CHAPTER IV

Seismic Response Control of Buildings Using Viscous-Based Devices*

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Introduction

The seismic design of buildings continues to evolve. There are two driving factors for this evolution. The first one is associated with more reliability and higher safety levels for densely populated city centres located in earthquake-prone areas. The second one is that economical limitations tighten the need to optimise craftsmanship and resources.

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The current building-design methodology is based on the ductility criterion. One advantage of this approach compared to the older, strength-based design, is that the forces in the structure are limited, which reduces the resistance demand and ultimately the size of structural elements. The deformations of the system are limited by the increased dissipation of seismic energy through controlled damage at pre-defined zones of the structure. Even though this design methodology achieves more efficient use of materials, resulting in lighter structures, it leads to high repair costs after a ULS earthquake. Also, the primary function of the main structural elements (e.g., columns and beams) is to maintain the integrity of the structure under earthquakes (i.e., the job of structural elements is either to dissipate energy or keep the integrity of the system for occupants' safety), so it is difficult to optimise their energy dissipation capacity. Therefore, the current design methodology may not be an optimal solution (see, [1-3]).

A possible solution, which is called structural control, has been studied for some time for both retrofitting of existing and design of new buildings. The main aim of this solution is to reduce the seismic response, which could prevent/or, at least, limit structural damage under severe earthquakes. Structural control systems, which can be classified as passive, active and semiactive systems, can lower the seismic response either by neutralising the seismic forces directly or by introducing additional elements designed specifically to dissipate seismic energy and/or change the dynamic properties of the structure during the earthquake.

Structural control systems can:

- Increase energy dissipation,
- Improve reliability (the elements can be standardized and produced in an industrial setting),
- Have low-cost repairs after an earthquake; but
- Increase initial costs

Each type of structural control has advantages and disadvantages. Active and semi-active control systems require advanced technological resources, such as energy supply, sensors, controllers, and devices that will generate forces in the structure [4]. Relatively simple passive control systems, which can be based on a variety of mechanisms [5], such as viscous (see [6-9]; Figure 1.1a), viscoelastic (see [8], [10-13]; Figure 1.1b), yielding (see [8], [14-19]; Figure 1.1c), or friction (see [8], [15], [20-22]; Figure 1.1d), can decrease the seismic response of the building and reduce damage (or even prevent under small ground excitations) in the main structural elements, such as beams, braces, or columns.

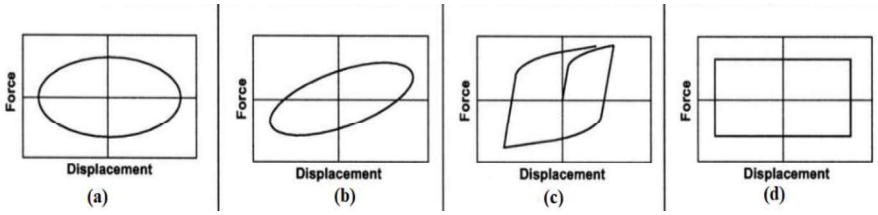


Figure 1.1. *Hysteretic behavior of (a) viscous, (b) viscoelastic solid, (c) metallic and (d) friction damper*

The application of any structural control mechanisms (e.g., active, semiactive, or passive) on moment resisting frame structures can however increase total base shear and foundation demand, which

are the concern of vibration control of the design of buildings or retrofit applications.

For example, Passive Viscous Damper (PVD), which is one of the commonly used damping devices**,** can add damping without increasing base-shear only for low-damping applications (i.e., in cases when the main structure remains linear elastic, which only happens for low level earthquake acceleration inputs). For high-level of structural damping, which is the case for most structures designed for severe earthquakes on the basis of a traditional performance-based seismic design and retrofit philosophy, where the main structure is expected to develop larger deformations and non-linear response, it is inevitable for PVDs to increase base shear and foundation demand [23-27]. This bounds the wide use of PVDs in new structures and retrofits.

Adaptable passive control approaches (sometimes called smart control; active, semi-active etc.,) have also been widely investigated as systems for improving the performance of passive control. By changing the configuration of the chambers inside Viscous Damper (VD) and filling it with different viscous fluids, one can modify both the passive viscous damping exponent and its coefficient during manufacturing [26].

In 1972, an active control approach, which was intended to be an alternative to traditional passive damping devices, was proposed by Yao (Yao, 1972) to improve the dynamic structural response. Altering damping inputs and device behaviour in response to changes in structural dynamics was the advantage of that control as well as showing an increase in robustness compared with passive

solutions. Nevertheless, such control needs larger power input to be practical in the need of actively producing large seismic mitigation forces.

Active control devices and their algorithms can be also complicated and could raise concerns about their robustness (in terms of energy requirements and algorithms under ground excitations) over the long term [28]. As a result, demanding significant costs for operation and adding complexity into vibration control of structural frames is inevitable for active controls.

As a solution, a semiactive system which is a combination of active and passive control systems requires a small external power source for its operation [26]. Semi-active control device function continues its operation as a passive device, even in case of a power failure [26]. The semi-active devices do not add energy to the system rather they store or absorb the vibration energy resulting from an excitation. They cannot, therefore, destabilize the structural frames [29], [30]. The semi-active control system can only alter the control action of a structure by changing the damping [31-32] or stiffness of the system [33].

It was already discussed that additional PVDs in non-linear structures or generally in structures with a high level of damping would likely increase base shear and foundation demand. Such increases would reduce the ability to use PVD (Passive Viscous Damper) in structural retrofitting applications without significant added cost.

Apart from potential semiactive control devices in literature (see [26], [34-38]), which provide damping forces in all four

quadrants of a viscous damper, there is also an ongoing research interest in manipulating the force-displacement hysteresis curve of the damper (Figure 1.2a) to achieve design objectives such as reducing drift without increasing base shear [30], increasing energy dissipation of the damper [31-32] or effective shock absorbers for vehicles [39-40]. The force-displacement loop can be reshaped by either decentralised semiactive control [30-32], or mechanically, by a passive damper [30], [40]. Reshaping the hysteresis loop has attracted interest of researchers in the field of control systems in earthquake engineering, as well as of vehicle researchers for shock absorbers [39-40].

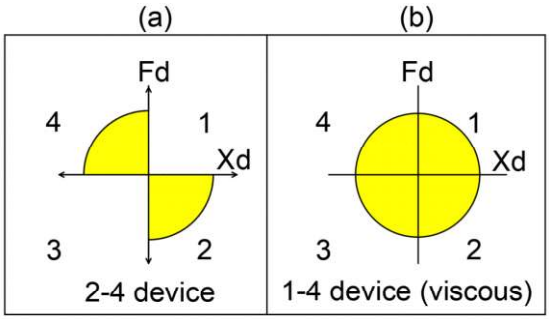


Figure 1.2. *Force- displacement relation of a conventional passive linear viscous damper*

Reshaped viscous dampers (Figure 1.2a) offer unique abilities similar to those seen for less robust and more complicated semi-active stiffness-based devices. The manipulated force-displacement relationship of the viscous dampers delivers an outstanding and appealing solution for reducing seismic response, with minimal risk of structural or foundation damage, which makes them convenient for more economic retrofit, as well as new designs. Unlike the passive control, the reshaped hysteresis loop doesn't

increase base shear since damper forces and columns forces do not occur at the same time.

A smart control (e.g., semiactive), which can reduce inter-storey drifts of a building, but reduce the base shear or/ doesn't increase base shear of the structure, could be a promising approach for mitigating structural damage during severe earthquakes.

Literature review of viscous-based control

Structural control systems, which can be classified as passive, active and semiactive systems, reduce the seismic response either by neutralising the seismic forces directly or by introducing additional elements designed specifically to dissipate seismic energy and/or change the dynamic properties of the structure during the earthquake.

Structural control systems (i) increase energy dissipation, (ii) improve reliability (the elements can be standardized and produced in an industrial setting), and (iii) reduce the cost of repairs after an earthquake; but (iv) they increase the initial costs

Each type of structural control has advantages and disadvantages. Active and semi-active control systems require advanced technological resources, such as energy supply, sensors, controllers, and devices that will generate forces in the structure [4].

2.1. Passive control

Passive control systems dissipate the energy that enters the system in an earthquake by yielding of materials, frictional sliding, or compression of fluids. The main advantages of passive control systems are that they do not need any external power source for their

control operations, they have simple working mechanisms, they absorb a significant amount of seismic energy from the structures, and they require little maintenance after installation [13], [26]. In a passive control system (PCS), the control forces applied to the building only depend on the structural motion [41]. Modern buildings are designed to dissipate energy through nonlinear deformations, the added cost of passive control systems needs to be justified by significant improvements in performance. Existing studies show that this can only be done by relatively extensive parametric studies for each structure, although there are some promising studies [2-3], that use sophisticated optimisation techniques to establish simple rules for designing passive systems.

Active control systems

Active control systems dissipate the energy of structures utilizing additional actuators based on acceleration, velocity, displacements, etc. measured by the sensors in vibration systems. Active control systems used in civil engineering applications raise considerable uncertainty (which is largely due to implementation issues) such as nonlinearities in both physical properties and disturbances, a limited number of actuators and sensors, complexities in the dynamics of the actuators, the scale of the forces and energy required for their operations (which can be quite large) [26], [42-43].

Semiactive control

Semiactive (SA) systems which are a combination of active and passive control systems requires a small external power source for its operation [26], as they use the movement of the building to

develop the control forces, with small external energy needed only to control the operation of the device [26]. As an active control system, it monitors the feedback from the control system and creates necessary command signals [44]. Control forces which are only engaged to deliver the resistive forces [36] initially act to oppose the motion and are improved through suitable algorithms. A semi-active control device continues its operation as a passive device, even in a power failure [26], [45-46]. The design and construction of an SA control system can be done even after installation. Note that the semi-active control system can only alter control action of a structure through damping (see [30]) or stiffness characteristics of the system (see [29]).

As follows are the mechanical properties and description of the smart-fluid damper (semi-active): A semi-active fluid viscous damper was proposed by Symans et al. [26], as a simple conversion of a standard passive damper, "*by drilling two ports in the cylindrical housing and connecting them with steel tubing and a control valve (see Figure 2.1). The amount of fluid which can pass through the external path is determined by the orifice opening within the control valve*." [26].

According to Symans and Constantinou [26], variable damping coefficients can be estimated as follows (see eq. 2.1):

$$C(v) = C_{min} + (C_{max} - C_{min})\exp(-\mu v n) \qquad (2.1)$$

where C(v) is the damping coefficient which is a function of command voltage v. μ and n are constant. The damper can generate any value within these C_{max} and C_{min} bounds.

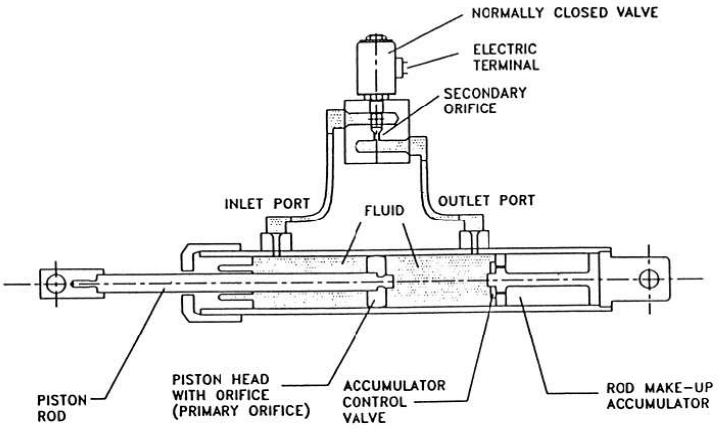


***Figure 2.1**: A Semiactive fluid damper [26]*

The general schematic diagram of a semi-active control system is given in Figure 2.2. This control system was first introduced in civil engineering structures by Hrovat et al. [45].

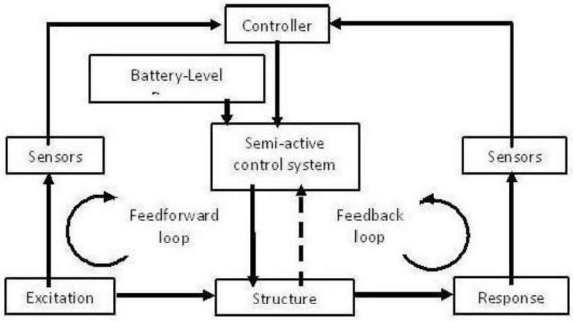


***Figure 2.2**. Schematic diagram of the semi-active control [45]*

Proposing an optimal control force to suppress building vibration has been an ongoing interest for engineers for many years. Many different control methods under different circumstances have been offered. However, none of them could be widely used in civil engineering design since each building needs different design

requirements for each type of building such as hospital, museum, school, skyscraper etc**.** Yet, in order to suppress the vibration over a wide frequency region, FVDs are often adopted in the structural systems to achieve a better system vibration performance [26]. Also, many researchers have studied the effects of viscous damping placed to different floors of buildings to examine the behaviour of SDOF systems (e.g., [47-48]).

Fluid viscous damper for seismic control

FVD which is known as one of the most commonly used passive damping devices was firstly applied for artillery rifle in 1897 [49]. In 1980s, it gained popularity in armies and navies of many countries; nevertheless, it was not publicly broadcasted due to the secretive nature of the research [50]. Fluid viscous dampers, which were manufactured at that time, were mostly based on the viscous effect between metal plates in the damper as depicted in Figure 2.3a. Due to viscosity dependent behaviour of the damper, it was highly sensitive to the working environment and the temperature. The fully developed FVD technology was declassified and made available for public practice in the late 1980s [51]. The developed fluid viscous dampers, which offered high damping capacity and wide range of manufacturing options, paved the way for many commercial applications such as bridges, buildings etc. Soong and Constantinou [52] proposed a modern fluid viscous damper (Figure 2.3b), which was widely embraced by mechanical and civil engineering structural applications. In this modernized FVD, the vibration energy is dissipated by the compressible silicone fluid which flows through the damper orifices and generates the resistance force. The modified damping principles of FVD by the help of late developments paved

the way for having a stable behaviour in a complex working environment [43]. These boosted the Fluid viscous dampers' acceptance in civil engineering and practical mechanical systems.

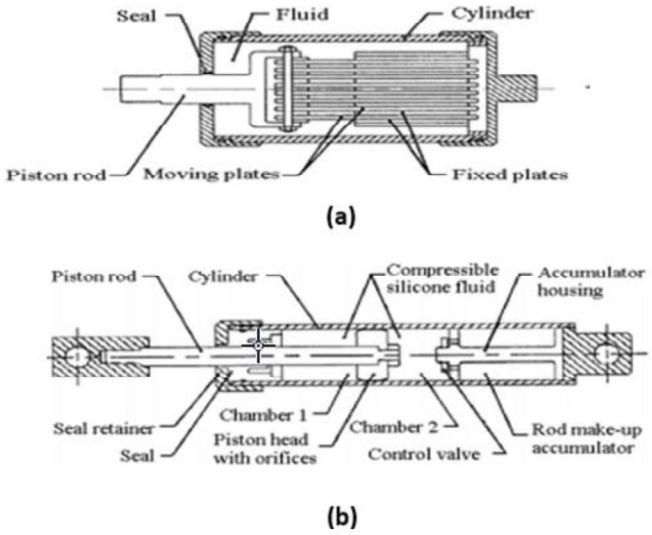


***Figure 2.3**. (a) Fluid viscous damper, (b) modern FVD [52]*

FVD is deemed to be the least space-intensive and the most cost-effective approach in the vibration control design of a system after a few decades of research followed in many theoretical and experimental studies [26], [43]. Some of the advantages of FVD are (see [43]):

1. Due to being out of phase with shear stresses and primary bending in a structure, FVD can be used to reduce both deflections and internal shear forces in a building structure for low damping applications.

2. FVD (passive) is self-sustaining and doesn't need to have the power to perform during excitation
3. FVD works at a fluid pressure level of important magnitude, which makes the dampers small, compact and easy to install.
4. Compared with other passive damping devices, fluid viscous dampers are cheaper, require less maintenance and are easier to install, which reduces the cost of the structure.
5. As a result of its successful use in large-scale applications for over 30 years, it gained trust in the military, civil structural engineering, and aerospace industries.
6. Ever since the increased demand to preserve commercial and public structures, such as sensitive instruments, mechanical components, nuclear reactors, and structural installations, under wind loadings, ground motions (e.g., earthquake), shocks and impact loads, FVD is widely employed by a wide range of engineering (mechanical, civil structural and aerospace).
7. Several different types of installation modes for FV damping devices have been developed and are in progress to meet the engineering demand with a cost-effective and sustainable approach. Some of these examples are shown in Figure 2.4.

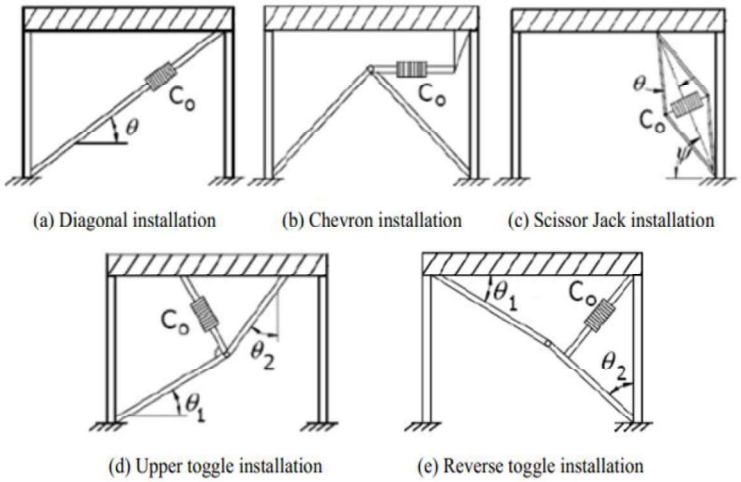


***Figure 2.4**. Typical installation modes of FV damping devices [53]*

The resistive damping force F_d generated by a fluid viscous damper with brace stiffness can be theoretically expressed by Maxwell modelling (eq. 2.2).

$$F_d = C_d * \dot{\delta}_{damper}^{a} = K_{brace} * \delta_{brace}\,,\ \delta_{total} = \delta_{damp} + \delta_{brace} \quad (2.2)$$

where $\dot{\delta}$ is the relative velocity between the two ends of the damper. C_d and a are the damping coefficient and velocity exponent respectively. δ_{brace} and δ_{damp} are brace and dashpot displacement respectively. Figure 2.5 shows the relationship between the relative velocity of typical fluid viscous dampers and the damping force under different values of a.

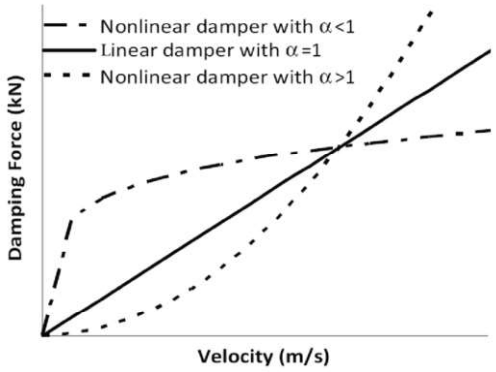


***Figure 2.5**. Force-velocity relationship of viscous damper [54]*

When the damping exponent (a) is larger or smaller than 1, the damper's dynamic characteristic is nonlinear, as the damping force acts in the opposite direction to that of the relative velocity between two ends of the damper itself. The damper's dynamic characteristic is otherwise linear (a=1). Through changing the configuration of the chambers inside the damper and filling with different viscous fluids, one can modify the viscous damping exponent and its coefficient. To meet the design requirements, fluid viscous dampers' dynamic characteristic can be modelled either as nonlinear or linear [54].

Traditional Design vs. Fluid Viscous Damper

To show the superiority of FVDs over the traditional vibration control methods, the resulting benefits of fluid viscous dampers must surpass those of the traditional design methods. Hence, the performance requirements for the structure regarding the desired response during and after an earthquake is vitally important in the decision. The energy dissipation of conventional seismic design is dependent on the inelastic response of its structural

components. Quantifying an element's hysteretic behaviour requires quantifying its displacement between stories. The conventional seismic design anticipates having an inelastic deformation to some extent after some earthquakes. However, the integrity of the structure cannot be compromised.

After the Northridge earthquake, scientists started to question the traditional connection details for maintaining structural integrity. Even though a large number of research studies in connection detailing of structural components has been conducted, rehabilitation may still be required depending on the extent of inelastic deformation [55]. Fluid viscous dampers enable the structure to remain elastic, while FVDs themselves satisfy the necessary damping for dissipation of the energy in the structure during ground motions. FVDs can achieve much higher damping forces than conventional structures without leading to large drifts of building structures during seismic events [26]. Applying FVDs would require a higher cost despite the benefit of eliminating repair costs after an earthquake. Viscous damper (VD) can be a futuristic solution to environmentally friendly building design by designing a deficient dual frame (bare frame + VD) for the sake of consuming less steel or concrete materials in a structure. To discuss FVDs with one of potential vibration control methods, if a brace application is selected, it would decrease the fundamental period (T) of the building. As a result, in cases where the structure is designed for high intensity near-field earthquakes with short predominant periods, the stiffer braced structures may provoke resonant behaviour. In addition, brace would increase axial forces in columns.

Passive FVD applications

The first use of FVDs in the seismic protection field was the Arrowhead Regional Medical Centre in the United States of America. 186 dampers were installed in the building parallel with rubber base isolation bearings to absorb quake energy [51]. After the Loma Prieta earthquake, Vincent Thomas Bridge was retrofitted to control the deformation of the suspended trusses with full-scale nonlinear fluid viscous dampers [56]. Another example of FVD applied is the Rion-Antirion Bridge project in Greece. NFVD (Nonlinear Fluid Viscous Damper) with lower-than-one power damping characteristic parameter was utilised to control displacements caused by an earthquake [57]. A considerable number of experimental and theoretical studies were conducted to investigate linear and nonlinear fluid viscous damper behaviour for a various number of structural engineering applications. A study conducted by McNamara et al. [58] aimed to investigate the vibration isolation performance of a 39-storey office building subjected to wind loadings and compare with other potential vibration isolation devices. They proved that FVDs were deemed the most cost-effective and the least space-intensive on the office building, which is followed by the installation of diagonal and toggle braces on several floors. A new design procedure for supplemental FVDs in practical bridge structures is also introduced to control the vibration during ground motions [59].

De Domenico et al [60] discuss nine different damper placement methodologies along with building heights in their review paper. They include iterative methods and simple methods. The

damper placement methods (which were selected from Figure 2.6) are:

- Sequential search algorithm (SSA) (which is classified as repetitive methodology)
- Uniform distribution (UD) (which adopts that the damping constants are identical at every storey)
- Storey-shear-proportional-distribution (SSPD) (it suggested to distribute the FVDs in proportion to the design story shears)
- Storey-shear-strain-energy (SSSE) distribution (it was offered to distribute the FVDs in proportion to the storey shear strain energy)
- Storey-shear-strain-energy-to-efficient-storeys (SSSEES) distribution (modification of SSSE was used for shear strain energy is larger than the average story shear strain energy)
- Stiffness-proportional distribution (SPD) (using Rayleigh damping constant)
- Gradient-based search methods (it employed the displacement transfer function)
- Fully-stressed analysis/redesign procedure (This method employs an iterative procedure to maximize the effect of the dampers on the performance index parameter)

- Optimal control theory (it targeted to minimize a performance cost function)
- Genetic algorithm (GA) (it automatically assumed different starting points and perform the search sequentially without computing any gradient)

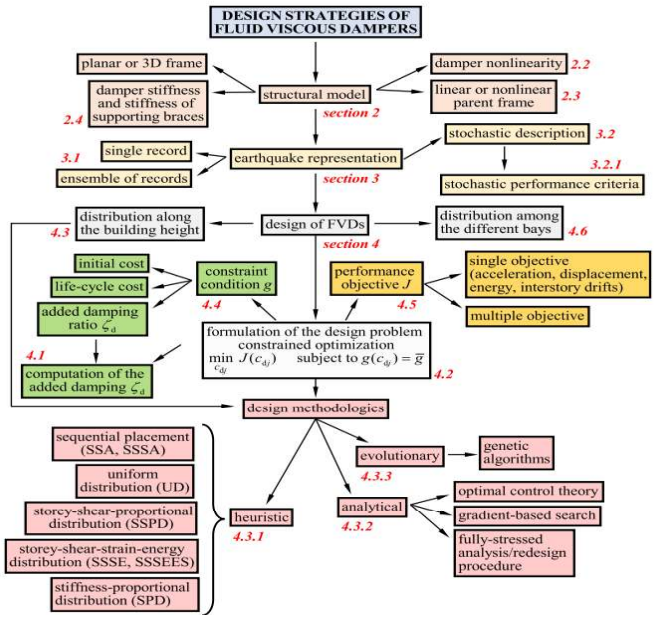


***Figure 2.6**. Design strategies of fluid viscous dampers [60]*

The design methodologies mentioned above assumed that the parent frame has a *linear elastic behaviour*. The nonlinearity of the frame response (considering buildings experiencing inelastic deformations or assuming a yielding structure) was included in the design of FVDs by some studies from the relevant literature (see [61-63]). Lavan et al. suggested the concept of weakening and damping, which tries to weaken the columns of structure (allowing nonlinearities in the structure) and add damping (with viscous

damper) to the structure for the sake of reducing acceleration (by reducing column forces) and displacement of the system (by using the advantage of viscous damper since it is out of phase with column forces). Lavan and Dargush presented a novel Genetic Algorithm (GA) for multi-objective seismic design optimization (acceleration and displacement). The algorithm is used for the concept of weakening and damping. Attard proposed a gradient-based optimization algorithm in nonlinear steel frame. An optimal damping ratio was computed in all modes of vibration. Whenever the damping ratio changes were negligible, the objectives were achieved.

Those nonlinear frame applications considered either damping ratio-based distribution or weakening of structure. All these aforementioned studies simply try to propose an optimal damping coefficient distribution in buildings, while achieving their design objectives.

In order to formulate effective design strategies in codes (e.g., EC8, ASCE), more work must be done in this field, and it would be desirable to incorporate more contributions into them. In fact, only the US structural code [64] and recently EC8 [65] provide specific recommendations for simplified structural analysis and design of dampers in buildings, but not sufficient information for an easy and rapid damper design [66].

The modal damping ratio associated with supplemental FVDs can be used to assess and quantify the effectiveness of damper distributions in buildings. The simplified formula proposed in the FEMA 356 [64] provisions, which is recalled here (see eq. 2.3), can

be used in a preliminary stage of analysis and design to determine the viscous damping ratio of the added FVDs.

$$\zeta_{\mathrm{d}} = \frac{T_1}{4\pi} \frac{\sum_{j=1}^{n_{\mathrm{d}}} c_{\mathrm{d}j} f_j^2 \left(\phi_{1j} - \phi_{1j-1}\right)^2}{\sum_{i=1}^{n} m_i \phi_{1i}^2} = \frac{T_1}{4\pi} \frac{\phi_1^T \mathbf{R}^T \mathbf{D} \mathbf{R} \phi_1}{\phi_1^T \mathbf{M} \phi_1} \tag{2.3}$$

where ϕ_1 is the first eigenvector of the undamped building structure (such that $\mathrm{K}\phi_1 = \mathrm{M}\phi_1\omega_1^2$), and $T_1 = 2\pi/\omega_1$ is the fundamental period.

With the use of damping correction factors, Eurocode 8 [65] also determines the damping ratio (ζ) for achieving the desired performance level. In Cl. 3.2.2.2 [65], EC8 provides a relationship (Eq. 2.4) between the total damping ratio and the damping correction factor.

$$\eta = \sqrt{\frac{10}{5+\zeta}} \geq 0.55 \tag{2.4}$$

By calculating the amount of supplemental damping needed, damper coefficients and damper placement can be determined after.

Passive Viscous Damper (PVD) can add damping without increasing base-shear for only low-damping applications (i.e., under small-earthquake accelerations). For high-level of added damping, which is the case for most structures designed for severe earthquakes on the basis of a traditional performance-based seismic design and retrofit philosophy, where the main structure is expected to develop larger deformations and non-linear response under large earthquake accelerations, it is inevitable for PVDs to increase base shear and foundation demand (see [23-27]). This limits the wide use of PVDs in new structures and retrofits. It is worth mentioning that to lessen

structural element yielding under earthquakes, base shear ought to be reduced as much as possible in a building design.

Therefore, adaptable passive control approaches (e.g., active, semi-active etc.,), which can offer smaller inter-storey drifts than corresponding passive control systems, but reduce /or doesn't increase the base shear, could be a promising approach for mitigating structural damage during severe earthquakes. Semiactive controls, for example, that could manipulate force-displacement loops of viscous dampers (by removing forces in some quadrants; motion away from equilibrium) when applied to a frame, would not require strengthening of columns and foundation and thus reduce structural damage by preventing base shear increase.

Semiactive FVD applications

To improve the performance of the conventional passive FVDs, after some experimental works, a study [26] stated that the semi-active fluid viscous damper (SAFVD) with variable characteristics performed better than passive control. SAFVDs offers some benefits to the system by offering adaptability during earthquakes (with variable characteristics), requiring a small power source, and having the potential of stabilizing the structure (due to velocity-dependent behaviour). The first use of SAFVDs in seismic control of a linear MDOF building was published by Kurata et al. [37] in the 1990s. The other applications of SAFVDs were introduced in vibration control of bridges [38]. Low-rise linear base-isolated structures equipped with SAFVDs were also studied [35]. The study stated that the semiactive control performed better than passive viscous damper. Another application of the semi-active fluid viscous dampers was conducted for an asymmetric 3-D high-rise

linear building under some single earthquakes [67]. The research concluded that the semi-active system reduced torsional effects of irregular tall building compared with uncontrolled structure. Oliveira et al. [68] have investigated a linear-SDOF structure equipped with semi-active fluid viscous dampers. They showed that the effectiveness of the semiactive control for passive and active systems. The same study was extended for a base isolated SDOF structure equipped with SAFVD. The investigation ended with similar results [68]. Ho et al. [36] have conducted an experimental study for linear-MDOF system against a long-period ground motion. They confirmed the effectiveness of SAFVDs against passive linear fluid viscous damper. i.e., By utilizing semiactive control, low acceleration transmissibilities can be achieved around the structural natural frequency and higher ground motion frequencies as commonly observed during Japanese earthquakes.

Apart from all semiactive control devices in literature [26], [34-37], which provide damping forces in all four quadrants, there is also an ongoing research interest in manipulating the force-displacement hysteresis curve of a damper to achieve design objectives such as reducing drift without increasing base shear (see [30]) or increasing energy dissipation of the damper (see [31-32]).

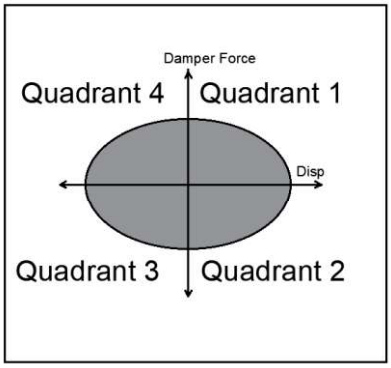


Figure 2.7*. Traditional force-displacement relation of fluid viscous damper*

The force-displacement loop (Figure 2.7) can be reshaped by either decentralised semiactive control [30-32], or mechanically, by a passive damper [30], [40]. By adding dampers (such as viscous dampers) to the building frame, the maximum base shear can be increased substantially, which in practice would require stronger foundations and columns. Reshaping the hysteresis loop (having forces in only quadrants 2 and 4) has attracted interest of researchers in the field of control systems in earthquake engineering due to not increasing base shear while reducing drifts, as well as of vehicle researchers for shock absorbers [39-40], [69].

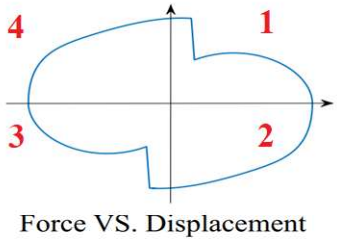


Figure 2.8. *Force-displacement relation of a shock-absorber for a vehicle [40]*

A variable damping viscous device, which can just adjust the level of damping, was first reported in NCEER-95-0011 [26]. In this device there was no individual control of specific quadrants of the hysteresis loop, but rather just change of damping in all four quadrants.Figure 2.9 shows the changes of the hysteretic loop and the changes of the control signal (and the resulting damper force) in time.

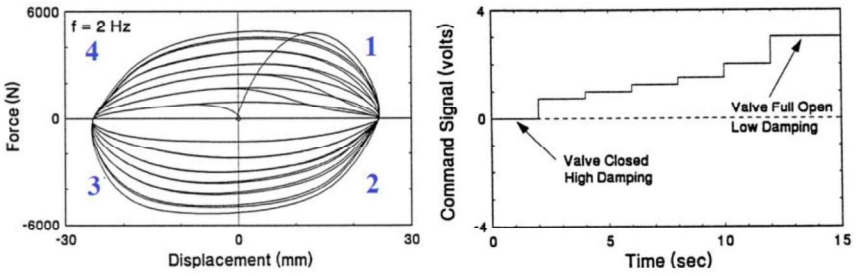


Figure 2.9. *Typical force- displacement loops for variable damper- from report NCEER 95-0011*

Tsopelas and Constantinou [70] developed a passive device, which was called fluid restoring force/damping. It operates only in quadrants 1 and 3, by introducing spring and viscous damping force in the device (Figure 2.10). However, as expected, these devices add damper forces at increasing displacements, in parallel with the increase of the restoring forces in the main structure, therefore increasing the total shear of the system.

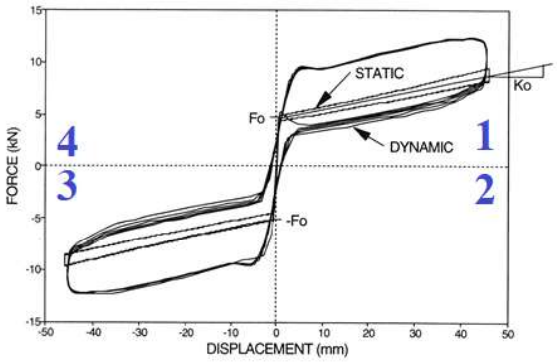


Figure 2.10 *The response of the device from report NCEER 94-0014*

The force-displacement relation of a device, and thus the entire structure, can be manipulated by either a readily reshaped (passive) device response or by direct control of the damping coefficient depending on the movement of the dampers in each direction, by a decentralized semiactive control strategy (e.g., [30-32]). The following examples discuss re-shaped hysteresis loops achieved by semiactive control. A resettable device, which is essentially a combination of hydraulic (or pneumatic) and spring elements in which the un-stretched spring length can be reset, is a semi-active approach to managing structural response energy. This means that a semiactive resettable device doesn't alter the damping of the structure but changes the stiffness of the structure [29], [33], [71]. The semiactive control devices based on the concept of variable stiffness are complex**,** increase the base shear (for Figure 2.11b and Figure 2.11c) and cannot generate very large control forces which are often required for seismic control of buildings.

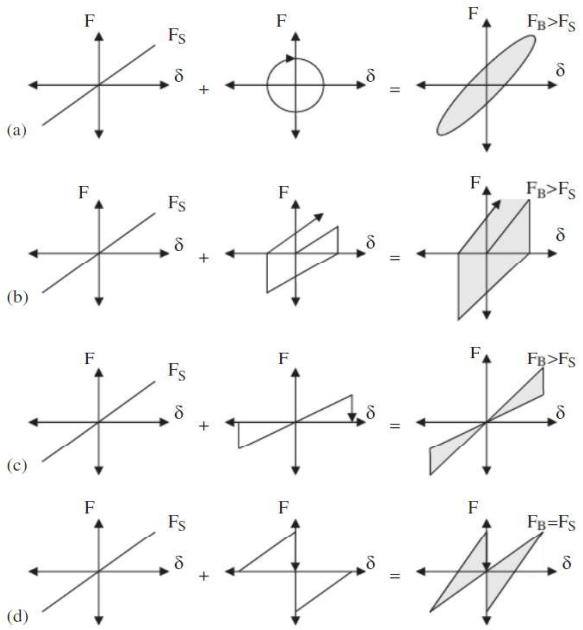


Figure 2.11. Resettable semi-active device [33]: Schematic hysteresis for (a) viscous damping; (b) a 1–4 device; (c) a 1–3 device; and (d) a 2–4 device. Quadrants are labelled in the first panel, and FB=total base shear, FS=base shear for a linear, undamped structure. FB > FS indicates an increase due to the additional damping

Viscous-based energy dissipation devices are well-known to be robust and provide significant forces (see [26]) when they are compared with complex stiffness devices (see [29], [33], [71]) or force-based devices (see [72-73])

Thus, presenting significant advantages over other devices, a fluid viscous damper is ideal for manipulating the force-displacement loop. Up to date however, there are only a few semiactive control systems that can provide viscous damping in selected quadrants.

A semiactive control of conventional viscous damper for building applications was proposed in 2003 by Kurino et al. [32]. Here the opening of the on/off valve is switched by a signal from a controller. Such control law simply locks the damper in quadrants (1 and 3) and opens the valve in quadrants 2 and 4 (Figure 2.12a). However, owing to experiences in the Great East Japan Earthquake of 2011, the demand for a more efficient control device in high-rise buildings was reported. In 2019, Fukuda and Kurino [31] updated their previous Maxwell-type viscous damper model with a Voight model, which was achieved by attaching an auxiliary oil tank to a conventional viscous damper (Figure 2.12b). These two studies [31-32] were only meant to increase energy dissipation of a conventional viscous damper by reshaping its hysteresis loop in selected quadrants (1 and 3). However, such control strategy can lead to an increase in maximum base shear of the building, which, in practice, would likely require strengthening of columns and foundations.

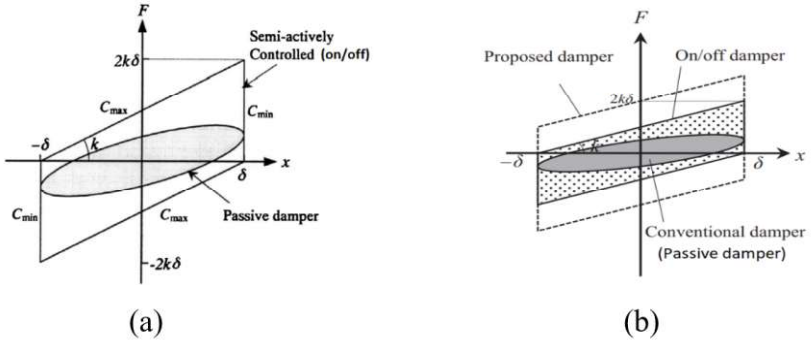


***Figure 2.12**. Force-displacement relation of semiactive damper under harmonic motion; (a) [32], (b) [31]*

Reducing damping force in quadrants 1 and 3, but increasing that in 2 and 4, when the restoring forces in the main structure are reducing, would be a promising response control strategy as it would lead to reduction of the total shear forces in the building. In a recent study [30] the authors adopted a decentralized semiactive control approach to investigate different control laws (1-4, 2-4 and 1-3; Figure 2.13) of a Single Degree of Freedom System (SDOF) subjected to a set of ground motions.

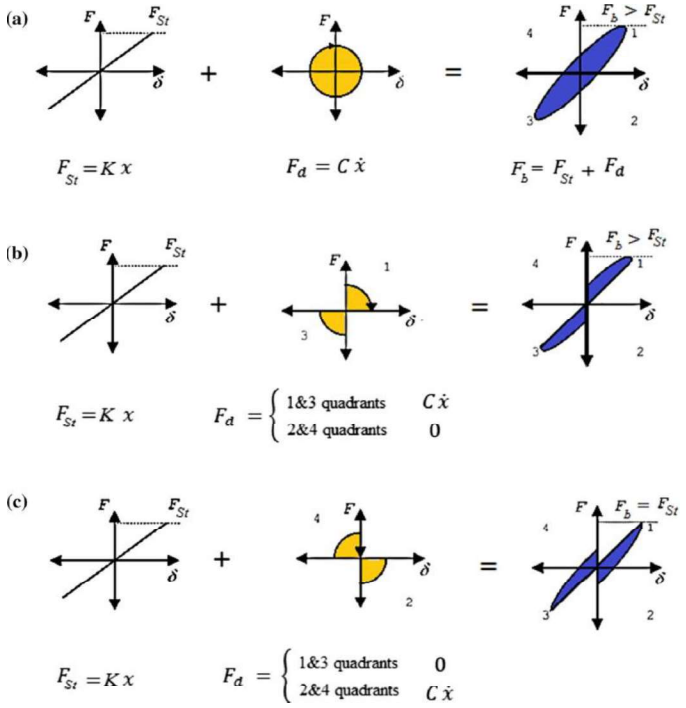


Figure 2.13. *Schematic hysteresis for (a) 1–4 device, (b) 1–3 device, and (c) 2–4 device. Fb = total base shear, FSt = base shear for a linear, un-damped structure. Fb > FSt indicates an increase in the total base shear due to the additional damping force* [30]

Conclusion

The outcomes of this chapter provided important insight into the area of enhancing the seismic performance of structures with viscous damper controls. The use of damping devices is a promising strategy for reducing seismic damage to buildings, and they are particularly effective at improving the response of existing, potentially deficient buildings. When applied to moment-resisting frames (MRF), they generally reduce the drifts but increase the total base shear and acceleration and thus increase the risk of damage to contents (due to greater acceleration) and foundations (due to larger total base shear). However, when used as an alternative to a passive viscous damper, the increase in shear forces and accelerations can be controlled, and the deformations of the structure can be reduced without exceeding the shear force limits by considering semiactive control systems.

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References

[1] A. Kiral and Z. Tonyali, “The February 6, 2023, Kahramanmaras-Turkiye Earthquakes: Seismo-Tectonic Evaluations and Effects on Reinforced Concrete Buildings,” in *Ege 8th International Conference on Applied Sciences*, Izmir, 2023, pp. 1–12.

[2] D. Domenico and I. Hajirasouliha, “Multi-level performance-based design optimisation of steel frames with nonlinear viscous dampers,” *Bull. Earthq. Eng.*, vol. 19, pp. 5015–5049, 2021.

[3] N. Nabid, I. Hajirasouliha, D. Escolano Margarit, and M. Petkovski, “Optimum energy based seismic design of friction dampers in RC structures,” *Structures*, vol. 27, no. February, pp. 2550–2562, 2020, doi: 10.1016/j.istruc.2020.08.052.

[4] H. C. Quintana and M. Petkovski, “Optimum performance of structural control with friction dampers,” *Eng. Struct.*, vol. 172, pp. 154–162, 2018, doi: 10.1016/j.engstruct.2018.06.017.

[5] M. C. Constantinou, A. S. Whittaker, Y. Kalpakidis, D. M. Fenz, and G. P. Warn, “Performance of seismic isolation hardware under service and seismic loading,” the University at Buffalo, State University of New York, 2007. [Online]. Available: http://mceer.buffalo.edu

[6] S. Akcelyan, D. G. Lignos, T. Hikino, and M. Nakashima, “Evaluation of Simplified and State-of-the-Art Analysis Procedures for Steel Frame Buildings Equipped with Supplemental

Damping Devices Based on E-Defense Full-Scale Shake Table Tests," *J. Struct. Eng.*, vol. 142, no. 6, pp. 1–17, Jun. 2016.

[7] Y.-Y. Lin, K.-C. Chang, and C.-Y. Chen, "Direct displacement-based design for seismic retrofit of existing buildings using nonlinear viscous dampers," *Bull. Earthq. Eng.*, vol. 6, no. 3, pp. 535–552, Aug. 2008, doi: 10.1007/s10518-008-9062-9.

[8] Y. M. Parulekar and G. R. Reddy, "Passive Response Control Systems for Seismic Response Reduction: A State-Of-The-Art Review," *Int. J. Struct. Stab. Dyn.*, vol. 9, no. 1, pp. 151–177, 2009, [Online]. Available: www.worldscientific.com

[9] Y. Xie, J. Zhang, and W. Xi, "Effectiveness evaluation and optimal design of nonlinear viscous dampers for inelastic structures under pulse-type ground motions," *Earthq. Eng. Struct. Dyn.*, vol. 47, no. 14, pp. 2802–2820, Nov. 2018.

[10] A. R. Ghaemmaghami and O. S. Kwon, "Nonlinear modeling of MDOF structures equipped with viscoelastic dampers with strain, temperature and frequency-dependent properties," *Eng. Struct.*, vol. 168, no. 7, pp. 903–914, 2018, doi: 10.1016/j.engstruct.2018.04.037.

[11] W.-H. Lin and A. K. Chopra, "Earthquake response of elastic SDF systems with non-linear fluidviscous dampers," *J. Eng. Mech.*, vol. 129, 2003, doi: 10.1061/ASCE0733-93992003129:6597.

[12] J. Xu and J. Li, "Stochastic dynamic response and reliability assessment of controlled structures with fractional derivative model of viscoelastic dampers," *Mech. Syst. Signal*

Process., vol. 72–73, pp. 865–896, May 2016, doi: 10.1016/j.ymssp.2015.11.016.

[13] A. Kıral and A. Gurbuz, "Using supplemental linear viscous dampers for experimentally verified base-isolated building: Case study," *J. Struct. Eng. Appl. Mech.*, vol. 7, no. 1, pp. 34–50, Mar. 2024, doi: 10.31462/jseam.2024.01034050.

[14] I. D. Aiken, D. K. Nims, A. S. Whittaker, and J. M. Kelly, "Testing of Passive Energy Dissipation Systems," *Earthqauke Spectra*, vol. 9, 1993.

[15] J. E. Martínez-Rueda, "On the evolution of energy dissipation devices for seismic design," *Earthq. Spectra*, vol. 18, no. 2, pp. 309–346, 2002, doi: 10.1193/1.1494434.

[16] K. C. Tsai, H. W. Chen, C. P. Hong, and Y. F. Su, "Design of Steel Triangular Plate Energy Absorbers for Seismic-Resistant Construction," *Earthqauke Spectra*, vol. 9, 1993.

[17] A. S. Whittaker, V. V Bertero, C. L. Thompson, and L. J. Alonso, "Seismic Testing of Steel Plate Energy Dissipation Devices," *Earthqauke Spectra*, 1991.

[18] M. Tehranizadeh, "Passive energy dissipation device for typical steel frame building in Iran," *Eng. Struct.*, vol. 23, pp. 643–655, 2001.

[19] M. Bayat and G. R. Abdollahzade, "Analysis of the steel braced frames equipped with ADAS devices under the far field records," *Lat. Am. J. Solids Struct.*, vol. 8, pp. 163–181, 2011.

[20] L. D. Aiken, J. M. Kelly, and A. S. Pall, "Seismic response of a nine-story steel frame with friction damped cross-

bracing," in *ninth world Conf. Earthq. Eng.*, Tokyo Kyoto, Japan, 1988.

[21] J. Enrique Martinez-Rueda and A. S. Elnashai, "A novel technique for the retrofitting of reinforced concrete structures," *Eng. Struct.*, vol. 17, no. 5, pp. 359–371, 1995.

[22] A. S. Pall and C. Marsh, "Response of Friction Damped Braced Frames," *J. Struct. Div.*, vol. 108, 1982.

[23] A. Filiatrault, R. Tremblay, and A. Wanitkorkul, "Performance evaluation of passive damping systems for the seismic retrofit of steel moment-resisting frames subjected to nearfield ground motions," *Earthq. Spectra*, vol. 17, no. 3, pp. 427–456, 2001.

[24] W. H. Lin and A. K. Chopra, "Asymmetric one-storey elastic systems with non-linear viscous and viscoelastic dampers: Earthquake response," *Earthq. Eng. Struct. Dyn.*, vol. 32, no. 4, pp. 555–577, Apr. 2003, doi: 10.1002/eqe.237.

[25] H. K. Miyamoto and J. P. Singh, "Performance of Structures with Passive Energy Dissipators," *Earthq. Spectra*, vol. 18, no. 1, pp. 105–119, 2002.

[26] M. D. Symans and M. C. Constantinou, "Development and Experimental Study of Semi-Active Fluid Damping Devices for Seismic Protection of Structures, Technical Report NCEER-95-0011," 1995. [Online]. Available: Technical Report NCEER-95-0011

[27] R. Vargas and M. Bruneau, "Effect of Supplemental Viscous Damping on the Seismic Response of Structural Systems

with Metallic Dampers," *J. Struct. Eng.*, 2007, doi: 10.1061/ASCE0733-94452007133:101434.

[28] P. I. Kogut and G. Leugering, "Optimal L1-Control in Coefficients for Dirichlet Elliptic Problems: W-Optimal Solutions," *J. Optim. Theory Appl.*, vol. 150, no. 2, pp. 205–232, Aug. 2011, doi: 10.1007/s10957-011-9840-4.

[29] J. G. Chase *et al.*, "Re-shaping hysteretic behaviour using semi-active resettable device dampers," *Eng. Struct.*, vol. 28, no. 10, pp. 1418–1429, Aug. 2006, doi: 10.1016/j.engstruct.2006.01.011.

[30] N. K. Hazaveh, G. W. Rodgers, J. G. Chase, and S. Pampanin, "Reshaping structural hysteresis response with semi-active viscous damping," *Bull. Earthq. Eng.*, vol. 15, no. 4, pp. 1789–1806, 2017, [Online]. Available: Netherlands

[31] R. Fukuda and H. Kurino, "Highly efficient semi-active oil damper with energy recovery system," *Japan Archit. Rev.*, vol. 2, no. 3, pp. 238–249, 2019, [Online]. Available: Japan

[32] H. Kurino, J. Tagami, K. Shimizu, and T. Kobori, "Switching Oil Damper with Built-in Controller for Structural Control," *J. Struct. Eng.*, vol. 129, no. 7, pp. 895–904, 2003.

[33] K. J. Mulligan, J. G. Chase, J. B. Mander, G. W. Rodgers, and R. B. Elliott, "Nonlinear models and validation for resetable device design and enhanced force capacity," *Struct. Control Heal. Monit.*, vol. 17, no. 3, pp. 301–316, Apr. 2008, doi: 10.1002/stc.298.

[34] M. Dan and M. Kohiyama, “System identification and control improvement of a semi-active-controlled base-isolated building using the records of the 2011 Great East Japan Earthquake,” in *Safety, Reliability, Risk and Life-Cycle Performance of Structures and Infrastructures - Proceedings of the 11th International Conference on Structural Safety and Reliability, ICOSSAR*, 2013.

[35] H. P. Gavin and U. Aldemir, “Optimal Control of Earthquake Response Using Semiactive Isolation,” *J. Eng. Mech.*, vol. 131, no. 8, pp. 769–775, 2005.

[36] C. Ho, Y. Zhu, Z. Q. Lang, S. A. Billings, M. Kohiyama, and S. Wakayama, “Nonlinear damping based semi-active building isolation system,” *J. Sound Vib.*, vol. 424, pp. 302–317, 2018, doi: 10.1016/j.jsv.2018.03.023.

[37] N. Kurata, T. Kobori, M. Takahashi, N. Niwa, and H. Midorikawa, “Actual Seismic Response Controlled Building with Semi-Active Damper System,” 1999.

[38] W. N. Patten, J. Sun, G. Li, J. Kuehn, and G. Song, “Field Test of An Intelligent Stiffener For Bridges At The I-35 Walnut Creek Bridge,” *Earthq. Eng. Struct. Dyn.*, vol. 28, pp. 109–126, 1999.

[39] C. T. Lee and B. Y. Moon, “Study of the simulation model of a displacement-sensitive shock absorber of a vehicle by considering the fluid force,” *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.*, vol. 219, no. 8, pp. 965–975, Aug. 2005, doi: 10.1243/095440705X34685.

[40] S. Nie, Y. Zhuang, Y. Wang, and K. Guo, “Velocity & Displacement-Dependent Damper: A Novel Passive Shock Absorber Inspired by the Semi-Active Control,” *Mech. Syst. Signal Process.*, vol. 99, pp. 730–746, Jan. 2018.

[41] O. Yoshida and S. J. Dyke, “Seismic Control of a Nonlinear Benchmark Building Using Smart Dampers,” *J. Eng. Mech.*, 2004, doi: 10.1061/ASCE0733-93992004130:4386.

[42] K. C. Chang, M. L. Lai, T. T. Soong, D. S. Hao, and Y. C. Yeh, “Seismic Behavior and Design Guidelines for Steel Frame Structures with Added Viscoelastic Dampers,” 1993.

[43] P. Guo, “Damping System Designs using Nonlinear Frequency Analysis Approach,” Department of Automatic Control and Systems Engineering, Faculty of Engineering, University of Sheffield, 2012.

[44] T. K. Datta, “A state-of-the-art review on Active Control of Structures,” *ISET J. Earthq. Technol.*, vol. 40, no. 1, pp. 1–17, 2003.

[45] D. Hrovat, P. Barak, and M. Rabins, “Semi-Active versus Passive or Active Tuned Mass Dampers for Structural Control,” *J. Eng. Mech.*, vol. 109, no. 3, pp. 691–705, 1983, doi: 10.1061/(asce)0733-9399(1983)109:3(691).

[46] T. A. Z. Rahman, A. As’arry, and N. A. A. Jalil, “Active Vibration Control of a Flexible Beam Structure Using Chaotic Fractal Search Algorithm,” *Procedia Eng.*, vol. 170, pp. 299–306, 2017, doi: 10.1016/j.proeng.2017.03.033.

[47] Z. Q. Lang, P. F. Guo, and I. Takewaki, “Output frequency response function based design of additional nonlinear viscous dampers for vibration control of multi-degree-of-freedom systems,” *J. Sound Vib.*, vol. 332, no. 19, pp. 4461–4481, 2013, doi: 10.1016/j.jsv.2013.04.001.

[48] I. Takewaki, “Optimal Damper Placement for Minimum Transfer Function,” *Earthq. Engng. Struct. Dyn*, vol. 26, pp. 1113–1124, 1997.

[49] D. P. Taylor and M. C. Constantinou, “Fluid viscous dampers in applications of seismic energy dissipation and seismic isolation,” 2010. [Online]. Available: www. taylordevices. com

[50] D. P. Taylor and M. C. Constantinou, “Development and testing of an improved fluid damper configuration for structures having high rigidity,” in *Proceedings of the 69th Shock and Vibration Symposium*, 1996.

[51] R. J. McNamara, D. P. Taylor, and P. Duflot, “Fluid Viscous Dampers to reduce Wind-induced Vibrations in Tall Buildings,” 2005. [Online]. Available: http://www.taylordevices.eu/pdfs/tall-building_1.pdf

[52] T. T. Soong and M. C. Constantinou, *Passive and Active Vibration Control in Civil Engineering*, vol. 345, no. May. 1994. doi: 10.1007/978-3-7091-3012-4.

[53] M. C. Constantinou, P. Tsopelas, W. Hammel, and A. N. Sigaher, “Toggle-Brace-Damper Seismic Energy Dissipation Systems,” *J. Struct. Eng.*, vol. 127, no. 2, pp. 105–112, 2001.

[54] A. Gherbi and M. Belgasmia, “Use of fluid viscous dampers in structural control: a case study,” *Int. J. Forensic Eng.*, vol. 4, no. 2, p. 119, 2018, doi: 10.1504/ijfe.2018.10019980.

[55] A. Hwang, “Practical Application Issues for the Structural Engineer,” Massachusetts Institute of Technology, 1998.

[56] H. B. Yun *et al.*, “Comparison of modeling approaches for full-scale nonlinear viscous dampers,” *JVC/Journal Vib. Control*, vol. 14, no. 1–2, pp. 51–76, 2008, doi: 10.1177/1077546307079396.

[57] S. Infanti, P. Papanikolas, G. Benzoni, and M. G. Castellano, “Rion-Antirion Bridge : Design And Full-Scale Testing,” 2004.

[58] R. J. McNamara, C. D. Huang, and V. Wan, “Viscous-damper with motion amplification device for high rise building applications,” in *Structures Congress 2000: Advanced Technology in Structural Engineering*, 2000. doi: 10.1061/40492(2000)123.

[59] J. S. Hwang and Y. S. Tseng, “Design formulations for supplemental viscous dampers to highway bridges,” *Earthq. Eng. Struct. Dyn.*, vol. 34, no. 13, pp. 1627–1642, 2005, doi: 10.1002/eqe.508.

[60] D. De Domenico, G. Ricciardi, and I. Takewaki, “Design strategies of viscous dampers for seismic protection of building structures: A review,” *Soil Dyn. Earthq. Eng.*, vol. 118, no. 1, pp. 144–165, Mar. 2019, doi: 10.1016/j.soildyn.2018.12.024.

[61] T. L. Attard, “Controlling All Interstory Displacements in Highly Nonlinear Steel Buildings Using Optimal Viscous Damping,” *J. Struct. Eng.*, vol. 133, no. 9, pp. 1331–1340, 2007.

[62] O. Lavan, G. P. Cimellaro, and A. M. Reinhorn, “Noniterative Optimization Procedure for Seismic Weakening and Damping of Inelastic Structures,” *J. Struct. Eng.*, vol. 134, no. 10, pp. 1638–1648, 2008, doi: 10.1061/(asce)0733-9445(2008)134:10(1638).

[63] O. Lavan and G. F. Dargush, “Multi-objective evolutionary seismic design with passive energy dissipation systems,” *J. Earthq. Eng.*, vol. 13, no. 6, pp. 758–790, 2009, doi: 10.1080/13632460802598545.

[64] FEMA-356, “American Society of Civil Engineers, Fema 356 Prestandard and Commentary for the Seismic Rehabilitation of Building,” *Rehabilitation*, no. November, 2000.

[65] CEN Eurocode 8, “CEN (European Committee for Standardisation). Eurocode 8: design of structures for earthquake resistance. General rules, seismic actions and rules for buildings. EN1998-1:2004. (EN 1998-1, Brussels; 2004),” 2004.

[66] G. Alotta, L. Cavaleri, M. Di Paola, and M. F. Ferrotto, “Solutions for the Design and Increasing of Efficiency of Viscous Dampers,” *Open Constr. Build. Technol. J.*, vol. 10, no. 1, pp. 106–121, 2016, doi: 10.2174/1874836801610010106.

[67] S. Pourzeynali and T. Mousanejad, “Optimization of Semi-Active Control of Seismically Excited Buildings Using Genetic Algorithms,” *Trans. A Civ. Eng.*, vol. 17, no. 1, 2010.

[68] F. Oliveira, M. A. Botto, P. Morais, and A. Suleman, “Semi-active structural vibration control of base-isolated buildings using magnetorheological dampers,” *J. Low Freq. Noise Vib. Act. Control*, vol. 37, no. 3, pp. 565–576, 2017, doi: 10.1177/1461348417725959.

[69] C. T. Lee and B. Y. Moon, “Simulation and experimental validation of vehicle dynamic characteristics for displacement-sensitive shock absorber using fluid-flow modelling,” *Mech. Syst. Signal Process.*, vol. 20, no. 2, pp. 373–388, Feb. 2006, doi: 10.1016/j.ymssp.2004.09.006.

[70] P. Tsopelas and M. C. Constantinou, “NCEER-Taisei Research Program on Sliding Seismic Isolation Systems for Bridges: Experimental and Analytical Study of a System Consisting of Sliding Bearings and Fluid Restoring Force/Damping Devices,” 1994.

[71] G. W. Rodgers, J. B. Mander, J. G. Chase, K. J. Mulligan, B. L. Deam, and A. Carr, “Re-shaping hysteretic behaviour - Spectral analysis and design equations for semi-active structures,” *Earthq. Eng. Struct. Dyn.*, vol. 36, no. 1, pp. 77–100, 2007, doi: 10.1002/eqe.624.

[72] L. M. Jansen and S. J. Dyke, “Semiactive Control Strategies for MR Dampers: Comparative Study,” *J. Eng. Mech.*, vol. 126, no. 8, pp. 795–803, 2000.

[73] F. C. Ponzo, A. Di Cesare, A. Telesca, A. Pavese, and M. Furinghetti, “Advanced modelling and risk analysis of rc buildings with sliding isolation systems designed by the italian seismic code,” *Appl. Sci.*, vol. 11, no. 4, pp. 1–16, 2021, doi: 10.3390/app11041938.