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PASSIVE CONTROL OF CIVIL ENGINEERING STRUCTURES

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ABSTRACT

Structural control has been a major research area in aerospace engineering aimed at solving very complex problems related with analysis and design of flexible structures. The efficiency of these strategies to improve the performance of several structural systems suggests its potential to reduce damage and control earthquake-induced response in civil structures. Therefore, this technology has been well accepted by structural engineers as a feasible approach to design improved earthquake resistant structures. The present paper provide a brief description of each control scheme describing the main properties of different anti-seismic solutions and presenting the most relevant developments in this area. Control methodologies and devices are highlighted identifying their advantages and limitations. The main focus of this paper is to present a comprehensive state-of-the-art of passive control system. Different passive techniques are described and the effectiveness in mitigating seismic hazard for structures is addressed.

Keywords: passive control, base isolation, energy dissipation.

INTRODUCTION

Passive control was among the first control scheme to mitigate vibrations in civil engineering structures such as buildings and long bridges with high level of seismic safety. This type of control do not require power to operate and therefore passive systems are non-controllable in the sense that is not possible to change the control forces or the device behaviour during the earthquake excitation.

Although the passive nature can be seen as a limitation to the adaptability of the control system, is also a source of reliability since passive systems are not affected by possible power outages during the seismic event but also because they have low maintenance requirements. Therefore, these systems are perceived as a reliable, economic and easy to realize technique to enhance structural safety and integrity allowing protecting not only structural and non-structural elements but also building contents for considerably large earthquakes.

Passive devices are designed to dissipate or transfer the seismic energy been transmitted to the structure and/or isolate the structure from external loadings in order to minimize structural and non-structural damage. Seismic isolation and passive energy dissipation/transfer are generally recognized as the most effective and relatively inexpensive anti-seismic protective systems.

This type of control systems are designed or tuned with uncontrollable and constant properties to protect the structure from a particular dynamic loading or response by dissipating the seismic energy using the structural vibration to convert kinetic energy to heat or by transferring energy among vibrating modes.

Passive dissipation devices take advantage of the mechanical properties of some materials such as rubber, steel, lead, viscous and viscoelastic materials or friction mechanisms to dissipate the seismic energy in order to reduce the plastic deformations in the structural elements, i.e., to reduce the inelastic dissipation demand of the structural elements (plastic hinges) and therefore limiting structural damage. Since they are designed to absorb or concentrate the input energy, some damage may occur in these devices, which require their substitution after the earthquake although the device replacement is usually easy to perform. Transferring energy among vibration modes is achieved with supplemental oscillators that operate as dynamic absorbers (Constantinou and Symans, 1993; Symans *et al.*, 2008).

The strategies based upon passive control are well known and accepted methodologies that have been applied successfully to civil engineering structures due to its effectiveness to enhance damping, stiffness and strength of new or existing structures for natural hazard mitigation (Soong and Spencer, 2002). Although their passive nature offers significant reliability compared to other control strategies since they do not require external energy to operate (they can operate during a power outages**,** no energy is injected into the system and they guarantee a stable response), the constant behaviour of passive devices is a significant limitation since the system does not perform with efficiency for other dynamic loading or structural configuration.

Passive control system are generally designed to provide one or a combination of the following functions:

1. Vertical rigidity or load capacity to support gravity loads in order to provide structural integrity (in the case of base isolation systems);
2. Lateral flexibility to elongate the natural period of the structure (period shift effect of base isolation systems);
3. Restoring force and re-centering capability to reduce residual displacements to manageable levels;
4. An energy dissipation mechanism to absorb the input energy and control the lateral deformation of flexible elements.

According with the operating principle, passive devices can be grouped into three basic types: isolators, supplemental damping devices and supplemental oscillators as shown in Table 1.

Isolators are essentially base isolation systems that uses a period shit effect and also energy dissipation to reduce the energy been transmitted to the structure. In this case, the stiffness of the system is reduced introducing a flexible layer or isolator between the ground (base of the building or foundations) and the structure. Rubber bearings have been extensively used to produce isolation devices and base isolation systems for vibration control and dampening due to its energy absorption capability.

Supplemental damping devices are based on kinetic energy to heat conversion to dissipate the seismic energy either by hysteretic or viscous dissipation mechanisms. Different types of dampers, sometimes in combination with base isolation systems, are used as passive dissipation devices to reduce the displacement demand of structural and non-structural elements.

Finally, energy transfer is obtained with additional oscillators.

Table 1 Description of typical passive control systems

Control strategy	**Passive Control system**
Isolators - base isolation systems (Period shit effect/Energy dissipation)	Natural Laminated Bearings
	Lead and High Damping Rubber Bearings
	Sliding Bearings
Energy dissipation (Kinetic energy to heat)	Metallic Yield Dampers
	Friction Dampers
	Viscoelastic Dampers
	Viscous Fluid Dampers
Energy transfer (Supplemental oscillators)	Tuned Mass Dampers
	Tuned Liquid Dampers

Anti-seismic passive control is an on-going research field and many innovative materials or control solutions have been proposed and develop to produce passive devices such as Shape Memory Alloys (SMA) dampers, electro inductive dampers (DECS), post-tensioned energy dissipating (PTED) steel connections, Scrap Tire Pads (STP) isolators, roll-n-cage (RNC) isolators, Rubber-Soil Mixtures (RSM), Scrap Tyre-Soil Mixtures (STSM), isolators made of geo-synthetic materials, BS cushion (treated asphalt-fiber seismic base isolation cushion), etc.

BASE ISOLATION

Passive isolation systems are the easiest, reliable and cost-effective structural control approach that can be used to protect buildings and bridges from the harmful effects of undesired strong seismic vibrations. They have been adopted most widely in the last decades as the prevailing mitigation technique in seismic prone regions either for new projects or to retrofit existing structures.

There are several potential seismic isolation solutions and the following represent some of the most acknowledged or original strategies that have been proposed for base isolation of civil structures (Naeim and Kelly, 1999; Özden, 2006; Tsang, 2008; Tsang *et al.,* 2009; Moustafa *et al*., 2009; Patil and Reddy 2012):

- Roller and ball bearings;
- Rubber layer as foundation;
- Sleeved pile isolation system;
- Rocking systems;
- Spring-based isolation systems;
- Metallic and lead-extrusion dampers;
- Synthetic liners and artificial soil layers;
- BS cushion;
- Scrap tire pads isolators;
- Roll-n-cage isolators.

Table 2 Usual types of isolation devices for base isolation systems

Isolation devices/systems	
Elastomeric Isolators	**Sliding Isolators**
Natural Rubber Bearings Low-Damping Rubber Bearings Lead-Plug Bearings High-Damping Rubber Bearings	Resilient Friction System Friction Pendulum System

Among the different base isolation systems and devices, elastomeric and sliding bearings are the most widely used strategy for vibration isolation in buildings and bridges. Although many other base isolation systems are available, they have seen little to no implementation in real applications. The major types of seismic isolation bearings are listed in Table 2.

Besides the typical base isolation systems, there are a significant amount of devices and isolation techniques that have been proposed and investigated with the purpose to create simple, effective and economic seismic isolation systems. These systems intend to improve the properties of current base isolation systems reducing their usual drawbacks while keeping the main advantages.

Some of these base isolation techniques are based on simple structural concepts like springs and rollers to create the isolation layer, namely spring-based and rolling-based isolation systems (rolling rods, rolling pendulum, Ball-N-Cone, multi-step isolation systems, mutually eccentric rotators, directional rolling pendulum, RoBall isolation systems, etc.) while other systems attempt to use innovative concepts like employing synthetic liners and artificial soil layers to create a flexible layer under the structure (e.g. geo-synthetic materials and rubber-soil mixtures).

New designs such as the Roll-n-Cage isolator and innovative materials such as shape memory alloy (SMA) bars used to dissipate energy and re-center the device have also been used to make base isolation systems (Casciati *et al.*, 2007; Moustafa *et al*. 2009).

Moreover, new base isolation solutions based on recycled materials are being tested not only with an environmental concern but mainly to develop inexpensive devices that can be used in developing countries either in relatively simple and less important structures or non-structural elements. Good examples of the latter type of isolation systems are those that use scrap or used tires to create scrap tire pads isolators or scrap tyre-soil mixtures.

Although each of these isolation systems has specific dynamic properties that provide a certain level of structural protection within the seismic design requirements and code provisions, there are still no wide-ranging seismic isolators capable to deal with the dynamic and variable nature of an earthquake or wind loading. Therefore, the selection of an isolation device must be carried out according with the control level to be achieved over the seismic response. However, with proper design and implementation, base isolation systems are both an effective and an inexpensive approach to seismic vibration mitigation.

There are a wide range of isolation devices that can be used to create seismic isolating systems for buildings and bridges. Although they all ensure that the essential requirements of a base isolation system are achieved, each device has their own characteristics.

The main advantages and disadvantages of each type of isolation device are summarized in Table 3.

Table 3 Advantages and disadvantages of typical devices for base isolation

Devices	Advantages	Disadvantages
Elastomeric Bearings	***General***	
	- Low in-structure accelerations - Low cost - Moderate in-structure accelerations.	- Large displacements and low damping - No restoring force mechanism - P-Δ influence
	High Damping Rubber Bearings	
	- Resistance to service loads. - Moderate to high damping.	- Strain dependent stiffness and damping and limited choice of stiffness and damping. - More complex analysis. - Scragging-change properties
	Lead Rubber Bearings	
	- Wide choice of stiffness and damping. - High damping level	- Cyclic change in properties.
Sliding bearings	***General***	
	- Low profile - Resistance to service loads - High damping levels - P-Δ influence	- High in-structure accelerations. - Properties are function of pressure and velocity and high initial stiffness - Sticking.
	Flat Sliding Bearings	
	- Slide plate separates from pad if uplift loads occur. - Simple in concept - No strain hardening - Earthquake and structure independent	- No restoring force.
	Friction Pendulum System Bearings	
	- Moderate to high damping. - Reduced torsion response. - Relatively wide damping range - Reduced structural torsion	- High cost - Fixed vibration period - Uplifted structure with motion
Rollers	- Very low structural accelerations. - Simple means and concept - Great horizontal flexibility	- No damping - No recentering mechanism - Not for heavy masses - Flattening of contact surfaces
Springs	- Provide 3D isolation - Commonly used for machinary	- No damping - Produces vertical accelerations - No recentering mechanism - Not for heavy masses
Hysteretic Dampers	- Control displacements Dampers - Low cost - Provide stiffness and damping - Wide damping range	- Add force to system.

Although the limitations of base isolation system can sometimes make impracticable their applicability, overall the advantages far outweigh the disadvantages. Thus, despite the disadvantages of base isolation systems, this control approach is the most widespread, reliable, efficient and economical solution for vibration mitigation of earthquake ground motions.

PASSIVE ENERGY DISSIPATION

Unlike isolation systems in which the seismic control response is achieved by cutting off the energy transmitted of the earthquake ground motion to the structure, this type of control systems utilize an energy dissipation mechanism located into the structure that aims to enhance energy dissipation in the structural system, i.e., to decrease foreseeable lateral forces in structural elements. Therefore, the principle of operation of these devices is to dissipate energy during the earthquake to reduce the inelastic energy dissipation demand (Constantinou and Symans, 1993).

This difference in approach between base isolation and energy dissipation represent a major distinctive feature of passive control systems since isolation devices prevent the seismic energy to be transmitted to the superstructure while energy dissipation devices require that the seismic forces are been transmitted from the foundation to the superstructure to enable such devices or systems to operate.

The concept behind supplemental damping consists of using a secondary damping system, usually a mass-spring-damper type element, coupled with a primary system (the building or bridge structure) with the objective to absorb a portion of the input seismic energy in order to reduce energy dissipation demands and prevent damage of the primary structure. This technique utilizes many different types of damping devices or dampers that operate on principles such as frictional sliding, yielding of metals and deformation of viscoelastic solids or fluids as illustrated in Fig. 1 (Housner *et al*., 1997; Soong and Dargush, 1997; Soong and Spencer, 2002).

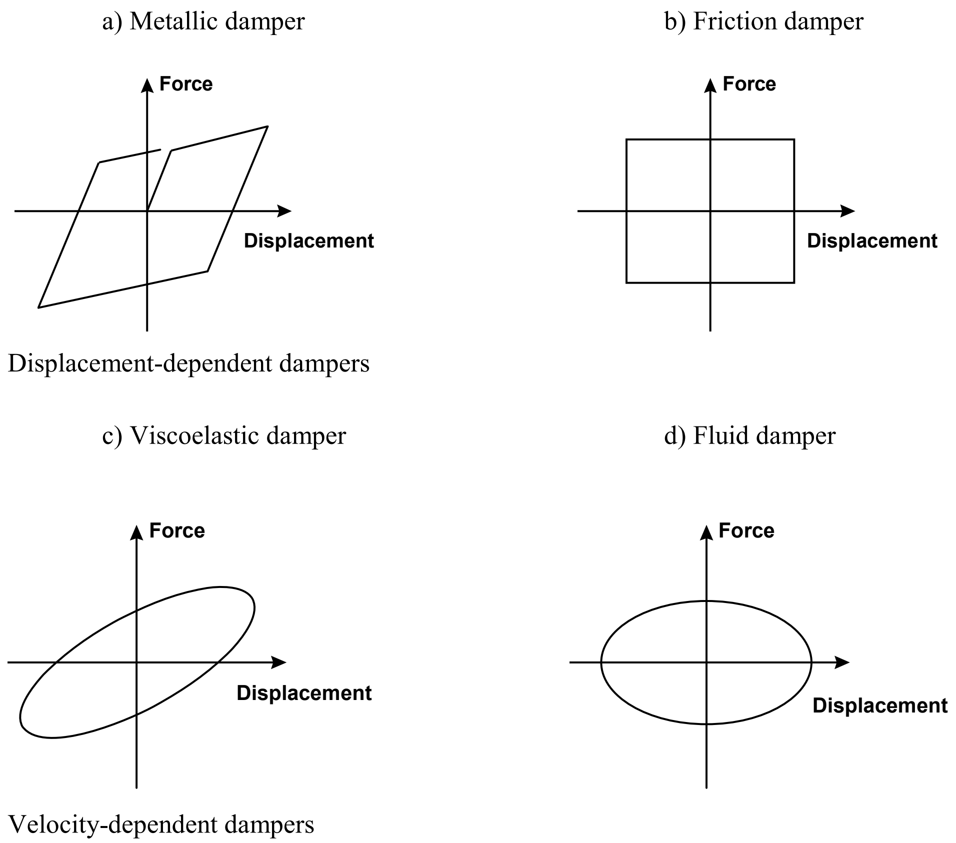

Fig. 1 Hysteresis loops of different types of dampers

Table 4 Classification of usual energy dissipation devices

Energy dissipation devices		
Displacement-dependent	**Velocity-dependent**	**Motion-activated**[1]
Metallic dampers Friction dampers	Viscous dampers Viscous shear walls	Tuned Mass dampers Tuned Liquid dampers
Viscoelastic dampers[2]		

[1] These devices will be addressed in a separate section.
[2] Viscoelatic dampers are displacement and velocity dependent.

The main types of energy dissipation devices classified according with their rate-dependence behavior are shown in Table 4 (Christopoulos and Filiatrault, 2006).

Usually, conventional dampers are unable to limit residual displacements after a seismic event and consequently there have been some attempts to create damper systems that incorporate re-centering capabilities. These energy dissipation devices have a particular rheological behavior characterized by a flag-shaped hysteretic loop that cannot be described by the basic hysteretic loop types depicted in Fig.1. They include self-centering devices such as phase transformation dampers (based on shape memory alloys), energy dissipation restraint systems, frictional-spring assemblies with re-centering capabilities, fluid restoring force/damping dampers and post-tensioned energy dissipating systems, etc. (Soong and Dargush, 1997; Constantinou *et al*., 1998; Hanson and Soong, 2001).

Passive dampers are usually installed in diagonal or chevron braces as shown in Fig. 2a-b, which may result in small damper displacements that are not large enough to dissipate significant amount of seismic energy. Therefore, several toggle systems have been proposed to magnify the damper displacement and the effective damping force as shown in Fig. 2c-d (Sigaher and Constantinou, 2003).

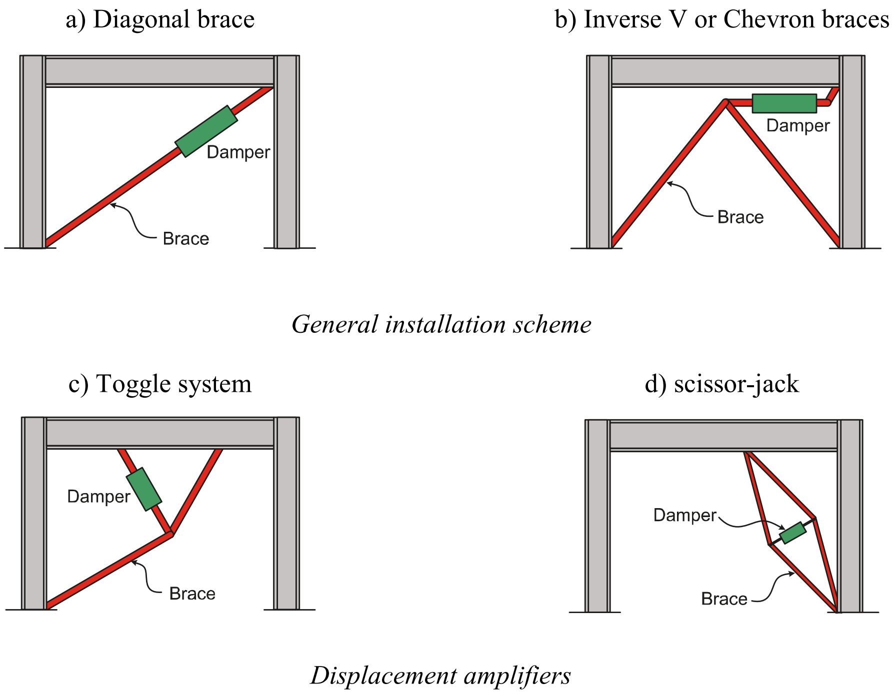

Fig. 2 Installation of passive dampers in buildings (Choi and Kim, 2010)

The main concern of supplemental damping design is the significant residual displacements in the structure after the earthquake. Thus, the re-centering capability of the system is an important characteristic that must be considered to minimize residual deformations. Many self-centering hysteretic systems have been proposed such as rocking systems, energy dissipating restraint devices, SMA dampers, Ring-Spring systems, post-tensioned frame and wall systems, etc. These new passive control systems incorporate yielding and self-centering properties allowing the structure to return to its original position after an earthquake.

Each of the mentioned systems has different properties and the selection of a specific device must be in accordance with the seismic and structural performance, reliability and other requirements that were proposed during the design procedure. The main advantages and disadvantages of common passive energy dissipation devices are enumerated in Table 5 (Symans *et al.*, 2008).

Table 5 Advantages and disadvantages of typical passive energy dissipation devices

Devices	**Advantages**	**Disadvantages**
Viscous fluid damper	- Activated at low displacements. - Minimum restoring force. - Linear behavior, therefore simplified modeling of damper. - Properties are largely frequency and temperature independent. - Proven record of performance in military applications.	- Possible fluid seal leakage (reliability concern).
Viscoelastic solid damper	- Activated at low displacements. - Provides restoring force. -Linear behavior, therefore simplified modeling of damper.	- Limited deformation capacity. - Properties are frequency and temperature dependent. - Possible debonding and tearing of VE material (reliability concern).
Metallic damper	- Stable hysteretic behavior. - Long-term reliability. - Insensitive to ambient temperature. - Materials and behavior familiar to practicing engineers.	- Device damaged after earthquake, may require replacement. - Nonlinear behavior, may require nonlinear analysis.
Friction damper	- Large energy dissipation per cycle. - Insensitive to ambient temperature.	- Sliding interface conditions may change with time (reliability concern). - Strong nonlinear behavior, may require nonlinear analysis. - No recentering mechanism with permanent residual displacement.

Several other possible supplemental damping solutions have been proposed or implemented to reduce seismic response of civil structures and the use of innovative materials and new designs opens up new possibilities for the passive control of buildings and bridges.

TUNED MASS DAMPERS

Tuned mass dampers (TMD) are another type of passive devices that are frequently used to control the response of buildings and bridges. Essentially, a TMD consist of a mass-spring-damper system that is attached to the main structure, usually on the top of the structure, in order to counteract the ground motion reducing the dynamic response of the structure.

The energy dissipation is achieved by the damper inertia force acting on the structure (Housner *et al.*, 1997; Soong and Spencer, 2002). These systems are mostly efficient to control wind-induced vibrations in slender structures such as towers and tall buildings and usually tuned dampers can be classified in three groups:

- Tuned Mass Damper (TMD);
- Tuned Liquid Dampers (TLD);
- Tuned Liquid Column Dampers (TLCD).

The classical configuration of a tuned damper is the so-called TMD that was previously addressed and consists of a secondary mass with properly tuned spring and damping elements, which provides a frequency dependent hysteresis that increases damping in the primary structure. Therefore, the effect of the TMD can be related with an increase in the damping of the structural system. This device is particularly effective to mitigate wind-excited responses for stationary narrow band excitations, but is less effective for broadband excitation such as earthquake. Several types of TMDs are available for practical implementation and common configurations are shown in Fig. 3 (Cheng *et al.*, 2008).

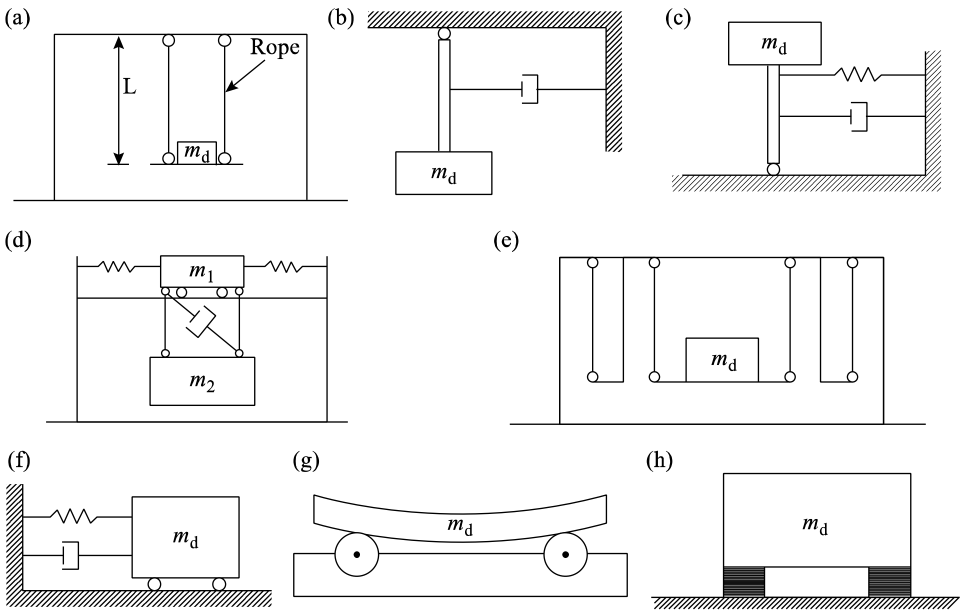

Fig. 3 Typical types of TMDs: a) simple pendulum, b) pendulum with damper, c) inverted pendulum, d) two-mass damper, e) multistage damper, f) sliding mass with spring and damper, (g) swinging mass on rotational bearings, and h) mass on rubber bearings.

Tuned liquid dampers (TLD) and tuned liquid column dampers (TLCD) operate on the same principle of TMDs but instead of using a mass-spring-dashpot system to absorb the wind or seismic energy, these systems use the movement of a liquid to obtain the same effect. While TLD uses the sloshing of the liquid in a tank to dissipate seismic energy (viscous action of a liquid and wave breaking), TLCD generates high-flow turbulence by the passage of a liquid through orifices to provide damping capacity (Fig. 4).

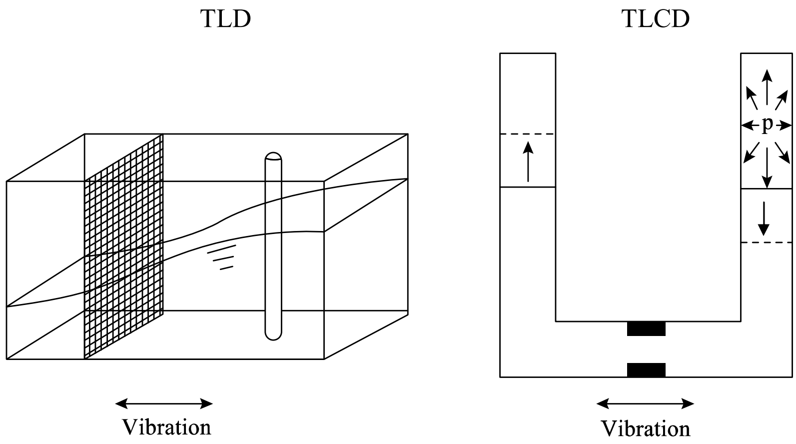

Fig. 4 Principle of operation of TLDs and TLCDs (Cheng *et al*., 2008)

Since they are passive devices, they do not depend on an external power source. In addition to these advantages, tuned mass dampers present the following general benefits (Maldonado-Mercado, 1995):

1. They can be considered in new design or in existing structures and the impact of these devices on the design of the structure is minimum (they do not interfere with the principal vertical and horizontal load paths of the structure).
2. A single unit can be effective in reducing vibrations induced by small earth- quakes, wind and traffic.
3. These devices can respond to small level of excitation and their properties can be adjusted in the field.

Besides, TLD and TLCD have some additional advantages such as low cost and maintenance (compared with TMDs), they are ease to install and their properties are easily tuned in the field by changing the liquid level (Chang and Hsu, 1998; Chang, 1999; Soong and Spencer Jr., 2002). Moreover, a single TLD can be effective in any direction of lateral vibrations and water used for TLD can serve a dual purpose as part of the building's fire protection supply (Cheng *et al*., 2008).

On the other hand, these devices have some disadvantages compared with other passive systems (Maldonado-Mercado, 1995):

1. TMDs require a large mass for their effectiveness (limited by the maximum weight that can be placed on top of the structure) and a large space is needed for their installation and operation (there must be enough space to allow the mass to move). Besides, some additional space must be required to install constraint systems to limit the mass movement.
2. TMDs require field adjustment during the installation procedure to fine-tune their functioning in according with the real natural frequencies of the structure. Periodic adjustments can also be required to keep their effectiveness during the service life of the structure.

3. Due to their passive nature, these devices are used to control the response of a structure for a specific vibration mode. Therefore, multiple devices are required to control the response of several vibration modes.
4. Although these devices can respond to low-level excitations, friction can limit their efficiency to control this type of excitation. Thus, particular attention should be taken to create a low friction device to ensure a suitable operation.

Likewise, TLD and TLCD have some additional disadvantages when compared with TMDs. First, these devices exhibit a highly nonlinear response due to liquid sloshing and the presence of orifices, which complicates the analysis and design process. In addition, they require more space than classical TMDs due to liquid mass density that is significantly lower than solid materials used in the TMDs.

CONCLUSIONS

The large diversity of passive control devices indicates the importance that has been devoted to structural control for vibration reduction in buildings and bridges in the last decades. A brief description of each passive control scheme was provided describing the main properties of different anti-seismic solutions. Passive control is an acknowledged prevailing technique for achieving high efficiencies and reliability. This approach has become a common and widespread structural control scheme with many applications in civil engineering. Any of the mentioned tuned damper systems represent an effective way to control the structural response to dynamic loads. They are easy to design and construct (a simple mass-spring-dashpot system is used) with low maintenance requirements and therefore these devices can be cost effective compared with other control strategies.

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