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A state-of-the-art review of structural control systems

Tarek Edrees Saaed[1], George Nikolakopoulos[2], Jan-Erik Jonasson[1] and Hans Hedlund[3]

Abstract

The utilization of structural control systems for alleviating the responses of civil engineering structures, under the effects of different kinds of dynamics loadings, has become a standard technology, although there are still numerous research approaches for advancing the effectiveness of these methodologies. The aim of this article is to review the state-of-the-art technologies in structural control systems by introducing a general literature review for all types of vibrations control systems that have appeared up to now. These systems can be classified into four main groups: (a) passive; (b) semi-active; (c) active; and (d) hybrid systems, based on their operational mechanisms. A brief description of each of these main groups and their subgroups, with their corresponding advantages and disadvantages, is also given. This article will conclude by providing an overview of some innovative practical implementations of devices that are able to demonstrate the potential and future direction of structural control systems in civil engineering.

Keywords

Seismic protection, structural control system, vibration mitigation

1. Introduction

The common method for designing buildings and most civil engineering structures is to use the static approach, which is based on the design to resist gravitational loads throughout structure lifetime. The determination of these loads is very straight forward based on occupancy requirements, and can significantly simplify the design process.

Structural engineers tend to deal with lateral forces like seismic loads and wind loads in a similar manner by using 'equivalent static loads', which are allowed by many design codes (De la Cruz, 2003). A seismic design relies on a combination of strength and ductility in a way that the structures are expected (or designed) to remain in an elastic range for normal earthquakes occurrence. In the case of large earthquakes, the structural design should depend on the ductility of the structures to prevent building damage. For this reason, the lateral resisting force system should have the ability to absorb and dissipate energy in a stable manner through plastic hinge regions of beams and column bases for a large number of cycles. These plastic hinges are part of irreparable, concentrated, and accepted damage to gravity load carrying systems, providing that the collapse is prevented and life safety is confirmed. Such structures depend almost upon their specific stiffness to withstand seismic forces and on their limited material damping to dissipate dynamic energy resulting from these random and variants dynamics loads. A dramatic improvement could be achieved by taking into account the dynamical behavior of structures to overcome the fixed capacities of load resistance and energy

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dissipation, which exist in the classical code design methods (Constantinou et al., 1998). In addition, recent buildings and important structures also should have the ability to maintain their functions after severe earthquakes, not just preventing collapse (Kobori, 1988), and may contain expensive equipment, such as electronic and industrial machineries, that are very sensitive to motion (Fisco and Adeli, 2011). Moreover, there are a large number of old buildings that are not detailed properly as ductile structures and have a limited lateral resistance. In order to enable the structures to resist such loadings, an increase in both structural strength and ductility is essential, while at the same time, this approach will increase the overall construction cost. In addition, increasing member sizes will attract more demanding forces on them, and there may not be any benefits from such solutions. In addition, it is very difficult to change the damping ratio for construction materials, such as reinforced concrete or steel. Due to all of these limitations, researchers have used natural and developed man-made materials with unusual properties, called smart materials, and systems that can be automatically adjusted to different kinds of excitations, called adaptive systems; later on, this led to the innovative concept of smart structures (Cheng et al., 2008).

Smart structure systems or structural control systems for civil engineering structures are a suitable solution to overcome these limitations and to provide safer and more efficient designs, through reflecting and absorbing the energy produced by different dynamic loadings such as seismic, wind and traffic effects. In this case, protection is achieved by allowing the structures to be damaged (Christenson, 2001).

The aim of this article is to review the state-of-the-art technologies in structural control systems by introducing a general literature review for all types of vibrations control systems that have been appeared up to now and present the current state of the art for each of them, while providing an overview of some innovative practical implementations, which are able to demonstrate the potential and future direction of structural control systems in civil engineering. A limited number of similar surveys have appeared in the literature that have focused on specific categories of structural control systems, while there has never been a full overview of all the existing technologies and a corresponding comparison.

The overall aim of this article is to provide a detailed description and relative applications of the most important technological advancements in the field, while acting as a full reference for interested readers. A survey of applications of passive energy dissipation systems for seismic protection of structures and their basic principles up to 2005 was presented by Symans et al. (2008). A very good survey of structural control systems that covers the period from 1990 to 1996 was presented by Housner et al. (1997), where valuable information was provided on passive, semi-active, hybrid, active control theories, sensors, and smart materials; the present article, the concentration will be on control systems devices. Therefore, the description of passive devices will be extended to include base isolation devices, other types of energy dissipation devices, and active control devices that have appeared up to now. The development in semi-active devices and their implementation in full-scale structures for the period 1996 to 2003 were covered by Spencer and Nagarajaiah (2003). Ikeda (2009) presented an extended list of 52 practical applications of active control systems to buildings in Japan from 1989 to 2007. Starting from this article, the list of applications will be extended to include recent applications to date.

The present article is structured as follows. In Section 2, a detailed description of structural control based on the operational mechanism is provided, this includes: passive, semi-active, active, and hybrid control approaches, while some recent and characteristic applications of these devices are presented in Section 3. Finally, in Section 4, conclusions are drawn.

2. Structural control systems

Structural control systems can be utilized to reduce the response of structures under different types of dynamic loads such as earthquakes, winds, traffic, and other kinds of service loads, thus, these systems have also been characterized in the literature as motion control systems. In general, these devices can be classified into four main groups (passive, active, semi-active, and hybrid) based on their operational mechanisms, as presented in Figure 1 (Cheng et al., 2008; Christenson, 2001; Constantinou et al., 1998; De la Cruz, 2003; Housner et al., 1997; Marko, 2006; Spencer and Nagarajaiah, 2003; Symans et al., 2008). In the following subsections, the main groups and subgroups of structural control systems are presented.

2.1. Passive control systems

Passive control systems aim to dissipate part of the input energy and include mainly isolation and energy dissipation devices. In the past, these systems have been considered as smart systems because 'they can generate a larger damping force when the structural response gets higher' (Cheng et al., 2008). Constantinou et al. (1998) presented a comparison among the performance-based categories of passive energy dissipation systems, while Symans et al. (2008) presented a

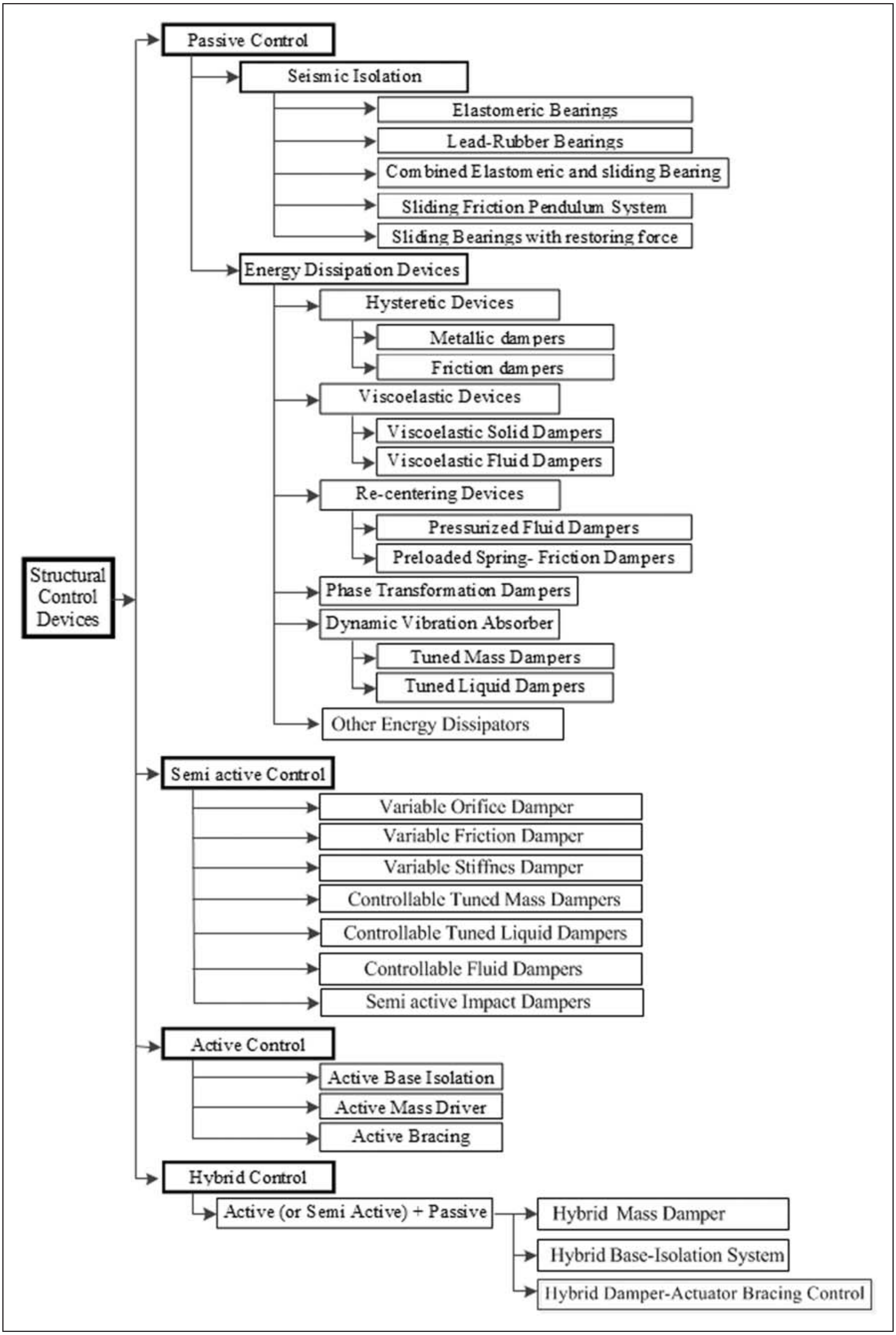

Figure 1. Structural control system categorization.

summary of construction, hysteretic behavior, physical models, advantages, and disadvantages of passive energy dissipation devices for seismic protection applications. In general smart structures, which utilize passive systems, can be considered as systems with a 'limited intelligence because these structures are unable to adapt to the excitation and global structural response', and thus are characterized by a limited control capacity. They are optimally tuned to protect the structures from a specified dynamic loading, but their efficiency will not be the optimal one for other cases and other types of dynamic loadings. The energy dissipation mechanism is totally dependent on the relative structure movement, and it is related only to the local structure response (Cheng et al., 2008). However, passive control devices are inherently stable, do not require any external energy to operate or structural response measurements and are simpler to design and construct (Christenson, 2001). A classification of these devices follows.

2.1.1. Seismic isolation devices. Seismic isolation devices base their operation on the principle of introducing a layer that is flexible in the horizontal direction and very stiff in the vertical direction for increasing the horizontal flexibility or increasing the rocking stability and thus, part of the input energy will be absorbed by the isolation system before the dissipation of energy. Due to the horizontal flexibility, seismic isolation devices will introduce a new vibration mode that does not contain significant inter-story drifts to the main structure. This capability will lengthen the fundamental periods of the structures and will keep them away from the main period contents of the excitation (De la Cruz, 2003). Seismic isolation devices are suitable for short to medium height buildings, with dominant vibration modes lying within a specified range. For instance, it is impossible to provide the horizontal flexibility required for structures under seismic excitations that have long period components (Marko, 2006). Seismic isolation is efficient against vibrations transmitted through the ground, such as traffic and seismic vibrations, but it is not efficient to resist wind loading due to the flexibility in the horizontal direction (De la Cruz, 2003). Isolation devices can be implemented at different locations within structures.

There are many common types of isolation systems whose mechanisms and structural behavior are well known (Marsico, 2008): elastomeric-based systems, low-damping natural and synthetic rubber bearings (LDRBs), lead-plug bearings (LRBs), high-damping natural rubber (HDNR) systems, isolation systems based on sliding, Teflon Articulated Stainless Steel (TASS) systems, friction pendulum systems (FPSs), and sleeved-pile isolation systems (SPISs).

The elastomeric-based systems consist of large natural rubber blocks without steel reinforcement, which were introduced in 1969. Later, steel plates were added to improve behavior and increase vertical stiffness, and many buildings were built with these devices. LDRBs contain two thick steel plates at the end and many steel shims. These bearings have been utilized in Japan, together with supplementary damping devices. LRBs are the same as LDRBs, but with a preformed hole (or holes). A lead plug is press-fitted into that hole, which will deform under horizontal movement in a pure shear, yields at low level stress and dissipates the energy in a hysteretic manner, which is almost stable over a number of cycles (De la Cruz, 2003). This system was used successfully to protect many buildings during earthquakes. In 1982, HDNR systems were introduced using extra-fine carbon black, oils or resins and other proprietary fillers in the UK, which led to an increase of the inherent damping of the natural rubber compound; this, in turn, eliminated the need for supplementary damping devices.

The isolation systems based on sliding owe their operation to the utilization of materials such as polytetrafluoroethylene (PTFE or Teflon) on stainless steel. The efficiency of these devices is influenced by factors such as temperature, interface motion velocity, degree of wear, and cleanliness of the surface. Theoretical analysis has been carried out on structures equipped with these devices (Cheng et al., 2008).

TASISEI Corp. in Japan developed the TASS system. In this system, the entire vertical load is carried using Teflon–stainless steel elements and re-centering forces provided by laminated neoprene bearings carrying no load. The FPS combines a sliding action and a restoring force by geometry. It consists of an articulated slider on a spherical surface that is covered with a polished stainless steel overlay. Due to the movement of the slider over the spherical surface, the mass will rise and provide the restoring force for the system. Finally, the SPIS is a solution available for reducing vibration transmission by piles through providing horizontal flexibility. In this system, the pile is enclosed in a tube with a suitable gap for clearance.

2.1.2. Energy dissipation devices. The main role of these relatively small elements, which are located between the main structure and the bracing system, is to absorb or divert part of the input energy. This will help to reduce the energy dissipation demand in the main structure. These devices can be classified as follows.

2.1.2.1. Hysteretic devices. As is clear from the name, these devices dissipate the energy by a mechanism that is independent of loading rate and which can be divided into two groups: metallic dampers, which utilize the yielding of metals to dissipate the energy, and friction dampers, which generate heat by dry sliding friction (Constantinou et al., 1998).

The very effective metallic damper mechanism was first used by Kelly et al. (1972) and made good progress in the following years. These dampers are based on inelastic deformations of metallic substances such as mild steel or lead to dissipate the energy. Two important factors must be addressed carefully in designing this type of damper. First, is the post-yielding deformation range in order to ensure that the damper will have a sufficient loading cycle without premature fatigue? Second, are the dampers stably hysteretic under repeated inelastic deformation? In addition, these devices have long-term reliability, relative insensitivity to temperature changes, stable properties in the long term, and are inexpensive. The disadvantages of these devices are the limited number of working cycles and their non-linear response (Marko, 2006). X-shaped and triangular plate dampers have received significant attention. The installation of these parallel plate devices within a frame bay between a chevron brace and the overlaying beam will make the dampers mainly resist the horizontal forces associated with inter-story drift via flexural deformation of the individual plates. Supplemental energy dissipation will result due to the plates yielding after a certain level of force. The tapered shape of the plate ensures uniform yielding throughout the length of the device (Constantinou et al., 1998). Another type of device is the yielding steel bracing system, which was developed in New Zealand in 1980, and which has undergone many modifications in Italy. This device is fabricated from round steel bars for cross-braced structures. The energy will dissipate through the inelastic deformation of the rectangular steel frame in the diagonal direction of the tension brace (Marko, 2006). The final type of metallic damper is the lead extrusion damper (LED), which was suggested for the first time in New Zealand by Robinson in 1987 by introducing the two types. The concept of these dampers is to extrude the lead by forcing a lead piston through a hole or an orifice (created either by constriction in the tube wall for the first type or by bulge on the central shaft for the second type), thereby changing its shape. The LED has a long life and does not need to be replaced or repaired after earthquake excitation due to the lead's capacity to restore its original shape after excitation. In addition, LEDs are insensitive to environmental and aging effects (Marko, 2006).

In friction dampers, the dissipation of energy is provided by the friction between two solid bodies sliding to one another (solid sliding friction mechanism). The aim of these devices is to slow down building motions by 'bracing rather than breaking' (Constantinou et al., 1998). Friction dampers have good performance characteristics and can dissipate a large amount of energy. They are less affected by load frequency, number of load cycles, or changes in temperature, and exhibit rigid plastic behavior (Marko, 2006). It is very important to ensure that the estimated friction response of the damper will be maintained during the life cycle of the damper. This response is influenced by surface conditions to a large extent, which are then affected by environmental effects (Constantinou et al., 1998). Some types of friction dampers include (Marko, 2006): (a) the X-braced damper; (b) the bracing damper system; (c) the improved Pall friction damper; (d) the uniaxial friction damper; (e) the energy dissipating restraint (EDR); (f) the slotted bolted damper; and (g) the concentrically braced frame.

The X-braced damper was proposed by Pall in 1982. The energy dissipation will be equal in both tension and compression braces due to the presence of the four links. This will occur only if the slippage of the device is sufficient to completely straighten any buckled braces. In the bracing damper system, a more detailed model for the Pall friction damper was proposed to take into consideration the individual axial and bending characteristics for each member of the bracing damper system. From experimental results, it has been found that minor fabrication details can significantly affect the overall performance of the friction dampers. The Pall friction damper was developed and improved in 2005 by a more detailed construction, which simplified the manufacture and assembly process for the damper, while keeping its mechanical properties unchanged at the same time. The uniaxial friction damper developed by Sumitomo Metal Industries Ltd is based on a more sophisticated design. It depends on the transmission of the force generated by the pre-compressed internal spring through the action of inner and outer wedges into a normal force on the copper alloy friction pads. These friction pads provide dry lubrication through graphite plug inserts. Experimental and numerical tests carried out by Aiken and Kelly (1990) show that this damper is able to dissipate about 60% of the input energy and has regular and repeatable rectangular hysteresis loops. In addition, this damper is unaffected by loading frequency and amplitude, number of cycles, and ambient temperature. Moreover, the base shear will not be significantly affected by damper placement. The device will not dissipate energy for forces smaller than a threshold. The EDR was introduced by Fluor Daniel. Although the design concept is similar to the Sumitomo damper because it also consists of an internal spring and wedges encased in a steel cylinder, but it has very different response characteristics. Steel and bronze friction wedges are used to convert the axial spring force into normal pressure acting outward on the cylinder wall. In this case, internal stops are used within the cylinder to bind the tension and compression gaps. For slotted bolted damper, there are many different variations based mainly on the sliding interface material. Fitzgerald in 1989 (Marko, 2006) proposed a damper utilizing slotted bolted connections as shown in Figure 2(a). The connection is composed of a gusset plate, two back to back channels, cover plates and bolts with washers, while the steel is utilized as a sliding interface. In 1991, Constantinou used graphite impregnated bronze plate to improve sliding interface friction characteristic.

A rotating slotted bolted friction damper with inclined slotted holes is another type of friction dampers that was proposed and tested successfully in 1999. Finally, the concentrically braced frame is considered one of the most efficient lateral load resisting system available due to its strength, stiffness, low weight, and simple construction. However, applying light tension only during an earthquake may lead to hazardous soft-story mechanisms due to irrecoverable tensile yielding, which can be treated using specially detailed sliding plates moving in the vertical plane (Grigorian and Yang, 1993).

2.1.2.2. Viscoelastic (VE) devices. These devices include a wide range of mechanisms that dissipate energy in a rate-dependent manner, i.e. their displacement characteristics depend on the frequency of the motion and relative velocity between the ends of the damper. The damping force in these devices is proportional to velocity, and the behavior is viscous. Research and development of VE devices for earthquake engineering started in the early 1900s, and they are mostly used in structures where it is expected to have shear deformations and can be classified into two main groups as follows.

VE solid dampers: solid VE dampers (Figure 2(b)) are usually made from copolymers or glassy substances that dissipate energy through shear deformation in the VE material. During deformation, the VE material will undergo features of both elastic solid and viscous liquid, and it will return to its original shape after each deformation cycle with heat generated as a result of energy dissipation. There are many types of VE dampers, for instance, the test results for bitumen rubber compound VE damper developed by Showa and Shimizu Corporations showed a 50% reduction in the seismic response, while a reduction in response of up to 60% was obtained for a half-scale three-story building (super-plastic silicone rubber VE shear damper) developed by Kumagai-Gumi Corporation. Recent experimental and numerical studies conducted by Xu (2007) confirmed the efficiency of solid VE dampers in reducing the seismic responses of structures.

VE fluid dampers: all passive devices mentioned up to this point have utilized solids to enhance structure efficiency against lateral loads. Fluid can also be utilized to obtain enhancement in structural efficiency. Significant efforts have been directed in recent years towards the development of viscous fluid dampers and converting the technology from military and heavy industry to structural engineering. Examples of these dampers include (Constantinou et al., 1998): (a) the cylindrical pot fluid damper; (b) the viscous damping wall system (VDW); and (c) the fluid viscous damper.

The cylindrical pot fluid damper is considered to be one of the simplest types of viscous fluid dampers (Figure 2(c)) that convert mechanical energy into heat during the dissipation process. The dissipation of energy occurs due to the piston motion, which will deform thick, highly viscous substances such as silicone gel. This device was used as a component in seismic isolation systems (Makris and Constantinou, 1990). Sumitomo Construction Company in Japan developed the VDW. The VDW is composed of two main parts (Figure 2(d)). The first one is an outer race steel casing attached to the lower floor, filled with a highly viscous fluid. The second part is an inner moving steel plate hanging from the upper floor and contained within the first part. It is also required to protect the system from fire or impacts by using cover walls of reinforced concrete or fireproof materials. Relative inter-story motion (velocity) shears the fluid, and this will work to dissipate energy. Experimental tests conducted by Arima et al. (1988) on a full-scale four-story steel frame fitted with a viscous wall system showed response reductions of 66–80%. Another example of this system is the 78 m high steel frame building in Shizuoka City in Japan, which reduced the building response by up to 70–80% (Marko, 2006). The cylindrical pot fluid damper and VDW system mentioned above depend on deformation of a viscous fluid contained in an opened container. The disadvantage of these devices is that to obtain maximum energy dissipation, it is necessary to use materials with large viscosities. This will lead to using materials that exhibit both frequency- and temperature-dependent behavior. Fluid viscous dampers are another class of VE fluid dampers that rely upon the flow of fluids within a closed container instead of an open one. The piston motion will force the fluid to pass through small orifices instead of deforming the fluid locally, resulting in high-energy dissipation levels. These dampers are not suitable for stiff structures due to high damper force demand. Although they have been invented for military purposes, nowadays they are utilized in seismic base isolation systems, for supplemental damping during seismic waves, and wind-induced vibrations (Constantinou et al., 1998).

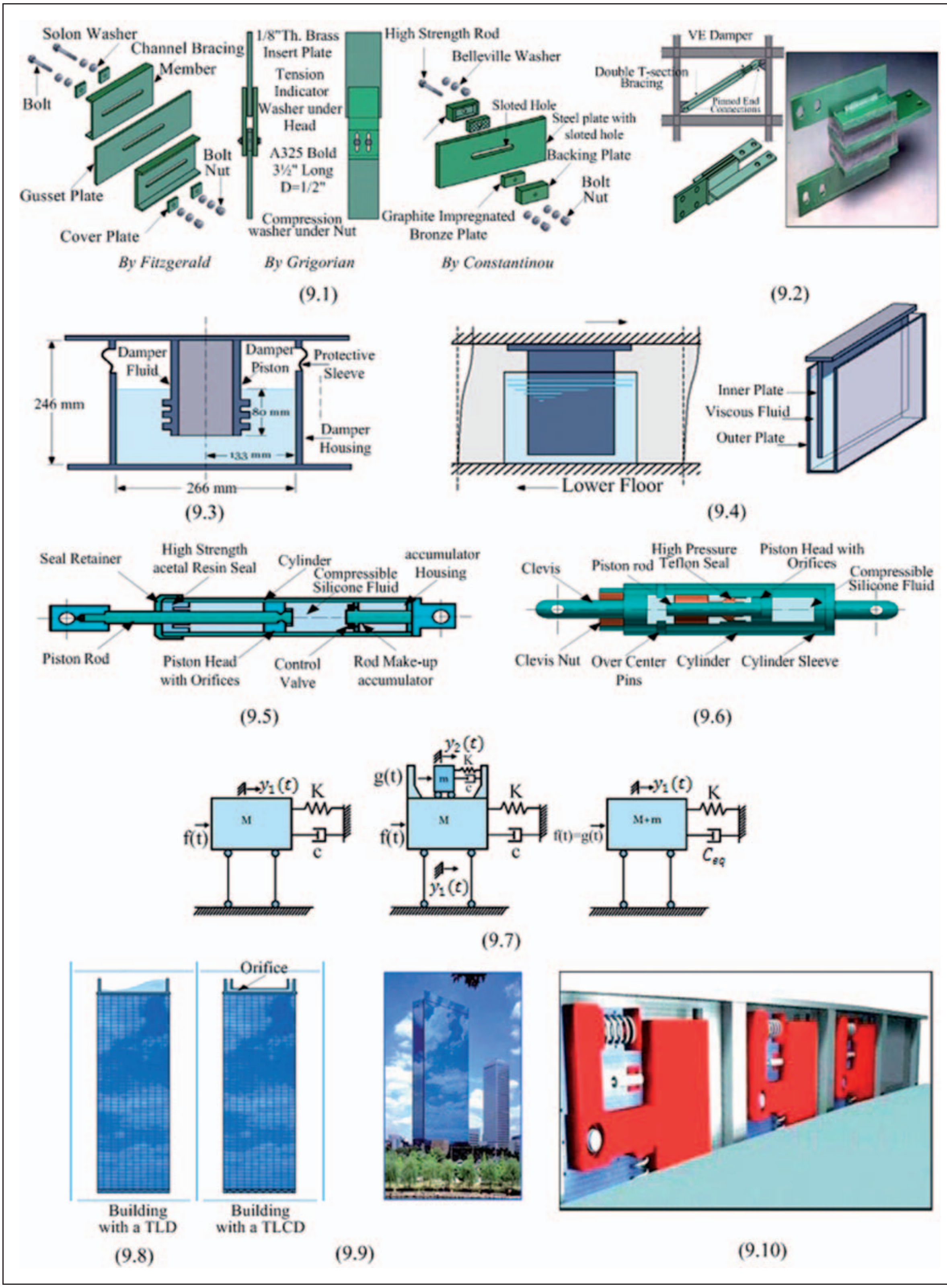

Figure 2. Different types of passive devices (Marko, 2006): (a) three types of slotted bolted dampers, (b) typical solid viscoelastic damper, (c) cylindrical pot fluid damper, (d) viscous damping wall system, (e) orificed fluid damper, (f) pressurized fluid damper, (g) models of the Single Degree of Freedom (SDOF) structure and tuned mass damper, (h) Crystal Tower Building in Chicago with a tuned liquid damper, (i) Crystal Tower Building in Chicago with a tuned liquid column damper, (j) tuned liquid column damper within shear wall Sumitomo Construction Company.

A typical orifice fluid damper is shown in Figure 2(e), which is composed of a cylindrical device that contains compressible silicone oil forced to flow by a stainless steel piston rod with a bronze head and with a fluidic control orifice design. For the change in volume, due to the rod positioning, an accumulator is provided (Constantinou and Symans, 1993).The main advantage of the fluid viscous damper is the capability to reduce both the deflection and stress at the same time, since the damper force is totally out of phase with the stresses resulting from the structure flexing. Moreover, these dampers are relatively insensitive to temperature changes. One of the main disadvantages of these devices is that it is difficult to reduce the peak structural response in the early stages of loading, mainly due to the dependence of the damper's resisting force on the velocity; thus, the utilization of a combination of tapered-plate energy absorbers and fluid dampers was suggested to overcome this shortcoming (Pong et al., 1994).

2.1.2.3. Re-centering devices. These devices possess an inherent re-centering capability due to a little residual deformation remaining after load removal (Constantinou et al., 1998). Examples of these devices are: (a) pressurized fluid dampers and (b) preloaded spring friction dampers.

The pressurized fluid dampers shown in Figure 2(f) were proposed by Tsopelas and Constantinou (1994) to provide both damping and re-centering capabilities for a base isolation system. Many factors play an important role in determining load resistance: initial pressurization, device stiffness due to silicone oil compressibility, seal friction, and damping due to the passage of fluid through orifices. The preloaded spring friction dampers are similar to pressurized fluid dampers, but the damper's resisting force is due to frictional wedges in addition to a preloaded internal spring (Constantinou et al., 1998).

2.1.2.4. Phase transformation dampers. A new material type called a shape memory alloy (SMA) is used in passive dampers. These metals have the ability to change status between martensitic and austenitic crystalline phases responding to reversible stress or temperature. For example, an SMA specimen will distort in an apparent manner under its low-temperature martensitic phase. If the temperature rises to a certain level, this will induce transformation to the austenitic phase, and the specimen will return to its original undistorted shape (Constantinou et al., 1998). There are many advantages of this type of material: it provides a self-centering mechanism, it is insensitive to environmental temperature changes (after being properly heat treated), it has excellent fatigue resistance, it is corrosion resistance, and finally it is capable of producing large control forces, even for slow response times. Until now, there have been no practical applications for this type of material, except for research and experimental investigations. Some investigations recommended a careful design for this type of damper due to the high sensitivity of SMAs to earthquake excitations, which may change the stiffness and consequently alter the first natural frequency of the structure toward the earthquake dominant frequency (Marko, 2006).

2.1.2.5. Dynamic vibration absorbers. The last class of passive systems is the dynamic vibration absorber, which is also used to reduce energy dissipation demand on the primary structural members under dynamic loadings. The reduction is achieved by transferring (rather than directly dissipating) some of the vibrational energy to the absorber. This system includes a mass, stiffness, and damping. The dynamic properties should be tuned to those of the primary structure. The primary applications of this system are for mitigation of wind loads. There are limitations to using these devices for seismic applications due to detuning that may occur as the primary structure yields, high damping level demand and an incapability to control higher modes in an efficient manner. The three main common types of these devices are: (a) tuned mass dampers (TMDs), (b) tuned liquid dampers (TLDs); and (c) tuned liquid column dampers (TLCDs) (Constantinou et al., 1998).

The TMD contains a mass that moves relative to the structure, and it is attached to the structure by a spring and a viscous damper in parallel, as presented in Figure 2(g). The TMD will be excited by the structural vibrations, and the kinetic energy generated due to these structural vibrations will be transferred from the structure to the TMD and absorbed by the damping component of the TMD. The TMD usually experiences large displacements. TMDs have been successfully applied in mitigation of wind and harmonic loads, and have been installed in a number of buildings, while there is not a general agreement about the efficiency of TMDs for seismic applications. The TLD has a similar mechanism to the TMD. Improvements of structural behavior are achieved by applying indirect damping to the structure. The dissipation of energy will happen due to the viscous action of fluid and wave breaking. The TLDs presented in Figure 2(h) consist of rigid tanks filled with liquid. The sloshing motion will absorb the energy and dissipate it through the viscous action of the liquid. Use of TLDs has many advantages compared with the use of TMDs: the motion is reduced in two directions at the same time, large stroke lengths are not required, there is no need for any activation mechanism, and there are lower maintenance costs. TLDs are insensitive to the frequency ratio between the primary and secondary systems (Marko, 2006). In addition, the TLCD has a similar mechanism to the TMD, and the improvements of structural behavior will be achieved by applying indirect damping to the structures. The TLCD consists of a liquid-filled tube-like container that is rigidly attached to the structure (Figure 2(i)). The dissipation of energy will happen due to the passage of liquid through an orifice in the tube with inherent head loss characteristics. It is possible to tune the vibration frequency of the device by changing the liquid column length. Major advantages of this system are the simplicity of implementation in existing buildings without any conflict with vertical and horizontal load paths (as shown in Figure 2(j)), there is no space requirement for large stroke lengths, and the damping can be controlled by adjusting the orifice opening. Research has shown that reduction in the displacement and acceleration responses could be up to 47% (Marko, 2006). De la Cruz (2003) made a comparison between the efficiency for each of the isolation systems, energy dissipaters, and mass dampers. Tait (2008) proposed a preliminary design procedure for initial TLD sizing and an initial damping screen design for a TLD equipped with damping screens. Love and Tait (2012) outlined a design methodology for designing a TLD tank under space restrictions conditions.

2.1.2.6. Other energy dissipators. According to Housner et al. (1997), there are many newly developed innovations that can be classified as passive energy dissipation devices in the following methods. (a) Using dampers to connect two adjacent structures at the roofs. This method was used to mitigate the vibration in high-rise buildings during strong earthquakes by optimizing the mass and stiffness ratio between the structures. (b) High-damping rubber damper. The main part of this device is unvulcanized rubber, which has low stiffness and high energy absorption ability compared with the vulcanized high-damping rubber material used for rubber bearings. (c) Rubber composite damper used for cable-stayed bridges. (d) V-stripe or U-stripe configurations of bridge cables. Moreover, Korkmaz et al. (2011) showed that using a damping trench at a certain distance from a building is effective to mitigate the traffic-induced vibrations on structural behavior of masonry buildings. The current state of passive control systems and their characteristics are summarized in Table 1.

2.2. Semi-active control

Semi-active control devices are a natural extension of passive devices. They are commonly called 'controllable or intelligent dampers' because they include adaptive systems to increase intelligence and efficiency. In order to improve the performance, their adaptive system regulates the damper behavior based on the collected information of excitation and structural response. The components of this system include: sensors (measure the input and/or output), a control computer (processes the measurement and generate a control signal to the actuator), a control actuator (acts to regulate the behavior of the passive device), and a passive damping device. The actuator in semi-active devices is used to control the properties of passive devices instead of directly applying a force to the structure. Therefore, this kind of devices requires a small power supply, such as batteries, which is a very important merit as the main power supply might fail during an earthquake and result in structure destabilization.

In spite of the complexity of these devices, when compared with the passive devices, they are still easy to manufacture, fail-safe, reliable to operate and capable of acting better than passive ones. The disadvantage of these devices is the limited control capacity because they are still working within the capacity of corresponding passive devices. Overall, these devices are very promising since they combine the positive merits of both passive and active devices. Examples of semi-active devices are given in the following paragraphs (Cheng et al., 2008).

2.2.1. Semi-active TMDs. These were developed in 1983 to control wind-induced vibrations in tall buildings and are still in the research stage. The damper is composed of a TMD and an actuator installed on top of the main structure. The characteristics of the TMD are: mass (m_d), damping (c_d), and stiffness (k_d), while the main structure characteristics are: mass (m), damping (c), and stiffness (k). SA represents the actuator and u is the control force generated by the actuator. The TMD damping will be continuously adjusted by the actuator control force u, while a small amount of external power is required to make this adjustment, as the mass of the TMD (m_d) is much smaller than the main structure mass (m) and the active control force is utilized to change the damping force of the TMD, which is less than the inertial force of the TMD (Cheng et al., 2008).

2.2.2. Semi-active TLDs. The semi-active concept was developed for both the TLDs and TLCDs mentioned previously and it is still in the research and development stage. For TLDs, a set of rotatable baffles were added in the liquid tank of a sloshing TLD. The orientation of these baffles is adjusted by an actuator according to application-specific algorithms. Since the natural frequency of the contained liquid changes with tank length, tuning of the TLD will be controlled by rotating

Table 1. State-of-the-art summary of passive control systems.

Control system	Key features	Applications
Seismic isolation	-LDRB, LRB, HDNR, TASS system, FPS, SPIS	Many buildings built with these devices
devices	-Safer and more economic than traditional structural systems	
Hysteretic devices	-Metallic dampers, friction dampers	Mostly used in structures
	-Energy dissipation independent of loading rate	
	-Long-term reliability	
	-Fabrication details significantly affect overall performance of friction dampers	
Viscoelastic devices	-Viscoelastic solid dampers, viscoelastic fluid dampers	Mostly used in
	-Displacement characteristics depend on frequency of motion and relative velocity between ends of damper	structures
Re-centering devices	-Possess inherent re-centering capability	Many buildings built with these devices
Phase transformation dampers	-Use shape memory alloys	Still in research stages
	-Self-centering mechanism -Insensitive to environmental temperature changes -Excellent fatigue resistance -Corrosion resistance -Capable of producing large control forces	
Dynamic vibration absorber	-TMD, TLD, TLCD	Successfully applied in mitigation of wind loads in a number of buildings
	-Reduction achieved by transferring some vibrational energy to absorber	
	-Dynamic properties should be tuned to those of the primary structure -Detuning may occur -No need for any activation mechanism -Less maintenance costs	

the baffles to a desired inclined position. When the baffles are in the horizontal position, the tank maintains its full length, while the tank will be divided into a number of shorter tanks if the baffles are in the vertical position. In this manner, the actuator is required only for rotating the light-weight baffles (Cheng et al., 2008).

For TLCDs, Yalla (2001) used a variable orifice to maintain the optimal damping conditions. According to the proposed control algorithm, an electropneumatic actuator is used to control a ball valve in order to change the cross section of the TLCD. This will improve the damping properties of the damper with a relatively low cost.

2.2.3. Semi-active friction dampers. The first form of this device was developed by (Constantinou et al., 1998) using an electromechanical actuator. Another type was developed by Chen and Chen (2004) using Piezoelectric and Translators (PZT) actuators in order to improve the efficiency of passive friction dampers. PZT is a smart material that is able to produce a significant amount of stress when exposed to an electrical field under restrained motion. This device is called a piezoelectric friction damper (PFD). It consists of four preloading units, four PZT stack actuators (to apply normal forces), a friction component (containing a thin steel plate with brake lining as a friction material bonded to its top and bottom surfaces) and a steel box for housing other components. The friction generated due to the relative movement of the isolation plate and the bottom plate will dissipate energy. The normal forces generated by the PZT stack actuator will be controlled by adjusting the electric field on the PZT actuators and thus the friction force is regulated to enhance real-time efficiency with rather a low cost (Cheng et al., 2008). This device can be adapted to varying excitations, caused by weak and strong earthquakes, while further improvements in force generation are needed (Chen and Chen, 2004).

2.2.4. Semi-active vibration absorbers. These types of devices are still under research, and their operating mechanism depend on adjusting both the stiffness and damping properties. Examples of this system are semi-active vibration absorbers (SAVAs), which are also called semi-active hydraulic dampers (SAHDs).

The damping capacity comes from the viscous fluid, while the stiffness is regulated by the opening of the flow valve (Cheng et al., 2008). A new device called an accumulated semi-active hydraulic damper (ASHD) was proposed by Shih et al. (2004). It is composed of a hydraulic jack, a directional valve and an accumulator. The optimal rate of energy dissipation is achieved by controlling the flow of the oil in the hydraulic jack (by a controlling algorithm) to regulate the acting direction of the device. Extended test results prove that the energy dissipation of ASHDs is extremely good with minimum energy requirements.

2.2.5. Semi-active stiffness control devices. A semi-active variable stiffness (SAVS) device was developed by Kobori in Japan. It consists of a balanced hydraulic cylinder, a double acting piston rod, a normally closed solenoid control valve and a tube that connects the two cylinder chambers. The fluid will flow freely and will unlock the beam brace connection when the valve is open, thus decreasing structural stiffness. In contrast, when the valve is closed, the fluid cannot flow and thus effectively locks the beam to the brace, resulting in increasing structural stiffness (Cheng et al., 2008; Spencer and Nagarajaiah, 2003).

2.2.6. Electrorheological (ER) dampers. This type of device uses smart ER fluids that contain dielectric particles suspended within non-conducting viscous fluids absorbed into the particles. The dielectric particles polarize and become aligned when they are exposed to electrical fields, resulting in resistance to the flow. ER fluids have the ability to undergo dramatic reversible increases to the flow in milliseconds. Thus, adjusting the electrical field will simply control the behavior of ER fluids. ER dampers were first proposed by Makris et al. (1995), where the smart properties of ER fluids were utilized to adjust damping force generation. This damper consists of a cylinder containing a balanced piston rod and a piston head.

Adjustment of the voltage V changes the electric field and therefore controls the behavior of the ER fluid, while regulating the capacity of the ER damper. The energy dissipation is a result of two effects: (a) ER effects due to shearing of the fluid and (b) friction effects owing to orificing of the viscous fluid. There are three factors that limit the utilization of the ER dampers for the response control of large structures: (a) limited yield stress (of the order of 5–10 kPa); (b) manufacturing impurities may reduce the applicability; and (c) high-voltage demand (about 4000 V) to control the ER fluid (Cheng et al., 2008).

2.2.7. Magnetorheological (MR) dampers. MR fluid was discovered by Jacob Rabinow in the early 1950s. This smart material has the ability to adapt its fluid properties when it is exposed to a magnetic field (Larrecq, 2010). MR fluid is a magnetic equivalent of ER fluid and typically composed of micron-sized, magnetically polarizable particles dispersed in a viscous fluid such as silicone oil. The particles in the fluid polarize when the MR fluid is exposed to a magnetic field, and the fluid displays viscoplastic behavior, thus offering resistance to fluid flow.

When subjected to a magnetic field, the MR fluid, such as an ER fluid, has the ability to reversibly change from a free-flowing linear viscous fluid to a semi-solid one in milliseconds. The control force produced by the MR fluid can be adapted by varying the strength of the magnetic field according to a control scheme. The magnetic field is applied perpendicular to the direction of fluid flow. When compared to ER fluids, the advantages of MR fluids are: (a) high yielding strength (of the order of 50–100 kPa); (b) stability over a broad range of temperatures (Cheng et al., 2008); (c) low production cost due to insensitivity to contaminants; and (d) low power requirements (20–50 W) (Jansen and Dyke, 2000). Experimental tests carried out by Wu and Cai (2006) showed that the MR damper is appropriate for cable vibration control in cable-stayed bridges. Moreover, the efficiency of implementing MR dampers for vibration suppression for a space truss structure using a fault-tolerant controller was confirmed by Huo et al. (2011).

2.2.8. Semi-active viscous fluid dampers. This device was evaluated by Shinozuka et al. (1992) for bridges. It utilizes a normally closed solenoid valve to control the intensity of the fluid through a bypass loop. Adjusting the valve opening according to the predefined control algorithm will control the damper behavior with a low power requirement. The fluid can easily flow through the valve when the opening of the valve is large, and hence develops less damping force. In contrast, when the opening is small, the damper provides a greater control force due to the difficulties in the flow. The energy dissipation mechanism is due to the friction between the flow, the bypass loop and orifices in the piston head (Cheng et al., 2008). The current state of the art in semi-active control systems are summarized in Table 2.

2.3. Active control systems

In spite of the cost efficiency and reliability of the passive and semi-active devices, these systems have a limited capacity and/or intelligence for structural seismic response control. For instance, passive systems have simple mechanisms and are easy to manufacture, but they are unable to adapt to ever-changing excitation because they neither sense excitation and response nor use external power.

In addition, some are effective for controlling one dominant vibration mode and are ineffective for other mode or loading types. Semi-active devices, as mentioned previously, are adaptable to excitations, but their efficiency is restricted within the limit of the maximum capacity of the passive devices on which they are based.

This need has led to the development of an area of active control systems (Cheng et al., 2008). An error-activated control system, proposed by Yao (1972), has the ability to automatically supply a force into the structure to counteract the unpredictable vibrations due to different kinds of dynamic loadings, thus reducing the dynamic response for different vibration modes.

Depending on the measurement of the global system response, active control systems can have optimal efficiency compared with passive control systems, which depends on the local responses only. Active control systems require significant energy to counteract the dynamics loadings, which cannot be ensured during severe natural hazards due to failure of the energy supply during such events. Moreover, active control systems are complicated; they require sensors and controller equipment, and give a shift in the dynamic behavior of the structure by adding or removing energy from it; this may result in an unwanted or even unstable condition (Christenson, 2001). The advantages of active control systems are (Cheng et al., 2008): (a) enhanced control effectiveness: this means there are no theoretical limits on the active control efficiency; (b) adaptability to ground motion: they refer to the system ability to sense the excitation and automatically adjust their control efforts; (c) selectivity of control objectives: the system can be designed for different objectives such as structural safety or human comfort; and (d) applicability to different excitation mechanism: this system can be used for a wide frequency range.

Interested readers can find valuable information concerning structural control theories and control strategies in Casciati et al. (2012), Chen et al. (2012) and Housner et al. (1997). Active control systems can also be categorized as follows:

2.3.1. Active mass damper (AMD) systems. As a result of the limited capability of TMDs and their applicability for structures with the first mode dominant (e.g. structures under wind loads), in the early 1980s, researchers evolved the AMD from TMDs that have utilized an active control mechanism in order to improve their applicability for a wide frequency band. The actuator installed between the primary (structure) and the auxiliary (TMD) system has been utilized to adjust the motion of the TMD according to predefined control

Table 2. State-of-the-art summary of semi-active control systems.

Control system	Key features	Applications
Semi-active tuned mass dampers	-TMD + actuator	Still in research stages
Semi-active tuned liquid dampers	-(TLD + actuator) or (TLCD + actuator)	Still in research stages
Semi-active friction dampers	-Electromechanical actuator -PZT actuators -Adapted to varying excitations	Still in research stages
Semi-active vibration absorbers	-SAVA, SAHD, ASHD -Adjusting both stiffness and damping properties -Energy dissipation extremely good with minimum energy requirements	Still in research stages
Semi-active stiffness control devices	-SAVS -Adjusting the stiffness SAVS	Still in research stages
Electrorheological dampers	-Use smart ER fluids -Limited yield stress -Manufacturing impurities may reduce applicability -High-voltage demand	Still in research stages
Magnetorheological dampers	-Use smart MR fluids -High yielding strength -Stable over broad range of temperatures -Low production cost -Small power requirements	Still in research stages
Semi-active viscous fluid damper	-Utilizes normally closed solenoid valve	Still in research stages

algorithms. Analytical and experimental studies showed that AMDs have an economic benefit in full-scale structures because both the control force and actuation are much smaller than other types of active systems. This is mainly because the actuator in other active systems generally acts on the structure directly, while the actuator in an AMD is utilized to drive the auxiliary mass only. However, the efficiency of this device is limited to the fundamental frequency, and less so for higher frequencies.

2.3.2. Active tendon systems. These devices are composed of a set of pre-stressed tendons whose tension is controlled by electrohydraulic servomechanisms. The system is installed between two stories of a building. The actuation cylinder is fixed on the lower floor. One end of the tendon is attached to the device piston, while the other end is connected to the upper floor. The inter-story drift resulting from earthquake excitations drives the relative movement of the actuator piston to the actuator cylinder and thus the changes in the tension of the prestress will apply a dynamic control force to the structure. Both experimental and simulation results indicated that an important reduction in structure response can be achieved by the utilization of active tendon systems. The advantages of this system are the applicability in both the pulsed and the continuous time modes and the possibility of using existing structural members, which will minimize the need for modifications in the structure.

2.3.3. Active brace systems. These devices can also utilize existing structural braces to install an active control device (actuator) onto a structure. The device can be integrated within the three common types of bracing systems: diagonal, K-braces, and X-braces. A large control force can be generated by the servo valve-controlled hydraulic actuator, which is mounted on the bracing systems between two adjacent floors. This system is composed of a servo valve, a servo valve controller, a hydraulic actuator, a hydraulic power supply, sensors, and a control computer with a predefined control algorithm. The control computer utilizes the control algorithm to process the sensor measurements and then order the control signal. This signal will be used by the servo valve to adjust the flow direction and intensity, thus the pressure difference will yield in the two actuator chambers. This pressure difference will produce the required control force to resist seismic loads on the structure.

2.3.4. Pulse generation systems. These devices produce the active control forces using pulse generators, which depend on pneumatic mechanisms that utilize compressed air instead of hydraulic actuators that use high-pressure fluids. Protection of a smart structure can be fulfilled by installing pulse generators at several locations within the structure. The pneumatic actuator will be triggered when a large relative velocity is detected at any pulse generator location, and a control force opposite to the velocity is applied to the structure. Tests conducted by Masri and Caughey (1988) showed that pulse generators were a promising device for seismic response control. The disadvantages of this system are: (a) even though the compressed gas energy used by pulse generators is cheap, it may not be powerful enough to drive full-scale buildings and (b) the high nonlinearity of these devices.

A current state-of-the-art summary of active control systems is given in Table 3.

Table 3. State-of-the-art summary of active control systems.

Control system	Key features	Applications
Active mass damper	-TMD + actuator -Efficiency limited to fundamental frequency -Economical in full-scale structures	Analytical and experimental studies
Active tendon systems	-Pre-stressed tendons + electrohydraulic servomechanisms -Applicability in both pulsed and continuous time modes -Possibility to use existing structural members (minimize the cost)	Analytical and experimental studies
Active brace systems	-Utilize existing structural braces + actuator -Can be integrated within three common types of bracing systems	Analytical and experimental studies
Pulse generation systems	-Pulse generators -Promising device for seismic response control -Cheap -Not powerful enough to drive full-scale buildings -High nonlinearity	Analytical and experimental studies

2.4. Hybrid control devices

As presented previously, active control systems are utilized to compensate for the restricted capacity and intelligence of passive and semi-active dampers. Their operation depends mainly on an external power supply, which limits their applications, requires complicated sensing, requires a signal-processing system, which reduces control reliability, and finally requires large force-generating equipment, which cannot be achieved within reasonable costs (Cheng et al., 2008). For these reasons, the three main groups of control systems (passive, active, semi-active) can be grouped into series or parallel combinations in order to select the best advantage of each group to yield the fourth group, which are called hybrid control devices, a category that has become an attractive solution since the 1990s.

The passive devices in this group can be used to achieve the major part of the response reduction necessary to keep the structures within the required performance range, while the active ones will be necessary to tune and finally adjust the response, for instance, to minimize the displacements and accelerations in order to protect the sensitive equipment in the structures. Hybrid devices have a larger capacity and greater efficiency than a passive system, and cost less (Cheng et al., 2008). Moreover, they are more reliable and require less energy than active devices since there is no need for large control forces, but they still require significant energy (Christenson, 2001; De la Cruz, 2003). According to Wu (2011), hybrid control systems are very efficient in protecting structures from different types of excitation with dissimilar intensity and frequency content. In addition, research carried out by Yan and Wu (2011) confirmed the reliability and efficiency of this kind of system. Owing to these important features, hybrid control systems have become very promising for seismic response reduction of civil engineering structures. More information about the merits of hybrid control systems and recent applications can be found in Khodaverdian et al. (2012) and Love et al. (2011). Typical hybrid control systems are shown below, and will be analyzed in the following.

2.4.1. Hybrid mass damper (HMD). This device is composed of either a combination of a passive TMD and an active control actuator, or a combination of an AMD to a TMD. The connection of the AMD to the TMD instead of the main structure will work to minimize the mass of the AMD, which will be 10–15% of that of the TMD. The energy and forces required to activate an HMD are far less than those related with a full AMD system with similar performance, mainly due to the fact that the AMD is designed to increase control efficiency for higher modes of the structure only, while the TMD is tuned to control the fundamental mode of the structure. Due to this feature, which makes HMDs an inexpensive control solution, these systems have been the most common control devices employed in full-scale building structure applications. However, space limitations can impede the use of an HMD system (Cheng et al., 2008).

2.4.2. Hybrid base isolation system. This type of device represents the majority of the hybrid control applications in the USA, which can be subdivided into two types (Housner et al., 1997). The first system was proposed and tested by Yoshioka et al. (2002), this system uses MR fluid dampers on the superstructure instead of the active tendon in the second system. The second was studied and tested by Cheng and Jiang (1998); this system is composed of a base isolation system between the foundation and the structure, and an active tendon control system on the superstructure.

2.4.3. Hybrid damper actuator bracing control. In the early 1990s, the hybrid damper actuator bracing control mounted by K-braces on the structure was developed by Cheng and Jiang (1998). Many passive devices can be used in this system, such as liquid mass dampers, spring dampers, and viscous fluid dampers. Owing to their powerful force-generating capacity, hydraulic actuators are proposed as the active device for the system. Extensive experiments and studies showed that this system has greater capacity than a passive system in decreasing seismic structural response, and it needs less active control force than an active control system to achieve a control objective. Moreover, the major advantage of this system is the possibility of either combining the damper and the actuator, or separating them. In addition, it is possible to use existing structural braces for fixing of control devices, and the active control force is applied directly to the structure. Thus, a hybrid bracing system costs less than a base isolated/actuator system and offers further control capacity than an HMD (Cheng et al., 2008). The current state of the art in hybrid control devices is given in Table 4.

Finally, a comparison of the different kinds of structural control systems is presented in Table 5.

3. Recent applications

According to Ikeda (2004), research and development in the field of active and semi-active vibration control of civil engineering structures in Japan can be categorized into four stages. In the first stage up to the late 1980s, the fundamental dynamics properties of active control were understood theoretically and

Table 4. State-of-the-art summary of hybrid control devices.

Control system	Key features	Applications
Hybrid mass damper	-TMD + active control actuator -or (AMD + TMD) -Inexpensive -Space limitations -Low activation forces	Most common control device employed in full-scale buildings
Hybrid base isolation system	-Base isolation system + active tendon control system. -Base isolation system + MR fluid dampers	Majority of hybrid control applications in USA
Hybrid damper actuator bracing control	-Hydraulic actuators + passive device -Mounted by K-braces on structure -Many passive devices can be used in this system -Possibility to either combine damper and actuator, or separate them -Costs less than a base isolated/actuator system -Offers further control capacity than HMD	Analytical and experimental studies

experimentally from the civil engineering viewpoint. Applying AMDs to a building for the first time in 1989 marked the start of the second stage. The 1995 Hyogo-ken Nanbu (Kobe) Earthquake opened the door to the third stage where buildings can be semi-actively controlled, even under large earthquakes. The integration of structural control and health monitoring declared the start of the fourth stage. As a result, there are about 70 active and semi-active control systems that have already been implemented to actual buildings in Japan since 1989, while Ikeda (2009) presented a list of 52 practical applications of active control systems to buildings in Japan from 1989 to 2007. The first full-scale application of active control to a building was applied to the Kyobashi Center Building in Tokyo. In addition, the same researcher presented another survey containing practical applications of semi-active control to buildings in Japan from 1990 to 2006. Spencer and Nagarajaiah (2003) presented a detailed summary of controlled buildings in Japan for the period 1989 to 2002 with information about control systems used and their actuation mechanism. In their survey, the Nihon-Kagaku-Miraikan, the Tokyo National Museum of Emerging Science and Innovation, which was constructed in 2001, is considered as the first implementation of MR dampers for civil engineering structures, while the Dongting Lake Bridge in Hunan, China, constructed in 2003, represents the first full-scale application of MR dampers for bridge structures. Kareem et al. (1999) presented a report regarding the number of installations for different types of damping devices in Japan during the 1990s, and give detailed examples of applications of different types of control systems in Australia, Canada, China, Japan, and the USA.

The base isolation system, which came into practical use in Japan from the 1980s, has been implemented in more than 2000 buildings, and its efficiency has been tested in magnitude 7 earthquakes.

According to Shinozaki et al. (2010), base isolation in Japan was used not only to improve the seismic performance, but to also allow more flexible architectural planning. Shinozaki et al. (2010) proposed the world's first semi-active base isolation system in a tall building and implemented it in the Metropolitan building in Tokyo in order to ensure high stability for the building and maintain its function. The system was composed of rubber bearings, 12 variable oil dampers, and 12 passive oil dampers.

Another example of an innovative isolation system is the core-suspended isolation system (CSI) that has been developed and implemented for the first time by Nakamura et al. (2011). The developed system also satisfies the architectural requirements such as transparent facades for suspended structures and functional and attractive open spaces underneath the suspended building. The CSI system consists of a reinforced concrete core on top of which a seismic isolation mechanism composed of a double layer of inclined rubber bearings is installed to create a pendulum isolation mechanism. A multi-level structure is then suspended from a hat-truss or an umbrella girder constructed on the seismic isolation mechanism. Fluid dampers are placed between the core shaft and the suspended structure to control the motion of the building. The building is a four-story building with a total area of $213.65\,m^2$ located in Tokyo.

In China, since the first application of rubber bearing in 1993 for an eight-story building, the application of seismic isolators proved that these systems are safer and

Table 5. Comparison between different kinds of structural control systems.

Seismic isolation devices	Passive control systems	Semi-active control systems	Active control systems	Hybrid control devices
-Dissipate part of input energy	-Absorb or diverge part of input energy	-Natural extension of passive devices	-Automatically supply a force into the structure	-Mixture
-Increase horizontal flexibility	-Dependent on relative movement	-Include adaptive systems	-Depends on global response	-Mixture
Lengthen fundamental periods of structures	-Related only to local structure response		-Ability to sense excitation and automatically adjust control efforts	
	-No structural response measurements			
Suitable for short to medium height buildings	Optimally tuned to specified dynamic loading	-Better than passive systems and less than active systems	-Optimal efficiency compared with passive control systems	-Suitable for all types of structures
-Efficient against vibrations transmitted through ground	-Not optimal for other types of dynamic loadings	-Capable of acting better than passive ones	-Designed for different objective	-Larger capacity than passive system
	-Unable to adapt to excitation and global structural response	Limited control capacity	-No theoretical limits on efficiency	
-Not efficient to resist wind	-Limited control capacity		-Wide frequency range	- Greater efficiency than passive system
-Safe	-Inherently stable	-Fail-safe	-Detuning may occur	-More reliable
		-Reliable		
- Economic	-No energy requirement	-Little power requirement	-Significant energy	- Costs less than active system
	-Simpler to design and construct	-Easy to manufacture	-Complicated	
		-Very promising		-Very promising

more economic than traditional structural systems. They have been successfully used in more than 500 full-scale implementations for buildings and bridges (Li and Huo, 2010). The Isolation House Buildings on Subway Hub located in the center of Beijing are considered as the largest isolated area in the world. There is a very large platform composed of a two-story RC frame that is used by the railway hub. The platform dimensions are 1500 m wide and 2000 m long. Over the top floor of the platform, there are 50 house buildings ($7 \sim 9$ Reinforced Concrete (RC) frames) built on a layer of rubber bearing. The total floor area is approximately 480,000 m^2 (Zhou et al., 2006).

In China, the TMD system may be formed by adding one or more stories supported by rubber bearings on the roof of main building structures to obtain good seismic-reduction effectiveness on displacements and accelerations.

The AMD control system was designed and implemented in the Nanjing Communication Tower in China. The physical size of the damper was limited to a ring-shaped floor area with inner and outer radii of 3 m and 6.1 m, respectively. The damper was elevated off the floor by steel supports with Teflon bearings to allow free access to the floor area (Li and Huo, 2010).

The hybrid TMD control system, which consists of two water tanks used as a mass block, was installed in Guangzhou TV and Sightseeing Tower. The tower, which is 610 m high, is a very flexible structure with a first period of about 10.03 s and is susceptible to the wind.

'Taipei 101' Tower was completed at the end of 2004, and is a famous application of TMDs in Taiwan. This tower is 508 m in height and has a 101-story structure with a five-story basement. The design of such a building is a challenge because both seismic and wind-induced effects should be taken into consideration. Therefore, the idea of a mega structure is utilized for the design of the structural system. For the lateral-resistant system, a combination of braced frames in the core, outriggers from core to perimeter, shear walls, supercolumns, and moment resisting frames has been designed to resist the lateral forces. Most importantly, the passive TMD system has been applied to improve the wind-resistant ability of such a tall building. This passive TMD system is composed of a ball-shaped mass block of 600 tons in weight with 41 layers of 125 mm thick round plates, eight sets of high-strength steel cables from the 92nd floor to the 87th floor for suspension of the mass block, eight primary viscous dampers allocated around the cradle for energy absorption, a bumper ring and eight sets of snubbed dampers installed underneath the mass block on the 87th floor for the control of unexpected oscillation amplitudes. In addition, there are two TMDs installed at the top of the pinnacle to control fatigue induced by cross-winds (Chang et al., 2009).

The mid-story isolation technique is among increasing practical applications in Taiwan. In mid-story isolation, the isolation system is typically installed on the top of the first story of a building in order to satisfy the architectural concerns of aesthetics and functionality. Moreover, this concept can improve the construction feasibility in highly populated areas where fixing the isolation system beneath the base of a building is very tough if the building separation and property line are of particular concern (Chang et al., 2009). Important installations of TMDs, TLDs, and TLCDs around the world are presented in Chaiviriyawong and Prachaseree (2010). The concept of coupled buildings has been extensively studied and implemented on Shanghai Shimao International Plaza in China by Lu et al. (2007). This tall building is composed of a main building that is 60 stories, of total height of 333 m, and its surrounding large podium structure, 10 stories of total height of 49 m. A set of 40 linking viscous fluid dampers were used successfully to link the podium structure to the main building in order to decrease seismic torsional response of the podium structure, resulting from large eccentricity of stiffness and mass distribution in podium structures.

Another innovative example of a coupled building was proposed and implemented by Koike et al. (2004) in Japan. This newly active vibration control system, which is called the active damping bridge, has been developed to reduce vibration by connecting adjacent high-rise buildings and applied to the three high towers of Harumi Island Triton Square in Tokyo. The test results showed that this technique would improve the damping of buildings two to three times in comparison with buildings without the bridge.

4. Conclusions

The state of the art for structural control systems was reviewed by briefly summarizing all the categories of these devices; these include: (a) passive; (b) semi-active; (c) active; and (d) hybrid systems. To demonstrate the structural control system potential and future directions in civil engineering, an overview of some innovative practical implementations of these devices was provided. The state of the art clearly indicates the huge capability for these systems and their importance in modern buildings. These systems can be used to achieve architectural requirements in addition to their original functions of controlling structure vibrations.

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Appendix 1

Abbreviations

AMD	active mass damper
ASHD	accumulated semi-active hydraulic damper
CSI	core-suspended isolation
EDR	energy dissipating restraint
ER	electrorheological
FPS	friction pendulum system
HDNR	high-damping natural rubber
HMD	hybrid mass damper
LDRB	low-damping natural and synthetic rubber bearing
LED	lead extrusion damper
LRB	lead-plug bearing
MR	magnetorheological
PFD	piezoelectric friction damper
PZT	piezoelectric and translators
SAHD	semi-active hydraulic damper
SAVA	semi-active vibration absorber
SAVS	semi-active variable stiffness
SMA	shape memory alloy
SPIS	sleeved-pile isolation system
TASS	teflon articulated stainless steel
TLCD	tuned liquid column damper
TLD	tuned liquid damper
TMD	tuned mass damper
VDW	viscous damping wall
VE	viscoelastic