

Modern technology and state-of-the-art techniques for supplemental energy dissipation

^{1*} Saswati Sahoo ² Suman Tripathy

^{1*} Assistant Professor, Dept. Of Civil Engineering, NIT BBSR,
Asst. Professor Dept. of Civil Engineering, GIET, BBSR

^{1*} sahoosawati351@gmail.com, tripathy.suman123@gmail.com

Abstract

Research and development of structural control systems have received a lot of attention in recent years, with a focus on reducing the reaction of buildings and bridges to wind and earthquakes. These fields have made significant efforts to turn the structural control idea into a practical technology, and today there are many such devices placed in a range of structures. This cutting-edge paper's main concern is with passive and active structural control systems. To improve structural damping, stiffness, and strength, passive systems use a variety of components and tools. Controllable force devices are integrated with sensors, controllers, and real-time information processing in active systems, which include active, hybrid, and semi-active systems. This study examines the state-of-the-art and state-of-practice of this fascinating and still-evolving technology, as well as a brief historical overview of their evolution. Their benefits and limitations in the context of seismic design and retrofit of civil engineering structures are also discussed.

1. Introduction

Innovative techniques for improving structural functionality and protection against man-made and natural dangers have been in various stages of study and development in recent years. In general, they can be divided into three major categories, as indicated in Table 1..

1. base isolation;
2. passive energy dissipation; and
3. active control.

Of the three, base isolation can now be considered a more mature technology with wider applications as compared with the other two [1].

Passive energy dissipation systems encompass a range of materials and devices for enhancing damping, stiffness and strength, and can be used both for seismic hazard mitigation and for rehabilitation of aging or deficient structures [2-4]. In general, such systems are charac-

terized by their capability to enhance energy dissipation in the structural systems in which they are installed. These devices generally operate on principles such as frictional sliding, yielding of metals, phase transformation in metals, deformation of viscoelastic (VE) solids or fluids and fluid orificing.

Active, hybrid and semi-active structural control systems are a natural evolution of passive control technologies. The possible use of active control systems and some combinations of passive and active systems as a means of structural protection against seismic loads has received considerable attention in recent years.

Active/hybrid/semi-active control systems are force delivery devices integrated with real-time processing evaluators/controllers and sensors within the structure. They act simultaneously with the hazardous excitation to provide enhanced structural behavior for improved service and safety. Research to date has also reached the stage where active systems have been installed in full-scale structures for seismic hazard mitigation.

The purpose of this paper is to provide an assessment of the state-of-the-art and state-of-the-practice of this exciting, and still evolving, technology. Also included in the discussion are some basic concepts, the types of structural control systems being used and deployed, and

Seismic isolation	PED	Semi-active and active control
Elastomeric bearings	Metallic dampers	Active bracing systems
Lead rubber bearings	Friction dampers	Active mass dampers
Sliding friction pendulum	VE dampers	Variable stiffness or damping systems
	Viscous fluid dampers	Smart materials
	Tuned mass dampers	
	Tuned liquid dampers	

their advantages and limitations in the context of seismic design and retrofit of civil engineering structures.

2. Basic principles

In what follows, basic principles of passive and active control are illustrated using a simple single-degree-of-freedom (SDOF) structural model. Consider the lateral motion of the SDOF model consisting of a mass m , supported by springs with total linear elastic stiffness k , and a damper with damping coefficient c . This SDOF system is then subjected to an earthquake load where $\ddot{x}_g(t)$ is ground acceleration. The excited model responds with a lateral displacement $x(t)$ relative to the ground which satisfies the equation of motion (schematically represented by Fig. 1a)

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_g. \quad (1)$$

Consider now the addition of a generic passive energy dissipation (PED) element into the SDOF model. The equation of motion for the extended SDOF model then becomes (schematically represented by Fig. 1b)

$$m\ddot{x} + c\dot{x} + kx + \Gamma x = -(m + \bar{m})\ddot{x}_g \quad (2)$$

where \bar{m} is the mass of the PED element and the force corresponding to the device is written as Γx , Γ representing a generic integrodifferential operator.

The specific form of Γx needs to be specified before Eq. (2) can be analyzed, which is necessarily highly dependent on the device type. It is seen from Eq. (2) that the addition of the Γx term in Eq. (2) modified the structural properties so that it can respond more favorably to the designed or anticipated ground motion. It is important to note that a passive structure with added PED elements is again a passive structure.

An active structural control system, on the other hand, has the basic configuration as shown schematically in Fig. 1c [5]. It consists of:

1. sensors located about the structure to measure either external excitations, or structural response variables, or both;

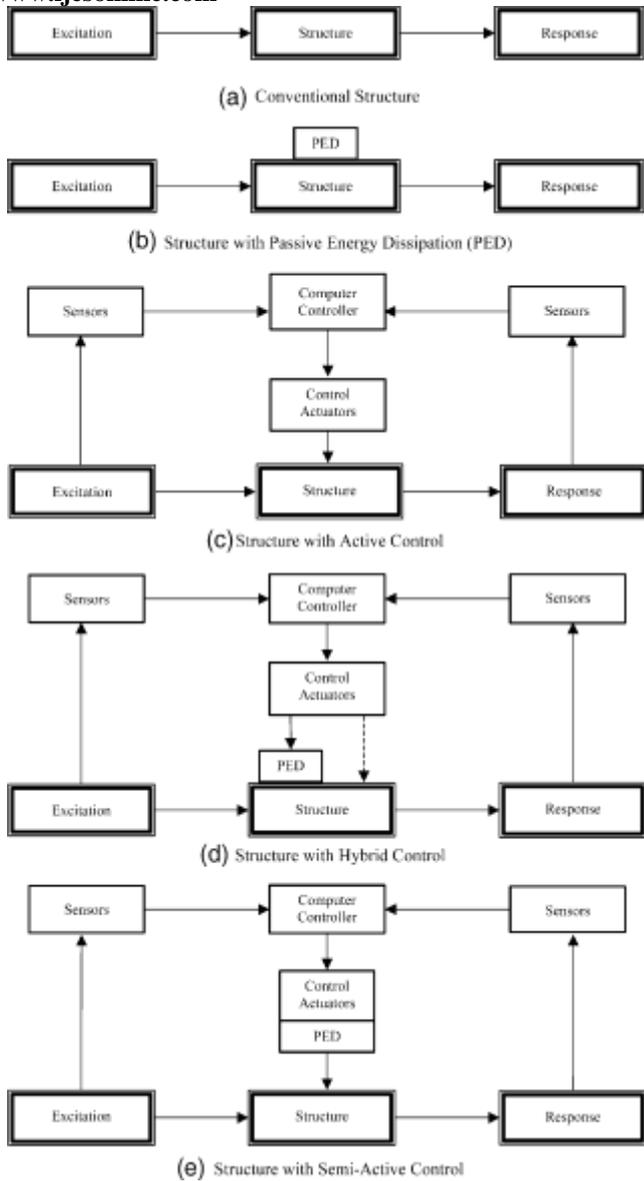


Fig. 1. Structure with various control schemes.

2. devices to process the measured information and to compute necessary control forces needed based on a given control algorithm; and
3. actuators, usually powered by external sources, to produce the required forces.

When only the structural response variables are measured, the control configuration is referred to as feedback control since the structural response is continually monitored and this information is used to make continual corrections to the applied control forces. A feedforward control results when the control forces are regulated only by the measured excitation, which can be achieved, for earthquake inputs, by measuring accelerations at the structural base. In the case where the information on both the response quantities and excitation are utilized for control design, the term feedback-feedforward control is used [6].

To see the effect of applying such control forces to the linear structure considered above, Eq. (1) in this case becomes

$$m\ddot{x} + c\dot{x} + kx = -mu(t) - m\ddot{x}_g, \quad (3) \text{ where } u(t) \text{ is the applied control force.}$$

Suppose that the feedback configuration is used in which the control force $u(t)$ is designed to be

gely due to implementation issues, that set it apart from the general field of feedback control. In particular, when addressing civil engineering structures, there is considerable uncertainty, including nonlinearity, associated with both physical properties and disturbances such as earthquakes and wind, the scale of the forces involved can be quite large, there are only a limited number of sensors and actuators, the dynamics of the actuators can be quite complex, the actuators are typically very large, and the systems must be fail-safe [5–10].

It is useful to distinguish among several types of active control systems currently being used in practice. The term *hybrid control* generally refers to a combined passive and active control system as depicted in Fig. 1d. Since a portion of the control objective is accomplished by the passive system, less active control effort, implying less power resource, is required.

Similar control resource savings can be achieved using the semi-active control scheme sketched in Fig. 1e, where the control actuators do not add mechanical energy directly to the structure, hence bounded-

$$u(t) = \frac{\Gamma x}{m}$$

and Eq. (3) becomes input/bounded-output stability is guaranteed. Semi-active control devices are often viewed as controllable passive devices.

A side benefit of hybrid and semi-active control systems

$$m\ddot{x} + c\dot{x} + kx + \Gamma x = -m\ddot{x}_g \quad (5)$$

It is seen that the effect of feedback control is again to modify the structural properties. In comparison with passive control, however, an important difference is that the form of Γx is now governed by the control law chosen for a given application, which can change as a function of the excitation. Other advantages associated with active control systems can be cited; among them are:

1. enhanced effectiveness in response control; the degree of effectiveness is, by and large, only limited by the capacity of the control systems;
2. relative insensitivity to site conditions and groundmotion;
3. applicability to multi-hazard mitigation situations; an active system can be used, for example, for motion control against both strong wind and earthquakes; and
4. selectivity of control objectives; one may emphasize, for example, human comfort over other aspects of structural motion during noncritical times, whereas increased structural safety may be the objective during severe dynamic loading.

While this description of active control is conceptually in the domain of familiar optimal control theory used in electrical engineering, mechanical engineering, and aerospace engineering, structural control for civil engineering applications has a number of distinctive features, the first is that, in the case of a power failure, the passive components of the control still offer some degree of protection, unlike a fully active control system.

3. Passive energy dissipation

A large number of passive control systems or PED devices have been developed and installed in structures for performance enhancement under earthquake loads. In North America, PED devices have been implemented in approximately 103 buildings and many bridges, either for retrofit or for new construction. Fig. 2 gives a distribution of these buildings as a function of the year in

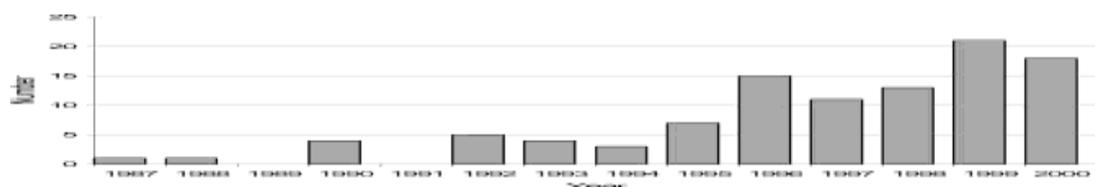


Fig. 2. Implementation of PED in North America for seismic applications.

which PED systems were installed. Discussions presented below are centered around some of the more common devices which have found applications in PED.

Metallic yield dampers

One of the effective mechanisms available for the dissipation of energy input to a structure from an earthquake is through inelastic deformation of metals. Many of these devices use mild steel plates with triangular or X shapes so that yielding is spread almost uniformly throughout the material. A typical X-shaped plate damper or ADAS (added damping and stiffness) device is shown in Fig. 3. Other configurations of steel yielding devices, used mostly in Japan, include bending type of honeycomb and slit dampers and shear panel type. Other materials, such as lead and shape-memory alloys, have also been evaluated [11]. Some particularly desirable features of these devices are their stable hysteretic behavior, low-cycle fatigue property, long term reliability, and relative insensitivity to environmental temperature. Hence, numerous analytical and experimental investigations have been conducted to determine these characteristics of individual devices.

After gaining confidence in their performance based primarily on experimental evidence, implementation of metallic devices in full-scale structures has taken place. The earliest implementations of metallic dampers in structural systems occurred in New Zealand and Japan. A number of these interesting applications are reported in [12,13]. More recent applications include the use of ADAS dampers in the seismic upgrade of existing buildings in Mexico [14] and in the USA [15]. The seismic upgrade project discussed in [15] involves the retrofit of a Wells Fargo Bank building in San Francisco, CA. The building is a two-story nonductile concrete frame structure originally constructed in 1967 and subsequently damaged in the 1989 Loma Prieta earthquake. A total of seven ADAS devices were employed, each with a yield force of 150 kips. Both linear and nonlinear analyses were used in the retrofit design process. Further, three-dimensional response spectrum analyses, using an approximate equivalent linear representation for the ADAS elements, furnished a basis for the redesign effort. The final design was verified with DRAIN-2D nonlinear time history analyses. A comparison of computed response before and after the upgrade is shown in Fig. 4. The numerical results indicated that the revised design was stable and that all criteria were met. In addition to the introduction of the bracing and ADAS dampers, several interior columns and a shear wall were strengthened.

A variation of the devices described above but operating on the same metallic yielding principle is the tension/compression yielding brace, also called the unbonded brace [16,17], which has found applications in Japan and the USA. As shown in Fig. 5, an unbonded brace is a bracing member consisting of a core steel plate encased in a concrete-filled steel tube. A special coating is provided between the core plate and concrete in order to reduce friction. The core steel plate provides stable energy dissipation by yielding under reversed axial loading, while the surrounding concrete-filled steel tube resists compression buckling.

Friction dampers

Friction dampers utilize the mechanism of solid friction that develops between two solid bodies sliding relative to one another to provide the desired energy dissipation. Several types of friction dampers have been developed for the purpose of improving seismic response

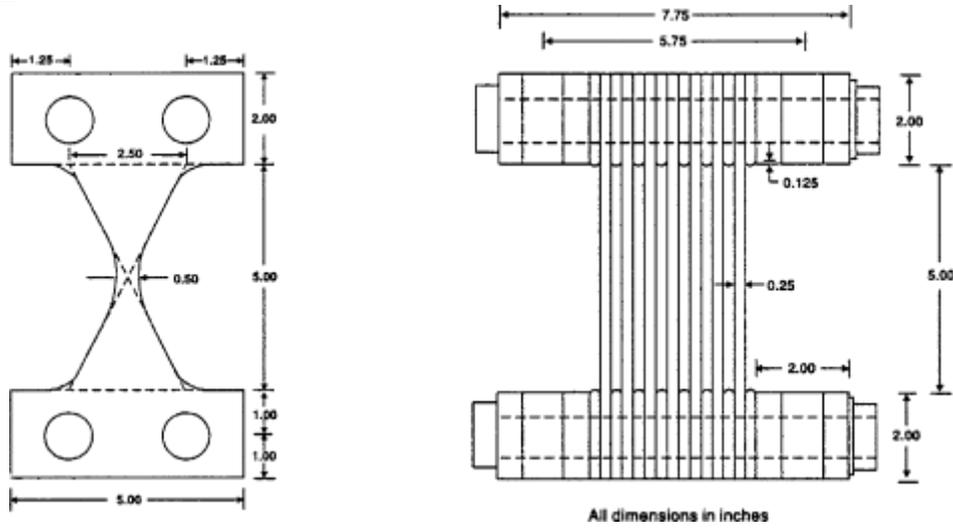


Fig. 3. ADAS device [11].

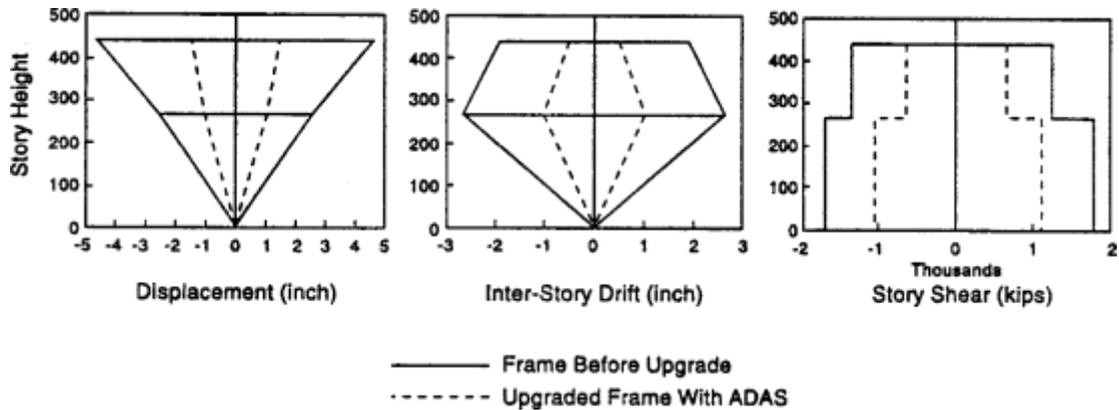


Fig. 4. Comparison of computed results for Wells Fargo Bank Building — envelope of response values in the X-direction [15].

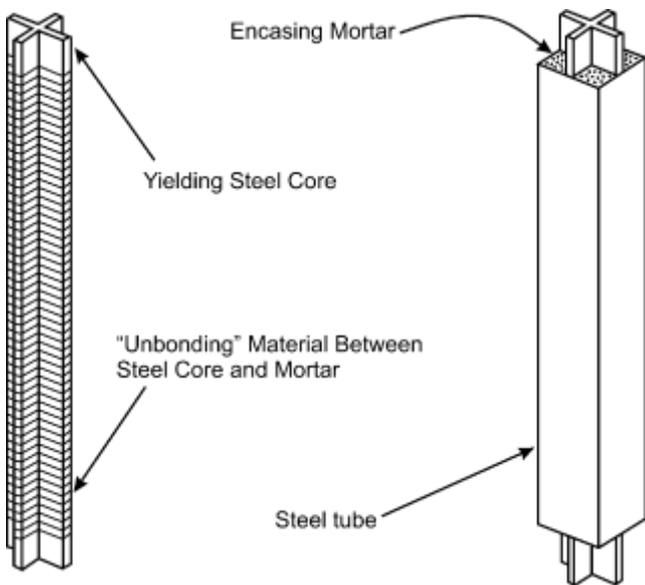


Fig. 5. Unbonded brace [17].

of structures. An example of such a device is depicted in Fig. 6. During cyclic loading, the mechanism enforces slippage in both tensile and compressive directions. Generally, friction devices generate rectangular hysteretic loops similar to the characteristics of Coulomb friction. After a hysteretic restoring force model has been validated for a particular device, it can be readily incorporated into an overall structural analysis.

In recent years, there have been a number of structural applications of friction dampers aimed at providing enhanced seismic protection of new and retrofitted structures. This activity in North America is primarily associated with the use of Pall friction devices in Canada and the USA [18]; and slotted-bolted connection in the USA [19]. For example, the applications of friction dampers to the McConnell Library of the Concordia University in Montreal, Canada are discussed in [20]. A total of 143 dampers were employed in this case. A series of nonlinear DRAIN-TABS analyses were utilized to establish the optimum slip load for the devices, which ranges from 600–700 kN depending upon the location within the structure. For the three-dimensional time-history analyses, artificial seismic signals were generated with a wide range of frequency contents and a peak ground acceleration scaled to 0.18g to represent expected ground motion in Montreal. Under this level of excitation, an estimate of the equivalent damping ratio for the structure with frictional devices is ca 50%. In addition, for this

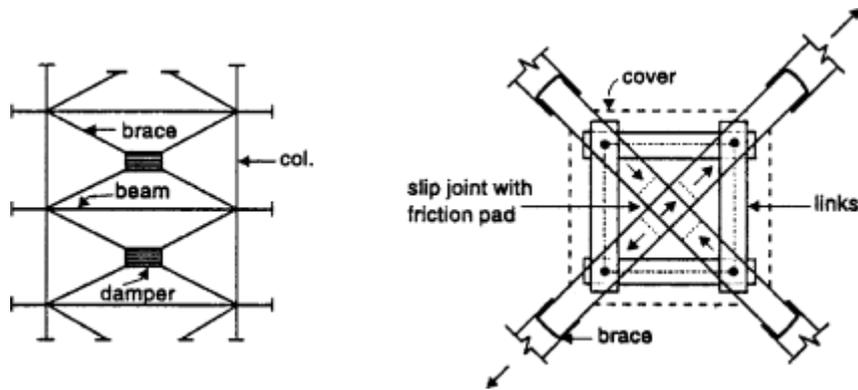


Fig. 6. X-braced friction damper [18].

library complex, the use of the friction dampers resulted in a net savings of 1.5% of the total building cost.

Viscoelastic dampers

Viscoelastic materials used in structural applications are usually copolymers or glassy substances that dissipate energy through shear deformation. A typical VE damper, which consists of VE layers bonded with steel plates, is shown in Fig. 7. When mounted in a structure, shear deformation and hence energy dissipation takes place when structural vibration induces relative motion between the outer steel flanges and the center plates. Significant advances in research and development of VE dampers, particularly for seismic applications, have been made in recent years through analyses and experimental tests (e.g., [21–23]).

A seismic retrofit project using VE dampers began in 1993 for the 13-story Santa Clara County building in San Jose, CA [24]. Situated in a high seismic risk region, the building was built in 1976. It is ca 64 m in height and nearly square in plan, with 51 m x 51 m on typical upper floors. The exterior cladding consists of full-height glazing on two sides and metal siding on the other two sides. The exterior cladding, however, provides little resistance to structural drift. The equivalent viscous damping in the fundamental mode was <1% of critical. The building was extensively instrumented, providing invaluable response data obtained during a number of past earthquakes. A plan for seismic upgrade of the building was developed, in part, when the response data indicated large and long-duration response, including torsional coupling, to even moderate earthquakes. The final design called for installation of two dampers per building face per floor level, which would increase the

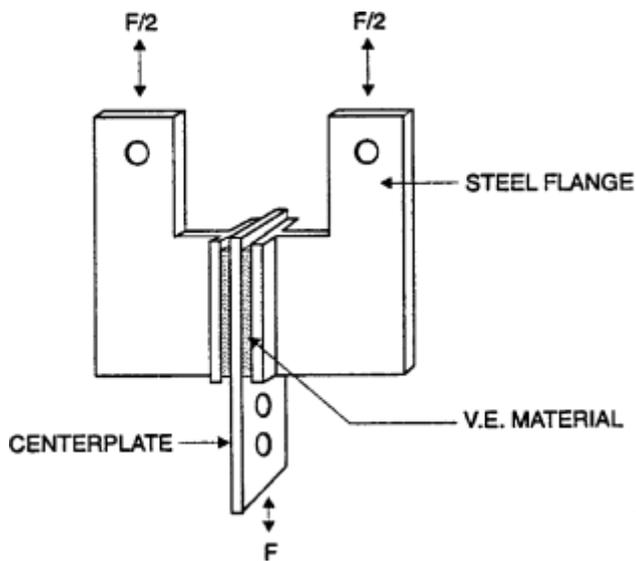


Fig. 7. Typical VE damper configuration.

equivalent damping in the fundamental mode of the building to about 17% of critical, providing substantial reductions to building response under expected levels of ground shaking. A typical damper configuration is shown in Fig. 8. More recent installations include the use of VE dampers to upgrade a concrete structure [25] and their use in a new construction [26].

In Japan, the Hazama Corp. developed similar devices by using similar materials, and the Shimizu Corp developed VE walls, in which solid thermoplastic rubbersheets were sandwiched between steel plates.

Viscous fluid dampers

The viscous fluid (VF) devices developed recently include viscous walls and VF dampers. The viscous wall, developed by Sumitomo Construction Company, consists of a plate moving in a thin steel case filled with highly VF. The VF damper, widely used in the military and aerospace industry for many years, has recently been adapted for structural applications in civil engineering. A VF damper generally consists of a piston within a damper housing filled with a compound of silicone or similar type of oil, and the piston may contain a number of small orifices through which the fluid may pass from one side of the piston to the other [27]. Thus, VF dampers dissipate energy through the movement of a piston in a highly VF based on the concept of fluid orificing. Viscous fluid dampers have in recent years been incorporated into a large number of civil engineering structures. In several applications, they were used in combination with seismic isolation systems. For example, in 1995, VF dampers were incorporated into base isolation systems for five buildings of the San Bernardino County Medical Center, located close to two major fault lines, in 1995. The five buildings required a total of 233 dampers,

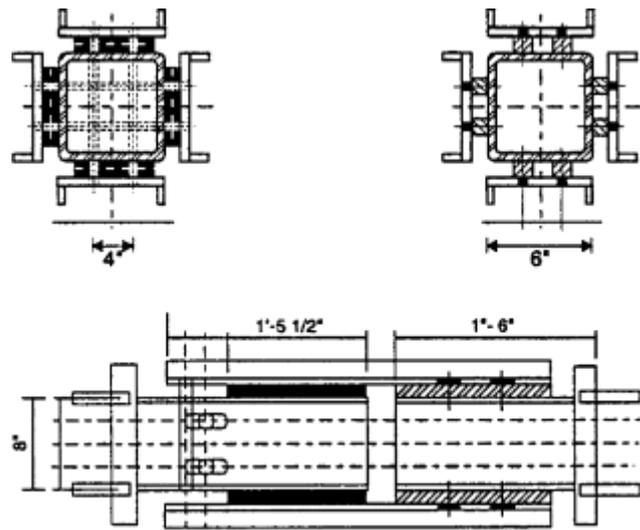


Fig. 8. Santa Clara County Building — VE damper configuration (longitudinal and cross-sectional views) [24].

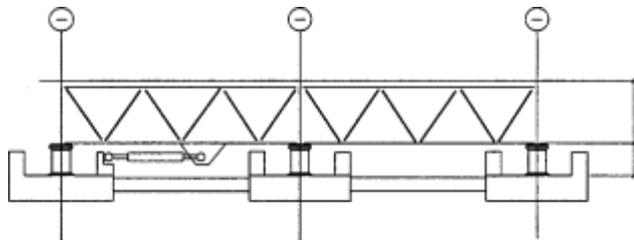


Fig. 9. San Bernardino County Medical Center—damper—base isolation system assembly [27].

pers, each having an output force capacity of 320 000 lb and generating an energy dissipation level of 3000 horse-power at a speed of 60 in/s. A layout of the damper-isolation system assembly is shown in Fig. 9 and Fig. 10 gives the dimensions of the viscous dampers employed.

Tuned mass dampers

Early applications of tuned mass dampers (TMDs) have been directed toward mitigation of wind-induced excitations. Recently, numerical and experimental studies have been carried out to examine the effectiveness of TMDs in reducing seismic response of structures. It is noted that a passive TMD can only be tuned to a single structural frequency. While the first-mode response of a MDOF structure with TMD can be substantially reduced, the higher mode response may in fact increase as the number of stories increases. For earthquake-type excitations, the response reduction is large for resonant ground motions and diminishes as the dominant frequency of the ground motion gets further away from the structure's natural frequency to which the TMD is tuned. It is also noted that the interest in using TMDs for vibration control of structures under earthquake loads has resulted in some innovative developments. An interesting approach is the use of a TMD with active capability, the so called active mass damper (AMD) or hybrid mass damper (HMD). Systems of this type have been implemented in a number of tall buildings in recent years in Japan, and they are described in the next section.

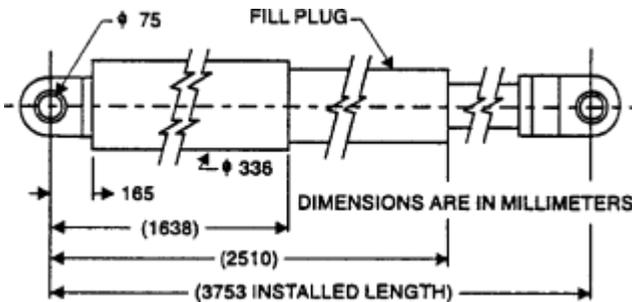


Fig. 10. Dimensions of VF damper for San Bernardino County Medical Center [27].

Tuned liquid dampers

The basic principles involved in applying a tuned liquid damper (TLD) to reduce the dynamic response of structures is quite similar to that discussed above for the TMD. In effect, a secondary mass in the form of a body of liquid is introduced into the structural system and tuned to act as a dynamic vibration absorber. However, in the case of TLDs, the damper response is highly non-linear due either to liquid sloshing or the presence of orifices. TLDs have also been used for suppressing wind-induced vibrations of tall structures. In comparison with TMDs, the advantages associated with TLDs include low initial cost, virtually free of maintenance and ease of frequency tuning.

The TLD applications have taken place primarily in Japan for controlling wind-induced vibration. Examples of TLD-controlled structures include airport towers and tall buildings.

4. Active, hybrid and semi-active control systems

The rapid growth of research interest and development of active/hybrid and semi-active structural control systems is in part due to several coordinated research efforts, largely in Japan and the USA, marked by a series of milestones listed in Table 2. Indeed, the most challenging aspect of active control research in civil engineering is the fact that it is an integration of a number of diverse disciplines, some of which are not within the domain of traditional civil engineering. These include computer science, data processing, control theory, material science, sensing technology, as well as stochastic processes, structural dynamics, and wind and earthquake engineering. These coordinated efforts have facilitated collaborative research efforts among researchers from diverse backgrounds and accelerated the research-to-implementation process as one sees today.

As alluded to earlier, the development of active, hybrid, and semi-active control systems has reached the stage of full-scale applications to actual structures. Table 3 lists these installations in building structures and towers, most of which are in Japan. In addition, 15 bridge towers have employed active systems during erection [28,29]. Most of these full-scale systems have been subjected to actual wind forces and ground motions and their observed performances provide invaluable information in terms of:

1. validating analytical and simulation procedures used to predict actual system performance;
2. verifying complex electronic-digital-servo-hydraulic systems under actual loading conditions; and
3. verifying capability of these systems to operate or shutdown under prescribed conditions.

Table 2
Active structural control research — milestones

Year	Event
1989	US Panel on Structural Control Research (US-NSF)
1990	Japanese Panel on Structural Response Control (Japan-SCJ)
1991	Five-year Research Initiative on Structural Control (US-NSF)
1993	European Association for Control of Structures
1994	International Association for Structural Control
1994	First World Conference on Structural Control (Pasadena, CA, USA)
1996	First European Conference on Structural Control (Barcelona, Spain)
1998	Chinese Panel for Structural Control
1998	Korean Panel for Structural Control
1998	Second World Conference on Structural Control (Kyoto, Japan)
2000	Second European Conference on Structural Control (Paris, France)
2002	Third World Conference on Structural Control (Como, Italy)

Described below are several of these systems together, in some cases, with their observed performances. Also addressed are several practical issues in connection with actual structural applications of these systems.

Hybrid mass damper systems

As seen from Table 3, the HMD is the most common control device employed in full-scale civil engineering applications. An HMD is a combination of a passive TMD and an active control actuator. The ability of this device to reduce structural responses relies mainly on the natural motion of the TMD. The forces from the control actuator are employed to increase the efficiency of the HMD and to increase its robustness to changes in the dynamic characteristics of the structure. The energy and forces required to operate a typical HMD are far less than those associated with a fully AMP system of comparable performance.

An example of such an application is the HMD system installed in the Sendagaya INTES building in Tokyo in 1991. As shown in Fig. 11, the HMD was installed atop the 11th floor and consists of two masses to control transverse and torsional motions of the structure, while hydraulic actuators provide the active control capabilities. The top view of the control system is shown in Fig. 12 where ice thermal storage tanks are used as mass blocks so that no extra mass was introduced. The masses are supported by multi-stage rubber bearings intended for reducing the control energy consumed in the HMD and for insuring smooth mass movements [30,31].

Sufficient data were obtained for evaluation of the HMD performance when the building was subjected to strong wind, with peak instantaneous wind speed of 30.6 m/s. An example of the recorded time histories is shown in Fig. 13, giving both the uncontrolled and controlled states. Their Fourier spectra using samples of 30-s durations are shown in Fig. 14, again showing good performance in the low frequency range. The response at the fundamental mode was reduced by 18 and 28% for translation and torsion, respectively.

Variations of such an HMD configuration include multi-step pendulum HMDs (as seen in Fig. 15), which have been installed in, for example, the Yokohama Landmark Tower in Yokohama [32], the tallest building in Japan, and in the TC Tower in Kaohsiung, Taiwan. Additionally, the DUOX HMD system which, as shown schematically in Fig. 16, consists of a TMD actively controlled by an auxiliary mass, has been installed in, for example, the Ando Nishikicho Building in Tokyo.

Active mass damper systems

Design constraints, such as severe space limitations, can preclude the use of an HMD system. Such is the case in the active mass damper or active mass driver (AMD) system designed and installed in the Kyobashi Seiwa Building in Tokyo and the Nanjing Communication Tower in Nanjing, China.

The Kyobashi Seiwa Building, the first full-scale implementation of active control technology, is an 11-story building with a total floor area of 423 m². As seen in Fig. 17, the control system consists of two AMDs where the primary AMD is used for transverse motion and has a weight of 4 ton, while the secondary AMD has a weight of 1 ton and is employed to reduce torsional motion. The role of the active system is to reduce building vibration under strong winds and moderate earthquake excitations and consequently to increase comfort of occupants in the building.

In the case of the Nanjing Communication tower (Fig. 18), numerous physical constraints had to be accounted for in the system design of the mass damper. The physical size of the damper was constrained to a ring-shaped floor area with inner and outer radii of 3 and 6.1 m, respectively. In addition, the damper was by necessity elevated off the floor on steel supports with Teflon bearings to allow free access to the floor area. The final ring

Table 3
Full scale implementation of active structural control

Location	Building	Year completed	Building use	Number of stories	Type of vibration control device ^a
Japan	Kyobashi Seiwa Building, Tokyo	1989	Office	11	AMD
	Kajima Research Laboratory No. 21, Tokyo	1990	Office	3	SAVS
	Shimizu Technology Laboratory, Tokyo	1991	Laboratory	7	AMD
	Sendagaya INTES Building, Tokyo	1992	Office	11	HMD
	Elevator Technology Laboratory	1992	Laboratory	(60 m)	AGS
	Hankyu Chayamachi Building, Osaka	1992	Office/Hotel	34	HMD
	Kansai International Airport, Osaka	1992	Control Tower	(88 m)	HMD
	Land Mark Tower, Yokohama	1993	Office/Hotel	70	HMD

	Osaka Resort City 200, Osaka	1993	Office/Hotel	50	HMD
	Long Term Credit Bank, Tokyo	1993	Office	21	HMD
	Ando Nishikicho Building, Tokyo	1993	Office	14	HMD
	NTT Kuredo MotomachBuilding, Hiroshima	1993	Office/Hotel	35	HMD
	Penta-Ocean Experimental Building, Tokyo	1994	Experimental	6	HMD
	Shinjuku Park Tower, Tokyo	1994	Office/Hotel	52	HMD
	Dowa Fire and Marine Insurance, Osaka	1994	Office	29	HMD
	Porte Kanazawa, Kanazawa	1994	Office/Hotel	30	AMD
	Mitsubishi Heavy Industry, Yokohama	1994	Office	34	HMD
	Hamamatsu ACT Tower, Hamamatsu	1994	Office/Hotel	(212 m)	HMD
	Riverside Sumida, Tokyo	1994	Office	33	AMD
	Hotel Ocean 45, Miyazaki	1994	Hotel	43	HMD
	RIHGA Royal Hotel, Hiroshima	1994	Hotel	35	HMD
	Hikarigaoko J City Building, Tokyo	1994	Office/Hotel	46	HMD
	Osaka WTC Building, Osaka	1995	Office	52	HMD
	Dowa Kasai Phoenix Tower, Osaka	1995	Office	28	HMD
	Rinku Gate Tower Building, Osaka	1995	Office/Hotel	56	HMD
	Hirobe Miyake Building, Tokyo	1995	Office/Residential	9	HMD
	Plaza Ichihara, Chiba	1995	Office	12	HMD
	Herbis Osaka, Osaka	1997	Hotel	38	AMD
	Nisseki Yokohama Building, Yokohama	1997	Office	30	HMD
	Itoyama Tower, Tokyo	1997	Office/Residential	18	HMD
	Otis Shibyama Test Tower, Chiba	1998	Laboratory	39	HMD
	Bunka Gakuen, Tokyo	1998	School	20	HMD
	Daiichi Hotel Oasis Tower, Ohita	1998	Office/Hotel	21	HMD
	Odakyu Southern Tower, Tokyo	1998	Office/Hotel	36	HMD
	Kajima Shizuoka Building, Shizuoka	1998	Office	5	SAHD
	Sotetsu Takashimaya Kyoto Building, Yokohama	1998	Hotel	27	HMD
	Century Park Tower, Tokyo	1999	Residential	54	HMD
USA	Highway I-35 Bridge, OK	1997	Highway Traffic	–	SAHD
Taiwan	TC Tower, Kaoshiung	1999	Office	85	HMD
	Shin-Jei Building, Taipei	1999	Office/Commerce	22	HMD
China	Nanjing Communication Tower, Nanjing	1999	Communication	(310 m)	AMD

^a AMD, Active mass dampers; SAVS, semi-active variable stiffness; HMD, hybrid mass damper; SAHD, semi-active hydraulic damper.

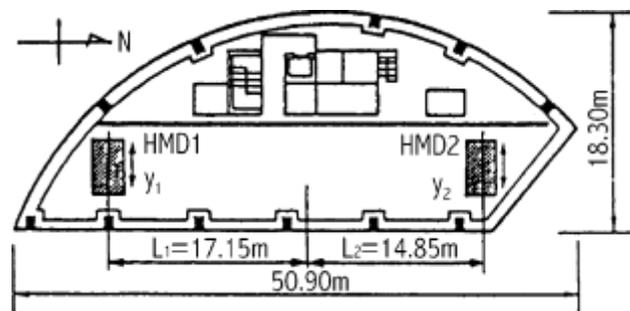
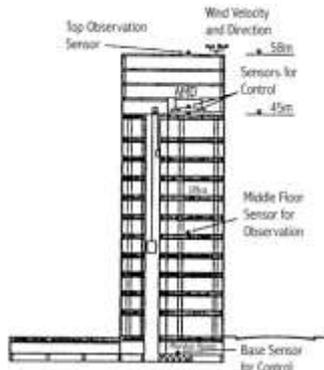


Fig. 11. Sendagaya INTES Building with hybrid mass dampers [30].

Fig. 12. Top view of HMD configuration [30].

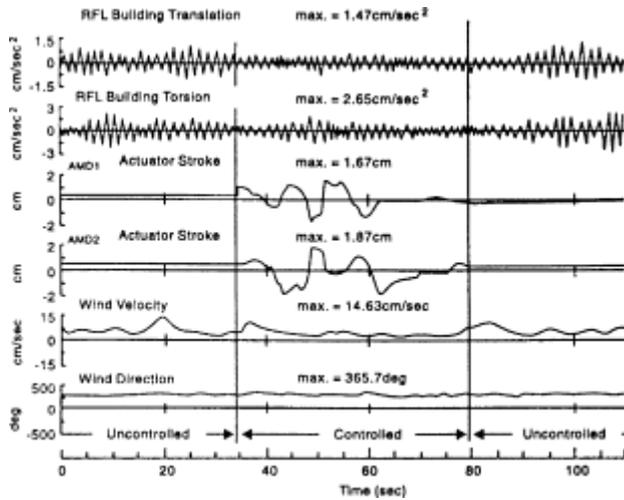
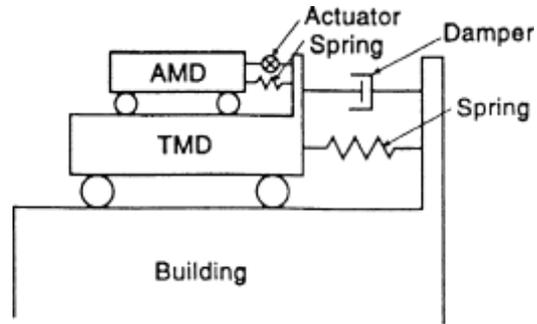


Fig. 13. Response time histories (1993) [30].



design allowed the damper to move ± 750 mm from its rest position. Simulations indicate that this stroke is sufficient to control the tower; however, a greater stroke would allow substantially more improvement in the

Fig. 16. Principle of DUOX system.

response. The strength of the observation deck limited the weight of the damper to 60 ton. Lack of sufficient lateral space made the use of mechanical springs impractical for restoring forces. Thus the active control actuators provide restoring force as well as the damping control forces.

The final design of the AMD is shown in Fig. 19, which uses three servo-controlled hydraulic actuators, each with a total stroke of ± 1.50 m and a peak control

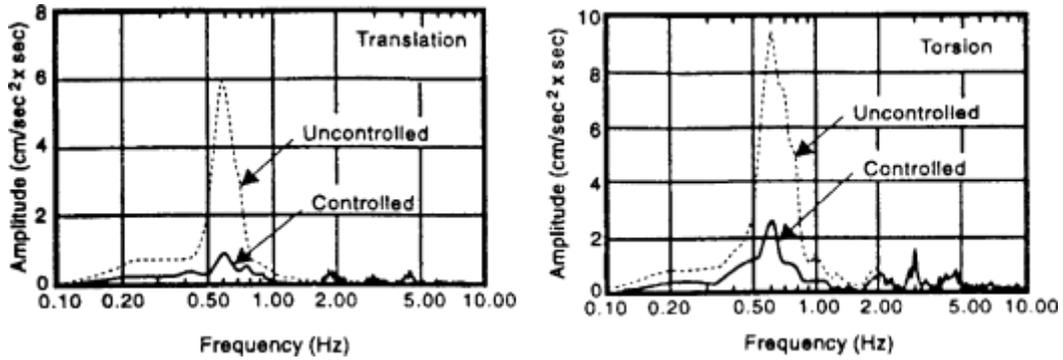


Fig. 14. Response Fourier spectra (1993) [30].

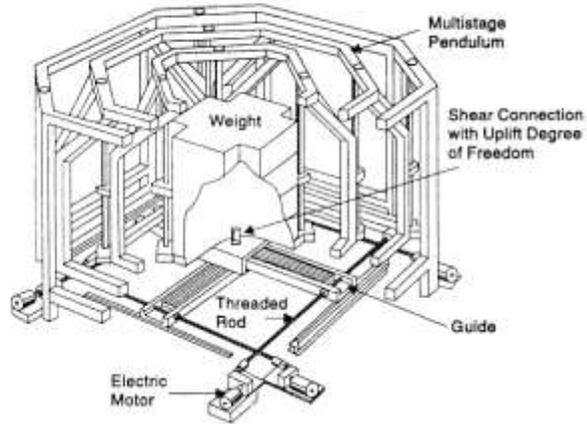


Fig. 15. Yokohama Landmark Tower and HMD [32].

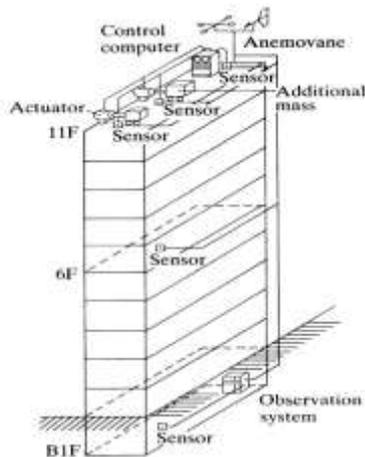


Fig. 17. Kyobashi Seiwa Building and AMD [9].

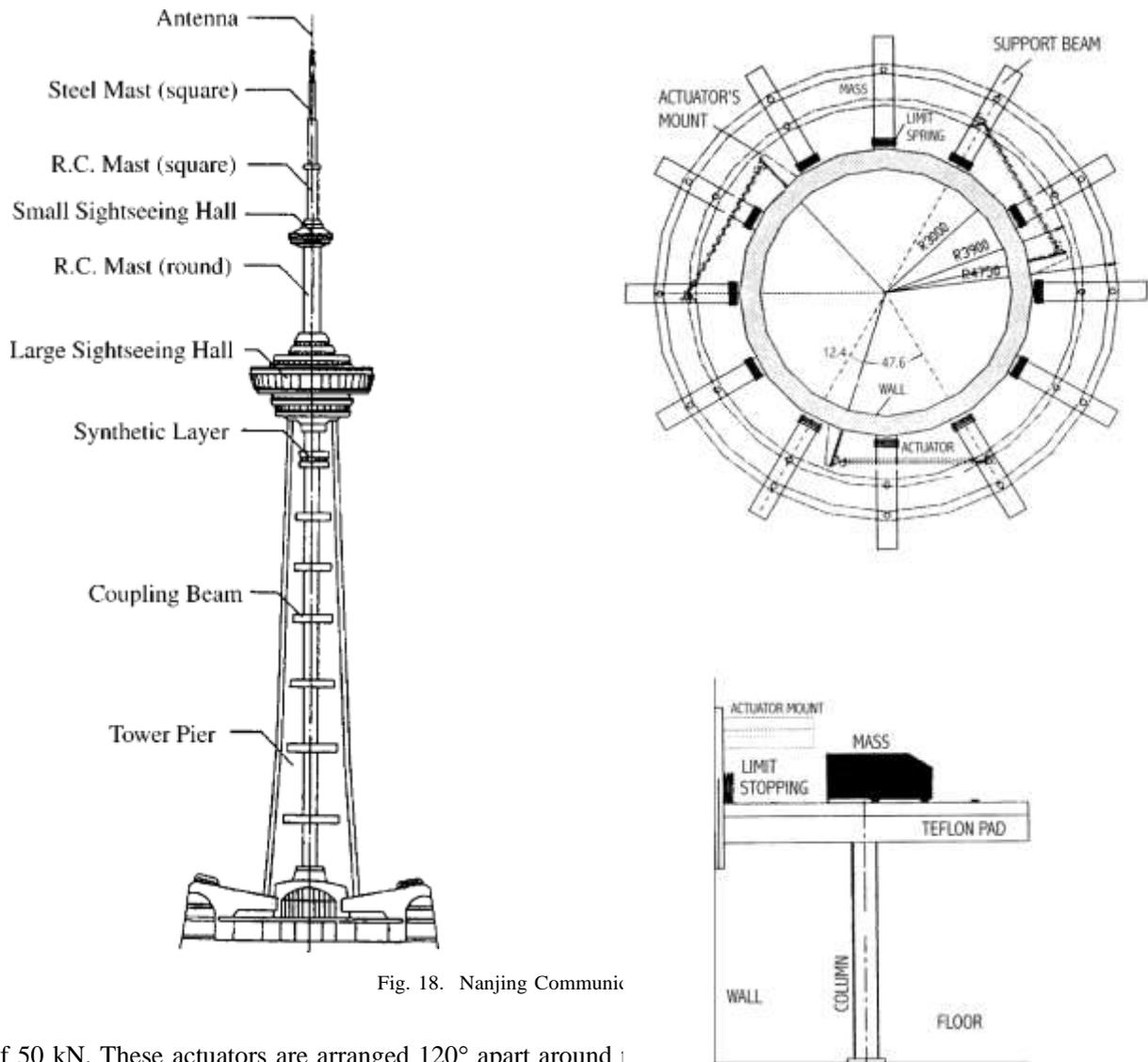


Fig. 18. Nanjing Communication Tower

force of 50 kN. These actuators are arranged 120° apart around the tower. The AMD provides three degrees of freedom: two orthogonal lateral directions of motion and torsional rotation, which is held in place by a wall. The design of AMD showing the mass ring and actuators is shown in Figure 19.

to zero. Since the frictional force between the Teflon bearings and the mass can have a critical influence on the response of the system, a detailed analysis was performed to verify system performance in the presence of friction [33].

Semi-active damper systems

Control strategies based on semi-active devices combine the best features of both passive and active control systems. The close attention received in this area in recent years can be attributed to the fact that semi-active control devices offer the adaptability of active control devices without requiring the associated large power sources. In fact, many can operate on battery power, which is critical during seismic events when the main power source to the structure may fail. In addition, as stated earlier, semi-active control devices do not have

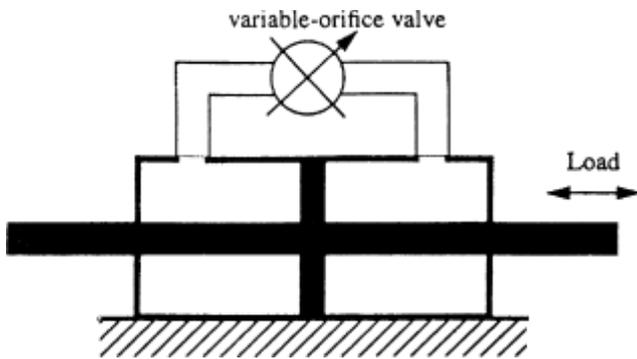


Fig. 20. Schematic of variable-orifice damper.

the potential to destabilize (in the bounded input/bounded output sense) the structural system. Extensive studies have indicated that appropriately implemented semi-active systems perform significantly better than passive devices and have the potential to achieve the majority of the performance of fully active systems, thus allowing for the possibility of effective response reduction during a wide array of dynamic loading conditions.

One means of achieving a semi-active damping device is to use a controllable, electromechanical, variable-orifice valve to alter the resistance to flow of a conventional hydraulic fluid damper. A schematic of such a device is given in Fig. 20. As described in Ref. [34], experiments were conducted in which a hydraulic actuator with a controllable orifice was implemented in a single-lane model bridge to dissipate the energy induced by vehicle traffic (Fig. 21), followed by a full-scale experiment conducted on a bridge on interstate highway I-35 to demonstrate this technology [35–37], as shown in Fig. 22. This experiment constitutes the first full-scale implementation of active structural control in the USA.

Conceived as a variable-stiffness device, a full-scale variable-orifice damper in a semi-active variable-stiffness system (SAVS) was implemented to investigate semi-active control at the Kabori Research Complex [38,39]. The overall system is shown in Fig. 23 where



Fig. 22. Highway I-35 Bridge with semi-active dampers [35].

SAVS devices were installed on both sides of the structure in the transverse direction. The results of these analytical and experimental studies indicate that this device is effective in reducing structural responses.

More recently, a semi-active damper system was installed in the Kajima Shizuoka Building in Shizuoka, Japan. As seen in Fig. 24 semi-active hydraulic dampers are installed inside the walls on both sides of the building to enable it to be used as a disaster relief base in post-earthquake situations [40,41]. Each damper contains a flow control valve, a check valve and an accumulator, and can develop a maximum damping force of 1000 kN. Fig. 25 shows a sample of the response analysis results based on one of the selected control schemes

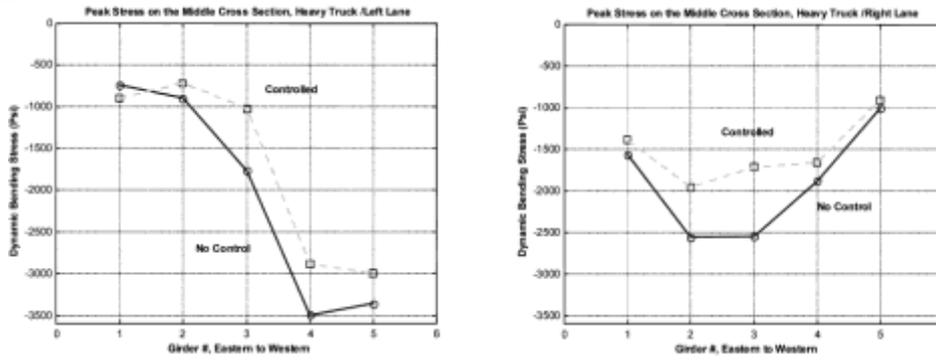


Fig. 21. Comparison of peak stresses for heavy trucks [36].

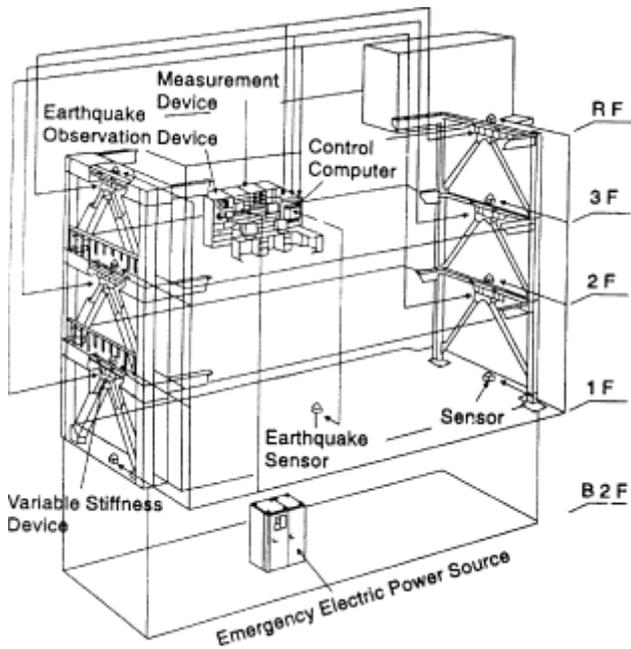


Fig. 23. SAVS system configuration [38,39].

and several earthquake input motions with a scaled maximum velocity of 50 cm/s, together with a simulated Tokai wave. It is seen that both story shear forces and story drifts are greatly reduced with control activated. In the case of the shear forces, they are confined within their elastic-limit values (indicated by the E-limit in Fig. 25) while, without control, they would enter the plastic range.

Semi-active controllable fluid dampers

Another class of semi-active devices uses controllable fluids, schematically shown in Fig. 26. In comparison with semi-active damper systems described above, an advantage of controllable fluid devices is that they contain no moving parts other than the piston, which makes them simple and potentially very reliable.

Two fluids that are viable contenders for development of controllable dampers are:

1. electrorheological (ER) fluids; and
2. magnetorheological (MR) fluids.

The essential characteristic of these fluids is their ability

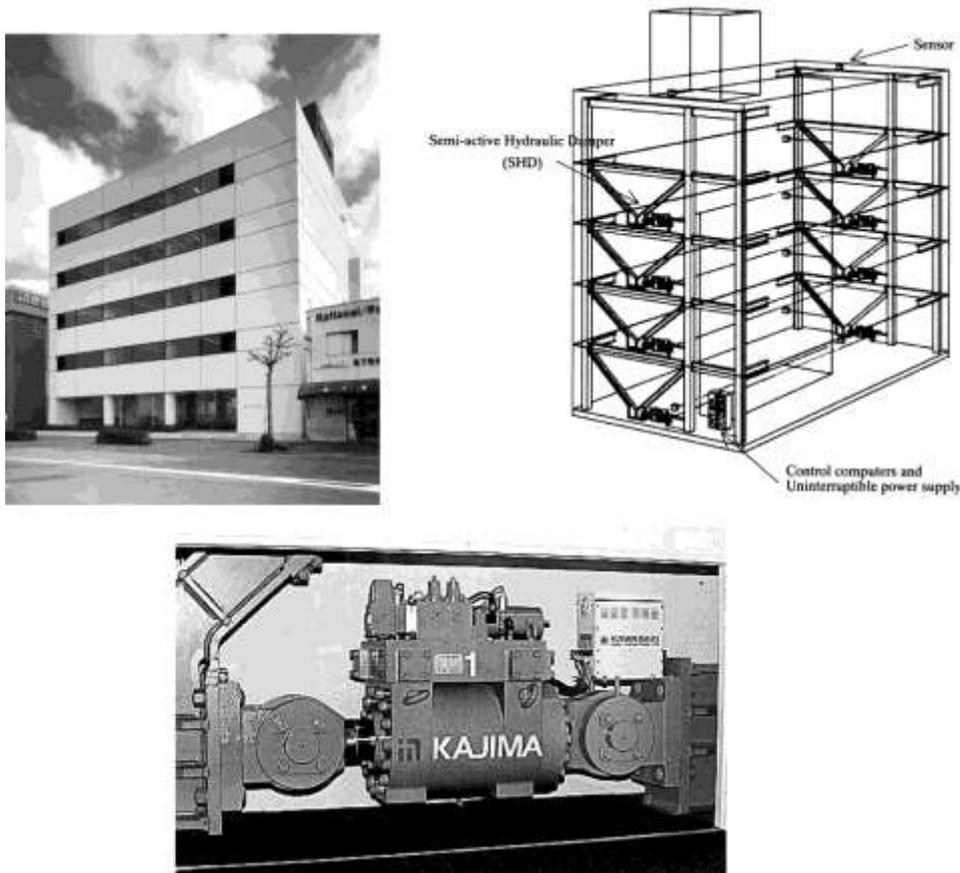


Fig. 24. Kajima Shizuoka Building and semi-active hydraulic dampers [41].

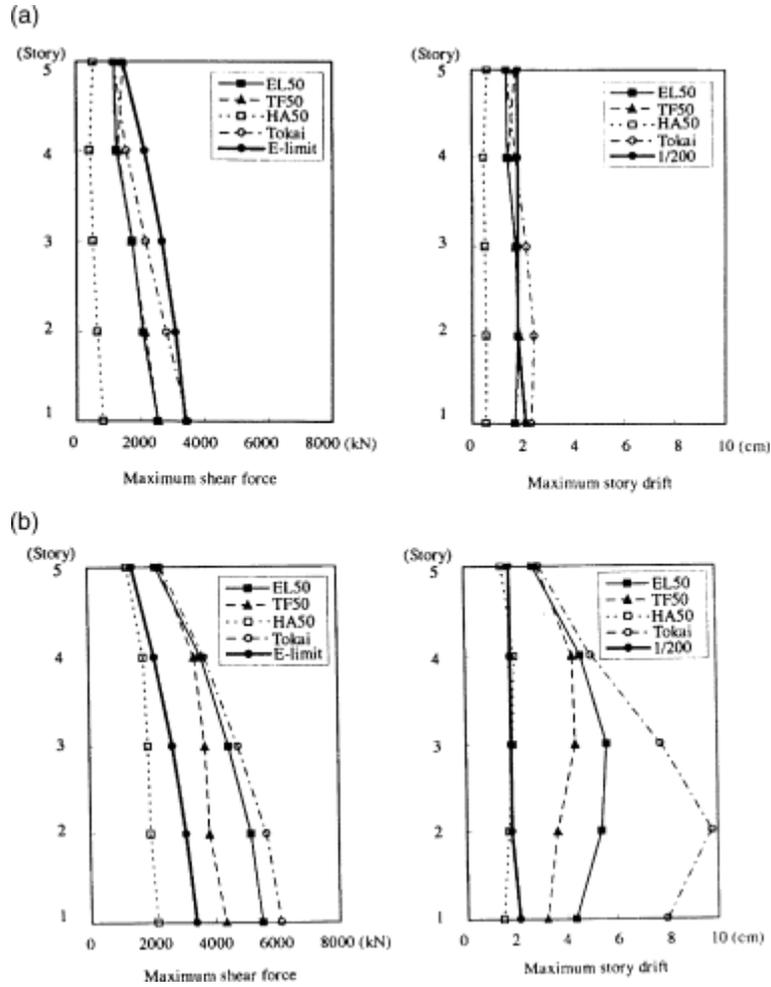


Fig. 25. Maximum Responses (El Centro, Taft and Hachinohe waves with 50 cm/s and assumed Tokai waves). (a) With SAHD control; (b) without control [41].

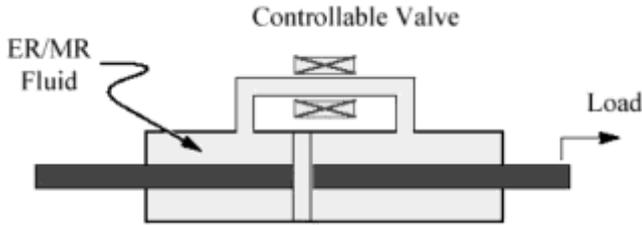


Fig. 26. Schematic of controllable fluid damper [42].

to reversibly change from a free-flowing, linear VF to a semi-solid with a controllable yield strength in milliseconds when exposed to an electric (for ER fluids) or magnetic (for MR fluids) field. In the absence of an applied field, these fluids flow freely and can be modeled as Newtonian. When the field is applied, a Bingham plastic model [42] is often used to describe the fluid behavior. In this model, the plastic viscosity is defined as the slope of the measured shear stress versus shear strain rate data. Thus, the total yield stress is given by

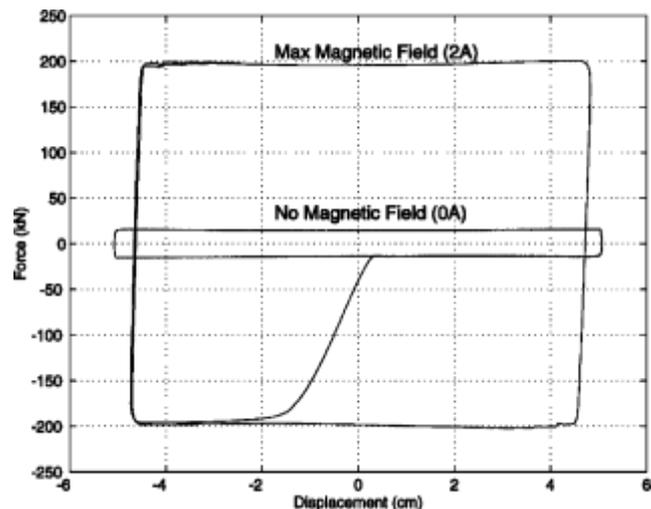
$$\tau = \tau_{y(\text{field})} \text{sgn}(\dot{\gamma}) + h_p \dot{\gamma} \quad (6)$$

where $\tau_{y(\text{field})}$ is the yield stress caused by the applied field, $\dot{\gamma}$ is the shear strain rate and h_p is the plastic viscosity, defined as the slope of the measured shear stress versus shear strain rate data.

Although the discovery of both ER and MR fluids dates back to the late 1940s [43,44], for many years research programs concentrated primarily on ER fluids. Nevertheless, some obstacles remain in the development of commercially feasible damping devices using ER fluids. For example, the best ER fluids currently available have a yield stress of only 3.0 to 3.5 kPa and cannot tolerate common impurities (e.g., water) that might be introduced during manufacturing or use. In addition, safety, availability and cost of the high voltage (e.g., ~4000 V) power supplies required to control the ER fluids need to be addressed.

Recently developed MR fluids appear to be an attractive alternative to ER fluids for use in controllable fluid dampers [45–47]. MR fluids typically consist of micron-sized, magnetically polarizable particles dispersed in a carrier medium such as mineral or silicone oil. It is indi-

cated in Ref. [46] that the achievable yield stress of an MR fluid is an order of magnitude greater than its ER counterpart and that MR fluids can operate at temperatures from -40 to 150°C with only modest variations in the yield stress. Moreover, MR fluids are not sensitive to impurities such as those commonly encountered during manufacturing and usage, and little particle/carrier fluid separation takes place in MR fluids under common flow conditions. The size, shape and performance of a given device is determined by a combination of $\tau_{y(\text{field})}$ and h_p . The design equations for most controllable damper geometries indicate that minimizing the ratio $h_p/\tau_{y(\text{field})}^2$ is



desirable. This ratio for MR fluids ($\approx 5 \times 10^{-11}$ s/Pa) is three orders of magnitude smaller than the corresponding ratio for today's best ER fluids. Thus, controllable devices using MR fluids have the potential of being much smaller than ER devices with similar capabilities. Further, the MR fluid can be readily controlled with a low power (e.g., <50 W), low voltage (e.g., ~12–24 V), current-driven power supply outputting only ~1–2 amps. Batteries can readily supply such power levels.

While no full-scale structural applications of MR devices have taken place to date, their future for civil engineering applications appears to be bright. A number of pilot studies have been conducted to assess the usefulness of MR dampers for seismic response reduction [48–53]. In Refs. [50–55], simulations and laboratory experiments have shown that the MR damper, used in conjunction with recently proposed acceleration feedback control strategies, significantly outperforms comparable passive configurations of the damper for seismic response reduction. In addition, the design of a full-scale, 20-ton MR damper has been reported [49,56,57] (see Fig. 27), showing that this technology is scalable to devices appropriate for civil engineering applications. At design velocities, the dynamic range of forces produced by this device is over 10 (see Fig. 28), and the total power required by the device is only 20–50 W. More-

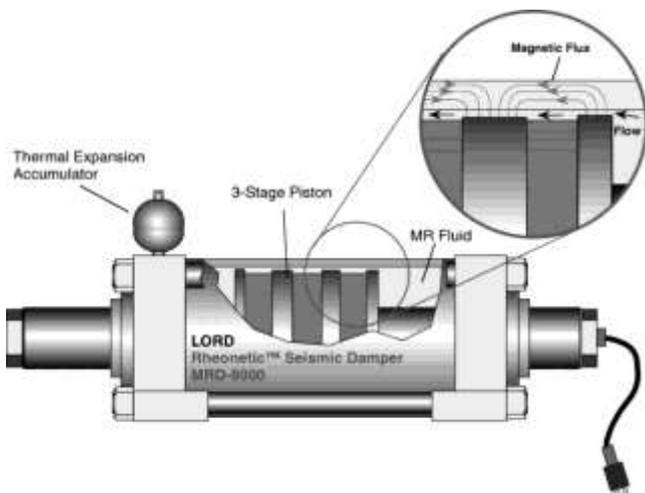


Fig. 27. Full-scale 20-ton MR fluid damper [53].

Fig. 28. Force–displacement loops at maximum and zero magnetic fields [53].

over, Sunakoda, et al. [58] have presented encouraging results regarding design, construction and commercial production of large scale MR dampers, which should greatly accelerate the introduction of this technology into practice.

5. Concluding remarks

An attempt has been made in this paper to introduce the basic concepts of passive and active structural control and to bring up-to-date their current development and structural applications in this exciting and fast expanding field. While significant strides have been made in terms of implementation of these concepts to structural design and retrofit, it should be emphasized that this entire technology is still evolving. Significant improvements in both hardware, software and design procedures will certainly continue for a number of years to come.

The acceptance of innovative systems in structural engineering is based on a combination of performance enhancement versus construction costs and long-term effects. Continuing efforts are needed in order to facilitate wider and speedier implementation. These include effective system integration and further development of analytical and experimental techniques by which performances of these systems can be realistically assessed. Structural systems are complex combinations of individual structural components. New innovative devices need to be integrated into these complex systems, with realistic evaluation of their performance and impact on the structural system, as well as verification of their ability for long-term operation.

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