as actuation devices in recent years are shape memory alloys, piezoelectic elements, electrorheological fluids and, more recently, magnetoreheological fluids.

One means of achieving a semi-active damping device is to use a controllable, electromechanical, variable-orifice valve to alter the resistance to flow of a conventional hydraulic fluid damper.

Another class of semi-active devices uses controllable fluids. For example, the magnetoreheological fluids are based on special fluids which are able to change their viscosity from liquid to semi-solid state within milliseconds, under the action of an applied magnetic field, so to produce, according to a preset control strategy the desired control forces.

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