State of the Art of Structural Control

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In recent years, considerable attention has been paid to research and development of structural control devices, with particular emphasis on alleviation of wind and seismic response of buildings and bridges. In both areas, serious efforts have been undertaken in the last two decades to develop the structural control concept into a workable technology. Full-scale implementation of active control systems have been accomplished in several structures, mainly in Japan; however, cost effectiveness and reliability considerations have limited their wide spread acceptance. Because of their mechanical simplicity, low power requirements, and large, controllable force capacity, semiactive systems provide an attractive alternative to active and hybrid control systems for structural vibration reduction. In this paper we review the recent and rapid developments in semiactive structural control and its implementation in full-scale structures.

Introduction

Supplemental passive, active, hybrid, and semiactive damping strategies offer attractive means to protect structures against natural hazards. Passive supplemental damping strategies, including base isolation systems, viscoelastic dampers, and tuned mass dampers, are well understood and are widely accepted by the engineering community as a means for mitigating the effects of dynamic loading on structures. However, these passive-device methods are unable to adapt to structural changes and to varying usage patterns and loading conditions. For example, passively isolated structures in one region of Los Angeles that survived the 1994 Northridge earthquake (Nagarajaiah and Sun 2000), may well have been damaged severely if they were located elsewhere in the region (Makris 1997).

For more than two decades, researchers have investigated the possibility of using active, hybrid, and semiactive control methods to improve upon passive approaches to reduce structural responses (Soong 1990; Soong and Reinhorn 1993; Spencer and Sain 1997; Housner et al. 1997; Kobori et al. 1998, 2003; Soong and Spencer 2002; Spencer 2002). The first full-scale application of active control to a building was accomplished by the Kajima Corporation in 1989 (Kobori et al. 1991). The Kyobashi Center building is an 11-story (33.1 m) building in Tokyo, having a total floor area of 423 m^2. A control system was installed, consisting of two AMDs—the primary AMD is used for transverse motion and has a mass of 4 t, while the secondary AMD has a mass of 1 t 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 of the building.

Hybrid-control strategies have been investigated by many researchers to exploit their potential to increase the overall reliability and efficiency of the controlled structure (Housner et al. 1994; Kareem et al. 1999; Nishitani and Inoue 2001; Yang and Dyke 2003; Casciati 2003; Faravelli and Spencer 2003). A hybrid-control system is typically defined as one that employs a combination of passive and active devices. Because multiple control devices are operating, hybrid control systems can alleviate some of the restrictions and limitations that exist when each system is acting alone. Thus, higher levels of performance may be achievable. Additionally, the resulting hybrid control system can be more reliable than a fully active system, although it is also often somewhat more complicated. To date, there have been over 40 buildings and about 10 bridges (during erection) that have employed feedback control strategies in full-scale implementations (Tables 1 and 2). The vast majority of these have been hybrid control systems.

Although extensive analytical and experimental structural control research has been conducted in both the United States and Japan in the last two decades, with the exception of one experimental system installed on a bridge in Oklahoma [Patten et al. (1999), discussed later in this paper], none of these full-scale active control installations are located in the United States. Many possible reasons can be cited for this disparity. For example, the civil engineering profession and construction industry in the United States are conservative and generally reluctant to apply new technologies. The absence of verified and consensus-approved analysis, design, and testing procedures represent additional impediments to the application of this technology. However, more notable is the lack of research and development expenditures by the U.S. construction industry. This situation stands in sharp contrast to the Japanese construction industry, which invests heavily in the development and implementation of new technologies. Even in Japan, few new structures with fully active control systems are being initiated. This situation is partly due to the modest number of tall buildings and long-span bridges being planned for the near future and partly due to a number of serious challenges that remain before active control can gain general acceptance by the engineering and construction professions at large. These challenges include (1) reducing capital cost and maintenance, (2) eliminating reliance on external power, (3) increasing system reliability and robustness, and (4) gaining acceptance of nontraditional technology.

Despite the impediments that exist to wider application of control to civil engineering structures, the future appears quite bright. Semiactive control strategies are particularly promising in addressing many of the challenges to this technology, offering the reliability of passive devices, yet maintaining the versatility and adaptability of fully active systems, without requiring the associated large power sources and can operate on battery power. Studies have shown that appropriately implemented semiactive damp-

Table 1. Summary of Controlled Buildings/Towers

Full-scale structure	Location	Year completed	Building usage	Scale of building	Control system	AMD/HMD Number	AMD/HMD Mass (ton)	Actuation mechanism
Kyobashi Center	Tokyo	1989	office	33 m, 400 ton, 11 stories	AMD[a]	2	5.0	hydraulic
Kajima Technical Research Institute No. 21	Tokyo	1990	office	12 m, 400 ton, 3 stories	AVS[b]			variable-orifice hydraulic damper
Sendagaya INTES	Tokyo	1991	office	58 m, 3,280 ton (1st mode), 11 stories	AMD	2	72.0	hydraulic
Shimizu Tech. Lab	Tokyo	1991	laboratory	30 m, 364 ton, 7 stories	HMD[c]	1	4.3	servo motor
Applause Tower (Hankyu Chayamachi Bldg.)	Osaka, Japan	1992	office/hotel/theater	162 m, 62,660 ton, 34 stories	AMD	1	480.0	hydraulic
Kansai Int. Airport Control Tower	Osaka, Japan	1992	control tower	86 m, 2,570 ton, 5 stories	HMD	2	10.0	servo motor
ORC 200 Bay Tower	Osaka, Japan	1992	office/hotel	200 m, 56,680 ton, 50 stories	HMD	2	230.0	servo motor
High-rise Housing Experiment Tower	Tokyo	1993	experiment	108 m, 730 ton, 36 stories	AGS[d]	1	0.8	servo motor
Landic Otemachi	Tokyo	1993	office	130 m, 39,800 ton, 21 stories	HMD	1	195.0	hydraulic
Nishimoto Kosan Nishikicho Bldg.	Tokyo	1993	office	54 m, 2,600 ton, 14 stories	HMD	1	22.0	servo motor
Yokohama Land Mark Tower	Yokohama, Japan	1993	office/hotel	296 m, 260,600 ton, 70 stories	HMD	2	340.0	hydraulic
Hamamatsu ACT Tower	Hamamatsu, Japan	1994	office/hotel/commerce	213 m, 107,534 ton, 45 stories	HMD	2	180.0	servo motor
Hikarigaoka J-City Tower	Tokyo	1994	office	112 m, 25,391 ton, 24 stories	HMD	2	44.0	servo motor
Hirobe Miyake Bldg.	Tokyo	1994	office/residential	31 m, 273 ton, 9 stories	HMD	1	2.1	servo motor
Hotel Phoenix Hotel Ocean 45	Miyazaki, Japan	1994	hotel	154 m, 83,650 ton, 43 stories	HMD	2	240.0	servo motor
MHI Yokohama Bldg.	Yokohama, Japan	1994	office	152 m, 61,800 ton, 34 stories	HMD	1	60.0	servo motor
NTT Kuredo Motomachi Bldg.	Hiroshima, Japan	1993	office/hotel	150 m, 83,000 ton, 35 stories	HMD	1	78.0	servo motor
Penta-Ocean Exp. Bldg.	Togichi, Japan	1994	experiment	19 m, 154 ton, 5 stories	HMD	1	0.5	servo motor
Porte Kanazawa (Hotel Nikko Kanazawa)	Kanazawa, Japan	1993	office/hotel	131 m, 27,600 ton, 30 stories	AMD	2	100.0	hydraulic
Riverside Sumida Central Tower	Tokyo	1994	office/residential	134 m, 52,000 ton, 33 stories	AMD	2	30.0	servo motor
Shinjuku Park Tower	Tokyo	1994	office/hotel	233 m, 130,000 ton, 52 stories	HMD	3	330.0	servo motor
Nissei Dowa Phoenix Tower	Osaka, Japan	1995	office	145 m, 26,800 ton, 29 stories	HMD	2	84.0	servo motor
Osaka WTC Bldg.	Osaka, Japan	1995	office	255 m, 80,000 ton, 55 stories	HMD	2	100.0	servo motor
Plaza Ichihara	Chiba, Japan	1995	office	58 m, 5,760 ton, 12 stories	HMD	2	14.0	servo motor
Rinku Gate Tower North Bldg.	Osaka, Japan	1996	office/hotel	255 m, 65,000 ton, 56 stories	HMD	2	160	servo motor
Herbis Osaka	Osaka, Japan	1997	hotel/office	190 m, 62,450 ton, 40 stories	HMD	2	320	hydraulic
Itoyama Tower	Tokyo	1997	office/residential	89 m, 9,025 ton, 18 stories	HMD	1	48	servo motor
Nisseki Yokohama Bldg.	Yokohama, Japan	1997	office	133 m, 53,000 ton, 30 stories	HMD	2	100	servo motor
TC Tower	Kau-Shon, Taiwan	1997	office/hotel	348 m, 221,000 ton, 85 stories	HMD	2	100	servo motor
Kaikyo-messe Dream Tower	Yamaguchi, Japan	1998	communication/ observatory deck	153 m, 5,400 ton	HMD	1	10	servo motor

Table 1. (*Continued*)

Full-scale structure	Location	Year completed	Building usage	Scale of building	Control system	AMD/HMD Number	AMD/HMD Mass (ton)	Actuation mechanism
Bunka Gakuen New Bldg.	Tokyo	1998	school	93 m, 43,488 ton, 20 stories	HMD	2	48	servo motor
Daiichi Hotel Ohita Oasis Tower	Ohita, Japan	1998	office/hotel	101 m, 20,942 ton, 21 stories	HMD	2	50	hydraulic
Odakyu Southern Tower	Tokyo	1998	office/hotel	150 m, 50,000 ton, 36 stories	HMD	2	60	linear motor
Otis Shibayama Test Tower	Chiba, Japan	1998	laboratory	154 m, 6,877 ton, 39 stories	HMD	1	61	hydraulic
Yokohama Bay Sheraton Hotel and Towers	Yokohama, Japan	1998	hotel	115 m, 33,000 ton, 27 stories	HMD	2	122	servo motor
Kajima Shizuoka Bldg.	Shizuoka, Japan	1998	office	20 m, 1,100 ton, 5 stories	semiactive damper	—	—	variable-orifice hydraulic damper
Laxa Osaka	Osaka, Japan	1998	hotel	115 m, 33,000 ton 27 stories	semiactive TMD	2	330	variable-orifice hydraulic damper
Century Park Tower	Tokyo	1999	residential	170 m, 124,540 ton, 54 stories	HMD	4	440	servo motor
JR Central towers	Nagoya, Japan	1999	hotel/office/ commerce	hotel: 226 m; office: 245 m, 300,000 ton	HMD	4(H) 2(O)	60(H) 75(O)	servo motor (H) hydraulic (O)
Nanjing Tower	Nanjing, China	1999	communication	310 m	AMD	1	60	hydraulic
Shin-Jei Bldg.	Taipei, Taiwan	1999	office/commerce	99 m, 22 stories	AMD	3	120	servo motor
Shinagawa Intercity A	Tokyo	1999	office/ commerce	144 m, 50,000 ton, 32 stories	HMD	2	150	servo motor
Incheon Int. Airport Air-Traffic Control Tower	Incheon, Korea	2000	air-traffic control	100 m	HMD	2	12	servo motor
Keio University Engineering Bldg.	Tokyo	2000	office/laboratory	29 m, 25,460 ton, 9 stories isolated	smart base isolation	—	—	variable-orifice damper
CEPCoo Gifu Bldg.	Gifu, Japan	2000	office	47 m, 18,000 ton, 11 stories	semiactive damper	—	—	variable-orifice hydraulic
Harumi Island Triton Square	Tokyo	2001	office/commerce	3 buildings: 195 m, 45 stories; 175 m, 40 stories; 155 m, 34 stories	couple building control	—	—	servo motor
Osaka International Airport Air-Traffic Control Tower	Osaka, Japan	2001	air-traffic control	69 m, 3,600 ton, 5 stories	HMD	2	10	servo motor
Cerulean Tower Tokyo Hotel	Tokyo, Japan	2001	hotel/office/parking	184 m, 65,000 ton, 5 stories	HMD	2	210	hydraulic
Hotel Nikko Bayside Osaka	Osaka, Japan	2002	hotel/parking	138 m, 37,000 ton, 33 stories	HMD	2	124	servo motor
Dentsu New Headquarter Office Bldg.	Tokyo, Japan	2002	office/commerce/ parking	210 m, 130,000 ton 48 stories	HMD	2	440	servo motor

[a]Active mass damper.
[b]Hybrid mass damper.
[c]Semiactive variable stiffness system.
[d]Active gyroscopic stabilizer.

Table 2. Summary of Actively Controlled Bridges

Name of bridge	Years employed	Height (m)/ Weight (tonf)	Frequency range (Hz)	Moving mass, mass ratio (%)[a]	Control algorithm	Number of controlled modes
Rainbow Bridge: Pylon 1	1991–1992	119/4,800	0.26–0.95	6 ton×2 (0.6)	Feedback control	3
Pylon 2	1991–1992	117/4,800	0.26–0.55	2 ton (0.14)	DVFB[b]	1
Tsurumi-Tsubasa Bridge	1992–1993	183/3,560	0.27–0.99	10 ton×2 (0.16)	Optimal regulator DVFB	1
Hakucho Bridge Pylon 1	1992–1994	127.9/2,400	0.13–0.68	9 tonf (0.4)	Suboptimal feedback control	1
Pylon 2	1992–1994	131/2,500	0.13–0.68	4 ton×2 (0.36)	DVFB	1
Akashi Kaikyo Bridge Pylons 1 and 2	1993–1995	293/24,650	−0.127	28 ton×2 (0.8)	Optimal regulator DVFB	1
Meiko-Central Bridge[c]: Pylon 1	1994–1995	190/6,200	0.18–0.42	8 ton×2 (0.98–1.15)	H_∞ feedback control	1
Pylon 2	1994–1995	190/6,200	0.16–0.25	(0.17–0.38)		1
First Kurushima Bridge: Pylon 1	1995–1997	112/1,600 t	0.23–1.67	6 ton×2 (0.15–2.05)	Suboptimal regulator control	3
Pylon 2	1995–1997	145/2,400 t	0.17–1.70	10 ton×2 (0.3–2.6)	H_∞ feedback control	3
2nd Kurushima Bridge: Pylon 1	1994–1997	166/4,407	0.17–1.06	10 ton×2 (0.41)	DVFB/H	2
Pylon 2	1995–1997	143/4,000	0.20–1.45	10 ton×2 (0.54–1.01)	Fuzzy control	>3
Third Kurushima Bridge: Pylon 1	1995–1996	179/4,500	0.13–0.76	11 ton×2 (0.3–2.4)	Variable gain DVFB	1
Pylon 2	1994–1996	179/4,600	0.13–0.76	11 ton×2 (0.3–2.4)	H_∞ output feedback control	1
Nakajima Bridge	1995–1996	71/580	0.21–1.87	3.5 ton×2 (1.0-10.6)	Fuzzy control	3

[a]Percent of first modal mass.

[b]Direct velocity feedback.

[c]Cable-stayed bridge. Others are suspension bridges.

ing systems perform significantly better than passive devices and have the potential to achieve, or even surpass, the performance of fully active systems, thus allowing for the possibility of effective response reduction during a wide array of dynamic loading conditions (Spencer and Sain 1997). Examples of such devices include variable-orifice fluid dampers, controllable friction devices, variable-stiffness devices, smart tuned mass dampers and tuned liquid dampers, and controllable fluid dampers. In this paper we review the main classes of semiactive control devices and present their full-scale implementation to civil infrastructure applications.

Semiactive Control Systems

Control strategies based on semiactive devices appear to combine the best features of both passive and active control systems and to offer the greatest likelihood for near-term acceptance of control technology as a viable means of protecting civil engineering structural systems against earthquake and wind loading. The attention received in recent years can be attributed to the fact that semiactive 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.

According to presently accepted definitions, a semiactive control device is one which cannot inject mechanical energy into the controlled structural system (i.e., including the structure and the control device), but has properties that can be controlled to optimally reduce the responses of the system (Spencer and Sain 1997). Therefore, in contrast to active control devices, semiactive control devices do not have the potential to destabilize (in the bounded input/bounded output sense) the structural system. Preliminary studies indicate that appropriately implemented semiactive 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 (Spencer and Sain 1997; Symans and Constantinou 1999a; Spencer 2002). Examples of such devices will be discussed in this section, including variable-orifice fluid dampers, variable-stiffness devices, controllable friction devices, smart tuned mass dampers and tuned liquid dampers, controllable fluid dampers, and controllable impact dampers.

Variable-Orifice Dampers

One means of achieving a semiactive damping device is to use a controllable, electromechanical, variable-orifice valve to alter the resistance to flow of a conventional hydraulic fluid damper. Such a device, schematically shown in Fig. 1, typically operates on approximately 50 W of power. The concept of applying this type of variable-damping device to control the motion of bridges experiencing seismic motion was first proposed by Feng and Shinozuka (1990) and studied analytically and experimentally by a number of researchers including Kawashima and Unjoh (1994), Sack and Patten (1993), Patten et al. (1996), Symans and Constantinou (1999b), Nagarajaiah (1994), Yang et al. (1995), and

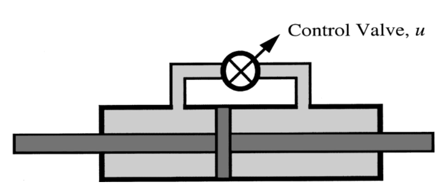

Fig. 1. Schematic of the variable-orifice damper

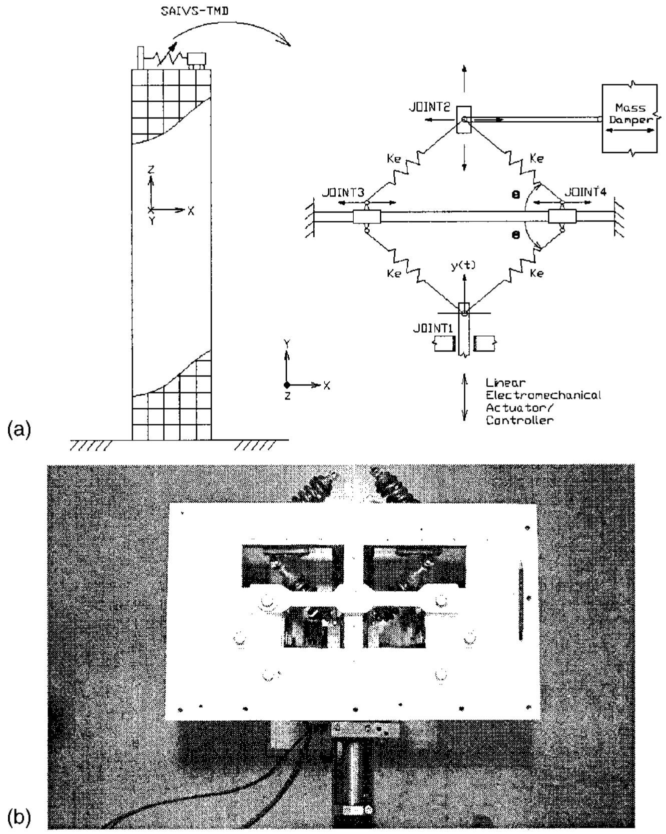

Fig. 2. SAIVS device (a) implemented as a STMD; (b) small-scale SAIVS device

Liang et al. (1995). Sack and Patten (1993) developed a hydraulic actuator with a controllable orifice, which was implemented by Patten et al. (1999) in a full-scale bridge on interstate highway I-35 in Oklahoma to demonstrate the technology, for reduction of vibrations induced by vehicle traffic. Symans and Constantinou (1999b) and Symans and Kelly (1995) have analytically and experimentally studied the application of variable fluid dampers for seismic response reduction of buildings and bridges (Iwan 2002). Jabbari and Bobrow (2002) and Yang et al. (2000) have studied an on-off controllable orifice hydraulic damper used as a resettable stiffness device.

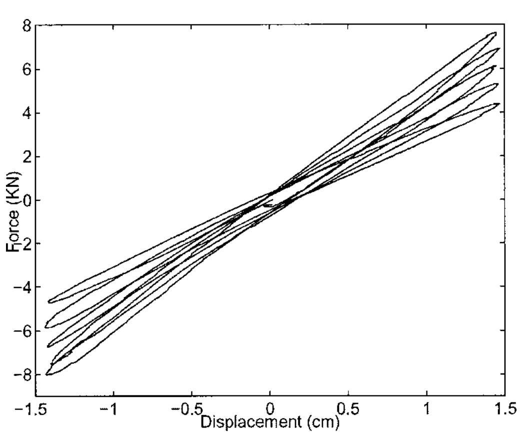

Fig. 3. Measured force-displacement loops of small-scale SAIVS device (note the smooth and continuous variation of stiffness)

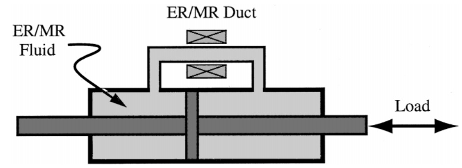

Fig. 4. Schematic of controllable-fluid damper

Variable-Stiffness Device

Conceived as a variable-stiffness device, Kobori et al. (1993) implemented a full-scale variable-orifice damper, using on-off mode, in a semiactive variable-stiffness system (AVS) to investigate semiactive control of the Kajima Research Institute building. Although variable-orifice dampers can be used for producing variable stiffness in an on-off mode—as a very high stiffness device due to hydraulic fluid compressibility (primarily due to entrapped air) when the valve is closed or a device with no stiffness when the valve is open—they cannot vary stiffness continuously between different stiffness states. Nagarajaiah (U.S. Patent No. 6,098,969; Aug. 8, 2000) has developed a semiactive continuously and independently variable-stiffness device (SAIVS); this scalable mechanical device is shown in Fig. 2. The force-displacement loops of the device are shown in Fig. 3; it is evident from the loops that the SAIVS device can vary the stiffness continuously and smoothly. Nagarajaiah and Mate (1998) have shown the effectiveness of SAIVS device in a scaled structural model by varying the stiffness smoothly and producing a nonresonant system.

Smart Tuned Mass Dampers

Many researchers have studied the advantages and effectiveness of tuned mass dampers (TMD) and multiple tuned mass dampers (MTMD). The TMD is very sensitive to tuning frequency ratio, even when optimally designed. The MTMD can overcome this limitation of the TMD; however, the MTMD cannot be retuned in real time, thus is not adaptable. TMDs with adjustable damping, first studied by Hrovat et al. (1983), offer additional advantages over TMDs. As an attractive alternative, a semiactive tuned mass damper (STMD), with variable stiffness, that has the distinct ad-

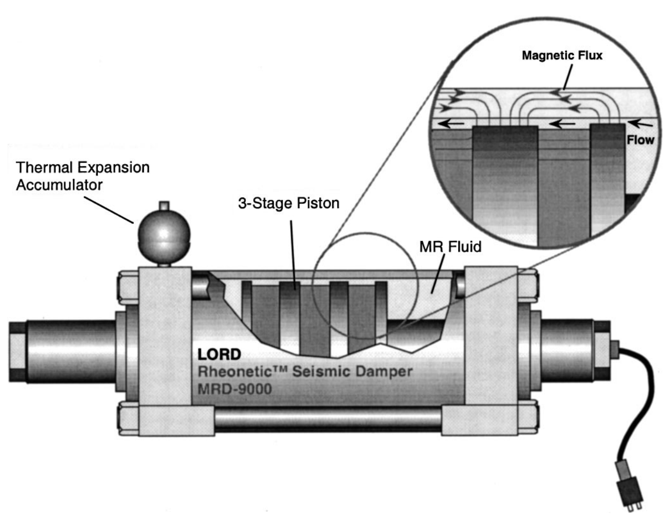

Fig. 5. Schematic of large-scale 20-t MR fluid damper

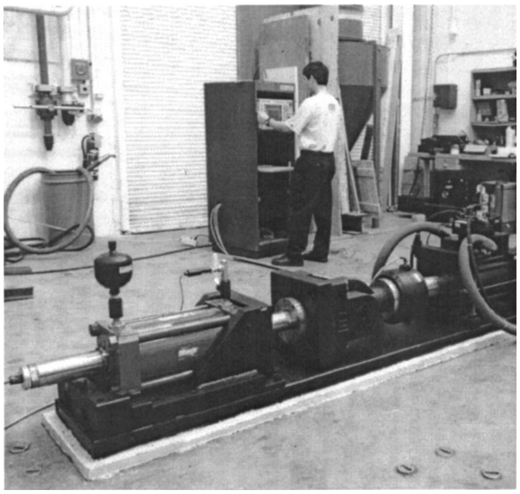

Fig. 6. Experimental setup of the large-scale 20-t MR fluid damper

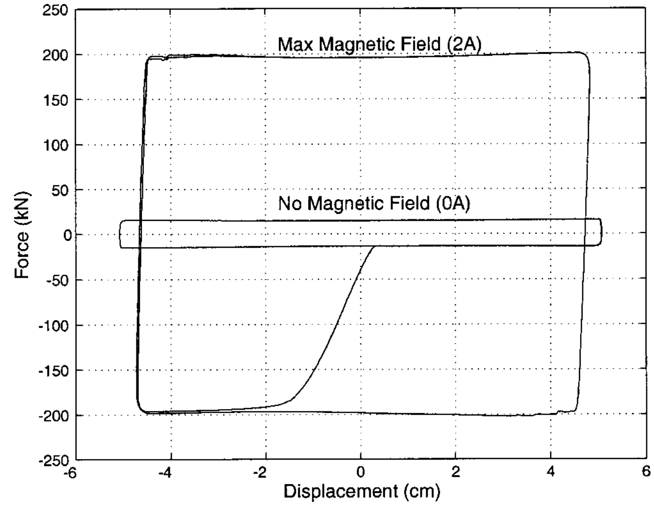

Fig. 7. Measured force-displacement loops at 5.4 cm/s

vantage of continuously retuning its frequency due to real time control thus making it robust to changes in building stiffness and damping, has been developed by Nagarajaiah and Varadarajan (2000) using the SAIVS device [Nagarajaiah, U.S. Patent No. 6,098,969 (2000)], as shown in Fig. 2; they have shown its effectiveness analytically and experimentally on a small-scale three story structural model. The variation of stiffness of the STMD is based on estimation of instantaneous frequency and a time frequency controller developed by Nagarajaiah and Varadarajan (2000). Varadarajan and Nagarajaiah (2003) have also shown the effectiveness of STMD in a tall benchmark building with response reductions comparable to an active tuned mass damper; however, with an order of magnitude less power consumption. Other STMDs that have been studied analytically are based on variable damping by Abe and Igusa (1996). Semiactive impact dampers have also been developed and studied, by Caughey and Karyeaclis (1989) and Masri (2000), and shown to be effective experimentally.

STMDs can also be based on (1) controllable tuned sloshing dampers (CTSD), and (2) controllable tuned liquid column dampers (CTLCD). TSD uses the liquid sloshing in a tank to add damping to the structure, similarly in a TLCD the moving mass is a column of liquid, which is driven by the vibrations of the structure. Because these systems have a fixed design, they are not as effective for a wide variety of loading conditions, and researchers are looking to improve their effectiveness in reducing structural responses (Kareem et al. 1999). Lou et al. (1994) proposed a semiactive CTSD device based on the passive TSD, in which the length of the sloshing tank can be altered to change the properties of the device. Abe et al. (1996) and Yalla et al. (2001) have studied semiactive CTLCD devices based on a TLCD with a variable orifice.

Variable-Friction Dampers

Various semiactive devices have been proposed which utilize forces generated by surface friction to dissipate vibratory energy in a structural system. Akbay and Aktan (1991) and Kannan et al. (1995) proposed a variable-friction device, which consists of a friction shaft that is rigidly connected to the structural bracing. The force at the frictional interface was adjusted by allowing slippage in controlled amounts. In addition, a semiactive friction-controllable fluid bearing has been employed in parallel with a seismic isolation system in Feng et al. (1993). Recently, variable-friction systems have been studied by Yang and Agrawal (2002) for seismic response reduction of nonlinear buildings. Garrett et al. (2001) have studied piezoelectric friction dampers experimentally.

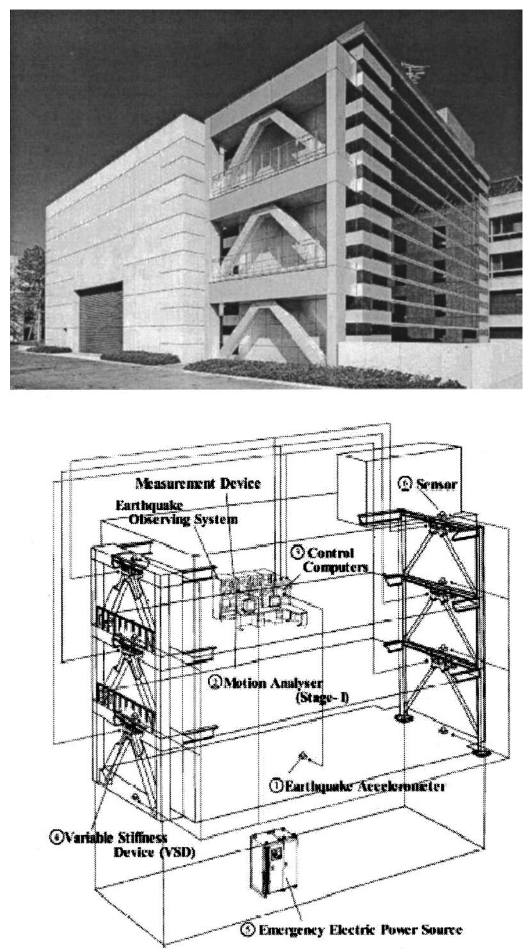

Fig. 8. Kajima Technical Research Institute with AVS system

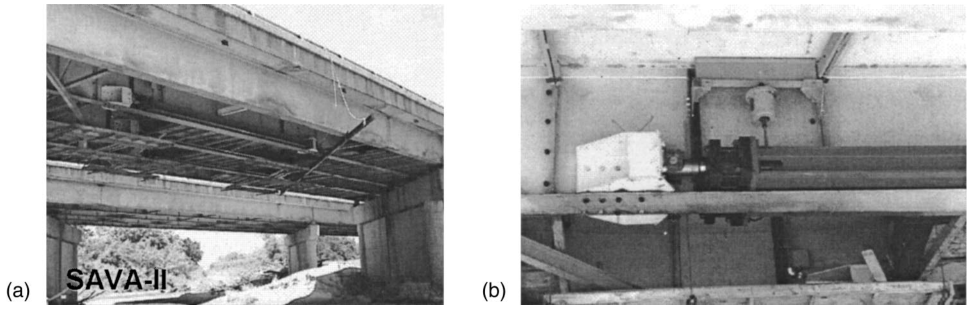

Fig. 9. (a) First full-scale implementation of smart damping in the U.S.; (b) SAVA-II variable orifice damper

Controllable-Fluid Dampers

Most semiactive dampers employ some electrically controlled valves or mechanisms to achieve changes in device characteristics. Such mechanical components can be problematic in terms of reliability and maintenance. One class of semiactive control devices uses controllable fluids in a fixed-orifice damper. As shown schematically in Fig. 4, the advantage of these controllable-fluid dampers is their mechanical simplicity; i.e., they contain no moving parts other than the damper's piston.

Two fluids that are viable contenders for development of controllable dampers are: (1) electrorheological (ER) fluids and (2) magnetorheological (MR) fluids. However, only MR fluids have been shown to be tractable for civil engineering applications (Spencer and Sain 1997). The essential characteristic of these fluids is their ability to reversibly change from a free-flowing, linear viscous fluid to a semisolid with a controllable yield strength in milliseconds when exposed to a magnetic field. In the absence of an applied field, these fluids flow freely and can be modeled as Newtonian. MR fluids typically consist of micron-sized, magnetically polarizable particles dispersed in a carrier medium such as mineral or silicone oil and can operate at temperatures from $-40°$ to 150°C with only modest variations in the yield stress. Further, MR fluid devices can be readily controlled with a low power (e.g., less than 50 W), low voltage (e.g., ~12–24 V), current-driven power supply outputting only ~1–2 A. Such power levels can be readily supplied by batteries.

Through simulations and laboratory model experiments, MR dampers have been shown to significantly outperform comparable passive damping configurations, while requiring only a fraction of the input power needed by the active controller (Spencer and Sain 1997; Spencer et al. 1997, 2000; Spencer 2002; Dyke et al. 1996, 1998; Nagarajaiah et al. 2000; Sahasrabudhe et al. 2000; Xu et al. 2000; Gavin et al. 2001; Yi et al. 2001; Ramallo et al. 2002; Yoshioka et al. 2002; Madden et al. 2002, 2003; Hiemenz et al. 2003; and Johnson et al. 2003; also see http://cee.uiuc.edu/sstl/). Moreover, the technology has been demonstrated to be scalable to devices sufficiently large for implementation in civil engineering structures. Carlson and Spencer (1996), Spencer et al. (1999), and Yang et al. (2002) have developed and tested a 20-t MR damper suitable for full-scale applications (see Fig. 5). Fig. 6 shows the test setup for the 20-t MR damper; the measured force-displacement loops for the damper are shown in Fig. 7.

Recently, Sodeyama et al. (2003) have also presented impressive results regarding design and construction of large-scale MR dampers.

Full-Scale Applications

The Kajima Technical Research Institute, shown in Fig. 8, was the first full-scale building structure to be implemented with semiactive control devices. The AVS is a hydraulic device with abypass valve used to switch the device between the on-off positions to engage and disengage the bracing system. Thus, the structural system varies between the configurations of a purely moment resistant framing system to a fully braced framing system. The building's stiffness is varied based on the nature of the earthquake to produce a nonresonant system. The observed responses during

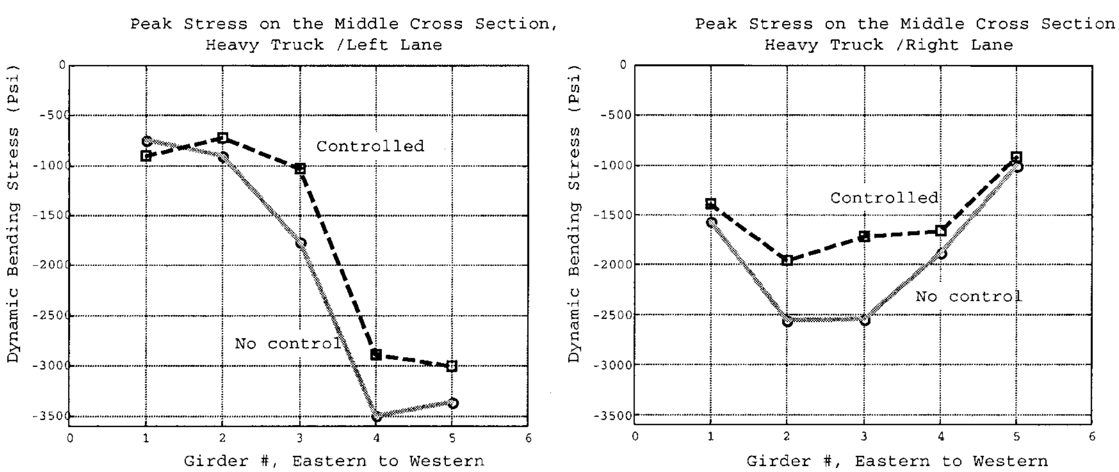

Fig. 10. Comparison of peak stresses for heavy trucks

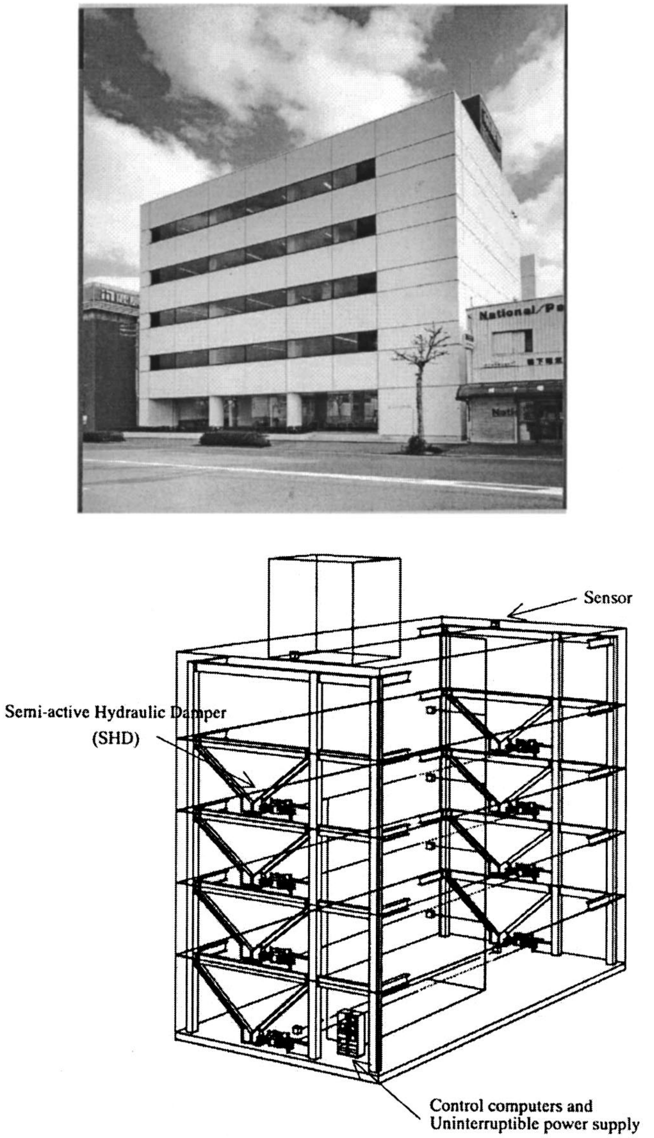

Fig. 11. Kajima Shizouka Building configured with semiactive hydraulic dampers

several earthquakes (Kobori et al. 1993) indicate the effectiveness of the AVS system in reducing the structural responses.

In the United States, the first full-scale implementation of semiactive control was conducted on the Walnut Creek Bridge, shown in Fig. 9, on interstate highway I-35 to demonstrate variable-damper technology (Patten et al. 1999). Fig. 10 shows

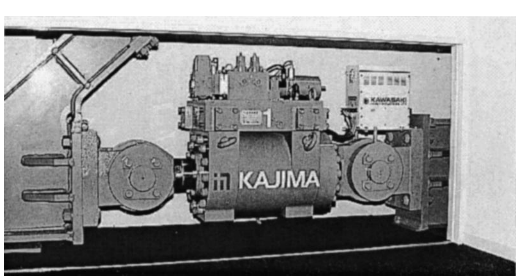

Fig. 12. Semiactive hydraulic damper manufactured by the Kajima Corporation

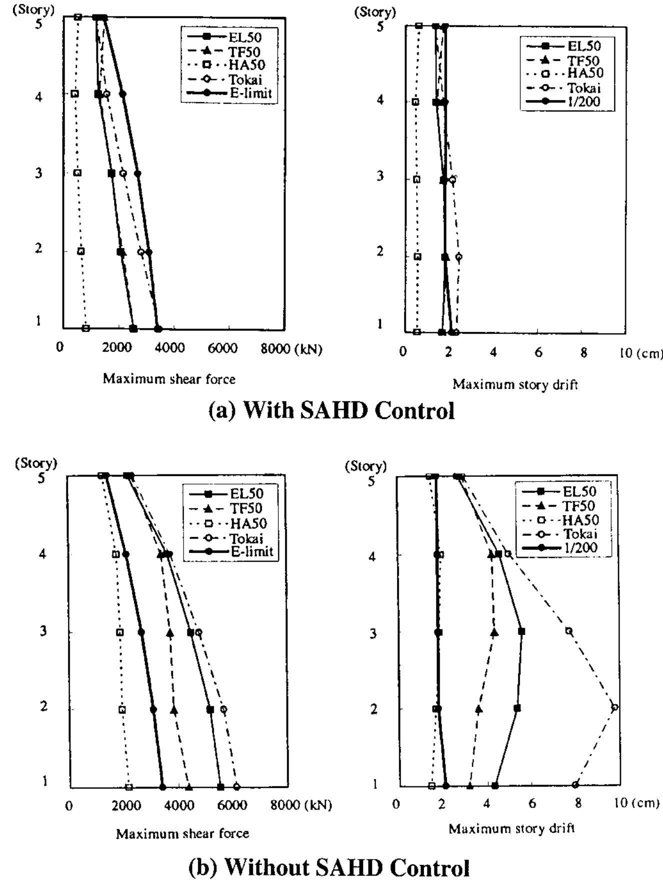

Fig. 13. Maximum responses (El Centro, Taft, and Hachinohe Waves with 50 cm/s and assumed Tokai waves)

the effectiveness of the SAVA system. This experiment constitutes the only full-scale implementation of semiactive control in the United States.

More recently, a smart damping system was implemented in the Kajima Shizuoka Building in Shizuoka, Japan. As seen in Fig. 11, semiactive hydraulic dampers are installed inside the walls on both sides of the building to enable it to be used as a disaster relief in earthquake situations (Kobori et al. 1998; Kurata et al. 1999, 2000, 2002; Niwa et al. 2000). Each damper contains a

Fig. 14. Construction site in the Siodome area in downtown Tokyo in 2002

Fig. 15. Siodome Tower under construction in the Siodome area

Table 3. Buildings Recently Completed or Currently Under Construction Employing Semiactive Hydraulic Dampers

Name	Stories	Height (m)	Number of semiactive dampers	Completion date
Chuden Gifu Building	11	56.0	42	March 2001
Niigata B-project	31	140.5	72	December 2002
Siodome M-Building	25	119.9	38	January 2003
Siodome N-Building	28	136.6	60	March 2003
Siodome Tower	38	172.0	88	April 2003
Mori Tower	54	241.4	356	May 2003
Siodome T-Building	19	98.9	27	May 2003
S-Hotel	30	104.9	66	December 2004
H-Building	23	100.4	28	August 2004

flow control valve, a check valve, and an accumulator, and can develop a maximum damping force of 1,000 kN (Fig. 12). Fig. 13 shows a sample of the response analysis results based on one of the selected control schemes and several earthquake input motions with a scaled maximum velocity of 50 cm/s, together with a simulated Tokai wave. Both story shear forces and story drifts are seen to be greatly reduced with control activated. In the case of the shear forces, they are confined within their elastic-limit values (indicated by *E*-limit); without control, they would enter the plastic range.

The use of the variable-orifice damper has blossomed in Japan. Fig. 14 shows the construction site in the Siodome area in downtown Tokyo. There are four buildings currently under construction in this area that will employ switching semiactive hydraulic dampers for structural protection. One of these structures, the Siodome Tower, is a 172 m tall, 38-story hotel and office complex installed with 88 semiactive dampers and two hybrid mass dampers (Fig. 15). In the Roppongi area of Tokyo, the Mori Tower, a 54-story building with 356 variable-orifice dampers and 192 passive dampers distributed throughout, is under construction (Fig. 16). Altogether, the Kajima Corporation is currently constructing or has recently finished nine buildings in Japan that employ semiactive hydraulic dampers for structural protection. Table 3 provides a summary of these nine buildings (Kobori 2003). When these projects are completed, a total of nearly 800 variable-orifice dampers will be installed in building structures in Japan.

Fig. 16. Mori Tower in the Roppongi area of Tokyo

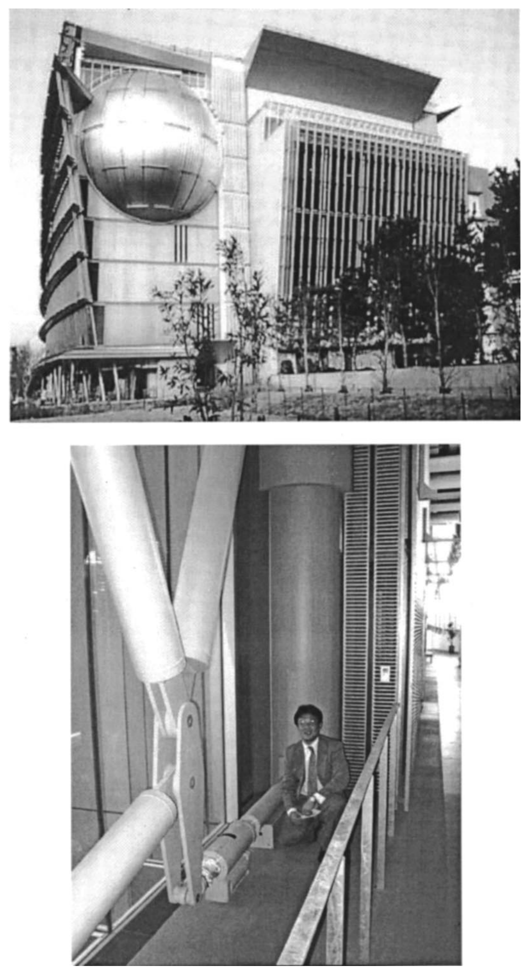

Fig. 17. Nihon-Kagaku-Miraikan, Tokyo National Museum of Emerging Science and Innovation, installed with 30-t MR fluid dampers manufactured by Sawan Tekki Corporation

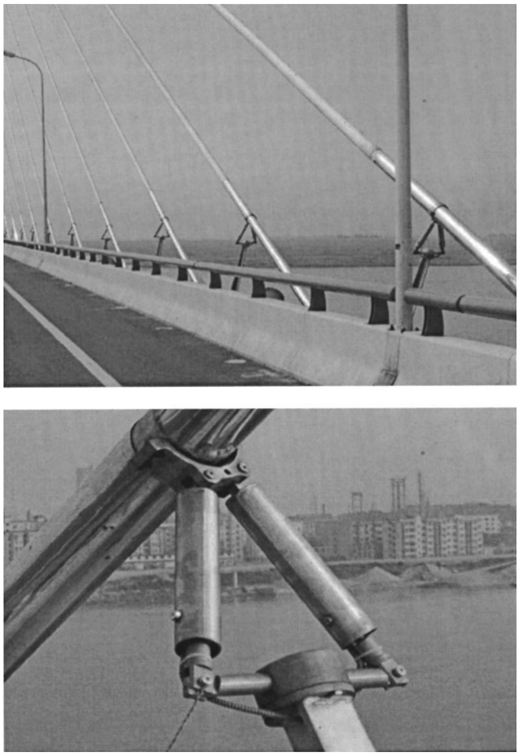

Fig. 18. MR damper installation on the Dongting Lake Bridge, Hunan, China

Fig. 19. Smart base isolated building using variable-orifice dampers at Keio University

In 2001, the first full-scale implementation of MR dampers for civil engineering applications was achieved. The Nihon-Kagaku-Miraikan, the Tokyo National Museum of Emerging Science and Innovation, shown in Fig. 17, has two 30-t, MR fluid dampers installed between the third and fifth floors. The dampers were built by Sanwa Tekki using the Lord Corporation MR fluid.

Retrofitted with stay-cable dampers, the Dongting Lake Bridge in Hunan, China constitutes the first full-scale implementation of MR dampers for bridge structures (Fig. 18). Long steel cables, such as are used in cable-stayed bridges and other structures, are prone to vibration induced by the structure to which they are connected and by weather conditions, particularly wind combined with rain, that may cause cable galloping. The extremely low damping inherent in such cables, typically on the order of a fraction of a percent, is insufficient to eliminate this vibration, causing reduced cable and connection life due to fatigue and/or breakdown of corrosion protection. Two Lord SD-1005 MR dampers are mounted on each cable to mitigate cable vibration. A total of 312 MR dampers are installed on 156 stayed cable. The technical support for this engineering project was provided through a joint venture between Central South University, The Hong Kong Polytechnic University, and the first writer. Recently, MR dampers have been chosen for implementation on the Binzhou Yellow River Bridge in China to reduce cable vibration. The installation is expected to be completed in October 2003.

Passive base isolation is a widely accepted protective system against strong earthquakes (Kelly 1997). Three types of seismic isolation systems, which are very effective in protecting structures from strong earthquakes, are lead-rubber bearing system, high-damping bearing system, and friction-pendulum spherical sliding bearings. However, recently there has been significant concern about the effectiveness of passive base isolation systems for protecting structures against near-source, high-velocity, long-period pulse earthquakes. An attractive solution may be to use smart dampers, such as MR dampers. Several researchers have shown the advantages of smart base isolated structures with passive base isolation and smart dampers (Yoshida et al. 1994; Nagarajaiah 1994; Spencer et al. 2000; Yoshioka et al. 2002; Ramallo et al. 2002; Makris 1997; Nagarajaiah et al. 2000; Madden et al. 2002, 2003; Saharabudhe et al. 2000). In 2000, the world's first smart base isolated building was constructed at the Keio University School of Science and Technology in Japan. This office and laboratory building, shown in Fig. 19, employs variable-orifice dampers in parallel with traditional damping mechanisms. Recently, 40-t MR fluid dampers were installed in a residential building in Japan (Fig. 20) along with laminated rubber bearings, lead dampers, and oil dampers to provide the best seismic protection (Fujitani et al. 2003).

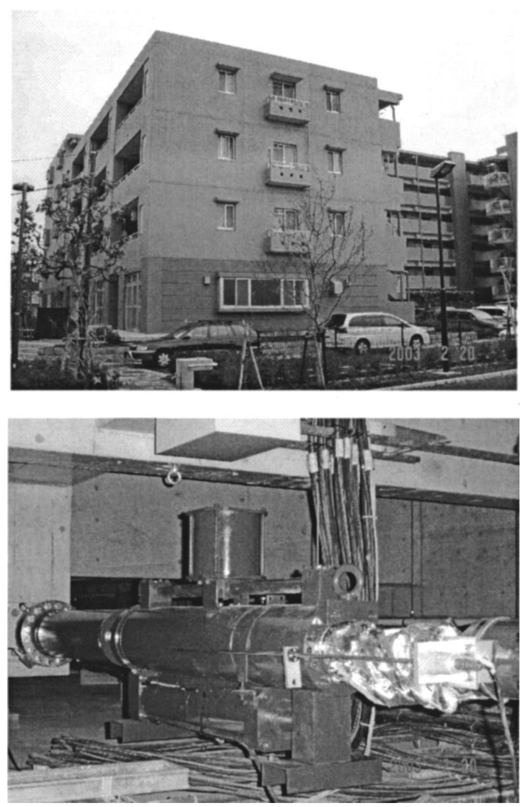

Fig. 20. Base-isolated building installed with 40-t MR fluid damper manufactured by the Sanwa-Tekki Corporation

Conclusions

Structural control technology offers many new ways to protect structures from natural and other types of hazards. Although in their infancy, semiactive structural control technology, and in particular, smart damping devices, appear to combine the best features of both passive and active control systems and to offer a viable means of protecting civil engineering structural systems against earthquake and wind loading. They provide the reliability and fail-safe character of passive devices, yet possess the adaptability of fully active devices. Because of their mechanical simplicity, low power requirements and high force capacity, MR dampers constitute a class of smart damping devices that mesh well with the demands and constraints of civil infrastructure applications and is seeing increased interest from the engineering community. More information regarding MR dampers and their application to civil engineering structures can be found at: ⟨http://cee.uiuc.edu/sst/ and at http://www.rheontetic.com⟩.

A number of aspects of the semactive and smart damping control problem merit additional attention. One particularly important area is system integration. Structural systems are complex combinations of individual structural components. Integration of semiactive and smart damping control strategies directly into the basic design of these complex systems can offer the optimal combination of performance enhancement versus construction costs and long-term effects. Because of the intrinsically nonlinear nature of semiactive and smart damping control devices, development of output feedback control strategies that are practically implementable and can fully utilize the capabilities of these unique devices is another important, yet challenging, task. Once the advantages of semiactive and smart damping control systems are fully recognized, a primary task is the development of prototype design standards or specifications complementary to existing standards.

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References

Abe, M., and Igusa, T. (1996). ''Semi-active dynamic vibration absorbers for controlling transient response.'' *J. Sound Vib.,* 1998(5), 547–569.

Abe, M., Kimura, S., and Fujino, Y. (1996). ''Control laws for semi-active tuned liquid column dampers with variable orifice openings.'' *Proc., 2nd Int. Workshop on Structural Control*, Kust, China.

Akbay Z., and Aktan, H. M. (1991). ''Actively regulated friction slip devices.'' *Proc., 6th Canadian Conf. Earthquake Engineering*, 367–374.

Carlson, J. D., and Spencer, B. F., Jr. (1996). ''Magneto-rheological fluid dampers for semi-active seismic control.'' *Proc., 3rd Int. Conf. on Motion and Vibration Control*, III, 35–40.

Casciati, F., ed. (2003). *Proc., 3rd World Conf. on Structural Control*, Wiley, New York.

Caughey, T. K., and Karyeaclis, M. P. (1989). ''Stability of semi-active impact damper, Part I–Global behavior; Part II–Periodic solutions.'' *J. Appl. Mech.*, 56(4), 926–940.

Dyke, S. J., Spencer, B. F., Jr., Sain, M. K., and Carlson, J. D. (1996). ''Modeling and control of magnetorheological dampers for seismic response reduction.'' *Smart Mater. Struct.,* 5, 565–575.

Dyke, S. J., Spencer, B. F., Jr., Sain, M. K., and Carlson, J. D. (1998). ''An experimental study of MR dampers for seismic protection.'' *Smart Mater. Struct.,* 7, 693–703.

Faravelli L., and Spencer, B. F., Jr., eds. (2003). *Proc., Sensors and Smart Structures Technology*, Wiley, New York.

Feng, M. Q., and Shinozuka, M. (1990). ''Use of a variable damper for hybrid control of bridge response under earthquake.'' *Proc., U.S. National Workshop on Structural Control Research*, USC Publication No. CE-9013.

Feng, M. Q., Shinozuka, M., and Fujii, S. (1993). ''Friction-controllable sliding isolation system.'' *J. Eng. Mech.,* 119(9), 1845–1864.

Fujitani, H., et al. (2003). ''Development of 400kN magnetorheological damper for a real base-isolated building.'' *Proc., SPIE Conf. Smart Structures and Materials*, Vol. 5057, SPIE—International Society for Optical Engineering, Bellingham, Wash.

Garrett, G. T., Chen, G., Cheng, F. Y., and Huebner, W. (2001). ''Experimental characterization of Piezoelectric Friction Dampers.'' *Proc., 8th SPIE Annual Conf. on Smart Structures and Material*, SPIE—International Society for Optical Engineering, Bellingham, Wash.

Gavin, H., Hoagg, J., and Dobossy, M. (2001). ''Optimal design of MR Dampers.'' *Proc., U.S.-Japan Workshop on Smart Structures for Improved Seismic Performance in Urban Regions*, K. Kawashima, B. F. Spencer, and Y. Suzuki, eds., 225–236.

Hiemenz, G. J., Choi, Y. T., and Wereley, N. M. (2003). ''Seismic control of civil structures utilizing semiactive MR braces.'' *Comput. Aided Civ. Infrastruct. Eng.,* 18, 31–44.

Housner, G. W., et al. (1997). ''Structural control: Past, present and future.'' *J. Eng. Mech.,* 123(9), 897–971.

Housner, G. W., Masri, S. F., and Chassiakos, A. G., eds. (1994). *Proc., 1st World Conf. on Structural Control.*

Hrovat, D., Barak, P., and Rabins, M. (1983). ''Semi-active versus passive or active tuned mass dampers for structural control.'' *J. Eng. Mech.,* 109(3), 691–705.

Iwan, W. D. (2002). ''Structural response control using active interaction between internal elements.'' *Proc., 3rd World Conf. on Structural Control*, Como, Italy, 57–68.

Jabbari, F., and Bobrow, J. E. (2002). ''Vibration suppression with resettable device.'' *J. Eng. Mech.,* 128(9), 916–924.

Johnson, E. A., Christenson, R. E., and Spencer, B. F., Jr., (2003). ''Semi-active damping of cables with sag.'' *Comput. Aided Civ. Infrastruct. Eng.,* 18(2), 132–146.

Kannan, S., Uras, H. M., and Aktan, H. M. (1995), ''Active control of building seismic response by energy dissipation.'' *Earthquake Eng. Struct. Dyn.,* 24(5), 747–759.

Kareem, A., Kijewski, T., and Tamura, Y. (1999). ''Mitigation of motions of tall buildings with specific examples of recent applications.'' *Wind Struct.,* 2(3), 201–251.

Kawashima, K., and Unjoh, S. (1994). ''Seismic response control of bridges by variable dampers.'' *J. Struct. Eng.,* 120(9), 2583–2601.

Kelly, J. M. (1997). *Earthquake resistant design with rubber*, 2nd Ed., Springer, New York.

Kobori, T. (2003). ''Past, present and future in seismic response control in civil engineering structures.'' *Proc., 3rd World Conf. on Structural Control*, Wiley, New York, 9–14.

Kobori, T., Inou, Y., Seto, K., Iemura, H., and Nishitani, A., eds. (1998). *Proc., 2nd World Conf. on Structural Control*, Wiley, New York.

Kobori, T., Koshika, N., Yamada, N., and Ikeda, Y. (1991). ''Seismic response controlled structure with active mass driver system. Part 1: Design.'' *Earthquake Eng. Struct. Dyn.,* 20 133–139.

Kobori, T., Takahashi, M., Nasu, T., Niwa, N., and Ogasawara, K. (1993). ''Seismic response controlled structure with active variable stiffness system.'' *Earthquake Eng. Struct. Dyn.,* 22, 925–941.

Kurata, N., Kobori, T., and Koshika, N. (2002). ''Performance-based de-

sign with semiactive control technique.'' *Earthquake Eng. Struct. Dyn.*, 31, 445–458.
Kurata, N., Kobori, T., Takahashi, M., Ishibashi, T., Niwa, J., Tagami, J., and Midorikawa, H. (2000). ''Forced vibration test of a building with semiactive damper system.'' *Earthquake Eng. Struct. Dyn.*, 29, 629–645.
Kurata, N., Kobori, T., Takahashi, M., Niwa, N., and Midorikawa, H. (1999). ''Actual seismic response controlled building with semiactive damper system.'' *Earthquake Eng. Struct. Dyn.*, 28, 1427–1447.
Liang, Z., Tong, M., and Lee, G. C. (1995). ''Real-time structural parameter modification (RSPM): Development of innervated structures.'' *Technical Report NCEER-95-0012,* National Center for Earthquake Engineering Research, Buffalo, New York.
Lou, J. Y. K., Lutes, L. D., and Li, J. J. (1994). ''Active tuned liquid damper for structural control.'' *Proc., 1st World Conf. on Structural Control*, TP1:70–79.
Madden, G. J., Symans, M. D., and Wongprasert, N. (2002). ''Experimental verification of seismic response of building frame with adaptive sliding base-isolation system.'' *Comput. Aided Civ. Infrastruct. Eng.*, 18, 19–30.
Madden, G. J., Wongprasert, N., and Symans, M. D. (2003). ''Analytical and numerical study of a smart sliding base isolation system for seismic protection of buildings.'' *Comput. Aided Civ. Infrastruct. Eng.*, 18, 19–30.
Makris, N. (1997). ''Rigidity-plasticity-viscosity: Can electrorheological dampers protect base-isolated structures from near-source earthquakes.'' *Earthquake Eng. Struct. Dyn.*, 26, 571–591.
Masri, S. (2000). ''An experimental study of an adaptive momentum exchange damper for structural control applications.'' *Proc., 2nd European Conf. on Structural Control*, ENPC, Champs-sur-Marne, France.
Nagarajaiah, S. (1994). ''Fuzzy controller for structures with hybrid isolation system.'' *Proc., 2nd World Conf. Structural Control*, Wiley, New York, TA2:67–76.
Nagarajaiah, S., and Mate, D. (1998). ''Semi-active control of continuously variable stiffness system.'' *Proc., 2nd World Conf. Structural Control*, Vol. 1, Wiley, New York, 397–405.
Nagarajaiah, S., and Sun, X. (2000). ''Response of base-isolated USC hospital building in Northridge Earthquake.'' *J. Struct. Eng.*, 126(10), 1177–1186.
Nagarajaiah, S., and Varadarajan, N. (2000). ''Novel semiactive variable stiffness tuned mass damper with real time tuning capability.'' *Proc., 13th Engineering Mechanics Conf.* (CD ROM), Riston, Va.
Nagarajaiah, S., Sahasrabudhe, S., and Iyer, R. (2000). ''Seismic response of sliding isolated bridges with MR dampers.'' *Proc., American Control Conference* (CD ROM).
Nishitani, A., and Inoue, Y. (2001). ''Overview of the application of active/semiactive control to building structures in Japan.'' *Earthquake Eng. Struct. Dyn.*, 30, 1565–1574.
Niwa, N., Kobori, T., Takahashi, M., Midorikawa, H., Kurata, N., and Mizuno, T. (2000). ''Dynamic loading test and simulation analysis of full-scale semiactive hydraulic damper for structural control.'' *Earthquake Eng. Struct. Dyn.*, 29, 789–812.
Patten, W. N., Sack, R., and He, Q. (1996). ''Controlled semiactive hydraulic vibration absorber for bridges.'' *J. Struct. Eng.*, 122(2), 187–192.
Patten, W., Sun, J., Li, G., Kuehn, J., and Song, G. (1999). ''Field test of an intelligent stiffener for bridges at the I-35 Walnut Creek bridge.'' *Earthquake Eng. Struct. Dyn.*, 28(2), 109–126.
Ramallo, J. C., Johnson, E. A., and Spencer, B. F., Jr. (2002). ''Smart base isolation systems.'' *J. Eng. Mech.*, 128(10), 1088–1099.
Sack, R. L., and Patten, W. (1993). ''Semiactive hydraulic structural control.'' *Proc., Int. Workshop on Structural Control*, USC Publication Number CE-9311, 417–431.
Sahasrabudhe, S., Nagarajaiah, S., and Hard, C. (2000). ''Experimental study of sliding isolated buildings with smart dampers subjected to near source ground motions.'' *Proc., Engineering Mechanics Conf.* (CD ROM), ASCE, Reston, Va.
Sodeyama, H., Sunakoda, K., Fujitani, H., Soda, S., Iwata, N., and Hata, H. (2003). ''Dynamic tests and simulation of magneto-rheological dampers.'' *Comput. Aided Civ. Infrastruct. Eng.*, 18, 45–57.
Soong, T. T. (1990). *Active structural control: Theory and practice*, Longman Scientific, Essex, U.K.
Soong, T. T., and Reinhorn, A. M. (1993). ''An overview of active and hybrid structural control research in the U.S.'' *Struct. Des. Tall Build.*, 2, 192–209.
Soong, T. T., and Spencer, B. F. (2002). ''Supplementary energy dissipation: State-of-the-art and state-of-the-practice.'' *Eng. Struct.*, 24, 243–259.
Spencer, B. F., Jr. (2002). ''Civil engineering applications of smart damping technology.'' *Proc., 5th Int. Conf. on Vibration Engineering*, Nanjing, China, 771–782.
Spencer, B. F., Jr., and Sain, M. K. (1997). ''Controlling buildings: A new frontier in feedback.'' *IEEE Control Syst. Mag.*, 17(6), 19–35.
Spencer, B. F., Jr., Johnson, E. A., and Ramallo, J. C. (2000). '' 'Smart' isolation for seismic control.'' *JSME Int. J., Der. C*, 43(3), 704–711.
Spencer, Jr., B. F., Dyke, S. J., Sain, M. K., and Carlson, J. D. (1997). ''Phenomenological model of a magnetorheological damper.'' *J. Eng. Mech.*, 123(3), 230–238.
Spencer, B. F., Jr., Yang, G., Carlson, J. D., and Sain, M. K. (1999). '' 'Smart' dampers for seismic protection of structures: A full-scale study.'' *Proc., 2nd World Conf. Structural Control*, Vol. 1, Wiley, New York, 417–426.
Symans, M. D., and Constantinou, M. C. (1999a). ''Semi-active control systems for seismic protection of structures: A state-of-the-art review.'' *Eng. Struct.*, 21(6), 469–487.
Symans, M. D., and Constantinou, M. C. (1999b). ''Seismic testing of a building structure with a semiactive fluid damper control system.'' *Earthquake Eng. Struct. Dyn.*, 26(7), 759–777.
Symans, M. D., and Kelly, S. W. (1999). ''Fuzzy logic control of bridge structures using intelligent semiactive seismic isolation systems.'' *Earthquake Eng. Struct. Dyn.*, 28, 37–60.
Varadarajan, N., and Nagarajaiah, S. (2003). ''Wind response control of building with variable stiffness TMD: EMD/HT.'' *J. Eng. Mech.*, in press.
Xu, Y. L., Qu, W. L., and Ko, J. M. (2000). ''Seismic response control of frame structures using magnetorheological/electrorheological dampers.'' *Earthquake Eng. Struct. Dyn.*, 29, 557–575.
Yalla, S., Kareem, A., and Kantor, C. (2001). ''Semiactive tuned liquid dampers for vibration control of structures.'' *Eng. Struct.*, 23, 1469–1479.
Yang, G., Spencer, B. F., Jr., Carlson, J. D., and Sain, M. K. (2002). ''Large-scale MR fluid dampers: Modeling and dynamic performance considerations.'' *Eng. Struct.*, 24(3), 309–323.
Yang, J. N., and Agrawal, A. K. (2002). ''Semi-active hybrid control systems for nonlinear buildings against near-field earthquakes.'' *Eng. Struct.*, 24(3), 271–280.
Yang, J. N., and Dyke, S. J. (2003). ''Kobori Panel Discussion: Future perspectives on structural control.'' *Proc., 3rd World Conf. on Structural Control*, Wiley, New York, 279–286.
Yang, J. N., Kim, J. H., and Agrawal, A. K. (2000). ''Resetting semiactive stiffness damper for seismic response control.'' *J. Struct. Eng.*, 126(12), 1427–1433.
Yang, J. N., Wu, J. C., Kawashima, K., and Unjoh, S. (1995), ''Hybrid control of seismic-excited bridge structures.'' *Earthquake Eng. Struct. Dyn.*, 24(11), 1437–1451.
Yi, F., Dyke, S., Caicedo, J. M., and Carlson, J. D. (2001). ''Experimental verification of multiinput seismic control strategies for smart dampers.'' *J. Eng. Mech.*, 127(11), 1152–1164.
Yoshida, K., Kang, S., and Kim, T. (1994). ''LQG control and *H*-infinity control of vibration isolation for multi-degree-of-freedom systems.'' *Proc., 1st World Conf. on Structural Control*, TP4:43–52.
Yoshioka, H., Ramallo, J. C., and Spencer, B. F., Jr. (2002). '' 'Smart' base isolation strategies employing magnetorheological damper.'' *J. Struct. Eng.*, 128(5), 540–551.