Semi-active control systems in bridge engineering: A review of the current state of practice

Abstract

In view of the grave socioeconomic consequences of earthquake damage to bridge structures, along with their critical role in modern and older road and rail networks, this article attempts to identify and summarise the current trends in the use of semi-active control technology in bridge engineering, as an enhanced seismic response control solution, combining increased adaptability and reliability, compared to passive and active schemes. In this context, representative analytical and experimental studies, as well as some full-scale applications of semi-active control devices are first reviewed and a brief description of relevant benchmark studies is subsequently presented, with a view to serving as a point of reference for further research and development. A framework of performance-based control principles aiming at the aforementioned objectives is finally set forth.

Keywords: bridges; structural control; semi-active control; seismic devices; earthquake engineering

1 Introduction

The smooth, efficient, and reliable operation of road and rail transport systems is vital to the economic growth and sustainability of most communities. Bridges lie at the core of these systems, which further act as lifelines for emergency relief after catastrophic events such as earthquakes, tsunamis, hurricanes, and other natural hazards. In this context, it seems logical to consider utilising the most advanced procedures available, such as structural control, to protect bridges exposed to natural hazards, such as earthquake that is the main focus of this paper. Structural control systems can be classified according to the following four categories based on their operational mechanisms[1, 2]:

- *Active* control systems: These are systems wherein an external (typically large) power source controls electrohydraulic or electromechanical actuator(s) that apply forces to the structure in a prescribed manner, based on feedback from sensors (optical, mechanical, electrical, chemical, etc.) that monitor either the excitation (feedforward/open loop control) or the structural response (feedback/closed loop control) or both (feedback-feedforward/closed-open loop control); the controlled forces can be used both to add and to dissipate energy in the structure. Active control systems are characterised from increased adaptability to a broad range of excitations.

- *Semi-active* control systems: External energy requirements in these systems are orders of magnitude lower than typical active control schemes. Typically, semi-active control devices do not add mechanical energy to the structural system; control forces are developed as a result of the structural response (i.e. reactions) while their intensity is adjusted from the external power source based on closed/open/closed-open control. Semi-active control devices are often viewed as controllable passive devices, combining the adaptability of active systems and the reliability (due to the low energy requirements) of passive systems.

- *Passive* control systems: External power source is not required for operation in this type of control scheme; passive control devices impart forces in response to the motion of the structure. The energy in a passively controlled structural system cannot be increased by the passive control devices; hence, these systems are inherently stable and relatively simple to design and construct. However, passive control systems are unable to adapt to structural changes and/or to excitations of different frequency content and intensity than that used for their design. In view of the previous, systems that can passively adapt their characteristics (i.e. adaptive passive) based on their internal construction (e.g. displacement-dependent behaviour of spherical sliding isolation bearings[3]) instead of sensors and controllers were developed, aiming at a system with improved characteristics compared to a purely passive one.

- *Hybrid* control systems: In this case, passive and semi-active or active control devices are combined in order to enhance the structural performance and alleviate the limitations of a purely active, semi-active or passive system, albeit at the expense of increased complexity and cost (especially of maintenance).

Implementation of the aforementioned control principles to mitigate undesirable vibrations of dynamically excited civil engineering structures in seismically prone areas has attracted the attention of the research community in the last four decades[1, 4-6]. Indeed, numerous (mainly passive) devices have been successfully deployed world-wide to mitigate vibrations induced in civil structures by earthquake, wind, and human activities. Yet, only a relatively limited number of active, semi-active, and hybrid control solutions have been deployed in full-scale bridge applications (Table 1, based on Ref. [5], and additional data collected by the authors). This fact can be predominantly attributed to the reluctance of designers and the construction industry to adopt new technologies which, in many cases, infer high capital and maintenance cost. Nevertheless, the socioeconomic consequences of earthquake damage to bridges can be grave (human casualties, emergency response operation interruption, long-term economic cost due to the need for alternative transportation routes during repair, retrofit, or replacement), while the performance of bridges during recent strong earthquakes was found to be not fully satisfactory (e.g. Maule, Chile 2010[7]), and the size of the bridge stock exposed to seismic risk is ever increasing. Hence, it is anticipated that 'non-conventional' technology for mitigating seismic risk to bridges will attract the interest of the engineering community in the years to come, inasmuch as it furnishes low-cost, reliable, and robust control systems with minimal energy requirements.

Among the different types of control techniques briefly introduced above, semi-active control emerges as a rational combination of efficiency and cost, since it makes it feasible to modify the characteristics of a structural system, for it to respond favourably to different types of excitation (i.e. increased adaptability compared to passive control systems), while having the potential of achieving the performance of pure active control systems without requiring large external power supply (a portable battery can be sufficient in most cases), and thus, resulting in enhanced reliability; this should be contrasted to the vulnerability of actively controlled structures to power failure. In this context, semi-active control was recently implemented mainly as a retrofit measure to control cable and/or deck vibrations in bridge structures across Asia, Europe, and the US (Table 1).

No.	Bridge	Location	Configuration	Construction	Mechanism	Objective	Implementation
1	Rainbow	Minato, JP	Suspension	1987-1993	HMD[a]	Construction	1991-1992
2	Tsurumi Tsubasa	Yokohama, JP	Cable-stayed	1987-1994	HMD	Construction	1992-1993
3	Hakucho Ohashi	Muroran, JP	Suspension	1985-1998	AMD[b], HMD	Construction	1992-1994
4	Akashi Kaikyo	Kobe, JP	Suspension	1988-1998	HMD	Construction	1993-1995
5	Meiko-Chuo (Central)	Nagoya, JP	Cable-stayed	-1998	AMD	Construction	1994-1995
6	1st Kurushima	Imabari, JP	Suspension	1988-1999	AMD, HMD	Construction	1995-1997
7	2nd Kurushima					Construction	1994-1997
8	3rd Kurushima					Construction	1994-1996
9	Nakajima	JP	Cable-stayed	-1996	HMD	Construction	1995-1996
10	Akinada	Hiroshima, JP	Suspension	1992-2000	AMD	Construction	1996-
11	Walnut Creek	Oklahoma, US	Composite beam/girder	-1972	SA-VD[c]	Retrofit	1999
12	Dongting Lake	Nanjing, CN	Cable-stayed	-1999	SA-MR[d]	Retrofit	2002
13	Binzhou Yellow River	Binzhou, CN	Cable-stayed	2001-2003	SA-MR	Design	2003
14	Eiland	Kampen, The Netherlands	Cable-stayed	-2003	SA-MR	Experimental investigation	2004
15	Franjo Tuđman	Dubrovnik, HR	Cable-stayed	1998-2002	SA-MR	Retrofit	2006
16	Alamillo	Seville, ES	Cable-stayed (cantilever-spar)	1989-1992	SA-MR	Retrofit	2007
17	Sutong Yangtze River	Nantong / Changshu, CN	Cable-stayed	2003-2007	SA-MR	Design	2007
18	Volgograd	Volgograd, RU	Steel box girder	1996-2009	MR-STMD[e]	Retrofit	2011
19	Russky	Vladivostok, RU	Cable-stayed	2008-2012	SA-MR	Design	2012

[a]Hybrid mass damper

[b]Active mass damper

[c]Semi-active variable orifice damper

[d]Semi-active magnetorheological damper

[e]Semi-active TMD with a magneto-rheological damper

Table 1: Summary of active, semi-active, and hybrid control techniques implemented in bridges during construction, permanently as part of the original design, as a retrofit strategy, and for research purposes

In the light of the previous remarks, the present study attempts to identify and summarise the current trends in the use of semi-active control devices and techniques in bridge seismic engineering as an enhanced seismic response control solution; representative analytical and experimental studies, as well as some full-scale applications of semi-active control devices are reviewed and a brief description of relevant benchmark studies is presented, with a view to serving as a point of reference for further research and development, rather than presenting a complete record of relevant studies. In this respect and due to space limitations, the studies discussed herein should only be seen as indicative of the number of relevant publications in the field, while an effort was made to cite primarily journal articles in lieu of conference proceedings or research reports. A framework of performance-based control principles for the future development of design procedures dealing with bridges of critical importance and complex structural configuration is set forth in the last section, since the adoption of semi-active structural control techniques within integrated performance-based seismic design methodologies with a view to meeting more efficiently and reliably multiple target design objectives has been fairly scarce [8, 9] and essentially restricted to buildings.

2 Application of semi-active control and related techniques to bridge structures

Semi-active dampers were originally proposed as motor vehicle shock absorbers in the 1920s and were studied extensively by mechanical engineers in the years that followed, primarily for automotive applications[2]. Within the field of structural engineering, the first application of semi-active structural control appears to have been proposed in the early 1980s[10] aiming at the response control of tall buildings subjected to environmental actions (i.e. wind loads). In the 1990s, this concept was adopted for seismic response control. Semi-active and hybrid control techniques are presented in this section, focussing on the devices adopted in bridge structures rather than on the control algorithms; details on the latter can be found elsewhere (e.g. Ref. [11]). A brief overview of relevant benchmark studies is subsequently given in Section 3. It is noted that the studies addressed herein refer mainly (albeit not exclusively) to seismic response control of motorway bridges and the term 'hybrid' is used to describe a control system that consists of passive and semi-active devices, which is narrower than its usual definition as a system combining passive with active and/or semi-active devices[2].

2.1 Variable Orifice Dampers

Variable orifice dampers are devices that use a controllable, electromechanical, variable-orifice valve to alter the resistance to flow of a conventional hydraulic fluid damper and hence control the damping coefficient. A schematic of such a device is given in *Figure 1*. The concept of applying this type of variable-damping device to control the motion of bridges experiencing seismic motion was first explored[13] in the case of a single-span girder bridge subjected to seismic motion in the longitudinal direction; the effectiveness of two different control algorithms (i.e. bang-bang and instantaneous optimal control) was examined numerically. Both numerical and experimental studies of a semi-active fluid damper controlled by a simple heuristic algorithm that used the relative displacement of the deck as feedback to adjust the damping coefficient and hence control the longitudinal response of a similar bridge, were presented soon afterwards[14]. In particular, large damping coefficients were adopted to prevent small deck vibrations due to braking loads and/or wind effects, reduced values were selected when bridge deck displacements under strong earthquake excitations exceeded a certain threshold value (in order to maximize energy dissipation), whereas if excessive deck responses were reached, the damping coefficient was set back to a large value (stopper function). Although the previous studies reported significant response reductions with regard to the uncontrolled state (i.e. isolated deck), a more modest improvement was actually achieved when compared to the case when the beneficial effect of passive dampers was present. The inherent difficulties in further improving the response of a well-designed passively controlled system were investigated in more detail in a different study[15] where different types of passive and hybrid (semi-active and active) protective systems for bridge applications were considered, namely: (i) lead-rubber bearings, (ii) lead-rubber bearings and passive dampers, (iii) lead-rubber bearings and variable dampers, (iv) lead-rubber bearings and actuators, (v) sliding bearings, and (vi) sliding bearings and actuators. Control methods were based on the theory of continuous sliding mode control (SMC), while an implementation of the approach adopted in Ref. [14] was also included. In a similar context, fuzzy logic control theory was applied to a hybrid seismic isolation system[16], consisting of elastomeric bearings and semi-active dampers, to control the level of damping force transferred to the substructure, while simultaneously ensuring sufficient damping to reduce the peak structural response; the semi-active control scheme was found capable of further reducing the peak deck relative displacements and absolute accelerations, albeit for a significantly higher allowable damping ratio, compared to a near optimum value of the passive case (i.e. elastomeric bearings and passive dampers).

The ability of variable dampers to improve the seismic response of isolated bridges that exhibit hysteretic behaviour of both columns and isolators under near-field ground motions, was studied by applying a linear quadratic regulator (LQR)- (also accounting for time delay)[17], and an SMC-based algorithm[18] in an idealised model of a five-span continuous isolated viaduct. Both studies reported similar and slightly improved performance of the semi-active scheme when compared with the active and passive cases, respectively. Finally, a semi-active variable orifice damping and stiffness device was installed in a motorway bridge to control traffic-induced vibration[19]; representing the first full-scale implementation of a semi-active structural control system in the US, this control scheme aimed at reducing the maximum displacement and velocity of the girders during the passage of a truck, while increasing the useful life of the structure by shedding loads away from parts of the girders that experienced in the past the largest stresses. The idea was further promoted by a different research group[20] which adapted the control mechanism to a ‘scissor-jack’ brace configuration aiming at improved control of forces and reduced size of control devices through amplification of the bridge deck deflections.

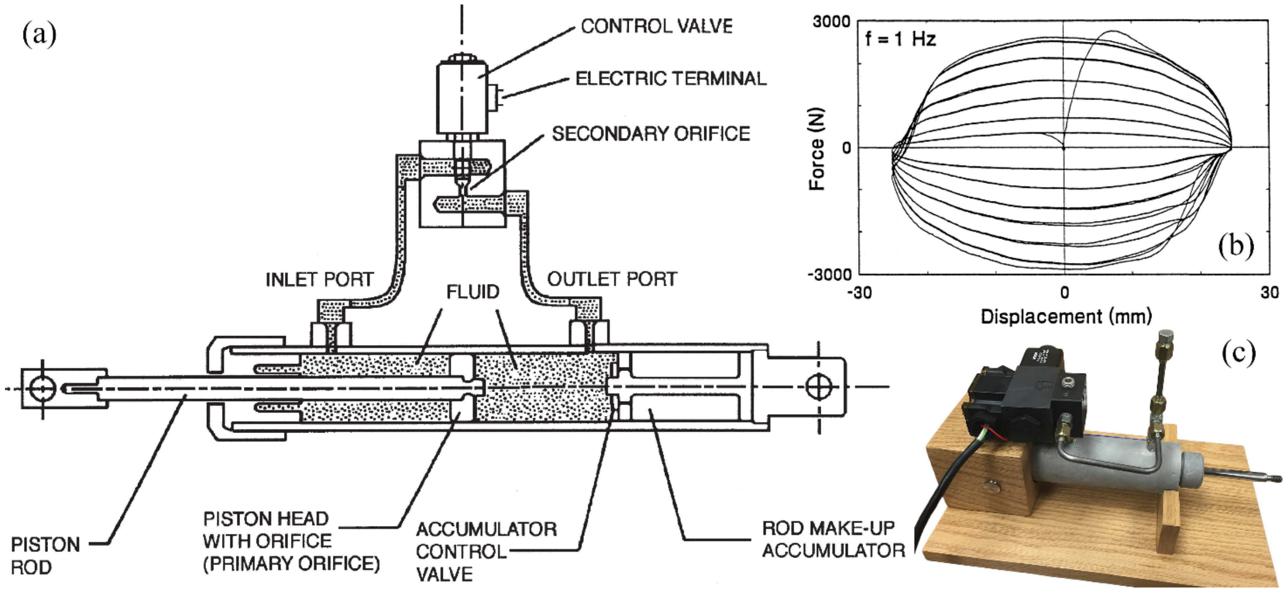

Figure 1: Variable orifice damper: (a) schematic, (b) typical force displacement response under sinusoidal excitation of 1.0 Hz [12], (c) device [courtesy of M. Constantinou]

2.2 Semi-active Stiffness Control

A semi-active stiffness control device was initially proposed[21] with a view to controlling the stiffness of a building and hence establishing a non-resonant condition during earthquakes. The semi-active stiffness device, consisting of a regulator valve inserted in a two-chamber cylindrical tube filled with oil, was connecting the primary beams of the structure with the bracing system, hence its open/close function (controlled by oil movement) was engaging or releasing the connection condition so as to include or exclude, respectively, the stiffness of the bracing system from the structure. To alleviate the problems associated with discontinuous modifications of stiffness (i.e. increased accelerations and excitation of higher modes), a semi-active instantaneously variable stiffness (SAIVS) device (*Figure 2*) capable of modifying stiffness in a continuous fashion was subsequently developed[22]. The device consisted of four sets of springs and frictional elements (telescopic tubes) arranged in a rhombus configuration as shown in *Figure 2(a)* that can be switched continuously to any desired position using an electromechanical actuator and thus modifying the provided resistance (i.e. stiffness) between a minimum and a maximum value. The SAIVS device was later implemented in bridges[23]; the performance of a single-span 1/20-scaled sliding base-isolated (sliding bearings and a passive damper) bridge model equipped with the SAIVS device was numerically and experimentally studied under three different near-fault earthquakes (applied in the longitudinal direction of the bridge). The SAIVS reduced the relative (to the piers and the ground) deck displacements further than the passive open (minimum SAIVS stiffness) and passive closed (maximum SAIVS stiffness) cases, while it maintained pier displacements and deck accelerations within the bounds of open and closed cases, and isolation level forces close to the minimum stiffness case.

A semi-active device, known as the magnetically controlled elastomeric (MCE) bearing, was developed[24] to counteract the unfavourable stiffening effect of elastomer under earthquakes of intensity lower than the design earthquake (that causes increase of spectral accelerations). MCE is a material whose modulus can be modified by the application of a magnetic field. Thus, the MCE bearing was designed to have high shear stiffness during small amplitude vibrations (e.g. vehicle braking loads in bridges) and strong earthquake excitations, in order to prevent structural vibrations and excessive response, respectively. On the contrary, its stiffness was reduced under earthquakes of low and moderate intensity to maintain the efficiency of the isolation effect. The use of MCE bearings in bridges with isolation devices located only on the short/stiff piers (aiming at the reduction of their shear response under weak ground motions) was also investigated[25].

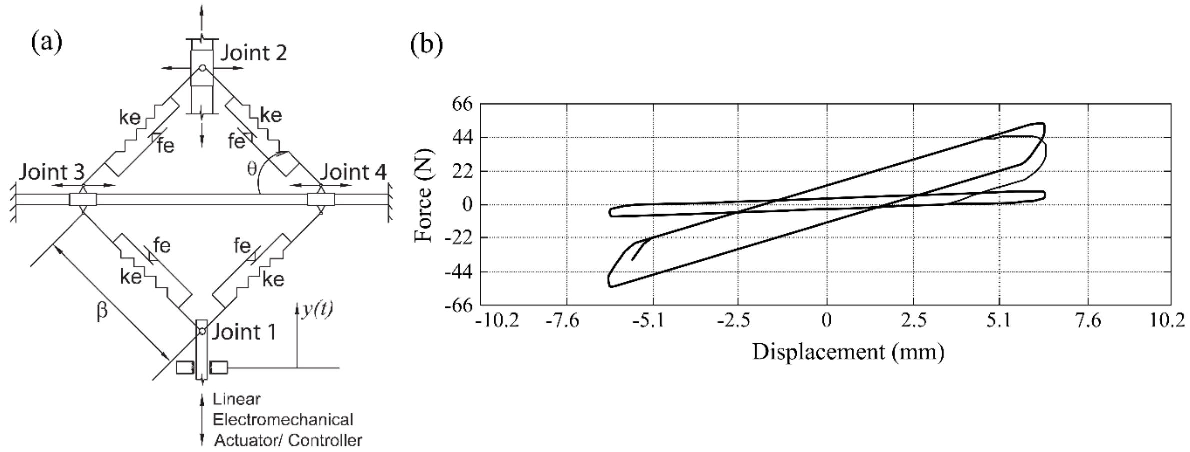

Figure 2: Semi-active instantaneous variable stiffness device[22]: (a) schematic, (b) typical force displacement response under harmonic excitation of 2.0 Hz

2.3 Friction Control Devices

Semi-active friction control devices have been utilized in the past either as energy dissipators commonly mounted within the lateral bracing of building structures or as components within sliding isolation systems. Semi-active friction dampers aim at the control of the normal force applied on the sliding surfaces of the device in order to ensure continuous slippage during intensity variations within the same or different loading histories (e.g. earthquake, wind) and hence maximise the dissipated energy when compared to the passive analogue. In practice, the normal force was regulated by hydraulic[26], piezoelectric[27], and electromagnetic[28] mechanisms. In the case of bridges, piezoelectric friction dampers were used[29] to semi-actively control the seismic response of a curved bridge, aiming at the reduction of the flexure-torsion coupling effect under different earthquake wave incidence angles. Following the concept of introducing the friction device as a component of the isolation system, a hybrid system using friction-controllable sliding bearings was developed[30], where the coefficient of friction at the sliding bearing interface and hence the friction force was controlled by adjusting the fluid pressure in the fluid chamber located inside the bearings (*Figure* 3). The effectiveness of this system for controlling a bridge model was numerically evaluated under natural and artificial accelerograms of different intensity, spectral shape, dominant frequency and duration, for two different control algorithms (bang-bang control and instantaneous optimal control), and it was demonstrated that the proposed hybrid sliding system was capable of isolating the bridge more effectively under a variety of ground motion characteristics, i.e. prevent excessive deck displacements under large earthquake intensities while maintaining accelerations at an acceptable level, and control deck accelerations under small to moderate earthquake intensities, compared to the case of passive sliding bearings with low and high coefficient of friction, respectively.

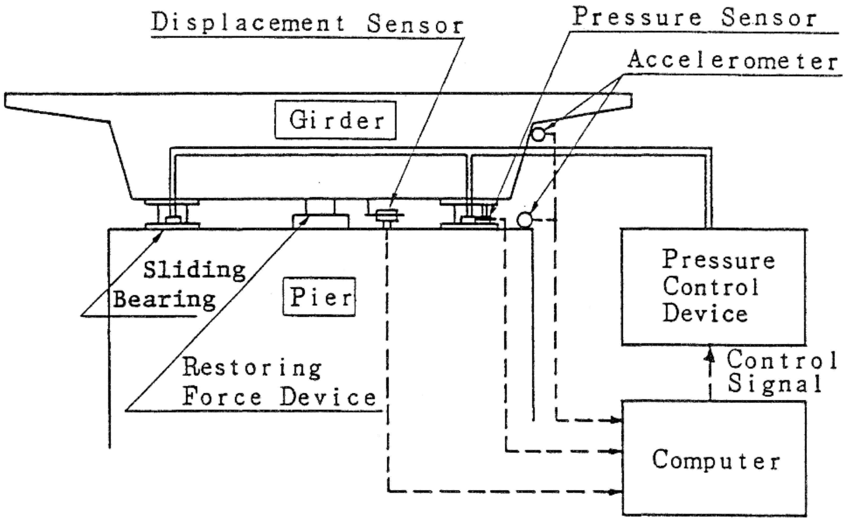

Figure 3: Hybrid isolation system consisting of semi-active sliding bearings and passive restoring force devices[31]

2.4 Controllable Fluid Dampers

This type of semi-active device uses controllable fluids instead of electrically controlled valves or mechanisms, aiming at increased reliability. The essential characteristic of controllable fluids is their ability to switch from a free-flowing linear viscous fluid to a semi-solid with controllable yield strength in milliseconds when exposed to an electric or magnetic field, for electrorheological (ER) and magnetorheological (MR) fluids, respectively. Although research initially concentrated primarily on ER dampers[32], certain features related to the limited range of achievable yield stress, the sensitivity to contaminants and extreme temperatures, and the increased voltage demand[1], prevented their implementation to large-scale civil structures. On the contrary, MR dampers[33] (*Figure 4*) have attracted considerable research in recent years, while nowadays they can be easily acquired on the market.

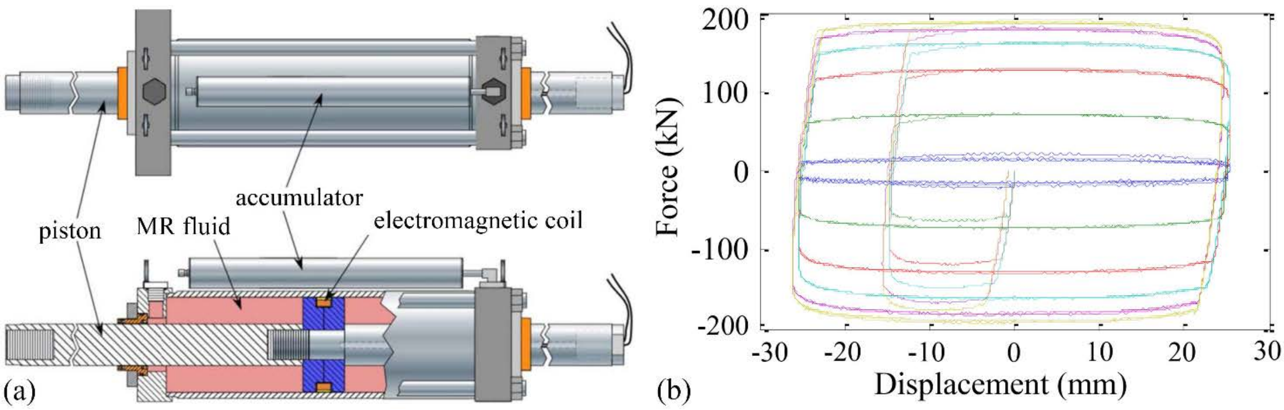

Figure 4: MR damper[34]: (a) schematic, (b) typical force displacement response under sinusoidal excitation with input frequency of 0.5 Hz and six voltage levels 0~2.5 V

Several research groups studied the application of MR dampers in motorway bridges with either a monolithic pier-to-deck connection (e.g. MR dampers located between the deck and the abutments[35]) or with isolated superstructures. With regard to the second (and more common) approach, analytical and experimental studies investigated different hybrid isolation systems consisting of a combination of passive devices (e.g. low[36] and high damping rubber bearings[37], sliding isolation bearings[38], rolling pendulum devices[39]) and MR dampers, with a view to mitigating the seismic structural response (e.g. deck displacements and accelerations, pier forces) compared to the uncontrolled (i.e. passive) state and/or focusing on specific research objectives, such as response under near-fault earthquakes[38-40], pounding effects[36, 40], real time hybrid testing[41], development of control algorithms[42-44], and so on.

The applicability of semi-active control (MR damper commanded by an LQR-based clipped optimal control algorithm) for seismic protection of isolated (with high-damping bearings) motorway bridges was investigated[37] through comparison with optimally designed passive (high-damping bearings) and active (LQR controlled) cases. Three design objectives were explored for each system, i.e. reduction of (a) pier response, (b) bearing response, and (c) both responses. The semi-active system showed similar performance to the passive system in case (a), i.e. increased pier response and somewhat reduced bearing response compared to the active strategy, it reached the active system performance in case (b), while all systems showed similar performance in the third case. The response of sliding isolated bridges with MR dampers was numerically and experimentally evaluated[38] using the earthquake records and the scaled bridge model described previously in Section 2.2 (an MR damper and restoring springs were used, in lieu of the SAIVS device and the passive damper); the proposed hybrid sliding system was found capable of reducing the bearing displacements further than the passive low-damping (MR damper with constant zero volts) and high-damping (MR damper with constant four volts) cases, while maintaining pier displacements, deck accelerations and isolation level forces within the response range of the latter cases. Two different damping force control schemes (i.e. friction-type damping force and two-step viscous damping force) realised through the use of MR dampers were also investigated[36], aiming at the alleviation of the detrimental effects in the bridge response due to pounding between the deck and the abutments or between segments of the deck at intermediate joints in multi-span motorway bridges. Both control schemes and in particular the friction-type approach, introduced on the basis of improving the performance of the common viscous damping force approach, were found capable of reducing the deck response and the pier inelastic deformations compared to the uncontrolled state (i.e. bridge deck resting on piers and abutments through elastomeric bearings); nevertheless, a direct comparison with a passive approach including common viscous dampers was not presented. The issue was addressed in a later study[40] where analytical and experimental investigations on a 1:20 scaled bridge model indicated that a hybrid semi-active scheme of MR dampers and elastomeric bearings can outperform relevant passive approaches of viscous dampers in minimising the pounding effects on the deck response (pier inelastic response was not considered in the latter work). In a similar context, comparative evaluation[45] of different semi-active control approaches (including MR dampers[33], variable friction[46], and variable stiffness devices[47]) applied to a 3-span motorway isolated bridge yielded promising results with regard to the performance of semi-active devices in reducing the structural response; based on the output provided[45], the MR damper and variable friction schemes resulted in improved performance compared to the passive one (i.e. low damping rubber bearings and viscous dampers), which nonetheless outperformed the variable stiffness scheme in various cases.

Implementation of MR dampers in cable-stayed and suspension bridges also attracted the interest of several research groups. Due to their low inherent damping, long steel cables are susceptible to vibrations induced by environmental conditions (i.e. combined light-to-moderate wind and rain) that result in reduced cable and connections life due to fatigue and/or breakdown of corrosion protection. Different approaches were explored to mitigate this problem; cross ties between adjacent cables that can shift the frequency of the cables out of the range of the excitation downgrade the aesthetics of the bridge, surface profiling is impractical for retrofit applications and it only applies to certain classes of vibration, while the effectiveness of passive dampers is significantly reduced when they are attached close to the cable anchorage (as dictated by bridge aesthetics) especially in the case of very long cables. In contrast, semi-active devices (e.g. MR dampers) were found to provide significant reductions in cable response, achieving performance comparable to active systems and overcoming the previous deficiencies of passive dampers[48-50]. Several numerical (see Section 3) and fewer experimental[51, 52] studies were also presented, focusing on the control of the deck and the tower structural response using MR dampers (installed between the deck and the towers). Recently, seismic fragility curves derived for a benchmark cable-stayed bridge[53] (see Section 3) as a means to select an optimum retrofit solution among semi-active (MR dampers), passive (MR dampers under constant voltage), and active (hydraulic actuators) schemes, indicated that the semi-active approach was the one having in most cases the best performance in terms of response reduction.

In many cases, research was directly motivated by real case-studies mainly associated with retrofit projects. The Dongting Lake Bridge in China, retrofitted with stay cable MR dampers, constitutes the first full-scale implementation of MR dampers in bridge structures[54, 55]. Two MR dampers were mounted on each cable of the bridge to reduce cable vibrations induced by weather conditions (wind combined with rain); a total of 312 MR dampers were installed on 156 stay cables. MR dampers were also attached to the 20 longest cables of the Shandong Binzhou Yellow River Bridge in China (i.e. 40 MR dampers), to supress possible cable vibration[56]. Furthermore, two control approaches[57] (i.e. cycle energy control (CEC) and controlled viscous damping (CVD)) for MR dampers on cables were implemented in a number of bridges either as part of their design or as a retrofit strategy. A prototype MR damper was connected perpendicular to the longest stay cable of the Eiland Bridge, The Netherlands, to experimentally validate the two approaches under real conditions and check the long-term performance of the MR damper. The CEC approach was implemented in Sutong Yangtze River Bridge (*Figure 5*), a cable-stayed bridge with a free span of 1080 m (12 MR dampers on the six longest cables and passive oil dampers on 19 additional cables). The same approach was adopted on the Franjo Tudjman Bridge in Croatia[58], and the Alamillo Bridge in Spain[59], where the CEC approach was used as a retrofit measure to counteract observed wind- and rain-induced vibrations. As far as the application of the second approach is concerned, 10 CVD controlled MR dampers were installed in the 5 longest cables of the Russky cable-stayed bridge in Russia (world record free span of 1104 m and stay cables of up to 580 m), along with passive oil dampers in 16 additional cables.

Figure 5: Sutong Bridge in China with CEC-controlled MR dampers (left), and Russky Bridge in Russia with CVD-controlled MR dampers (right) [courtesy of F. Weber]

2.5 *Controllable Tuned Mass Dampers and Tuned Liquid Dampers*

A tuned mass damper (TMD) consists, in general, of a secondary mass with properly tuned spring and damping elements, providing a frequency-dependent hysteresis that effectively increases damping in the primary structure as long as it remains tuned to the first mode of the latter (e.g. building, bridge). Similar in concept, the tuned liquid damper (TLD) and tuned liquid column damper (TLCD) impart indirect damping to the system and thus improve structural performance; a TLD absorbs structural energy by means of viscous actions of the fluid and wave breaking, while in a TLCD, energy is usually dissipated by the passage of liquid through an orifice with inherent head loss characteristics. The fundamental frequency of TLDs and TLDCs is dependent on the geometry of the containers (i.e. tanks and tubes respectively) and similarly to TMDs these devices are also prone to detuning. TMDs, TLDs and TLCDs have been intensively studied and implemented in full-scale civil engineering structures[60] to counteract primarily wind-induced vibrations.

Controllable tuned mass and liquid dampers constitute a semi-active alternative of the aforementioned passive devices, aiming at the alleviation of their sensitivity to frequency and damping variations of the primary structure through continuous adjustment of their stiffness and damping; in practice, this is commonly realised by combining (within the same device) other semi-actively controlled mechanisms (e.g. SAIVS[61], MR dampers[62], variable orifices[63]). As an example, TMDs with adjustable damping were studied to counteract wind-induced vibrations in tall buildings, providing additional advantages over passive TMDs[10]. Regarding bridge structures, different types of TMDs with adjustable characteristics were investigated by means of counteracting cable vibrations in cable-stayed bridges[64] or more commonly aerodynamic instabilities (e.g. flutter and buffeting) of decks mainly in suspension bridges. In the latter case, a semi-active lever-type TMD was presented[65] with its frequency modified through the controlled movement of a mass block along a horizontal rigid bar, whereas a different research group[66] proposed a two-degree-of-freedom TMD tuned to the frequencies corresponding to the vertical and torsional modes of the bridge with damping adjusted by a semi-active hydraulic damper; both previous studies reported improved performance of the semi-active approach compared to relevant passive schemes. A semi-active TLCD with adaptive frequency tuning capacity (adjusted by controlling the air pressure at the two ends of a container) was studied[67] to control the buffeting response of a long span cable-stayed bridge during construction. To obtain the same objective (i.e. supress wind-induced vibrations during construction), an alternative semi-active technique was also presented[68]; the TMD control approach was based on an electromechanical device consisting of a pendulum coupled to an alternator that was used to convert the mechanical energy of the oscillating pendulum into electric energy, which in turn was dissipated through an exterior resistor via Joule effect. With regard to earthquake induced excitation, a passive, a semi-active and an active tuned mass damping system were investigated[69] for the case of motorway bridges.

Moving towards real applications, a semi-active TMD with a magneto-rheological damper (MR-STMD) (*Figure 6*) was installed as a retrofit measure on the Volgograd Bridge (Russia) after it exhibited large wind-induced vibrations[70, 71]. The main feature of the MR-STMD concept is that the real-time controlled MR damper (used instead of passive dampers in common TMDs) emulates a controllable stiffness force that modifies the stiffness of the passive springs and thereby tunes the MR-STMD frequency to the actual frequency of the bridge, and a controllable friction force that generates frequency-dependent energy dissipation.

Figure 6: Installed MR-STMDs in Volgograd Bridge, Russia [courtesy of F. Weber]

2.6 Negative Stiffness Devices

The concept of hysteresis loops with negative stiffness was introduced in structural engineering[72, 73] in an attempt to prevent the transfer of large damping forces, developed in long-period base isolated structures with high values of damping ratios, into the main structure while maintaining large energy dissipation. This is common in isolated bridges under earthquake excitations, where damping devices and isolators are mounted in parallel, in an effort to limit excessive relative displacements of the bridge deck by introducing additional hysteretic damping (supplied by the damping devices). In view of the previous considerations, the pseudo-negative stiffness (PNS) damper was realised[73] using a variable damper and a PNS algorithm that introduced negative slopes in the variable damper hysteresis loops. The concept of this device can be described referring to *Figure 7(a)* that shows the hysteresis loop of a common passive damper installed in parallel with an isolator whose force-displacement response is presented in *Figure 7(b)*. It is interesting to note that the common damper tends to produce a total force (*Figure 7(c)*) larger than the isolator force (i.e. increased as damping is increased). On the other hand, if the damper hysteresis loops are inclined negatively (*Figure 7(d)*), the total force could be essentially the same as the isolator force (increase is relatively small for large damping); thus, by introducing negative slope in the damper hysteresis loops, one can obtain the same energy dissipation without having total force significantly higher than the isolator force. The approach was investigated and effectively applied in both cable-stayed[72, 74] (with negative stiffness dampers employed between the tower and the deck) and common motorway bridges[71] (see also Section 3) using variable orifice and MR dampers as negative stiffness devices, while the concept of negative stiffness was also applied to semi-actively control wind-induced vibrations in stay cables[56, 75, 76].

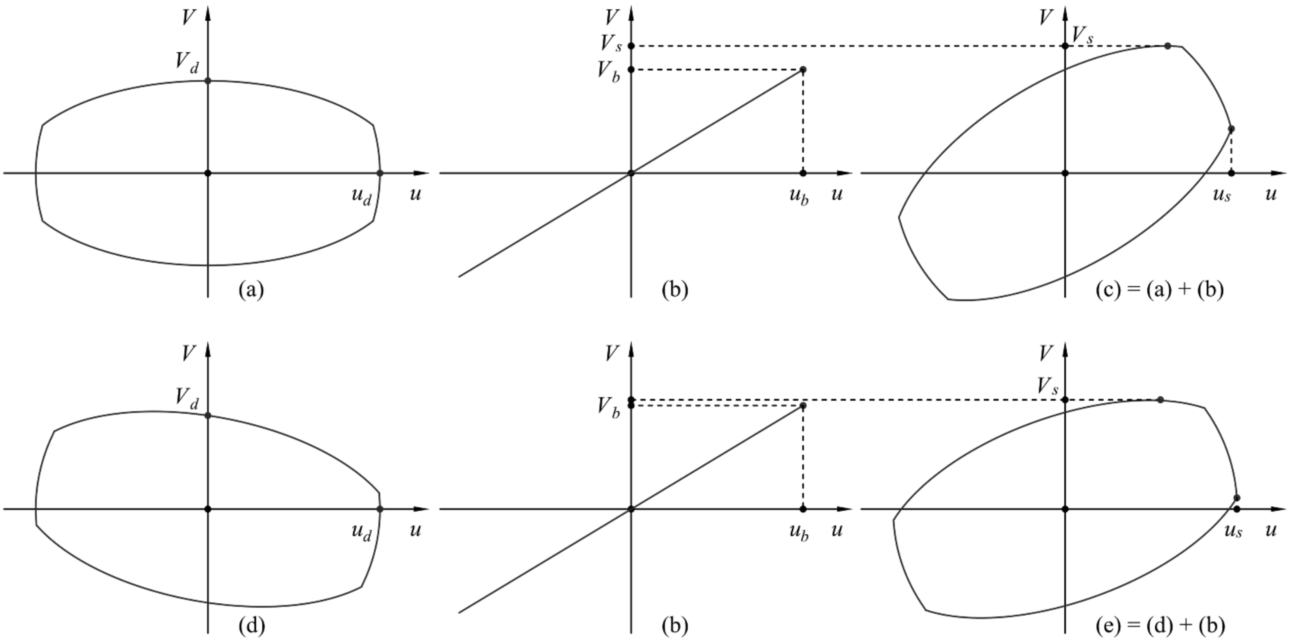

Figure 7: Hysteresis loops of (a) passive damper, (b) isolator, (d) PNS damper, (c, e) damper plus isolator

3 Overview of Benchmark Studies

Two different benchmark problems for seismic response control of cable-stayed and common (without cables) motorway bridges were presented to investigate the comparative effectiveness of various protective systems in reducing critical response quantities. The first benchmark problem based on the Bill Emerson Memorial cable-stayed bridge in the US was developed[77, 78] during two distinct phases. At Phase I, a linear three-dimensional evaluation model was developed to represent the complex behaviour of the full-scale benchmark bridge and evaluation criteria were selected, associated with the deck, tower, cable, and control device response along with power and resource requirements. Each participant was given the task of defining (in terms of devices, sensors, and algorithms), evaluating, and reporting on their proposed control strategies (passive, active, semi-active, or a combination). A simulation model and a sample control design were provided to facilitate direct comparison of the various control strategies. Phase II of the benchmark problem considered more complex structural behaviour, including multi-support excitations, excitations applied to arbitrary directions, and stability evaluation of the proposed strategy. Studies that contributed to this benchmark were presented at the 3rd World Conference on Structural Control[79]. Additional papers were also published in Volumes 129(7) and 10(3-4) of the Journal of Structural Engineering (ASCE) and the Journal of Structural Control, respectively. The aforementioned studies along with additional ones published independently, included applications (with regard to semi-active control) of stiffness control devices[47, 80], friction control devices[47, 81], controllable fluid dampers[82-86], negative stiffness devices[87], and hybrid base isolation systems[88, 89].

A second benchmark control problem based on the 91/5 Overpass in southern California was subsequently proposed[90]; a full-order nonlinear model (in contrast with the previous benchmark) of the bridge was used as the evaluation model to preserve the effects of column and isolator nonlinearity and a realistic implementation of the control system (also accounting for soil–structure interaction, bi-directional application of ground motion). A set of appropriate evaluation criteria with regard to the structure response and the control strategy were defined. Researchers were once more required to define their control devices, sensors and algorithms, and critically evaluate the effectiveness of their proposed scheme (passive, active, semi-active or a combination). Two different phases of the benchmark problem were considered according to the following. During Phase I[91, 92] the deck of the bridge was considered fixed to the outrigger. Three types of sample controllers were presented, namely, nonlinear viscous dampers, MR dampers, and ideal hydraulic actuators; a total of 16 control devices were proposed to be placed between the deck and the abutments for each sample control system. An H_2/LQG and a clipped-optimal control algorithm were selected for the active and the semi-active case, respectively. A different model of the bridge was developed during Phase II, by installing lead–rubber bearings between the deck and the outrigger, to simulate the behaviour of a base-isolated motorway bridge[93]. A sample Lyapunov semi-active controller using MR dampers was also developed during this phase.

Studies that contributed to the motorway benchmark bridge were published in Volume 16(5-6) of the Journal of Structural Control and Health Monitoring. Examples of the aforementioned studies along with additional ones published independently, include applications of friction control devices[94], controllable fluid dampers[95-100], and negative stiffness devices[101, 102]. A comparative study of the contributions was also presented[103] focusing on the comparison of the proposed passive, semi-active, and active techniques with the corresponding sample controllers.

4 Summary and Conclusions

Motivation for implementation of semi-active control techniques in bridge engineering emanates from the intention to economically design bridge structures of critical importance and complex structural configuration under challenging and diverse loading conditions while meeting multi-objective performance criteria involved in performance- and resilience-based design. On the other hand, implementation of advanced control techniques has not yet been well addressed in a comprehensive way as a (performance-based) design option that can result in the same (or superior) performance compared to other design alternatives (e.g. adoption of passive control schemes) but at a lower cost (in a life-cycle context). In this respect, further development of current performance-based design procedures to account for the improvement in structural performance due to a rational implementation of structural control devices, in line with the current trends in the use of structural control in bridge engineering, constitutes a decisive step for the wider acceptance of semi-active technology and should be sought within the following framework of objectives, specifically referring to seismic loading but which can also be adapted to other dynamic loadings:

- Design bridge structures that can respond favourably to earthquakes with different frequency content (e.g. proximity to active seismic faults, local site conditions, site affected by different seismic sources) and various intensity levels, associated with multiple performance levels such as serviceability-operationality, damage limitation, and life safety;
- Enhance the effectiveness of standard passive control systems by introducing novel control devices and hybrid control (e.g. increase the effectiveness of a base isolation system on relatively soft ground);
- Address and reconciliate the widely varying requirements emerging from the application of different types of actions (e.g. braking loads from vehicles, wind, earthquake);
- Reduce the bridge response by establishing a non-resonant state under earthquake excitations;
- Increase the bridge design working life using life-cycle cost considerations.

As a means to this end, the present study serves as a point of reference for future research and development as it is anticipated that due to the critical role of bridges in transport networks, structural control technology will increasingly attract the interest of the engineering community in the years to come. An overview of representative studies (both numerical and experimental) and full-scale applications of semi-active control devices and techniques for enhanced seismic response control of bridges was presented, providing an insight into the current trends and the feasibility of applying advanced control technology to bridges. Among the semi-active devices presented, extensive research and full-scale applications (mainly as a retrofit strategy) suggest that MR dampers might be an appealing and promising alternative to the reduced adaptability and reliability of passive and active control schemes, respectively.

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