Novel Displacement Dependent Viscous Damper for Semiactive Control of the Seismic Response of Multi-Storey Buildings

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Abstract

Semiactive (SA) control devices offer significant advantages over passive devices for control of the seismic response of multistorey buildings, but the currently proposed systems suffer from high complexity, leading to increased response lags and concerns about their robustness. An ideal semiactive control should be simple, offering fast response and sufficient control forces while limiting the storey shear and the deformations of the building. Friction based SA systems offer large control forces but are slow and require high energy input. Viscous fluid dampers, which are the focus of this study, offer fast response with very small energy requirements, but introduce difficulties in controlling the maximum storey shear.

This study builds on a recently proposed semiactive control system (2-4DDD: Direction and Displacement Dependent) based on fluid viscous dampers in which the damper forces are controlled by the deformations of the structure (storey drift). This means that the aim of the semiactive control is to maintain a predefined relationship between the damper force and the storey drift.

This study first assesses the performance of 2-4DDD when applied in a realistic scenario of earthquake response of two typical multistorey moment resisting frames (low- and medium-rise buildings) equipped with fluid viscous dampers installed in a Chevron brace configuration and subjected to 5 recorded strong earthquakes with different predominant frequency ranges. Unlike all previous research, in which the SA systems were applied to simplified, linear-elastic MDOF systems, this investigation is carried out by the means of time history simulations of nonlinear response, including development of plastic hinges in the main structure. Performance is assessed by evaluating story drift, which is directly associated with structural damage, and total base-shear which is a measure of the risk of ground floor failure.

The study then introduces two new SA control algorithms designed to control the shape of the structural hysteresis (the relationship between storey shear and inter-storey drift): 2-4DVD (Displacement and Velocity Dependent) and 2-4VDD (Velocity and Displacement Dependent); and a design methodology for the vertical distribution of control parameters for each system. Their performance is again assessed by non-linear time history simulations. The results of the new SA system 2-4DVD, compared with a passive non-linear viscous damper (PNLV) and the existing 2-4DDD viscous damper, show that the new control algorithm is (i) more effective than both in terms of reduced displacement (for the same or less total base shear), and (ii) more robust over a range of ground motions than the 2-4DDD. The 2-4VDD, introduced as a potential improvement in the total base shear of 2-4DVD control, produced lower maximum total base shear by 20-26%, but with significantly increased maximum damper forces (up to over 80%); and can be used in cases where the base shear in the main structure is critical.

To my family . . .

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List of Acronyms

PVD	Passive Viscous Damper
MDOF	Multi-Degree of Freedom
2-4DDD	Quadrants 2 and 4, Displacement and Direction Dependent
2-4DVD	Quadrants 2 and 4, Displacement and Velocity Dependent
2-4VDD	Quadrants 2 and 4, Velocity and Displacement Dependent
SA	Semi Active
FVD	Fluid Viscous Damper
NFVD	Nonlinear Fluid Viscous Damper
UD	Uniform Distribution
SAFVD	Semi Active Fluid Viscous Damper
SDOF	Single-Degree of Freedom
ULS	Ultimate Limit State
Cd	Damping Coefficient (viscous)
$\boldsymbol{F_d}$	Damper force
$\boldsymbol{F_{lim}}$	Brace buckling limit
DCF	Damper Controlled frame
$\boldsymbol{a}$	Viscous damper velocity exponent
$\boldsymbol{K_s}$	Brace stiffness
UDD	Uniform Damage Distribution
UCd	Uniform damping coefficient distribution
$\boldsymbol{G}$	maximum damping coefficient amplitude.
$\boldsymbol{A_{2-4}}$	Variable of quadrants 2 and 4 in the 2-4DVD control
$\boldsymbol{A_{1-3}}$	Variable of quadrants 1 and 3 in the 2-4DVD control
$\boldsymbol{C_{d,in}}$	Initial damping coefficient in the 2-4DVD control
$\boldsymbol{K}$	Energy unit constant in the 2-4DVD control
$\boldsymbol{P}$	A constant in the 2-4DVD control
$\boldsymbol{F_{i,c}^{j}}$	Max column force, $\boldsymbol{i}$ storey at $\boldsymbol{j}$ time step

$\boldsymbol{F_{i,d}^{j}}$	Max damper force, $\boldsymbol{i}$ storey at $\boldsymbol{j}$ time step
$\boldsymbol{D}$	A constant in the 2-4VDD control
$\boldsymbol{H}$	maximum damping coefficient amplitude.
$\boldsymbol{3S}$	3-storey.
PLV	Passive Linear Viscous
DE1	Design Earthquake 1
PNLV	Passive Non-Linear Viscous
TCd	Trapezoidal Cd (damping coefficient)
PNLVA03	Passive Non-Linear Viscous Alpha=0.3
PNLVA05	Passive Non-Linear Viscous Alpha

CHAPTER 1 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.

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.

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 (Quintana 2013). Relatively simple passive control systems, which can be based on a variety of mechanisms (Constantinou et al. 2007), such as viscous (see (Lin et al. 2008; Parulekar and Reddy 2009; Akcelyan et al. 2016; Xie et al. 2018);**Figure 1. 1a**), viscoelastic (see (Lin and Chopra 2003a; Parulekar and Reddy 2009; Xu and Li 2016; Ghaemmaghami and Kwon 2018); **Figure 1. 1b**), yielding (see (Whittaker et al. 1991; Aiken et al. 1993; Tsai et al. 1993; Tehranizadeh 2001; Martínez-Rueda 2002; Parulekar and Reddy 2009; Bayat and Abdollahzade 2011); **Figure 1. 1c**), or friction (see (Pall and Marsh 1982; Aiken et al. 1988; Enrique Martinez-Rueda and Elnashai 1995; Martínez-Rueda 2002; Parulekar and Reddy 2009)**; 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.

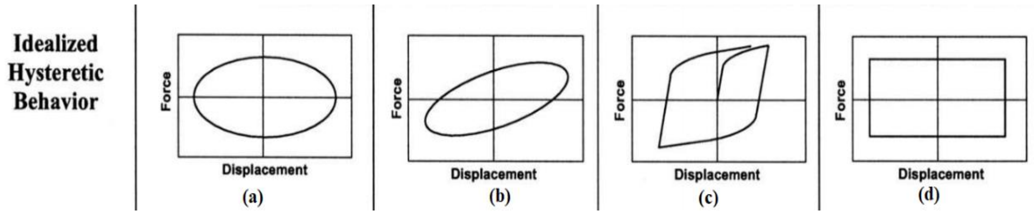


Figure 1. 1: Hysteretic behavior of viscous (a), viscoelastic solid (b), metallic (c) and friction damper (d)

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 (Symans and Constantinou 1995; Filiatrault et al. 2001; Miyamoto and Singh 2002; Lin and Chopra 2003b; Vargas and Bruneau 2007). 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 (Symans and Constantinou 1995).

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 (Kogut and Leugering 2011). 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 (Symans and Constantinou 1995). Semi-active control device function continues its operation as a passive device, even in case of a power failure (Symans and Constantinou 1995). 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 (Chase et al. 2006; Hazaveh et al. 2017a). The semi-active control system can only alter the control action of a structure by changing the damping (Kurino et al. 2003; Fukuda and Kurino 2019) or stiffness of the system (Mulligan et al. 2008).

It was already discussed that additional PVDs in non-linear structures or generally in structures with a high level of damping (see chapter 5) 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 (Symans and Constantinou 1995; Kurata et al. 1999; Patten et al. 1999; Gavin and Aldemir 2005; Dan and Kohiyama 2013; Ho et al. 2018)), 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. 2**a) to achieve design objectives such as reducing drift without increasing base shear (Hazaveh et al. 2017a), increasing energy dissipation of the damper (Kurino et al. 2003; Fukuda and Kurino 2019) or effective shock absorbers for vehicles (Lee and Moon 2005; Nie et al. 2018). The force-displacement loop can be reshaped by either decentralised semiactive control (Kurino et al. 2003; Hazaveh et al. 2017a; Fukuda and Kurino 2019), or mechanically, by a passive damper (Hazaveh et al. 2017a; Nie et al. 2018). 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 (Lee and Moon 2005; Nie et al. 2018).

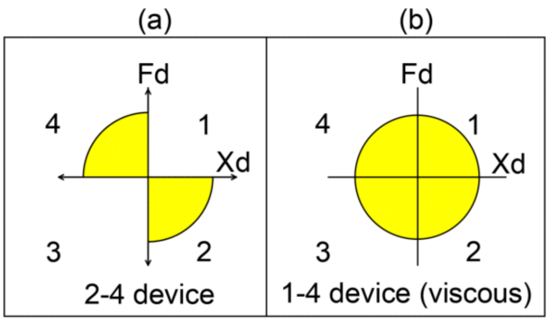


Figure 1. 2: Force- displacement relation of a conventional passive linear viscous damper

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.

1.1 Scope of the research

This research is mainly focused on the seismic performance of novel fluid viscous damper mechanisms, with re-shaped hysteretic response, which is achieved by semiactive control.

The selection of a proper passive viscous damper, considering both linear and nonlinear dampers, is also part of this investigation, as a basis for more complete assessment of the efficiency of the semiactive controllers.

The development of design procedures for semiactive controllers applied to non-linear MDOF systems is also within the scope of this study.

1.2 Thesis Outline

CHAPTER 1 introduces the rationale for and the main scope of this research. Dissipation systems like passive viscous dampers can be used to improve seismic building performance. However, such vibration control applications can result in an increase in total base shear and thus foundation demand especially for structures designed for extreme earthquakes (e.g., high-level of added damping).

Hence, a semiactive viscous damper, which can offer a reduction in drift without increasing base shear, could be a promising approach for mitigating structural damages during earthquakes. The overall goal of this study is to introduce novel semiactive control strategies and algorithms and a design procedure for their use in MDOF systems, to mitigate structural damage or meet the design needs under earthquakes.

CHAPTER 2 presents a review of the literature on control systems in earthquake engineering.

CHAPTER 3 outlines the aim, objective and methodology for the study.

CHAPTER 4 presents in detail the methodology for the fulfilment of the aim and objectives of this research. This chapter also covers two design methodologies with two algorithms for the semiactive controls.

CHAPTER 5 presents a study of passive fluid viscous dampers. The aim is to select a passive control system that will be used for comparison with the semiactive systems investigated in this research. The investigation is carried out using simulations of non-linear seismic response of two typical multistorey buildings (MRFs) equipped with passive viscous dampers, subjected to a set of strong earthquakes, and a variation of viscous damper parameters such as vertical coefficient distribution and two different velocity exponents.

CHAPTER 6 presents the results of the study of two decentralized semiactive viscous damper control algorithms: 2-4DDD, proposed in an earlier study ((Hazaveh et al. 2017a)) and 2-4DVD, a new algorithm which reshapes the structural hysteresis with the aim of producing the same level of total base shear with reduced deformation (drift) of buildings (3- and 7-story). The performance of the two semiactive controls in Multi-Degree-of-Freedoms is assessed by comparing the resulting inter-story drifts with passive control (under the circumstances of having the same /or similar base shear).

CHAPTER 7 introduces 2-4VDD**,** another new semiactive control, designed to further reduce the total base shear of the frames produced by 2-4DVD under a set of ground motions.

The design methodologies for the use of both 2-4DVD and 2-4VDD in MDOF systems is presented in chapter 4.

CHAPTER 8 summarises the conclusions of the research, and

CHAPTER 9 discusses the future work that can be undertaken to take this research further.

CHAPTER 2 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 (Quintana, 2013).

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 (Quintana 2013), they have simple working mechanisms, they absorb a significant amount of seismic energy from the structures, and they require little maintenance after installation (Symans and Constantinou 1995). In a passive control system (PCS), the control forces applied to the building only depend on the structural motion (Yoshida and Dyke 2004). 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 (Nabid et al.

2020; Domenico and Hajirasouliha 2021) that use sophisticated optimisation techniques to establish simple rules for designing passive systems.

2.2 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) (Chang et al. 1993; Symans and Constantinou 1995; Guo 2012)

2.3 Semiactive control

Semiactive (SA) systems which are a combination of active and passive control systems requires a small external power source for its operation (Symans and Constantinou 1995), 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 (Symans and Constantinou 1995). As an active control system, it monitors the feedback from the control system and creates necessary command signals (Datta 2003). Control forces which are only engaged to deliver the resistive forces (Ho et al. 2018) 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 (Hrovat et al. 1983; Symans and Constantinou 1995; Rahman et al. 2017). 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 (Hazaveh et al. 2017a)) or stiffness characteristics of the system (see (Chase et al. 2006)).

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. (Symans and Constantinou 1995), 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*." (Symans and Constantinou 1995).

According to Symans and Constantinou (1995), variable damping coefficients can be estimated as follows (see eq. 2.1):

$$C(v) = C_{min} + (C_{max} - C_{min})\exp(-\mu v n) \quad (2.\ 1)$$

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.

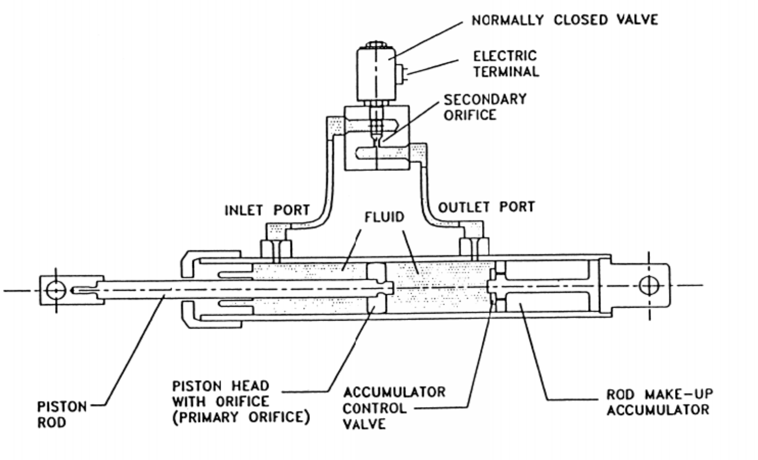


Figure 2. 1: A Semiactive fluid damper (Symans and Constantinou 1995)

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. (Hrovat et al. 1983).

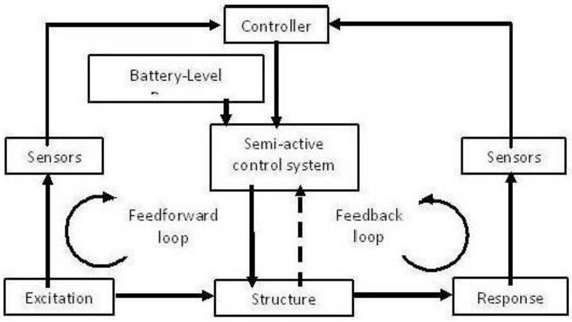


Figure 2. 2: Schematic diagram of the semi-active control system (Hrovat et al. 1983)

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 (Symans and Constantinou 1995). 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., (Takewaki 1997; Lang et al. 2013)).

2.4 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 (Taylor Device Inc 2020). 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 (Taylor and Constantinou 1996). 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 (Taylor Device Inc 2020). 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 (Soong and Constantinou 1994) 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(Guo 2012). These boosted the Fluid viscous dampers' acceptance in civil engineering and practical mechanical systems.

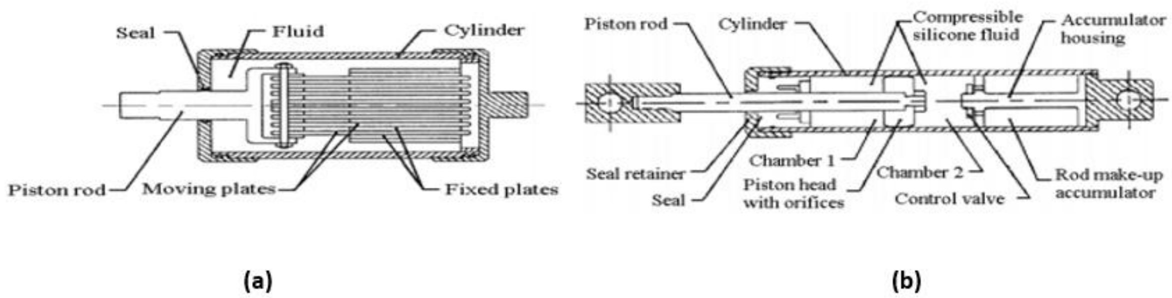


Figure 2. 3: Fluid viscous damper (a-left), modern FVD (b-right) (Soong and Constantinou 1994)

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 (Symans and Constantinou 1995; Guo 2012).

Some of the advantages of FVD are (see (Guo 2012)):

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.**

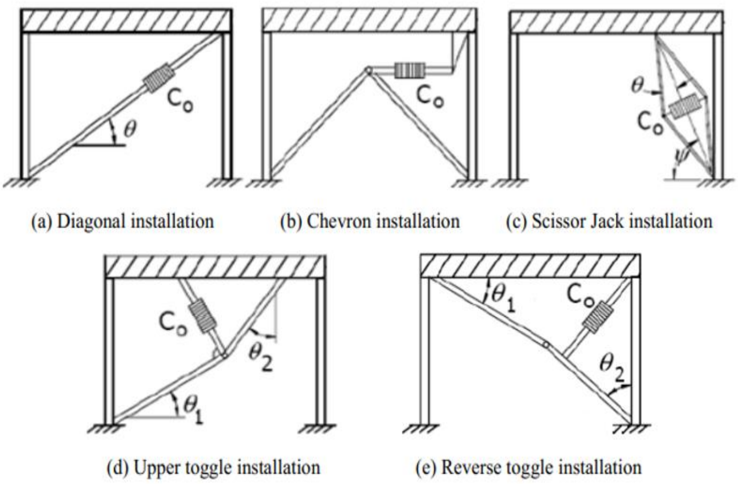


Figure 2. 4: Typical installation modes of FV damping devices (Constantinou et al. 2001)

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).

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

where $\dot{\delta}$ is the relative velocity between the two ends of the damper. $\boldsymbol{C_d}$ 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.

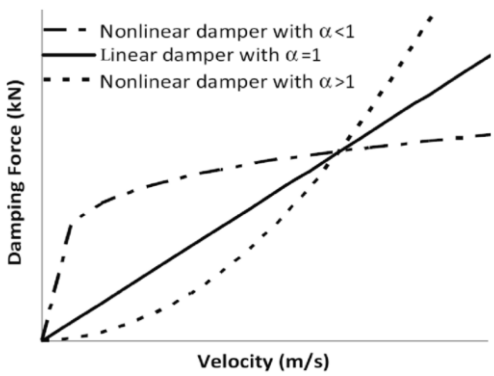


Figure 2. 5: Force-velocity relationship of viscous damper (Gherbi and Belgasmia 2018)

When the damping exponent (α) 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 (α=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 (Gherbi and Belgasmia 2018)

2.5 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 (Hwang 1998). 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 (Symans and Constantinou 1995). 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.

2.6 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 (McNamara et al. 2005). 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 (Yun et al. 2008). 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 (Infanti et al. 2004). 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. (McNamara et al. 2000) 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 (Hwang and Tseng 2005).

De Domenico et al (De Domenico et al. 2019) 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)

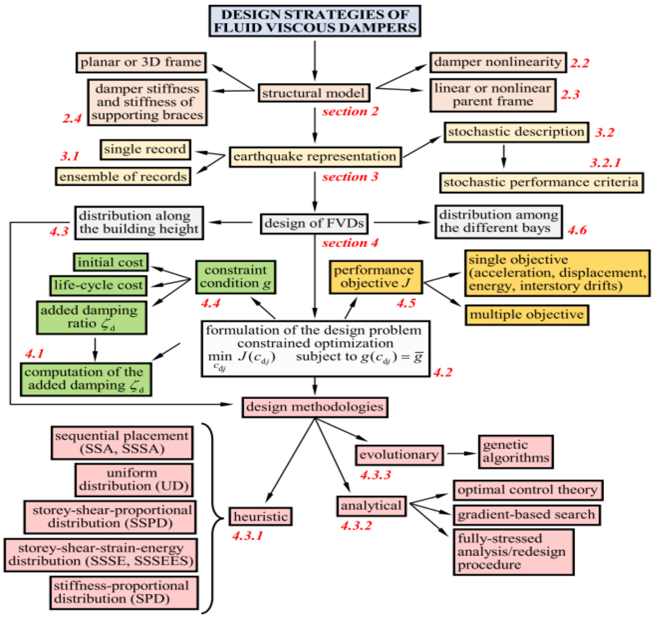


Figure 2. 6: Design strategies of fluid viscous dampers (De Domenico et al. 2019)

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 (Attard 2007; Lavan et al. 2008; Lavan and Dargush 2009)). 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 (FEMA-356 2000) and recently EC8 (CEN 2013) provide specific recommendations for simplified structural analysis and design of dampers in buildings, but not sufficient information for an easy and rapid damper design (Alotta et al. 2016).

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 (FEMA-356 2000) 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.

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

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

With the use of damping correction factors, Eurocode 8 (CEN 2013) also determines the damping ratio (ζ) for achieving the desired performance level. In Cl. 3.2.2.2 (CEN 2013), Eurocode 8 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 (Symans and Constantinou 1995; Filiatrault et al. 2001; Miyamoto and Singh 2002; Lin and Chopra 2003b; Vargas and Bruneau 2007)). 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.

2.7 Semiactive FVD applications

To improve the performance of the conventional passive FVDs, after some experimental works, a study (Symans and Constantinou 1995) 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. (Kurata et al. 1999) in the 1990s. The other applications of SAFVDs were introduced in vibration control of bridges (Patten et al. 1999). Low-rise linear base-isolated structures equipped with SAFVDs were also studied (Gavin and Aldemir 2005). 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 (Pourzeynali and Mousanejad 2010). The research concluded that the semi-active system reduced torsional effects of irregular tall building compared with uncontrolled structure. Oliveira et al. (Oliveira et al. 2017) 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 (Oliveira et al. 2017). Ho et al. (Ho et al. 2018) 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 (Symans and Constantinou 1995; Kurata et al. 1999; Gavin and Aldemir 2005; Dan and Kohiyama 2013; Ho et al. 2018), 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 (Hazaveh et al. 2017a)) or increasing energy dissipation of the damper (see (Kurino et al. 2003; Fukuda and Kurino 2019)).

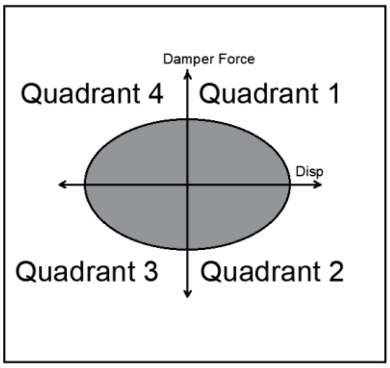


Figure 2. 7: Traditional force-displacement relation of fluid viscous damper

The force-displacement loop (**Figure 2. 7**) can be reshaped by either decentralised semiactive control (Kurino et al. 2003; Hazaveh et al. 2017a; Fukuda and Kurino 2019), or mechanically, by a passive damper (Hazaveh et al. 2017a; Nie et al. 2018). 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 (Lee and Moon 2005, 2006; Nie et al. 2018).

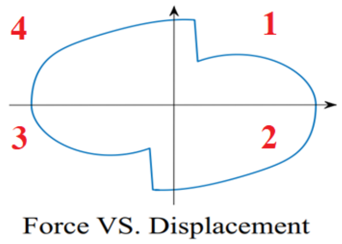


Figure 2. 8: Force-displacement relation of a shock-absorber for a vehicle (Nie et al. 2018)

A variable damping viscous device, which can just adjust the level of damping, was first reported in NCEER-95-0011 (Symans and Constantinou 1995). 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.

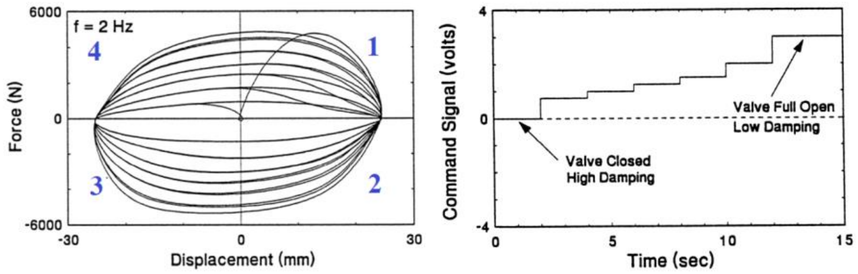


Figure 2. 9: Typical force- displacement loops for variable damper-from report NCEER 95-0011

Tsopelas and Constantinou (Tsopelas and Constantinou 1994) 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.

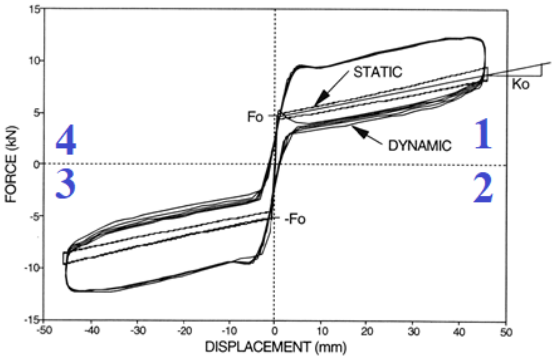


Figure 2. 10: the response of the device from report NCEER 94-0014

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., (Kurino et al. 2003; Hazaveh et al. 2017a; Fukuda and Kurino 2019)). 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 (Chase et al. 2006; Rodgers et al. 2007; Mulligan et al. 2008). The semiactive control devices based on the concept of variable stiffness are complex**,** increase the base shear (for **Figure 2. 11**b and **Figure 2. 11**c) and cannot generate very large control forces which are often required for seismic control of buildings.

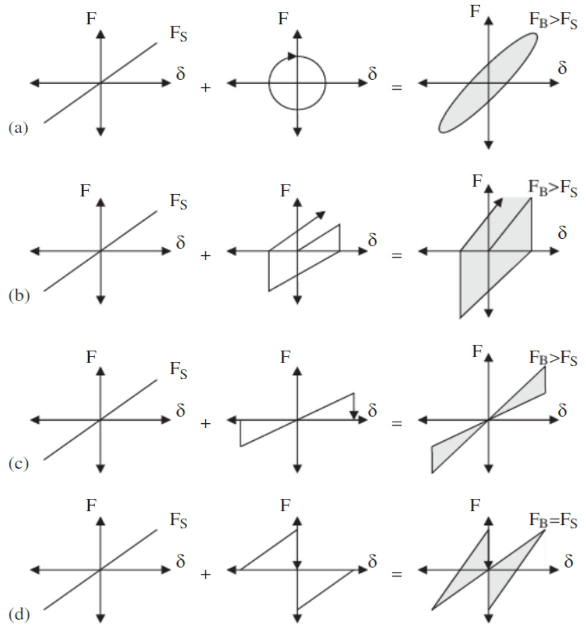


Figure 2. 11: Resettable semi-active device (Mulligan et al. 2008): Schematic hysteresis for (a) viscous damping; (b) a 1–4 device; (c) a 1–3 device; and (d) a 2–4 device. Quadrants are labelled in the first panel, and F_B=total base shear, F_S=base shear for a linear, undamped structure. F_B > F_S indicates an increase due to the additional damping

Viscous-based energy dissipation devices are well-known to be robust and provide significant forces (see (Symans and Constantinou 1995)) when they are compared with complex stiffness devices (see (Chase et al. 2006; Rodgers et al. 2007; Mulligan et al. 2008)) or force-based devices (see (Jansen and Dyke 2000; Ponzo et al. 2012)).

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. (Kurino et al. 2003). 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. 12**a). 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 (Fukuda and Kurino 2019) 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. 12** b). These two studies (Kurino et al. 2003; Fukuda and Kurino 2019) 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.

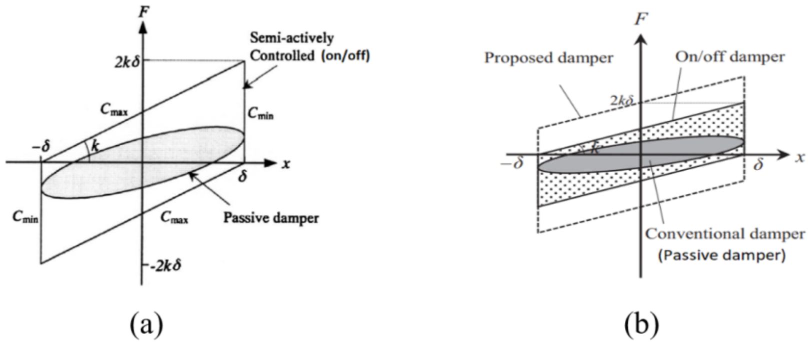


Figure 2. 12: Force-displacement relation of semiactive damper under harmonic motion; a (Kurino et al. 2003), b (Fukuda and Kurino 2019)

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 (Hazaveh et al. 2017a) 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.

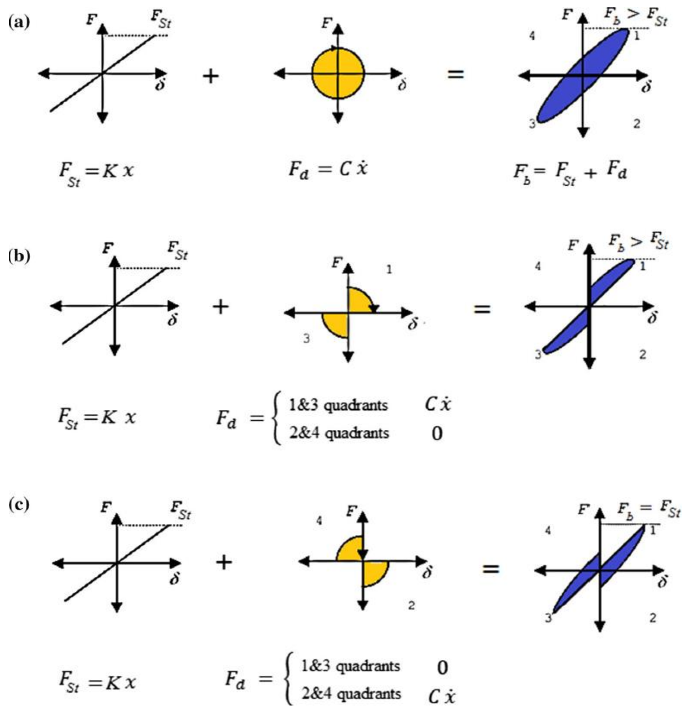


Figure 2. 13: Schematic hysteresis for a: 1–4 device, b: 1–3 device, and c: 2–4 device. Fb = total base shear, FSt = base shear for a linear, un-damped structure. Fb > FSt indicates an increase in the total base shear due to the additional damping force (Hazaveh et al. 2017a)

The study generally concluded that the 2-4 control law (i.e., damping force in quadrants 2 and 4 only) (**Figure 2. 13**c) offered reduced drift and acceleration demands with minimal risk of increased foundation demand on Single-Degree Freedom-Systems (SDOFs). However, such control laws (see (Hazaveh et al. 2017a)) may not be ideal for multi-degree freedom systems (MDOFs), where the response in higher modes interferes with the response wave of the fundamental mode, leading to high-frequency oscillations in the hysteresis loop. This leads to sudden changes in damper velocities caused by abrupt closings and openings between quadrants and reduces the energy dissipation. Also, it may not be a good strategy to be considered for a frame designed for high added damping because having damping forces in only quadrants 2 and 4 (zero force in quadrants 1 and 3) might unnecessarily limit the damper's energy capacity. Allowing the viscous damper to have some forces at small displacement in the dashpot would (i) increase the energy dissipation capacity of the damper without increasing the shear forces in the frame and (ii) it would result in a more stable response, providing smooth transitions between quadrants in MDOFs under a wide range of earthquakes.

If a semiactive control strategy can introduce a novel reshaped viscous damper loop (smooth changes between quadrants), then it could be a solution for the case raised by the 2-4 control law proposed by Hazaveh et al. (Hazaveh et al. 2017a) in MDOF systems.

CHAPTER 3 Aim, Objectives and Outline of Methodology

3.1 Aim

The aim of this research is to examine the potential of existing passive and semiactive control systems for mitigation of the response of realistic (non-linear) multistorey buildings to strong earthquakes and to propose a new semiactive algorithm for improved performance (compared with passive and existing semiactive control).

3.2 Objectives

To achieve the aim, the following objectives are foreseen:

Objective 1: Design a range of typical multi-storey buildings on which passive and decentralized semiactive control algorithms will be tested.

Objective 2: Identify a passive fluid viscous damper system that will be used as a reference system for comparison with the investigated semi-active systems.

Objective 3: Identify the constants of existing (2-4DDD; 2-4 Displacement and Direction Dependent) and new SA control algorithms (2-4DVD; 2-4 Displacement Velocity and Dependent and 2-4VDD; 2-4 Velocity and Displacement Dependent), needed for the design of the SA systems and assessment of their performance.

Objective 4: Conduct a comparative study of the seismic performance of the selected passive control and semiactive control system and newly proposed (improved) semiactive control systems.

3.3 Outline of Methodology

The objectives will be achieved by the following methodological steps:

1. Design of two (3 and 7 storeys) multistorey moment resisting frame (MRF) buildings for ultimate limit state (ULS), in accordance Eurocode 8 (Eurocode8, 2004); with an expectation that the buildings will also comply with the life safety requirements of performance-based design (Objective 1)

2. Perform a detailed parametric study for the damping parameters of linear and non-linear passive dampers (damping coefficients, velocity exponents) and their distribution across the selected buildings as a basis for selecting the reference passive system for further study. The selection will be made through comparing the maximum response (peak inter-story drift and base shear) obtained in simulations of non-linear, time history simulations of response of various passively controlled buildings to a range of selected real earthquakes (with different peak ground acceleration, frequency content and duration). (Objectives 2 and 4)

    - Investigate two potential passive viscous damping coefficient distributions, which are uniform and trapezoidal with two different velocity exponents, for a set of nonlinear MRFs under a wide range of earthquake frequencies.

Examine three decentralized semiactive viscous damping devices, which were aimed to reshape the resulting structural hysteresis loop for control of the seismic response of nonlinear multi-storey buildings under a wide range of earthquake frequencies.

- These semiactive control investigations first aim to increase the energy dissipation of the damper (which was previously examined by Hazaveh et al (Hazaveh et al. 2017a)) by allowing some forces in quadrants 1 and 3.

- Second, minimize the effect of higher modes in the hysteresis loop, and finally

- Propose design methodologies for such new force-displacement relations (semiactive controls).

3. Perform a detailed parametric study for identifying the parameters of the existing and newly proposed SA systems (constants of the different algorithms and their distribution across the analysed buildings) using non-linear, time history simulations of response to the selected earthquakes (Objective 3 and 4)

4. Perform a comparative study of the performance of the selected reference passive and two SA systems (existing 2-4DDD and newly proposed 2-4DVD); using non-linear, time history simulations of the response of the two buildings (3 and 7 storey) to the full range of selected earthquakes, and comparing the maximum drifts, shear in the columns of the main structure, total base shear in the structure and number and spatial distribution of plastic hinges in the main structure. (objective 4)

5. Perform a comparative study of the seismic performance of 2-4DVD and a new improved algorithm 2-4VDD, using non-linear time history simulations of seismic response to all 4 earthquakes (objective 4).

CHAPTER 4 Methodology

4.1 Non-linear time history analysis

The investigation of the performance of the passive and semiactive control systems was conducted by simulating the inelastic dynamic response of multi-storey buildings subjected to time histories of a variety of seismic excitations. All up-to-date research of semiactive systems for control of seismic response is based on an assumption that the main structure remains linear elastic during the earthquake, and in most cases the structure is treated either as an SDOF, or in best cases, as a very simple MDOF system where the entire floor is represented by a single linear element. In this study the main structure of a multi-storey building is represented in detail by a full 2-D structural model, in this case a moment resisting frame, comprising column, beam and brace elements, with 6 degrees of freedom (3 per node). Moreover, this is the first study of semiactive control where the main structural elements can (and do) undergo plastic deformations, which is a far more realistic scenario, as observed on many multistorey buildings under strong earthquakes. The assessment of the efficiency of the proposed control algorithm is made in terms of building response and the required control forces in the dampers. The building response is represented by a detailed set of time histories of important response parameters, such as inter-storey drift, ductility demand on elements, axial load on columns, and storey shear, including base shear (used here as an important response parameter), as well as development of plastic hinges in the elements (their number and spatial distribution also used as a criterion for assessing performance).

The response of the passive control systems can be simulated with the standard OpenSees non-linear time domain analysis (by simply using "*uniaxialMaterial ViscousDamper*" in OpenSees) since the damping coefficients (Cd) remain constant during the analysis. To achieve semi-active control, where Cd values change as a function of the deformations of the building (i.e., movement of the damper element), the standard non-linear dynamic time domain analysis in OpenSees was upgraded. A new procedure was introduced in the step-by-step solution of the dynamic equations:

- In each time step the new Cd is calculated by the proposed algorithms (2-4DVD or 2-4VDD) and updated (by simply using "*updateParameter*" in OpenSees) for each damper, depending on the changes in their drift, effectively changing their force-displacement (hysteretic) behaviour.
- Now Cd becomes function of drift (Cd=f(x); which is the control algorithm) and the semiactively controlled damping force is $Fd = f(x)\dot{x}^{\alpha}$.
- It took an average of less than 3 minutes for the simulation to end in the 3-story frame.
- Yet for the 7-story frame, the time history simulation took just over 2 hours due to small analyse time step (small time step is due to avoiding convergence issue in the simulation).

4.2 Reference structures and seismic excitations

4.2.1 Adopted typical structures

The structural system for the typical multistorey buildings considered in this study is a steel moment resisting frame (MRF) equipped with viscous dampers installed as a Chevron-brace configuration. During earthquakes the structural response would vary depending on the force in the viscous dampers (Fd), between that of an MRF (when $Fd = 0$) and a dual frame (MRF+braces; when $0 < Fd < Flim$ ($brace\ buckling\ limit$)).

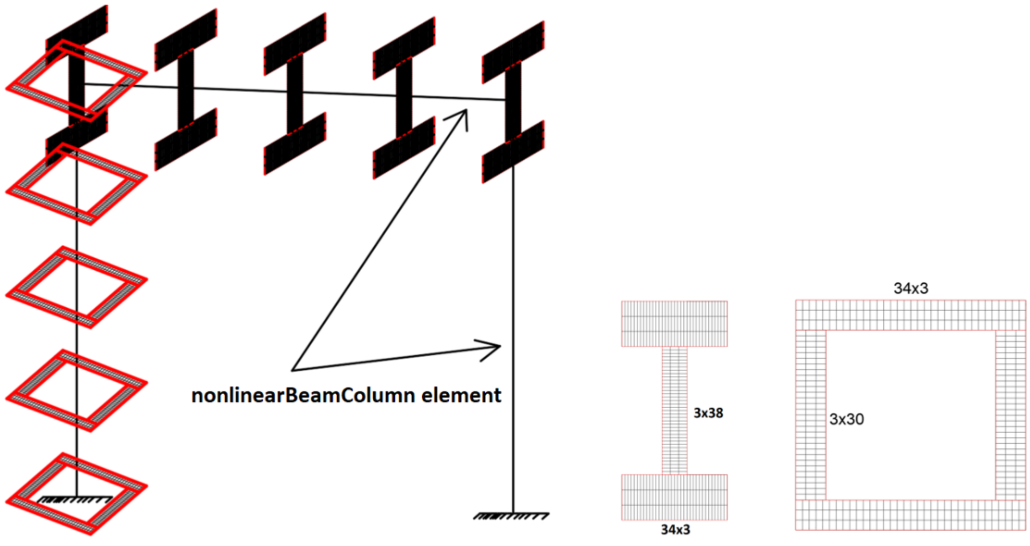
The two buildings used in the study, modelled as two-dimensional (2D) structures (**Figure 4.** ***2***) were designed as dual frames, in accordance with the ductility-based design approach of Eurocode 8 (Eurocode8 2004), using Sap2000 (CSI 2002).

The nonlinear dynamic response of the buildings to selected time histories of seismic excitations was simulated using OpenSees (Open System for Earthquake Engineering Simulation; (McKenna 1997).

The steel beams and columns of the frame (class1 cross-sections) were modelled with a distributed-plasticity approach, using force-based nonlinear elements ("*nonlinearBeamColumn*") with five Gauss–Lobatto integration points per element. The steel beams and columns of the structure are modelled with bilinear steel (Steel01; strain-hardening ratio of 0.01) material in OpenSees.

Kostic and Filippou (2012) recommended that beam sections (wide flange) and column sections (hollow square tube) should be at least 40 fibres and 52 fibres, respectively. In this study, to increase the accuracy of the results, the steel cross-sections of the wide flange beams were discretized with a 34 × 3 fibre element grid along the width and thickness of the flange as well as a 38 × 3 fibre element grid along with the height and thickness of the web, respectively. The steel cross-sections of hollow square columns were discretized with a 30 × 3 fibre element grid along with the inner height of square section and the thickness of the hollow section, and a 34 × 3 fibre element grid along with the outer width of square section and the thickness of the hollow section, respectively. Geometric nonlinearities, P-Delta transformation, were also considered in the modelling stage. The models used for the beams and columns are shown in **Figure 4. 1.** Substandard frames in high-seismic regions are designed according to Eurocode 8 (Eurocode8 2004) for gravity loads and horizontal loads.

Response spectrum for low seismic activity areas (peak ground acceleration (PGA)=0.18 g) using ground type C (shear wave velocity 180- 360 m/s) and behaviour factor q = 6.5 is employed.



(a) (b)

Figure 4. 1: (a) Schematic of OpenSees model with distributed plasticity, (b) idealized element model for distributed plasticity with fiber sections of beams and columns

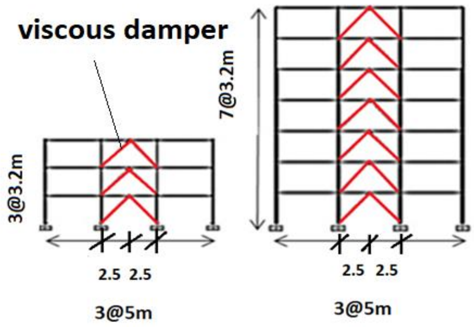


Figure 4. 2: Schematic of the frames with the VDs (beams and columns: force-based distributed plasticity beam-column elements with five integration points along their length).

The Damper Controlled frames (DCFs) consist of three and seven storeys, and three bays. The total height of the structures (3 and 7 stories) is 9.6 and 22.4 respectively. The width of both frames is 15m. Specifications of the frames and designed sections, which are used for the beams, columns and braces, are given in **Table 4. 1**, **Table 4. 2**, **Table 4. 3**. Tubular column and I beams were chosen for simplification of the design (i.e., avoiding miscalculations in the OpenSees during assigning fiber sections).

Table 4. 1: Specifications of the frames

Number of Stories	Weight of frame (KN)	Design base shear (KN)	Period of the frame
3	1115.7	110.4	0.927
7	2959.6	198.96	1.65

Table 4. 2: Designed sections for 3-story frame

Story level	Brace	Column	Beam
1	Tube 100x100x17.5	Tube 200x200x28	HE200B
2	Tube 100x100x10	Tube 200x200x14.2	HE180B
3	Tube 90x90x5	Tube 200x200x12.5	HE140B

Table 4. 3: Designed sections for 7-story frame

Story level	Brace	Column	Beam
1	Tube 120x120x22.2	Tube 260x260x40	HE280B
2	Tube 120x120x17.5	Tube 240x240x40	HE260B
3	Tube 120x120x14.2	Tube 220x220x40	HE240B
4	Tube 120x120x12.5	Tube 220x220x25	HE220B

5	Tube 100x100x12.5	Tube 200x200x22.2	HE200B
6	Tube 90x90x12.5	Tube 180x180x22.2	HE180B
7	Tube 70x70x12.5	Tube 160x160x22.2	HE140B

4.2.2 Fluid Viscous Damper (FVD) modelling

The dampers are modelled as linear viscous dashpots using the “twoNodeLink” element with the “ViscousDamper” material in OpenSees (Akcelyan et al. 2016). The input parameters for such damper are the velocity exponent, α, velocity coefficient, Cd, and the brace stiffness K_s (**Figure 4. 3**a) excluding the axial stiffness of the damper. Viscous damper application doesn't adjust the period of frames since the periods are the product of an *Eigen* analysis (i.e., if there is no movement, then force in the damper is zero). Before dynamic analysis, however, *Rayleigh* damping needs to be calculated, but *Rayleigh* has a stiffness proportional coefficient that depends on the total stiffness of a frame. The length of the viscous damper, which was employed, was around 1m. The rest is supported by a brace (**Figure 4. 3**b). Therefore, the damper supporter (brace) contributes to the damping of the frame. To have a reasonable plan in the design stage, the author used 75% of brace-Rayleigh damping (with a 2% damping ratio) due to the unknown exact contribution of a viscous damper to the structure.

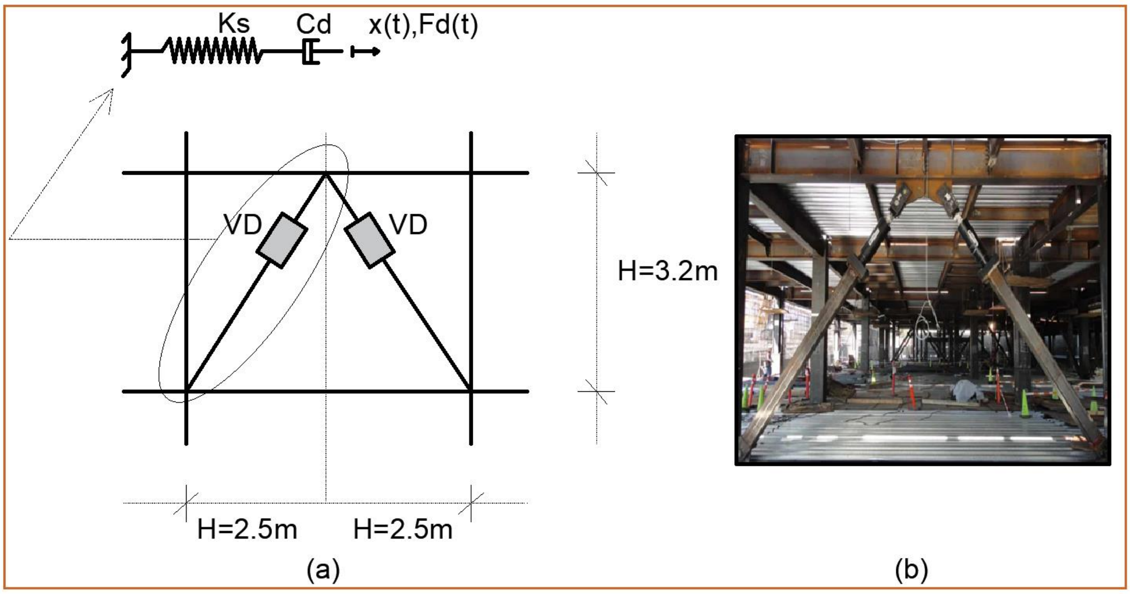


Figure 4. 3: Maxwell type model of viscous damper with its schematic representation (a), and a real building application of chevron type viscous damper (b) (Taylor Device Inc 2020)

4.2.3 Recorded earthquakes

In this study, four different recorded (real) earthquakes, with different predominant frequency ranges**,** were selected (from PEERs database) to opt for optimal passive and semiactive control under a wide range of earthquake frequencies. The acceleration spectrum of earthquakes versus their periods are given in **Figure 4. 4.** The records are given in **Table 4. 4**.

Table 4. 4: Selected natural ground motion records

Earthquake	Mw	Abbr	Station ID/component	PGA (g)	scale
1992 Cape Mendocino	6.9	CAP	CAPEMEND/PET000	0.590	1.4
1999 Duzce	7.2	DUZ	DUZCE/DZC270	0.535	1.0
1994 Northridge-01	6.69	PAR	PARDEE/PAR-L	0.5575	1.0
Chuetsu-oki, Japan	6.8	CHU	Kashiwazaki, NPP/SG01EW	0.444	1.0
Kobe	6.9	KOBE	Takatori/TAK090	0.6155	1.0

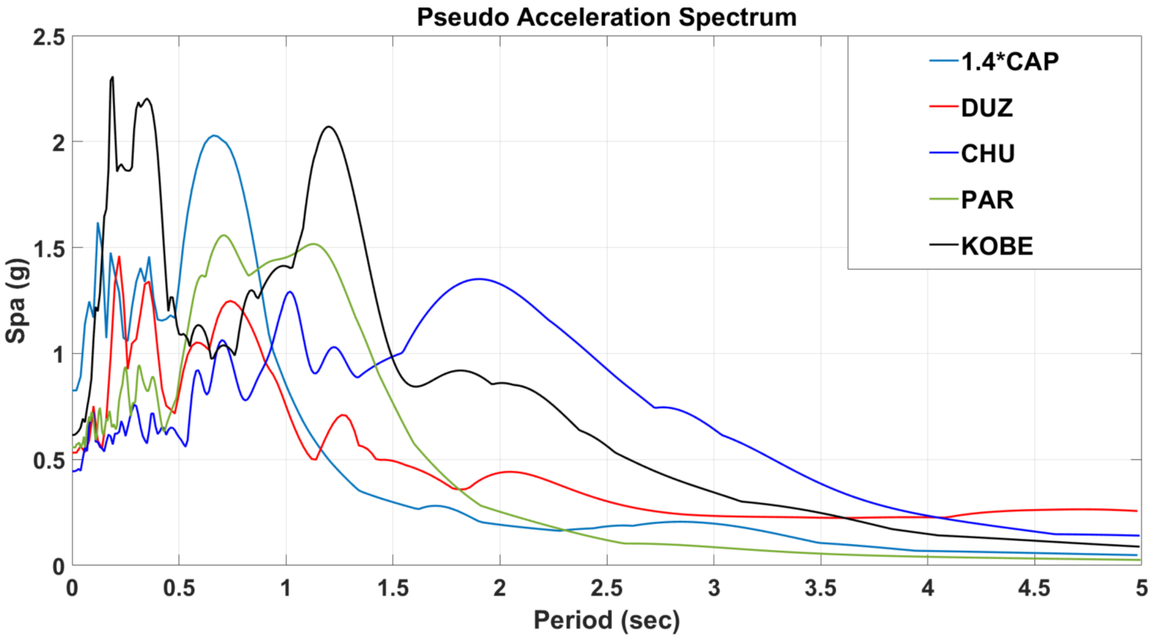


Figure 4. 4: Response spectrum of the selected earthquakes

4.3 Modelling assumptions

It was assumed that the beam and column elements in the frame structures used for the seismic simulations may behave nonlinearly (and considering the P-Delta effect in columns) during the ground excitations. It was also assumed that the nonlinear beam-column connections included adequate appropriate detailing and provided sufficient capacity of rotation. The diagonal braces used in the design (damper-bracing) systems were assumed with an elastic behaviour, but there is an axial force limitation in order not to exceed the buckling resistance of the braces.

4.4 Architectures of control

A centralised or decentralised control strategy can be achieved by different application of control systems in frames (i.e., the network of communication between computers and sensors) (Casciati et al. 2006). The word centralisation here refers to the control signals generated by one central computer. The global feedback from all sensors is assessed by the central controller which then feeds the control devices (**Figure 4. 5**a) (Lynch and Law 2002). A decentralized system generates control signals with a posteriori information obtained from local sensors. It reinforces the reliability of the controller (Casciati et al. 2012) (**Figure 4. 5**c). When it comes to a partially decentralised system, a transference of information between local computers are the case in the control signal generation. It assesses the overall response of the building (**Figure 4. 5**b).

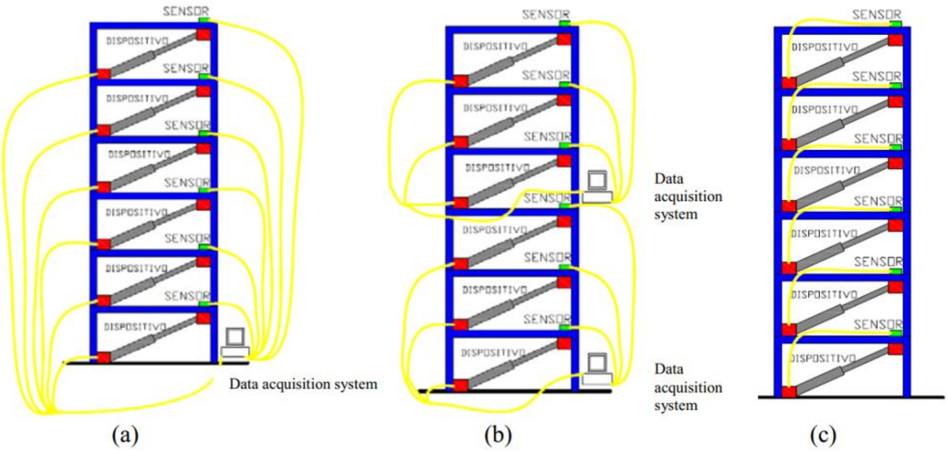


Figure 4. 5: Control strategies, (a) centralized, (b) partially centralized, (c) complete decentralized (Ruiz-Sandoval and Morales 2008)

4.4.1 Semiactive control assumptions

It is assumed that there is no time delay. I.e., time delay resulting from control valve opening and closing is ignored in this study since the point of this study is to prove the advantage of reshaping the hysteresis loop of the conventional passive viscous damper.

4.5 Examination of passive control

A viscous-based passive control was investigated for a 3-storey building under four earthquakes having different predominant frequency ranges: low, medium**,** and high. Non-linear simulations were performed using the *OpenSees* software. The inter-story drift of the passive control systems was monitored to select the required passive damping coefficients. A target inter-storey drift was set to be 6.4 cm and 4.8cm (2 % and 1.5% drift/height coefficient). The selected damping coefficient was the one that kept the maximum inter-story drift close to the target (6.4cm).

In MDOF systems, a proper distribution of passive damping coefficient is important to achieve a desired structural response under a set of earthquakes (i.e., response spectrum compatible earthquakes). Different damping coefficient distribution methods were investigated. The best among them was adopted for a comparison with the semiactive controls investigated in the subsequent stage.

Some of the adopted potential passive viscous damper distributions along the building height are:

Low-rise frame (3-story):

1) Linear viscous damper (alpha=1)

a) Uniform coefficient distribution (1/1/1)

b) Trapezoidal coefficient distribution (0.5/0.75/1)

2) Nonlinear viscous damper (alpha<1)

a) Uniform coefficient distribution (1/1/1) with Alpha=0.3

b) Trapezoidal coefficient distribution (0.5/0.75/1) with Alpha=0.3

c) Uniform coefficient distribution (1/1/1) with Alpha=0.5

d) Trapezoidal coefficient distribution (0.5/0.75/1) with Alpha=0.5

Note that only 3-story building controlled by passive viscous damper was investigated.

The study also investigated Uniform Damage Distribution (UDD) which is a strategy intending to increase the energy dissipation of structural elements (e.g., bare frame) or dual frame (e.g., viscous damper). This strategy was only used for a nonlinear viscous damper in order to provide a basis for a brief discussion by comparing the results of UCd (Uniform damping coefficient Cd Distribution) and UDD.

A two-phase iterative process, which was also adopted by another study (Lavan 2015), was employed for the UDD of viscous damper:

Phase 1: perform an analysis using the current/initial added damping coefficient.

Phase 2: update damping coefficient based on the inter story drift using the following recurrence relation (which was firstly used by Hajirasouliha (Hajirasouliha et al. 2012) for redistributing material from strong to weak parts of a structure until a state of uniform deformation or damage prevails).

$$C_{di}^{(j+1)} = C_{di}^{(j)} * \left(\frac{d_i^{(j)}}{d_i^{targ}}\right)^q$$

where $C_{di}^{(j)}$ is damping coefficient of the story i at iteration j; $d_i^{(j)}$ is peak inter story drift of the story i at iteration j; d_i^{targ} is target drift of the story i; q is a convergence parameter (with a suggested value of 2).

4.6 Examination of existing semiactive control

The force-displacement relations which were used for vibration control of a system in literature (Hazaveh et al. 2017a), were selected to develop a novel hysteresis loop for multi-degree-of-freedom structural frames (MDOFs).

4.6.1 The three control laws

A study (Hazaveh et al. 2017a) investigated three different control laws for viscous dampers, which were achieved by semiactive control. The aim was to reshape the structural hysteresis loop and investigate the effects of the new loops on structural response.

The three control laws used in study (Hazaveh et al. 2017a) are:

- 1–4 control law: conventional passive viscous dampers (i.e., no control)
- 1–3 control law: motion away from equilibrium
- 2–4 control law: motion towards equilibrium (**Figure 4. 6** or **Figure 4. 7a**)

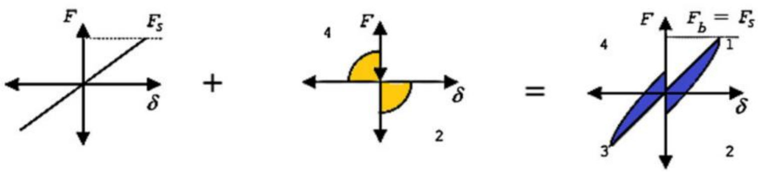


Figure 4. 6: Schematic hysteresis for 2–4 device (Hazaveh et al., 2017a)

Study (Hazaveh et al., 2017a) introduced equation 4.2 and 4.3 to achieve 1-3 devices and 2-4 devices (or 2-4DDD) respectively.

2-4 device (or 2-4DDD) has zero force in quadrants 1 and 3 but has damping forces in quadrants 2 and 4.

1-4 (viscous) device $\{F_d = C_d \times \dot{x}$ **(4.1)**

1-3 device $\begin{cases} if\ sgn(x) \neq sgn(\dot{x}) & F_d \approx 0 \\ if\ sgn(x) = sgn(\dot{x}) & F_d = C_d \times \dot{x} \end{cases}$ **(4.2)**

2-4 device

$$\begin{cases} if\ sgn(x) \neq sgn(\dot{x}) & F_d = C_d \times \dot{x} \\ if\ sgn(x) = sgn(\dot{x}) & F_d \approx 0 \end{cases} \tag{4.3}$$

where F_d denotes the damper force, C_d represents the damping coefficient, $\dot{x}$ stands for the relative story velocity, x is story drift, and $sgn()$ is the sign function returning + or -.

4.7 Development of new semiactive algorithms

For nonlinear structures or with high levels of added damping, viscous dampers can reduce drift demand, but can also increase base shear demand as they provide resistive forces in all four quadrants of the force-displacement loop. Three semiactive (SA) viscous damping control methods (**Figure 4. 7**), which manipulate the overall hysteresis behaviour of the structural frame, are investigated in this research. Specifically, the control is intended to remove forces that would increase the base shear of the system.

The system is based on a decentralized control strategy: the control loop is closed in each device, and control equipment such as the controller and sensors separately work in each device. The proposed SA controls can be represented by a simple equation. **Figure 4. 7** has three different control laws: (a) 2-4DDD (Displacement and Direction Dependent) which has been proposed by a study (Hazaveh et al. 2017a); (b) 2-4DVD (Displacement and Velocity Dependent), which has been inspired by the study (Hazaveh et al. 2017a), is proposed in this thesis; (c) 2-4VDD (Velocity and Displacement Dependent), which has been considered for further investigation of 2-4DVD, is also proposed.

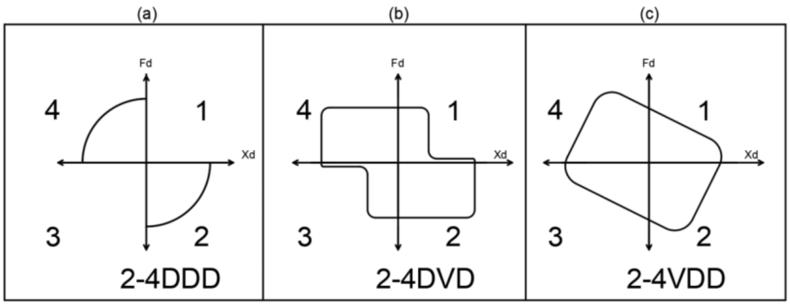


Figure 4. 7: New semiactive control devices based on the 2-4 strategy

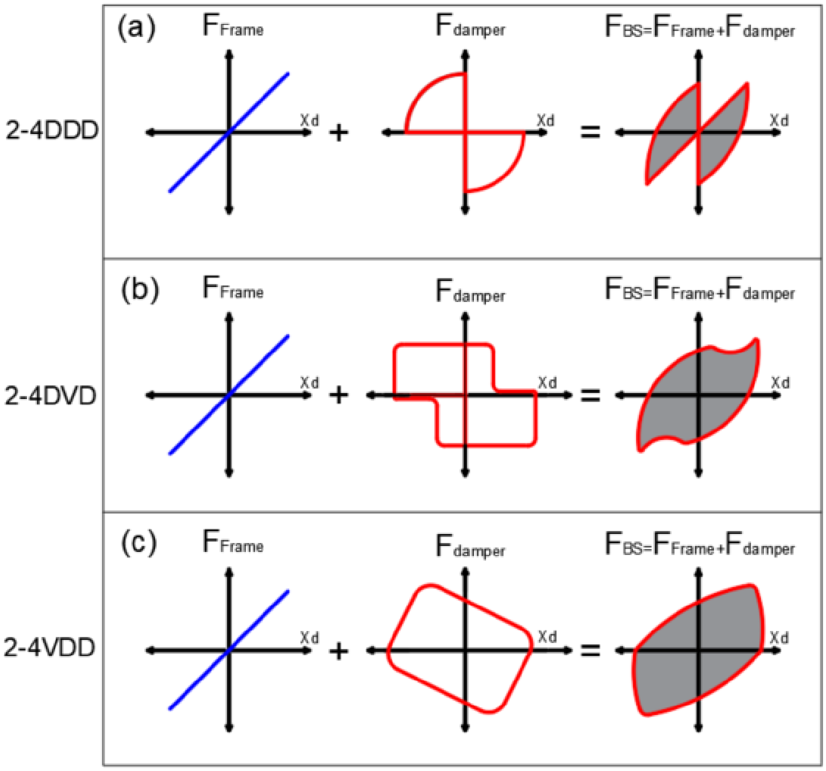


Figure 4. 8: Schematic device hysteresis loop for (a) a 2-4DDD; (b) 2-4DVD; and (c) 2-4VDD. F_{BS} = total base shear, F_{Frame} = base shear for a linear undamped structure. F_{damper} indicates base shear for the damper.

The left column of **Figure 4. 8** depicts the frame without devices. The middle column describes the device responses, while the right column displays the schematic representation of a damped system. Note that it is only meant to schematically represent the bare frame and combination of forces for a simple system.

4.7.1 New semiactive control algorithms: a novel 2-4 Displacement & Velocity Dependent (2-4DVD) Viscous Damper

The orifices of the damper not only have to be closed in quadrants 2 and 4 from peak dashpot displacement back towards zero displacements but also, have to be partially locked in quadrants 1 and 3. I.e., it must have full damping resistance in quadrants 2 and 4 and a portion of damping resistance in quadrants 1 and 3. The proposed algorithm shown in **Figure 4. 7**b is presented in Eq. 4.4. yet to identify a proper P parameter in 2-4DVD control, a parametric study will be also conducted over a range of P values in chapter 6. The initial damping coefficient $C_{d,in}$ is updated based on a ratio which is the energy (under the curve of force-displacement of viscous damper) of the damper at j time divided to (j-1). The parameter P and K have different duties in the algorithm. Parameter P specifies the force length (along displacement loop) in quadrants 1 and 3 (i.e., the bigger P the algorithm has, the earlier the algorithm cuts forces in quadrants 1 and 3). Parameter K ,however, states the forces in quadrants 2 and 4 (i.e., the bigger K the algorithm has, the bigger damping forces the algorithm generates in quadrants 2 and 4).

The conventional force-displacement relation of viscous damper is manipulated to achieve 2-4DVD via a simple algorithm.

Damping coefficients are updated with ratio $\frac{A}{F_{d,i}^{j-1}}$ at every control step. The algorithm is as follows:

$$\begin{gathered}
if\ sgn\,(\delta) \neq sgn(\dot{\delta}),\ F_{d,i}^{j} = C_{d,2-4} \times \dot{\delta},\quad C_{d,2-4} = \frac{A_{2-4} \times C_{d,in}}{F_{d,i}^{j-1}}, \\
A_{2-4} = \frac{K}{1+e^{\left(0.01*\left|\delta_i^{j-1}\right|-10\right)}},\quad \frac{A_{2-4}}{F_{d,i}^{j-1}} \leq G \\
if\ sgn\,(\delta) = sgn(\dot{\delta}),\ F_{d,i}^{j} = C_{d,1-3} \times \dot{\delta},\ C_{d,1-3} = \frac{A_{1-3} \times C_{d,in}}{F_{d,i}^{j-1}}, \\
A_{1-3} = \frac{K}{1+e^{\left(P*R*\left|\delta_i^{j-1}\right|-10\right)}},\ \frac{A_{1-3}}{F_{d,i}^{j-1}} \leq G\ \ ,C_{d,1-3} > 30\ Ns/m
\end{gathered} \tag{4. 4}$$

$$\begin{cases} if\ \delta = m, & R = 100 \\ if\ \delta = cm, & R = 1 \\ if\ \delta = mm, & R = 0.1 \end{cases}$$

Where

* $F_{d,i}^{j-1}$ denotes the $(j-1)^{th}$ control time (i.e., previous control time step) and i^{th} element damper force ,

* $C_{d,2-4}$ represents the damping coefficient of quadrants 2 and 4, similarly $C_{d,1-3}$ symbolises the damping coefficient of quadrants 1 and 3,

* $\dot{x}$ stands for the relative story velocity, x is story drift, and $sgn()$ is the sign function returning + or -,

* A represents a variable in time which is constant K dependent (see recommendation given for K; K is energy unit constant; it need to be set before a full simulation),

* the constant R is given in eq. 4.4 ,

* P (which needs to be set before simulation; A designer can identify the parameter P by simple assigning several different values of it and find the value which provides the smallest drift among all) can be selected with parametric studies (e.g., **Figure 4. 10**),

* $C_{d,in}$ indicates initial damping coefficient chosen.

$C_{d,1-3} > 30\ Ns/m$ represents minimum damping coefficient. This value should not be zero or close to zero for a realistic design in practice (i.e., from equation 4.4, A_{1-3} can go to zero for some drift. It should be prevented by limiting minimum damping coefficient). This given value can be set up by simply assigning very small coefficient in the damper and compare the results with bare frame case (without damper). Those two results should be close to each other (the difference cannot be zero but close; it is acceptable).

The ratio $\frac{A_{1-3}}{F_{d,i}^{j-1}}\ or\ \frac{A_{2-4}}{F_{d,i}^{j-1}}$ should be smaller than a given value (G) in order to impose a limit to the maximum value of damping coefficient. The value of G can be easily set up by one- or two-simulations, after the selection of K. For instance, the first simulation can be performed without any limitation of G (which would be used as a reference result for the following simulation) and in the second one G can be limited to a certain number, such as 300, 400 or more.

For an initial K assignment:

K has an energy unit (e.g., N*m or N*cm or KN*m or KN*cm etc.,), it can be initialized as follows:

$$K = C_{d,in} \times \dot{x} \times x$$

For instance, if $C_{d,in} = 10^5\ Ns/m$, then $\dot{x}$= 1m/s (could be any value, but 1 is recommended for the simplification of the equation) and x=1m (which is unrealistic drift for a building). The whole point of such assumptions is to assign large $\boldsymbol{K}$ at the beginning.

Note that relevant section (**Figure 4. 11**) of this thesis will recommend a simple design methodology by using this initial K assignment. This initial value is not of vital importance. It will be simply used in an iterative process (**Figure 4. 11**).

Parametric studies are also conducted to further investigate the role of each parameter in the damper hysteresis loop.

• *Three*-different K (where P is constant) is opted to investigate the force-drift ratio. It can be concluded that larger K increases damper forces in quadrants 2-4 (**Figure 4. 9**)

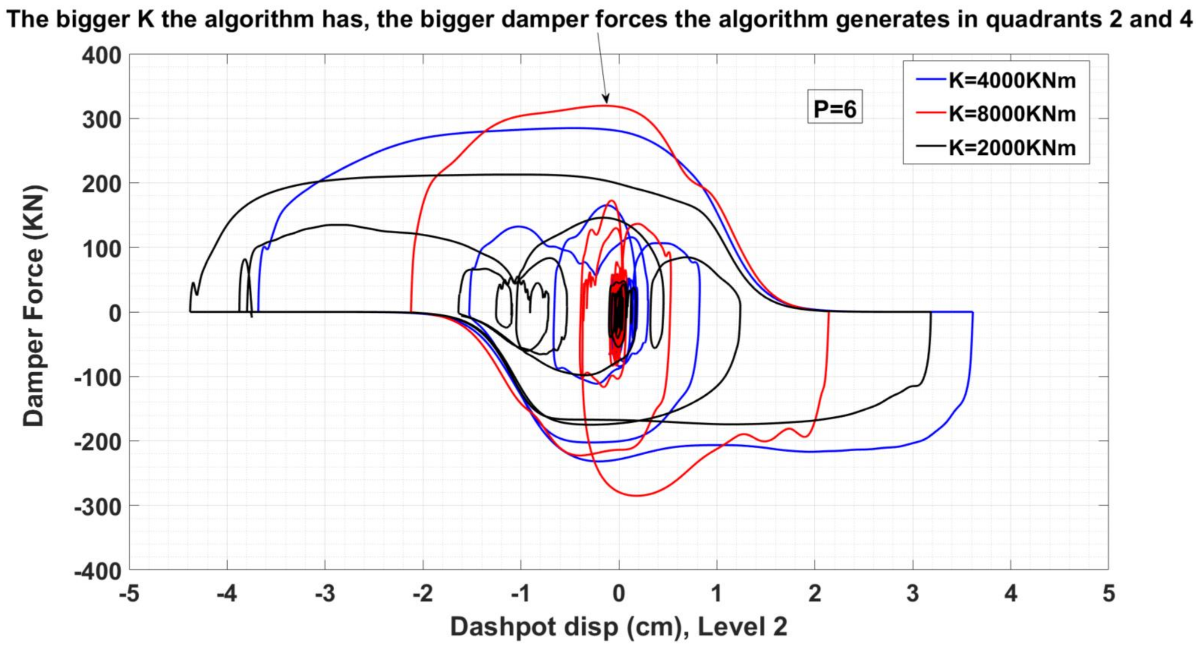


Figure 4. 9: Showing damper force (one damper) vs dashpot displacement in level 2 in 3-story frame for parameter investigation of 2-4DVD- three different K with constant P

Large K means large damper forces in quadrants 2 and 4 as well as larger damper forces in quadrants 1 and 3 for small drifts.

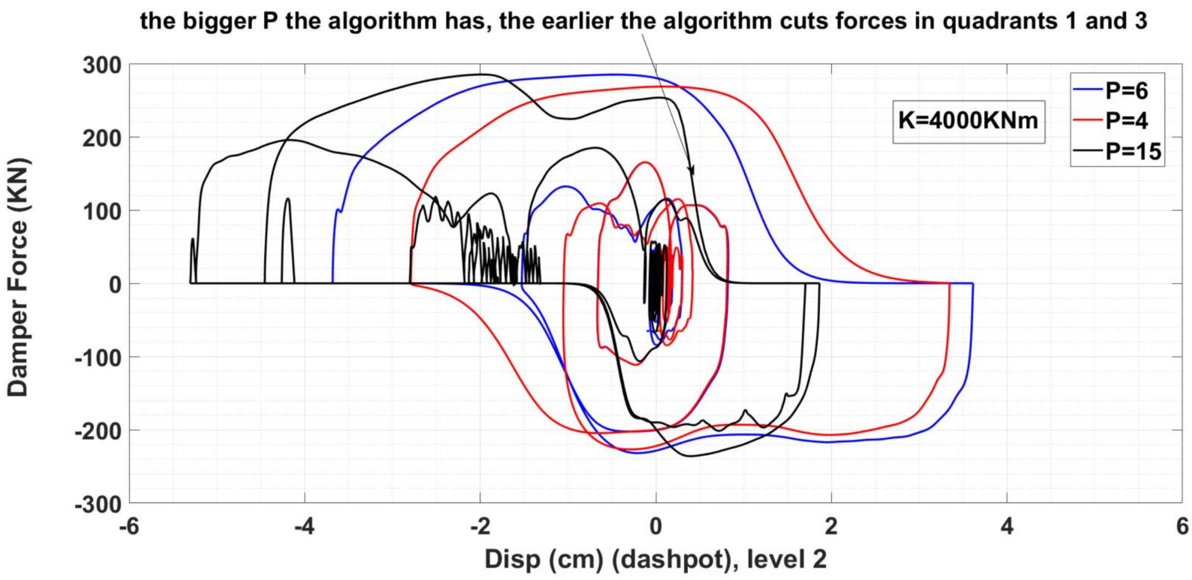


Figure 4. 10: parameter investigation of 2-4DVD (constant K with three P values)-in floor 2 in 3-story frame-one damper under 100% CAP

- Three P values (where K is constant) are also chosen to examine the response in the hysteresis loop of the damper. The Parameter P reshape the force displacement loop of the damper in quadrants 1 and 3. As discussed before, large P value in the algorithm cuts forces in quadrants 1 and 3 and vice versa.
- Note that small P is not recommended (e.g., smaller than 20), because it would unnecessarily reduce the energy dissipation capacity of the damper.
- As shown in **Figure 4. 10**, a large P value cuts damper forces in the early stages in quadrants 1 and 3.
- The parameter P reshapes the force-displacement loop of viscous damper in quadrants 1 and 3. Therefore, an optimal P value, which provides the smallest drift, will be opted in CHAPTER 6 by conducting parametric investigations.

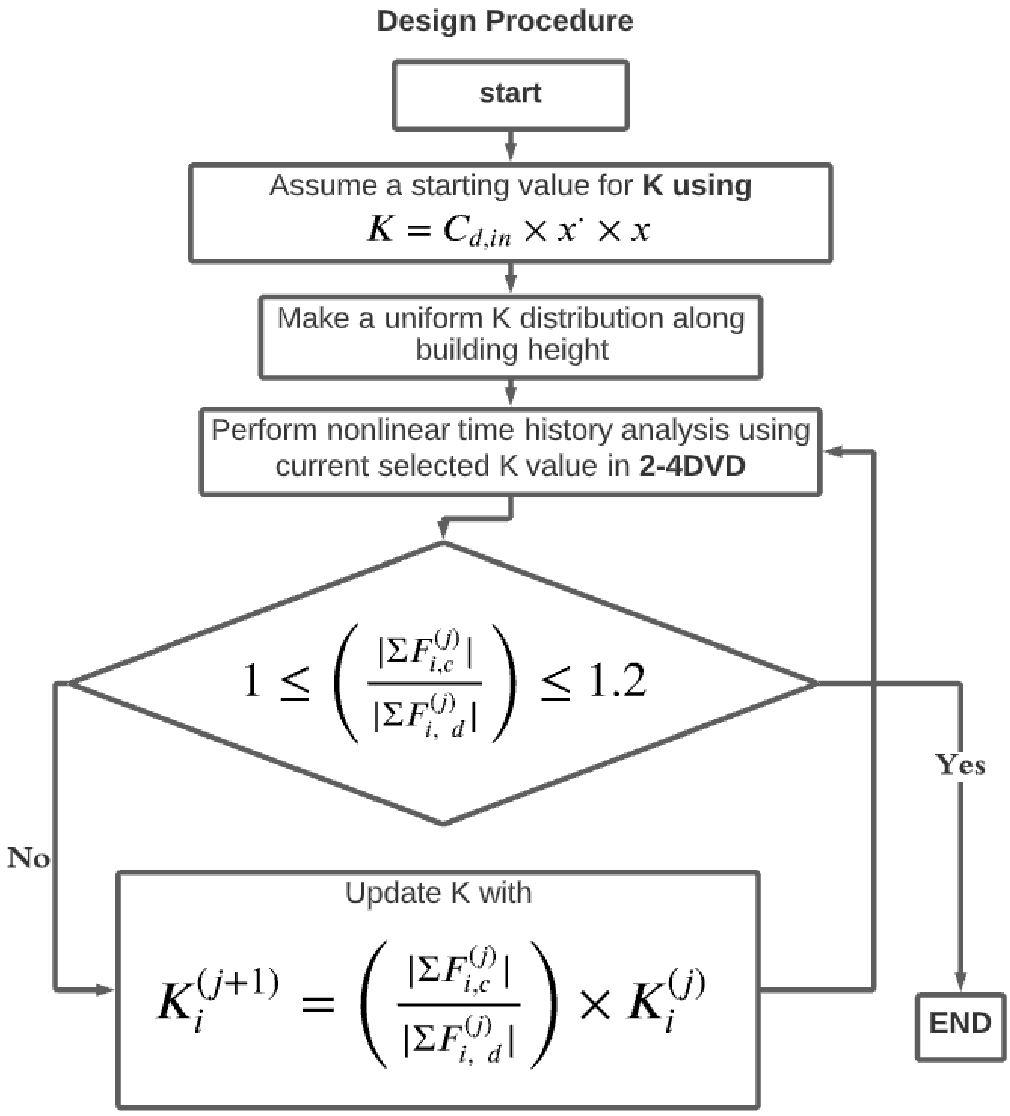


Figure 4. 11: Proposed design methodology for 2-4DVD

4.7.2 New semiactive control algorithms: a novel 2-4 Velocity & Displacement Dependent (2-4VDD) Viscous Damper

The 2-4VDD control is slightly different from 2-4DVD. Forces in quadrants 2 and 4 are larger than those in 2-4DVD (see the simplified shape in Figure 4. 7c). The proposed algorithm is presented in Eq. 4.5. By having larger damping forces in quadrants 2 and 4 than the 2-4DVD, the 2-4VDD is designed to improve the energy dissipation capabilities of the damper.

To investigate the role of K and D parameters used in the control algorithm, several D and K values were examined (see Figure 4. 11 and Figure 4. 12). A parametric study will be also conducted over a range of D values in chapter 7.

As discussed before, based on the energy (under the curve of force-displacement of a viscous damper), the damper's initial damping coefficient is updated by dividing the energy of j time by (j-1). The following algorithm is adopted to achieve the 2-4VDD control.

$$\begin{cases} if\ sgn\ (x) \neq sgn(\dot{x}), \quad F_{d,i}^{j} = C_{d,i,2-4} \times \dot{x}, \quad C_{d,i,2-4} = \frac{A_{2-4} \times C_{d,in}}{F_{d,i}^{j-1}}, \\ A_{2-4} = \frac{K}{e^{\left(tanh\left(-Q \times \left|\delta_i^{j-1}\right|\right)\right)}}\ , \quad \frac{A_{2-4}}{F_{d,i}^{j-1}} \leq H, \\ if\ sgn\ (x) = sgn(\dot{x}),\ F_{d,i}^{j} = C_{d,i,1-3} \times \dot{x},\ C_{d,i,1-3} = \frac{A_{1-3} \times C_{d,in}}{F_{d,i}^{j-1}}, \\ A_{1-3} = \frac{K}{e^{\left(D \times tanh\left(Y \times \left|\delta_i^{j-1}\right|\right)\right)}}\ , \quad \frac{A_{1-3}}{F_{d,i}^{j-1}} \leq H, \quad C_{d,1-3} > 30\ Ns/m \end{cases} \tag{4.5}$$

$$\begin{cases} if\ \delta = m,\ Q = 100, \quad Y = 10 \\ if\ \delta = cm,\ Q = 1, \quad Y = 0.1 \\ if\ \delta = mm,\ Q = 0.1, \quad Y = 0.01 \end{cases}$$

Here, j is the control time step, , $F_{d,i}^{j}$ and $F_{d,i}^{j-1}$ are is the i^{th} element damper force in the current and previous control time step, respectively , $C_{d,2-4}$ represents the damping coefficient of quadrant 2 and 4, and similarly $C_{d,1-3}$ symbolises the damping coefficient of quadrant 1 and

3, $\dot{x}$ stands for the relative story velocity , x is the inter-story drift, $sgn()$ is the sign function returning + or -, A is a variable dependent on the constant K (see recommendation given for K), Q and Y (which are used for the choice of units) are specified in eq.4.5, the constant D can be selected with parametric studies (discussed in detail in chapter 7), $C_{d,in}$ represents initial damping coefficient selected for the design.

Due to having a limitation of maximum damping coefficient, H can be easily set by one- or two-simulations. For instance, the first simulation can be run without any limitation in maximum damping coefficients H (i.e., $\frac{A}{F_{d,i}^{j-1}}$ is just assumed to be infinitely large) and in the second one H can be limited to a certain value (e.g. 300 or 400). For example, for the frames adopted in this study, $H = 400$ was able to provide the same response as the one achieved by infinite (very large) H. The logic, which was used for an initial assignment of the K value in 2-4DVD, can be used for 2-4VDD as well.

- Three-different K values (where D is constant) were chosen to investigate the force-displacement loop. It showed that large K increased damper forces in quadrants 2 and 4 (**Figure 4. 12**).

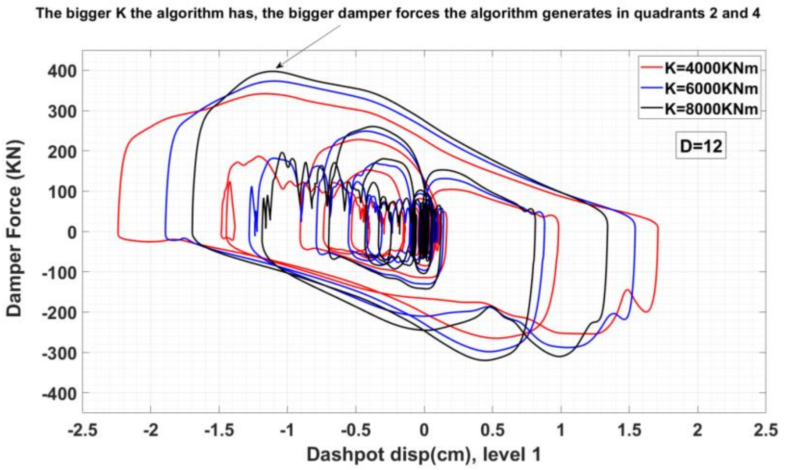


Figure 4. 12: Investigation of 2-4VDD algorithm for three K and a constant D- (image from level 1 of 3-story frame under 100%PAR)

• Three D values (where K is constant) are similarly chosen to investigate the effects of parameter D in force-displacement loop of the damper. The parameter D is important for quantifying the damper forces in quadrants 1 and 3.

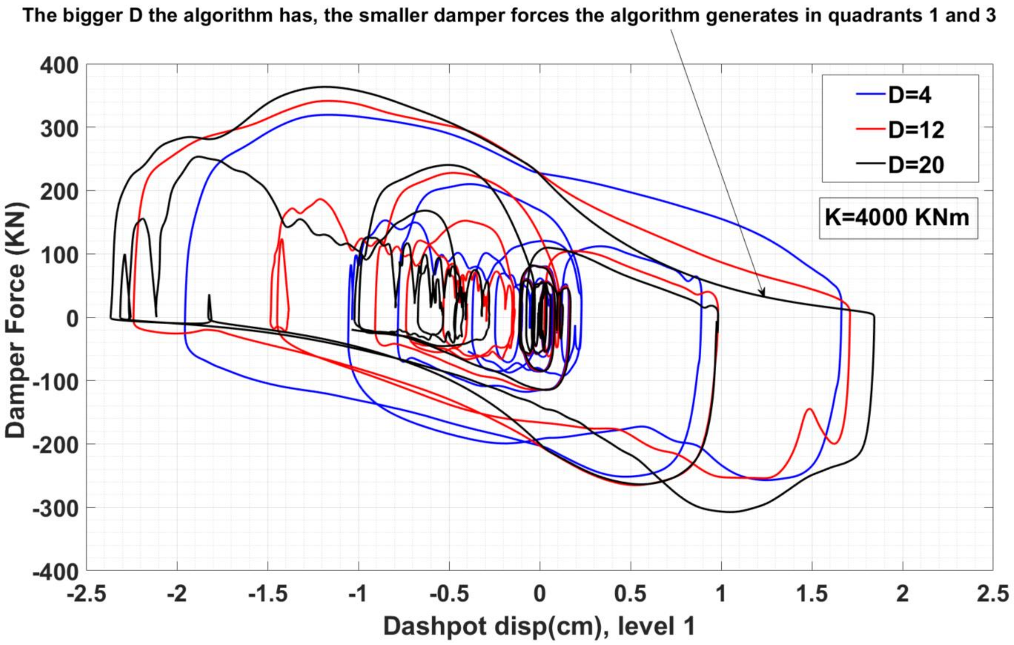


Figure 4. 13: 2-4VDD examination with different *D* values with constant *K* - (image from level 1 of 3-story frame) under 100%PAR

• As it is shown in **Figure 4. 13**, large D value cuts damper forces in early stages in quadrants 1 and 3.

• Note that large D is not recommended (such as larger than 20) due to reducing the energy dissipation capacity of the damper as well as causing unstable response under some earthquakes.

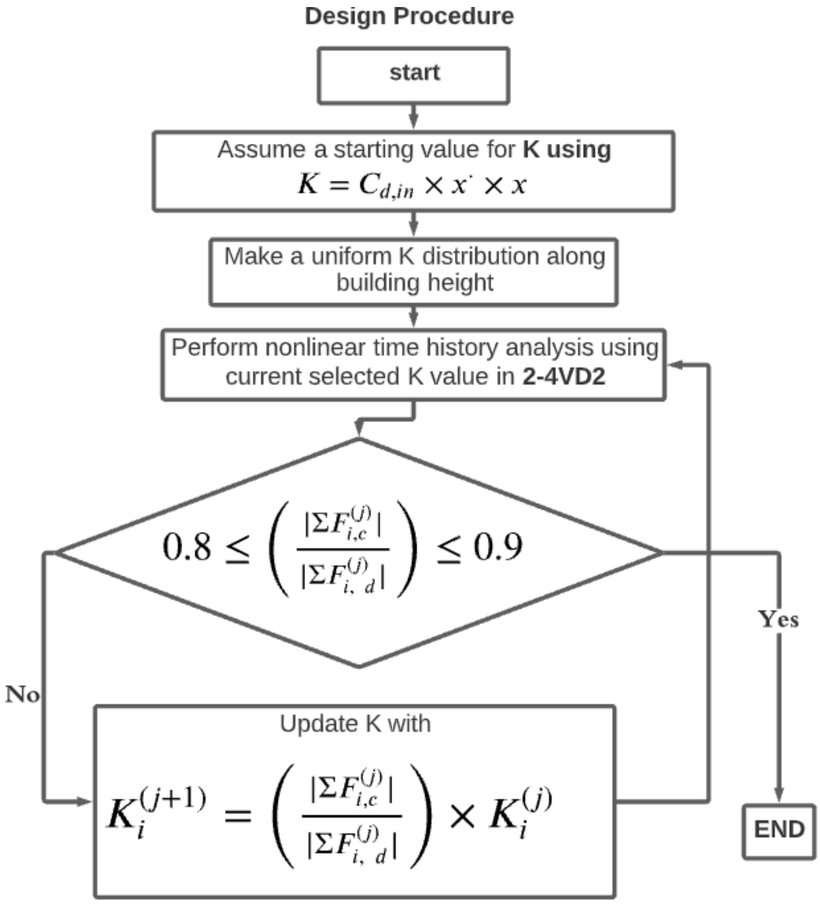


Figure 4. 14: Proposed algorithm for iterative procedure of 2-4VDD.

where $\left|\sum F_{i,c}^{(j)}\right|$ and $\left|\sum F_{i,d}^{(j)}\right|$ are absolute total column and damper forces of the story ***i*** at iteration ***j*** respectively; 0.8 and 0.9 are assumed limits of an acceptable tolerance range; $K_i^{(j)}$is parameter K in story i at iteration j. As it was discussed above, the K value is just an initial assignment, it will be updated by the proposed design procedure (**Figure 4. 14**).

4.8 Summary for methodology

This chapter introduced two typical multistorey steel moment resisting frames (MRFs) equipped with viscous dampers installed as a Chevron-brace configuration. The two buildings used in the study were designed as dual frames, in accordance with the ductility-based design approach of Eurocode 8 (Eurocode8 2004), using Sap2000 (CSI 2002). The dampers were modelled as linear viscous dashpots using the “twoNodeLink” element with the “ViscousDamper” material in OpenSees (Akcelyan et al. 2016). Four different recorded (real) earthquakes, with different predominant frequency ranges**,** were selected from the PEERs database. Different damping coefficient distribution methods (uniform and trapezoidal) were investigated. The best among them was adopted for a comparison with the semiactive controls investigated in the subsequent stage. For nonlinear structures or with high levels of added damping, viscous dampers can reduce drift demand, but can also increase base shear demand as they provide resistive forces in all four quadrants of the force-displacement loop, which would reduce the ability to use PVD in structural retrofitting applications and new buildings.

Three semiactive (SA) viscous damping control methods (2-4DDD, 2-4DVD and 2-4VDD), which manipulate the overall hysteresis behaviour of the structural frame, were investigated in this research. Specifically, the semiactive control was intended to remove forces that would increase the base shear of the system. The system was based on a decentralized control strategy: the control loop was closed in each device, and control equipment such as the controller and sensors separately work in each device. The proposed SA controls could be represented by a simple equation. The initial damping coefficient was updated based on a ratio which was the energy (under the curve of force-displacement of the viscous damper) of the damper at j time divided by (j-1). The relevant section of this thesis recommended a simple design methodology by using an initial K parameter in the algorithm. The initial K parameter was not of vital importance. It was simply used in an iterative process. Parametric studies were also conducted to further investigate the role of each parameter in the damper hysteresis loop.

A novel semiactive control called the 2-4VDD was also proposed in this chapter. It was slightly different from the 2-4DVD. Forces in quadrants 2 and 4 were larger than those in 2-4DVD. By having larger damping forces in quadrants 2 and 4 than the 2-4DVD, the 2-4VDD was designed to improve the energy dissipation capabilities of the damper. As discussed before, based on the energy (under the curve of force-displacement of a viscous damper), the damper's initial damping coefficient was updated by dividing the energy of j time by (j-1).

Several numerical investigations in Chapter 6 and 7 will be conducted for identifying optimal parameters of P and D in the equation.

CHAPTER 5 Results: Viscous-based passive control

The 3-story-MRF used in this study was designed to have two inter-storey drift limits (2% and 1.5%) under the most critical among the four selected earthquake (E1, E2, E3 and E4). Two different types of dampers were investigated: linear and non-linear viscous with constant damping coefficient Cd. Since the frame is a multi-degree-of-freedom (MDOF) system, several distributions of damping coefficients along the height of the structure were also investigated. For the sake of simplicity of this study, two of simplest damping coefficient distribution methods in literature are adopted. The investigated damper type-distribution combinations are as follows:

1) Linear viscous damper (LV)

1a. Uniform coefficient distribution (1/1/1)

1b. Trapezoidal coefficient distribution (0.5/0.75/1)

2) Nonlinear viscous damper (NLV)

2a. Uniform coefficient distribution (1/1/1) with Alpha=0.3

2b. Trapezoidal coefficient distribution (0.5/0.75/1) with Alpha=0.3

2c. Uniform coefficient distribution (1/1/1) with Alpha=0.5

2d. Trapezoidal coefficient distribution (0.5/0.75/1) with Alpha=0.5

5.1 Drift Limit 2%

As it is shown in **Table 5. 1** (see **Table A. 1** for more detail), the larger coefficient the damper has, the smaller the frame maximum drift it gets. Each earthquake produces different drifts in the frame so that the largest coefficient under any of the four earthquakes should be taken to achieve the target drift. For example, for 3S-PLV-UCd-DE1 (3S; 3-storey, PLV; Passive Linear Viscous, UCd; Uniform Cd distribution, DE1; Design Earthquake 1), the desired response (2% drift) was achieved by assigning Cd=9 KNs/cm (see **Table 5. 1**), this value is then used for the simulations of response to all four earthquake inputs.

Table 5. 1: Two different Cd values with corresponding max drift in the 3-story frame

	Cd KNs/cm)	Max Drift (cm) Earthquake E1	E2	E3	E4
3S-PLV-UCd	8.6	6.5	4.1	**6.4**	5.6
	9.0	**6.3**	4.0	6.3	5.5

A brief discussion from **Table A. 1** is as follows:

- 3S-PLV-UCd-DE1 has the biggest damping coefficient in uniform Cd distribution, which is sufficient for the design in all four earthquakes inputs (i.e., if the frame is designed for E1, it is safe under all four earthquakes). More details can be found in ***Table A. 1.***
- Likewise, 3S-PNLV-UCd-DE3 (PNLV; Passive Non-Linear Viscous) has the biggest damping coefficient which can keep the drift below the 2% limit (i.e., 6.4cm) in all four earthquakes.
- Therefore, the following analyses will adopt different type-distribution combinations, but only for the "best" passive nonlinear and linear viscous damper, which were achieved by designing the frame for E1 and E3 respectively.

1. Comparison of two coefficient distributions (uniform and trapezoidal) for passive linear viscous damper -(1a & 1b)

This subsection compares passive linear viscous (PLV) dampers with uniform (UCd) and trapezoidal (TCd) coefficient distributions in the 3-story MRF (3S) under different design earthquakes (i.e., DE1).

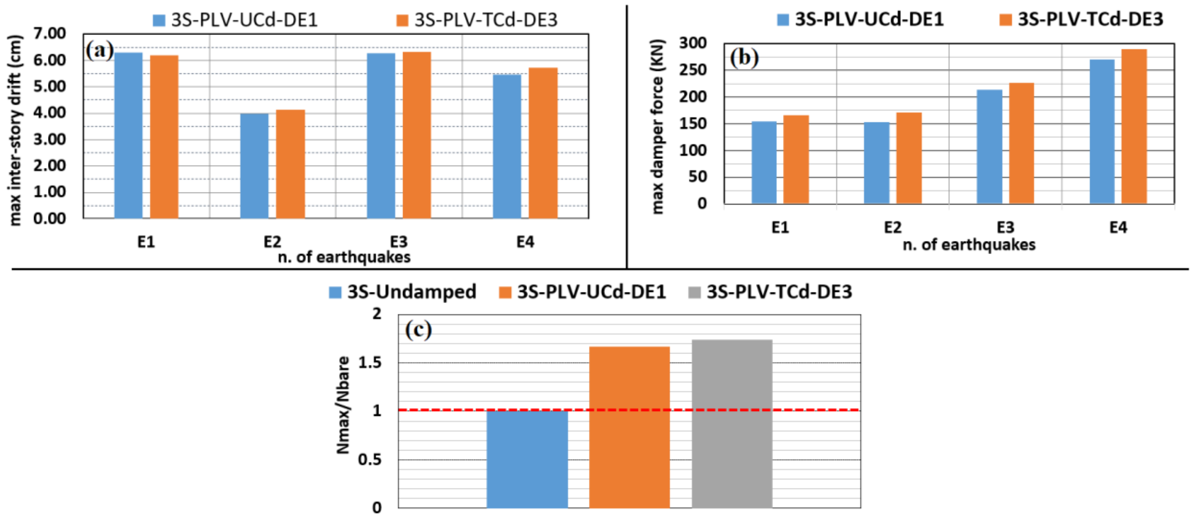


Figure 5. 1: Seismic performance assessment of (a) maximum inter story drift, (b) maximum damper force (one damper) and (c) axial load ratios $Nmax/Nbare$= maximum axial load of the most critical column of dual frame / axial load of the most critical column of bare frame

Figure 5. 1 represents nonlinear response history analysis of a 3-story frame equipped with two types of coefficient distribution methods for each representative ground motion. They are 3S-PLV-UCd-DE1 and 3S-PLV-TCd-DE3. The results show that:

The uniform distribution (3S-PLV-UCd-DE1) leads to smaller damping forces than trapezoidal distribution (3S-PLV-TCd-DE3), as shown in **Figure 5. 1**b. From **Figure 5. 1**a, these two-coefficient distribution methods resulted in almost the same drifts under a set of ground excitations, yet both 3S-PLV-UCd-DE1 and 3S-PLV-TCd-DE3 increased the peak axial load of the bare frame by more than 60%. Increases in column loads with passive viscous damper would likely require strengthening of columns in retrofitting or new buildings. Generally, uniform Cd distribution (or 3S-PLV-UCd-DE1) is slightly better than trapezoidal Cd distribution (or 3S-PLV-TCd-DE3). **Table 5. 2** tabulates the maximums in the response parameters.

Table 5. 2: Comparison of responses of frame with and without viscous damping Systems. For 2% drift limit

Frame Notation[a]	Max story drift ratio	[b]Cd (KNs/cm)	Max total damper force (KN)	Max plastic rotation (scaled to bare frame)	Max base shear (Scaled to bare frame)	Max number of Plastic hinges
3S-Undamped	6.08%	—	—	1	1	22 (22)[c]
3S-PLV-TCd-DE3	2%	F1=0.5*12.5 F2=0.75*12.5 F3=12.5	1264.9	0.30	1.34	12[d](22)
3S-PLV-UCd-DE1	2%	9	1286.7	0.29	1.37	12(22)

Note: [a]3S=3-storey. LV=Linear Viscous. [b]**Cd** = damping coefficient. TCd=Trapezoidal Cd. DE3= Design Earthquake 3 (Earthquake No: 3). UCd= Uniform Cd. DE1= Design Earthquake 1 (Earthquake No: 1). [c]Value in parenthesis (22) indicates the total number of potential plastic hinge. [d]Value of 12 indicates the maximum number of plastic hinges formed under any of the four earthquakes.

Table 5. 2 presents damped and undamped structural responses. They are 3S-Undamped", 3S-PLV-TCd-DE3 and 3S-PLV-UCd-DE1. The maximum total damper force required, maximum plastic hinge rotation, maximum base shear, and the maximum number of plastic hinges formed are obtained from nonlinear response-history analysis under the four ground motions. The maximum number of plastic hinges and their positions (**Figure 5. 2**) are included as a measure of the risk of formation of a collapse mechanism in the structure. The addition of the damper minimized structural damage (plastic hinge rotation) by 71% compared to the bare frame. For instance, from the right column of **Table 5. 2**, it revealed that the number of hinges in the bare frame was 22 out of 22, yet both types of passive control resulted in 12 out of 22 hinges. The maximum rotation of hinges is important as it impacts on the required level of ductility. The number of plastic hinges (or hinge pattern) in the frame could be used as

it represents the distribution of structural damage. Concentrated structural damage in a structural frame could lead to a soft story failure.

However, from the results in "max. base shear" (in the same table), the damper applications increased the base shear of the frame up to 37% (as well as the axial load of the column by over 60%, **Figure 5. 1**). Some supplemental strengthening of foundations and columns in view of capacity design principles may be required. Especially, a design may give alarms for safety level if the frame is being retrofitted.

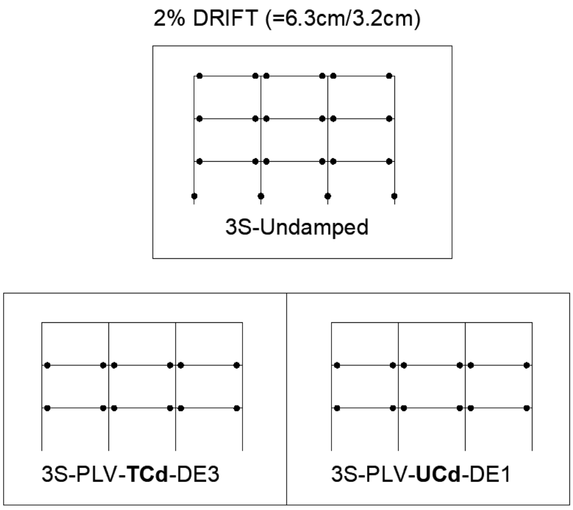


Figure 5. 2: Hinge pattern of the 3-story MRF with and without dampers under the most critical ground motion (i.e., CAP)

2. Comparison of uniform and trapezoidal coefficient distribution for passive nonlinear viscous damper with alpha=0.3 (PNLVA03) - (2a & 2b):

The comparison of the passive nonlinear viscous dampers (PNLV) with two different damping coefficient distributions (UCd and TCd) and a nonlinear velocity exponent alpha=0.3 under a set of 4 earthquakes shows that the structure with uniform distribution **3S**-PNLVA03-

UCd-DE3 (Passive Non-Linear Viscous Alpha=0.3 Uniform Cd-Design earthquake 3), which is designed for E3, is safe for all earthquake inputs. Similarly, a frame with trapezoidal distribution, 3S-PNLVA03-TCd-DE4, which is designed for E4, can keep the frame below the drift limit (2%) (see **Table 5. 3**; see **Table A. 1** for more details).

Table 5. 3: Max drift of the 3-story frame with two different passive control strategies (UCd and TCd) under four different ground motions

		Max Drift (cm)			
		Earthquake			
	Cd (KNs/cm)	E1	E2	E3	E4
3S-PNLVA03-UCd	2.5	4.3	2.9	6.3	6.3
3S-PNLVA03-TCd	4.0	4.0	2.9	6.0	6.5

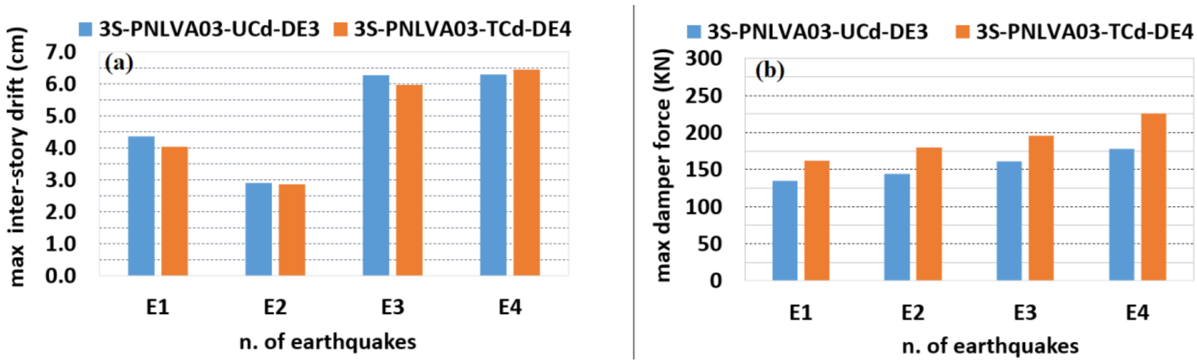


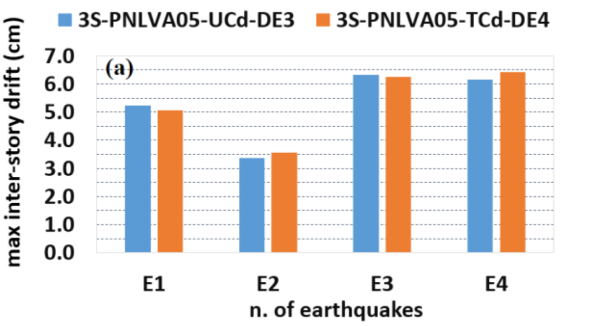
Figure 5. 3: Maximum drift and damper force (one damper) profile under four natural records

Figure 5. *3* presents the response of the analysed frame when excited by the four sets of seismic motions. Inter story drifts and damper forces were calculated as the peak values obtained from nonlinear response-history analyses for each ground motion. The inter-story drift resulting from 3S-PNLVA03-UCd-DE3 and 3S-PNLVA03-TCd-DE4 are similar. However, the required peak damper force for the frame with uniform dampers (3S-PNLVA03-UCd-DE3) is smaller than that of the structure with trapezoidal distribution (3S-PNLVA03-TCd-DE4). Since for similar drift, the uniform damping coefficient distribution (PNLVA03-UCd- DE3)

resulted in smaller damper forces than trapezoidal damping coefficient distribution (3S-PNLVA03-TCd-DE4), the uniform Cd distribution would be a lower cost of the viscous dampers.

3. Comparison of passive nonlinear viscous damper for uniform and trapezoidal damping coefficient distribution with alpha=0.5 (PNLVA05) (2c & 2d)

3S-PNLVA05-UCd-DE3 and 3S-PNLVA05-TCd-DE4 are selected from the set of non-linear time history simulations in which two-different coefficient (Cd) distributions with the same velocity exponent 0.5 were compared with each other under the four earthquakes. The maximum inter-story drifts and required damper forces are shown in **Figure 5. 4**. The results are similar to those obtained for the velocity exponent alpha=0.3 (**Figure 5.** *3*); showing again that uniform Cd distribution is better than trapezoidal distribution, as it achieves the same drifts with smaller damper forces. Note that such statement is valid for the case where the trapezoidal damping coefficient distribution is 0.5/0.75/1. Different trapezoidal damping coefficient distributions may slightly change the difference between uniform and trapezoidal .



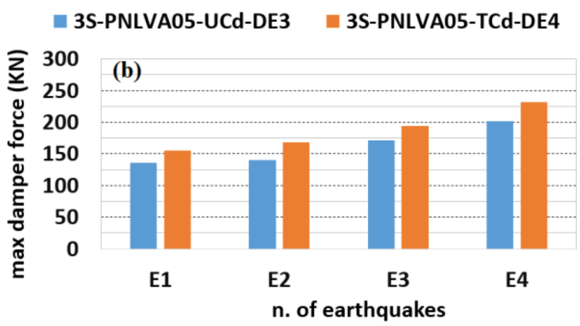


Figure 5. 4: seismic-performance comparison of two different damping distribution, maximum inter story drift and maximum damper force (one damper) under the four ground motions.

Once again (see **Figure 5. 3**), uniform distribution of Cd requires fewer damper forces than trapezoidal distribution (see **Figure 5. 4**).

4. Passive nonlinear viscous damper (2a & 2c), linear viscous damper and bare frame comparison

Once it was established that the simpler uniform distribution (UCd) had at least equal or better performance than the trapezoidal distribution, the focus can be turned on the performance of different UCd systems: two nonlinear viscous dampers (PNLV, alpha=0.3 and 0.5), and the linear viscous damper (PLV). The comparison of the three damper systems is shown in **Figure 5. 5**, in terms of maximum inter-story drift (**Figure 5. 5**a), maximum damper force required (**Figure 5. 5**b), and the resulting maximum axial load (**Figure 5. 5**c), which is also compared to the bare frame (without dampers). From this figure it can be summarized that nonlinear viscous dampers with velocity exponent 0.3 (3S-PNLVA03-UCd-DE3) are superior to the other two damper systems, with lowest damper forces for all earthquakes, at inter-storey drifts which are either lowest (E1 and E2) or similar (E3 and E4) to those in the other systems. It is also slightly better than the other two in terms of axial load increase in the column (which is located near the supporting brace) (**Figure 5. 5**c). The energy dissipation of both linear and nonlinear viscous dampers is almost same for life safety design (2%), yet the improved performance (nonlinear viscous damper has smaller damper force than linear viscous damper) dependents on the specific earthquake history due to damper' velocity dependent response.

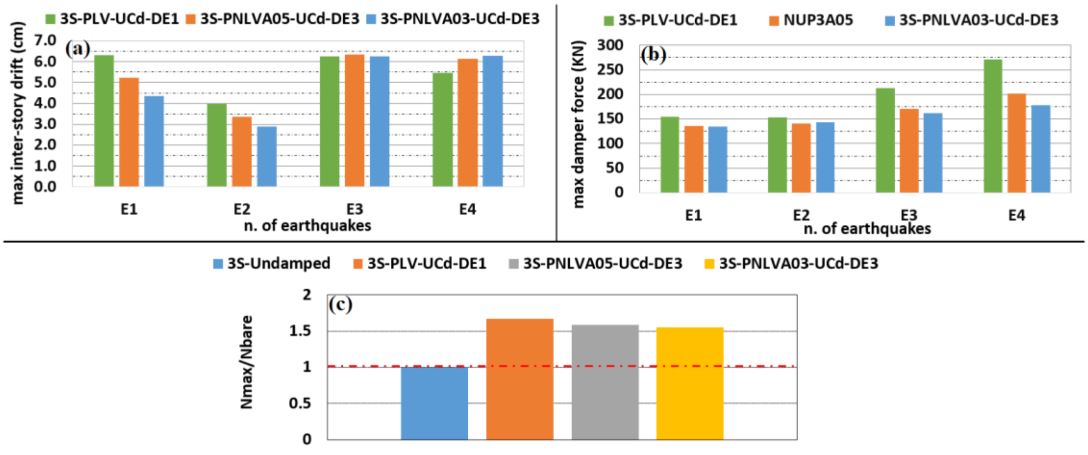


Figure 5. 5: Comparing seismic performance of 3S-PLV-UCd-DE1, 3S-PNLVA05-UCd-DE3 and 3S-PNLVA03-UCd-DE3 in maximum inter story drift and maximum damper force (one damper) (a and b) and maximum axial loads ratio (c). N_{max} represents the maximum axial load of each control under all four earthquakes. N_{bare} refers to the maximum axial load of bare frame under four earthquakes.

Table 5. 4: comparison of response of frame with and/ without additional damping. Different type of passive viscous damper (0.3 and 0.5) along with uniform and trapezoidal coefficient distribution. Designed for 2% drift

Frame Notation	Max. story drift ratio	Cd (KNs/cm)	Max total damper force (KN)	Max. plastic rotation (scaled to bare frame)	Max base shear (Scaled to bare frame)	Max number of plastic hinges
3S-Undamped	6.08%	__	__	1	1	22 (22)
3S-PLV-UCd-DE1	2%	9	1286.6	0.29	1.36	12(22)
3S-PNLVA05-UCd-DE3	2%	3.5	1078.3	0.29	1.32	12(22)
3S-PNLVA03-UCd-DE3	2%	2.5	1011.3	0.289	1.34	12(22)

Table 5. 4 summarises the results of **Figure 5.** ***5***. As it was previously mentioned, the maximum results in **Table 5. 4** are obtained from nonlinear response-history analysis of the frame under all four ground motions. The results in the table can be evaluated that for life safety (2% drift) design frame, linear (3S-PLV-UCd-DE1), nonlinear-0.5 (3S-PNLVA05-UCd-DE3) and nonlinear-0.3 (3S-PNLVA03-UCd-DE3) do not show any significant differences. However, 3S-PNLVA03-UCd-DE3 is better than the other two types of controls since it requires smaller damper forces which may reduce the cost of the damper. The location of hinges in the frame is also shown in **Figure 5. 6** to give an indication of the risk of formation of failure mechanism.

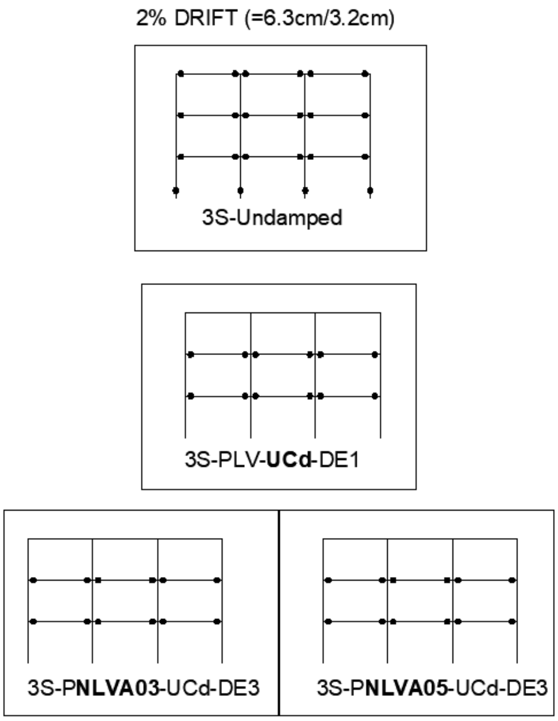


Figure 5. 6: Hinge pattern of 3-story MRF for different type of viscous dampers and bare frame under the most critical ground motion

5.2 Drift limit 1.5 %

This subsection investigates a lower design drift limit of 1.5%. It only compares linear and nonlinear uniform damping coefficient distribution methods with the bare frame since it was already shown that uniform coefficient distribution was generally better than trapezoidal distribution. The maximum total damper force required to achieve the design drift, maximum plastic rotation, maximum base shear, and the maximum number of plastic hinges and their distribution were obtained from nonlinear response-history analysis for all four ground motions.

Table 5. 5: Comparison of response of frame with linear and nonlinear passive viscous dampers and without dampers; all designed for 1.5% drift

Frame Notation	Max. story drift ratio	Cd (KNs/cm)	Max total damper force (KN)	Max. plastic rotation (scaled to bare frame)	Max base shear (Scaled to bare frame)	Max number of plastic hinges
3S-Undamped	6.08%	__	__	1	1	22 (22)
3S-PLV-UCd-DE3	1.5%	14	1575	0.240	1.55	12(22)
3S-PNLVA03-UCd-DE4	1.5%	3.65	1318	0.245	1.40	8(22)

Table 5. 5 presents the maximum response values of the analysed structures under the four ground motions. The table covers the linear viscous dampers (3S-PLV-UCd-DE3), non-linear viscous dampers with alpha=0.3 (3S-PNLVA03-UCd-DE4) and the bare frame (3S-Undamped). The results suggested that the non-linear dampers (PNLVA03-UCd-DE4) performed better than the linear ones (3S-PLV-UCd-DE3) in terms of maximum base shear, number and distribution of plastic hinges and total damper forces required to achieve the design drift.

For the non-linear dampers (PNLV) the maximum number of plastic hinges (**Figure 5. 7)** was 8 out of 22, i.e., 30% lower than that for the linear damper system (LV; 12 out of 22), with the peak damper force reduced by 16%, and maximum base shear by 10%. The maximum plastic rotation for PNLV was only 2% higher than that of the PLV.

This indicates that for lower storey drifts (still exceeding the linear elastic range of the structure) the non-linear viscous damper outperforms the linear dampers. The added energy dissipation of the non-linear viscous damper results in reduced forces in the system for the same levels of structural deformation.

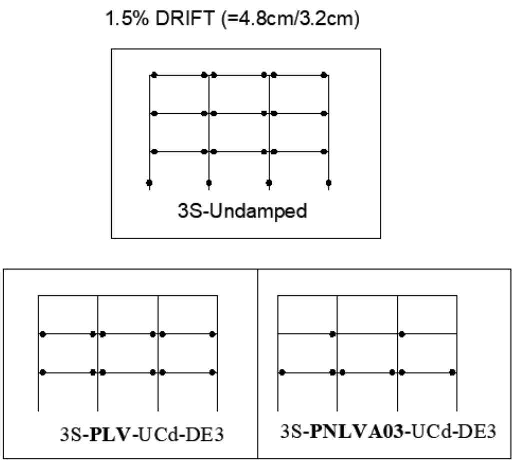


Figure 5. 7: The location of hinges of the 3-story MRF for different type of viscous dampers (PLV and PNLV) and the bare frame. Designed for 1.5% drift.

5.3 The concept of UDD:

Uniform Drift/Damage Distribution (UDD) proposed by Hajirasouliha (Hajirasouliha et al. 2012) is a performance-based design strategy that results in uniformly distributed deformations along the height of building. The aim provides increased energy dissipation while avoiding excessive deformations concentrated in one floor, which may lead to creation of a collapse mechanism. The UDD concept redistributes material (i.e., for RC structures, the material is column sizes, yet for dual frame with viscous dampers, the material is damping coefficient; damping coefficients are updated based on the inter story drift) from strong to weak parts of a structure until a state of uniform deformation or damage prevails in a bare frame. **Table 5. 6** presents the response of a system with uniform nonlinear damping coefficient distribution (3S-PNLVA03-UCd-DE4), system designed for UDD (3S-NLVA03-UDD-DE3) and the bare frame (3S-Undamped), all subjected to the full set four seismic motions.

Table 5. 6: comparison of response of bare frame with the concept of UCd and UDD. Designed for 1.5% drift.

Frame Notation	Max. story drift ratio	Cd (KNs/cm)	Max total damper force (KN)	Max. plastic rotation (scaled to bare frame)	Max base shear (Scaled to bare frame)	Max number of plastic hinges
3S-Undamped	6.08%	-	-	1	1	22 (22)
3S-PNLVA03-UCd-DE4	1.5%	3.65	1318.3	0.245	1.4	8(22)
3S-PNLVA03-UDD-DE4	1.5%	F1≅ 0.794 F2≅ 6 F3≅ 1.38	1153.7	0.249	1.29	18(22)

The main findings of this investigation can be summarised that As discussed before, passive viscous damper improved the performance of the bare frame. 3S-PNLVA03-UDD-DE4 increased the number of hinges in the frame compared to 3S-PNLVA03-UCd-DE4 The location of these hinges can also be found in **Figure 5. 8**.

However, the concept of UDD (3S-NLVA03-UDD-DE4) reduced "max base shear" and "total damper force" required (by 12% in comparison with UCd) for the passive control. Small damping forces may be important to reduce the cost of the application of such passive control. Based on the estimation of Gidaris and Taflanidis (Gidaris and Taflanidis 2015) of the upfront damper cost at storey level j, the following approximate formula can be used:

$$\text{Upfront Damper Cost}_{\,j}[\$] = 96.88 \text{ x}\left(F_{dj,max}[KN]\right)^{0.607} \qquad (5.1)$$

While this simplified formula is approximate, it is used here for comparison purposes only. The UDD concept reduced the cost of damper by about 2,000$. 3S-PNLVA03-UCd-DE4 ended up with the same "Max. plastic rotation" as 3S-PNLVA03-UDD-DE4. **Figure 5. 9** also compares the hysteresis loop of the damper and the drift of the frame for 3S-PNLVA03-UCd-DE4 and 3S-PNLVA03-UDD-DE4 under CAP earthquake (the most critical earthquake).

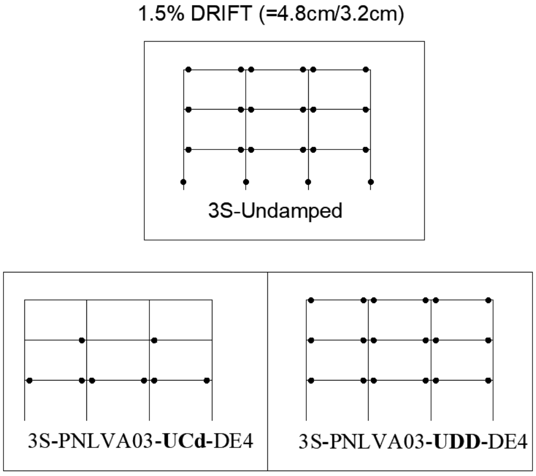


Figure 5. 8: Location of plastic hinges in 3 story MRF frames designed for 1.5% drift: undamped; Uniform Damper Coefficient; and Uniform Damage Distribution.

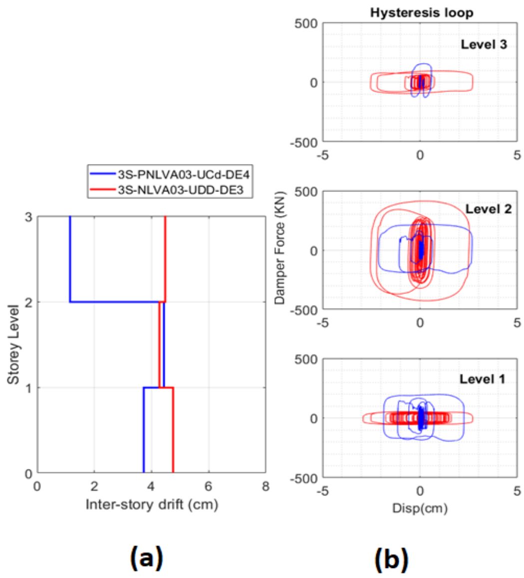


Figure 5. 9: Comparison of UDD and UCd in terms of (a) max storey drift of the frame and (b) damper force of one damper under CAP earthquake.

5.4 Summary of results for passive control investigations

This chapter presents the analysis of passive control of typical 3-story steel frame, designed in accordance with the ductility-based design approach of Eurocode 8. The analysis was conducted by the means of non-linear time history simulations of response to a set of four recorded earthquakes selected to represent seismic excitations with different characteristics (peak acceleration, frequency content and duration).

This analysis focussed on an investigation of the effects of:

- Different damping coefficient distributions (uniform and trapezoidal) for both linear and nonlinear viscous dampers
- Different velocity exponents (alpha=0.3 and 0.5) for the nonlinear viscous dampers, and
- The concept of UDD (Uniform Drift/Damage Distribution) and UCd (Uniform Damping Coefficient Distribution)

The main findings of this chapter can be summarized as follows:

- Uniform coefficient distribution is more promising than trapezoidal distributions due to requiring less maximum damper forces (thus reducing the cost of the damper).
- The use of any passive viscous damper increases the axial load and the base shear of the structure (**Figure 5. 1**c, **Figure 5. 5**c, **Table 5. 6**).
- For life safety (2% drift) design frame, the differences in performance between linear (3S-PLV-UCd-DE1), nonlinear-alpha=0.5 (3S-PNLVA05-UCd-DE3) and nonlinear-alpha=0.3 (3S-PNLVA03-UCd-DE3) are relatively small, but 3S-PNLVA03-UCd-DE3 results in smaller damper forces than the other two, which may reduce the cost of the dampers.
- For 1.5% drift limit, the passive nonlinear damper (PNLVA03-UCd-DE4) showed a significantly better performance than the passive linear damper (3S-PLV-UCd-DE3) by 30% and 10% in terms of the maximum number of plastic hinges and the maximum base shear respectively.
- The concept of UDD (3S-NLVA03-UDD-DE4) reduced “max base shear” (by 7.8%) and “total damper force” (by 12%) in comparison with UCd. It also increased the number of hinges by 125% compared with UCd.

- Due to requiring smaller damper forces and resulting in smaller drifts (especially for 1.5% drift), it is recommended to have a nonlinear viscous damper with a small velocity exponent (e.g., 0.3 or less) and consider a uniform coefficient distribution among floors.

- Especially, for a 1.5% drift design, the UDD can also be considered. I.e., the UDD increases the number of hinges in the frame, resulting in smaller damper forces than UCd. This could reduce the cost of the viscous damper.

CHAPTER 6 Results: Comparison of the novel 2-4 Displacement & Velocity Dependent Viscous Damper (2-4DVD) with the 2-4DDD Viscous Damper

6.1 Introduction

The semiactive control can be used to improve the performance of passive fluid dampers by modifying or reshaping the overall structural hysteretic response.

This chapter builds on a recently proposed semiactive control system (Hazaveh et al., 2017a) (called 2-4DDD) based on fluid viscous dampers in which the damper forces are controlled by the deformations of the structure (storey drift). This means that the aim of the semiactive control is to control the damper force dependent on the storey drift.

This chapter introduces novel semiactive control system (2-4DVD), designed to control the shape of the structural hysteresis (the relationship between storey shear and inter-storey drift). The system is tested on two typical multistorey structures (low- and medium-rise buildings) comprising a steel moment-resisting frame (MRF) and fluid viscous dampers installed in a Chevron brace configuration. The investigation is carried out by the means of time history simulations of nonlinear response (including plastic hinges in the main structure) to 4 recorded earthquakes with different predominant frequency ranges. Performance is assessed by evaluating story drift, which is directly associated with structural damage, and total base-shear which is a measure of the risk of ground floor failure. The results of the new semiactive control (2-4DVD), which manipulates force-displacement loop of viscous damper, are compared with a non-linear passive viscous damper (PNLVA03-UCd) and a simple manipulation of force-displacement loop of viscous damper called the 2-4DDD (proposed by Hazaveh et al (Hazaveh et al., 2017a)).

6.2 Comparison of hysteretic loops for nonlinear passive and the two semiactive dampers (2-4DDD and 2-4DVD)

It was already shown that additional PVDs in non-linear structures or generally in structures with a high level of damping (see chapter 5) would likely increase base shear and foundation demand. Such increases would reduce the ability to use PVD in structural retrofitting applications due to requiring strengthening of the existing structure and foundations.

It is possible to reshape the structural hysteresis loop to meet design needs by adopting semi-active viscous damping devices (see (Hazaveh et al., 2017a)). Manipulating the hysteresis loop of the damper, and thus of the whole structural system, was proposed by author (Hazaveh et al., 2017a). It was called 2-4DDD (see **Figure 4. 6**).

Unlike the passive control, the 2-4DDD control doesn't increase base shear since damper forces and columns forces do not occur at the same time. **Figure 6. 1** proves that when the total shear force in the columns reaches one of its peaks at 6.37s, the damper forces are zero. The use of such control will not add damper forces to column forces, thus base shear will not be increased.

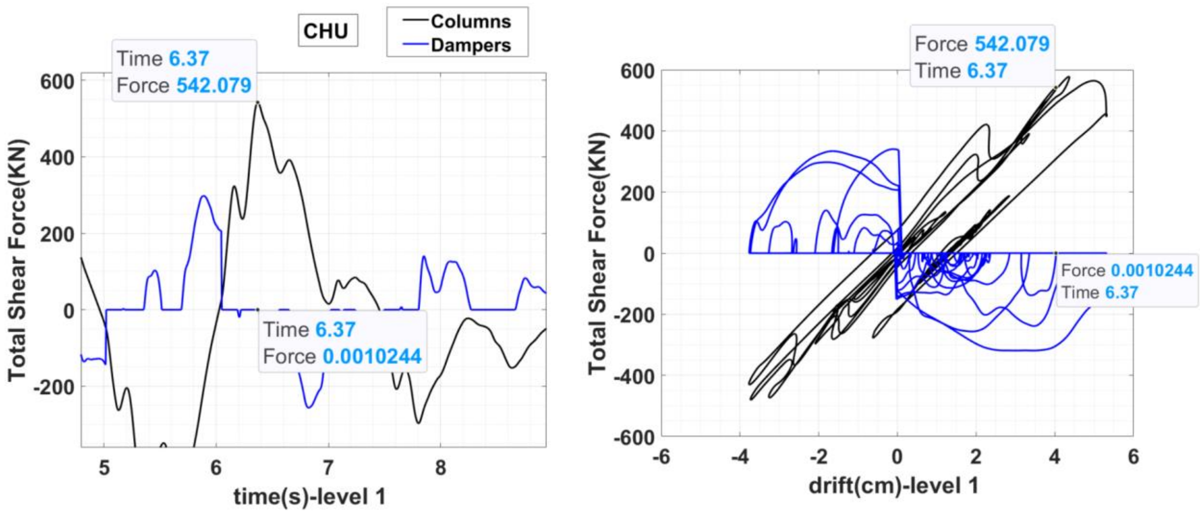


Figure 6. 1: Time history of total shear forces for 2-4DDD control and columns under CHU earthquake in the 3-story frame

The orifices of the 2-4DDD damper are closed in quadrants 2 and 4 so that it only resists motion from peak dashpot displacement back towards zero displacements. This means that there is no damping resistance in quadrants 1 and 3, when the structure is moving away from zero displacements towards the peak.

The orifices of the 2-4DVD damper are not only closed in quadrants 2 and 4, from peak dashpot displacement back towards zero, but also, they are partially closed in quadrants 1 and 3. This means that it has full damper resistance in quadrants 2 and 4 and a portion of the damping resistance in quadrants 1 and 3. Since the parameter *P* in the algorithm (2-4DVD; see Eq. 4.4) changes the amount of damping forces in quadrants 1 and 3, a parametric study has been conducted over a range of *P* values for the sake of achieving the smallest storey drift and total base shear.

6.3 Parametric study for parameter *P* in 2-4DVD control

Figure 6. 2 presents maximum drift of 3-story building controlled by the 2-4DVD system vs five parameter *P* values by adopting the proposed design methodology discussed in **Figure 4. 11.** A detailed presentation of the results (drift and total base shear) is plotted in **Figure 6. 3.** The figure shows the inter-story drift of the frame vs five parameters and base shear of the frame. The response of the frame under parameter P for 4 and 6 was close to each other (see **Figure 6. 2**), but in terms of total base shear (see **Figure 6. 3**), parameter P=6 gives the best results due to achieving slightly less base shear (just 2% less).

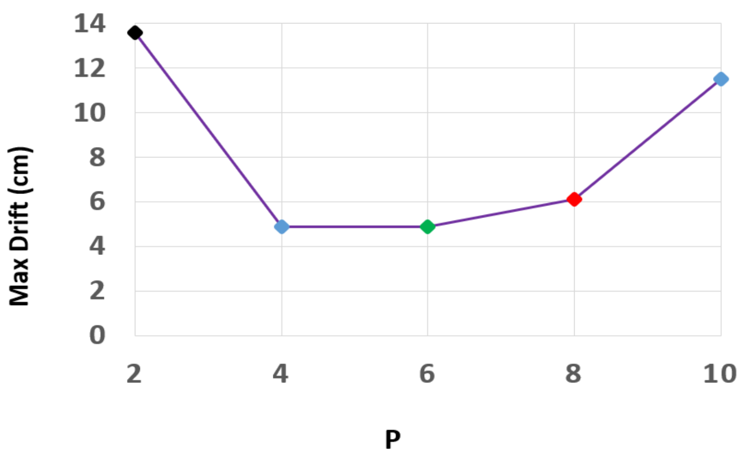


Figure 6. 2: Maximum drift vs P parameter for 2-4DVD in 3-story frame under E1

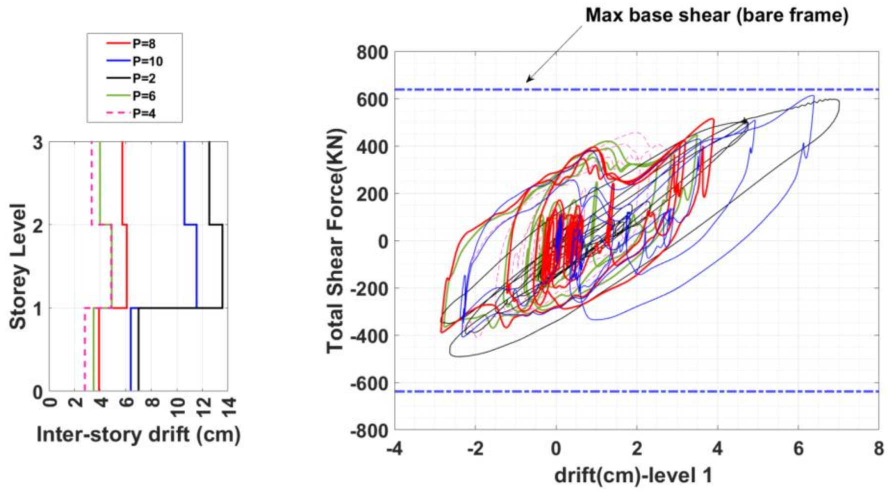


Figure 6. 3: Total base shear vs drift and inter-story drift of the 3-story frame under E1.

2-4DVD control is further investigated in the 7-story building. Again, the results in **Figure 6. 4** and **Figure 6. 5** show that the smallest drift and base shear in the response of the frame under 60%E1 is achieved for the parameter P=6.

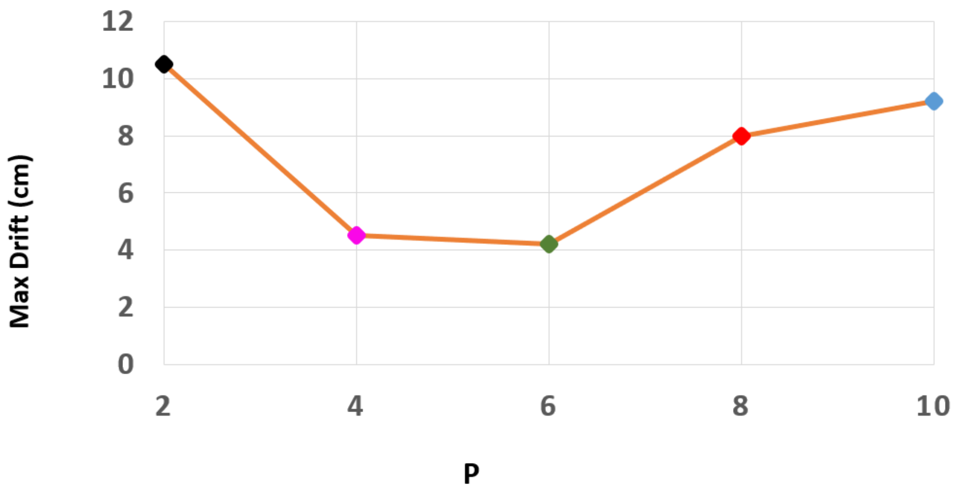


Figure 6. 4: Maximum drift vs P parameter for 2-4DVD in 7-story frame under 60%E1

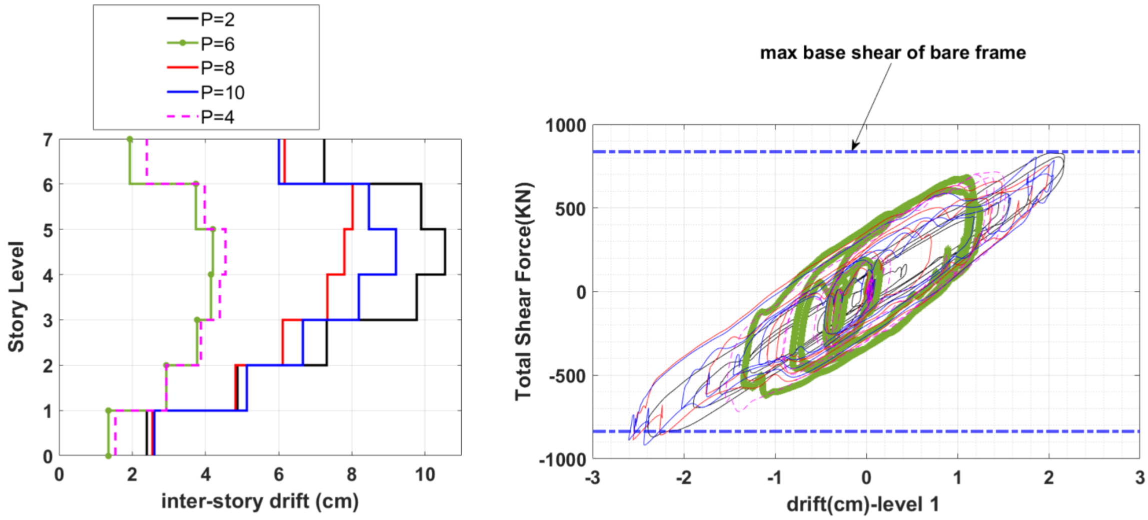


Figure 6. 5: Total base shear vs drift and inter-story drift of the 7-story frame under 60%E1.

The parametric study shows that P=6 can be selected for the proposed 2-4DVD algorithm for both the 3-story and 7-story buildings analysed in this study.

6.4 Response of the buildings to different earthquakes

In order to obtain the most representative responses for comparison of the performance of the different control systems, the analysed 3-story (low rise) and 7-story (medium rise) buildings were subjected to a set of 4 recorded earthquakes, selected to represent excitations with different characteristics (peak acceleration, predominant frequency range and duration).

6.4.1 Response of the 3-story building to different earthquakes

6.4.1.1 Response to E1 (CHU-100%)

The response of the 3-story frame equipped with 2-4DDD, passive nonlinear viscous damper and 2-4DVD under E1 is presented in **Table 6. 1** and **Figure 6. 7.** The results show the limits of PNLVA03 which produces the highest base shear of the building, 100% of the bare frame, as well as largest plastic rotation at 0.63 of that of the bare frame, but the same number of plastic hinges as 2-4DDD (**Table 6. 1**). The 2-4DDD system shows a better performance than the passive system, with plastic rotation at 0.38 in the columns, without any increase in the number of plastic hinges in the frame (**Figure 6. 6** and **Table 6. 1**), while the improvement in maximum base shear is relatively modest at 0.88 (compared to 1). The proposed 2-4DVD, shows a further, significant improvement, especially in limiting the drift (to only 17%) and the number of plastic hinges (to 18%), with the shear also reduced to 0.68 of the bare frame. The distribution of plastic hinges (**Figure 6. 6**) shows that the structure controlled by 2-4DVD remains mainly linear elastic, with hinges in only 4 beams.

Table 6. 1: Comparison of response of bare frame with passive nonlinear viscous damper and two reshaped hysteresis loops of viscous damper under E1

Frame Notation	Max. plastic rotation (scaled to bare frame)	Max base shear (scaled to bare frame)	Max number of plastic hinges (scaled to bare frame)
3S-Undamped	1	1.0	1
3S-PNLVA03-E1	0.63	1	0.82
3S-(2-4DDD)-E1	0.38	0.88	0.82
3S-(2-4DVD)-E1	0.17	0.68	0.18

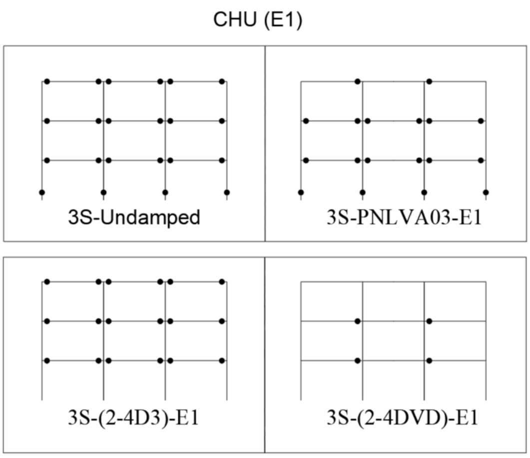


Figure 6. 6: The location of hinges of 3-story MRF for undamped, passive control, 2-4DDD and 2-4DVD under E1

The comparison of the performance of analysed systems (passive, 2-4DDD and 2-4DVD) is even better illustrated in **Figure 6. 7**, showing the maximum drift of the three systems, the hysteretic loops of the two semiactive systems, showing the separate loops for columns and dampers, and a combined plot of the total base shear hysteresis (column shear plus damper force projection) for the three systems. The combined drift profiles and hysteretic loops give a clear picture of the superior performance of the 2-4DVD control.

Figure 6. 7 also compared the response of 3S (3-Story) controlled by 2-4DDD and 2-4DVD under E1 excitation in terms of drift, total shear force and total base shear. The total base shear of the bare frame is taken as a limit for the evaluation of the performance. The comparison also considered PNLVA03-UCd (passive nonlinear viscous damper alpha 0.3-uniform Cd distribution) in base shear.

Total base shear in **Figure 6. 7** states that PNLVA03-UCd can reduce drift up to a certain point without increasing base shear (a reference to base shear of bare frame) whereas 2-4DDD or 2-4DVD can reduce drift more than PNLVA03-UCd without increasing base shear.

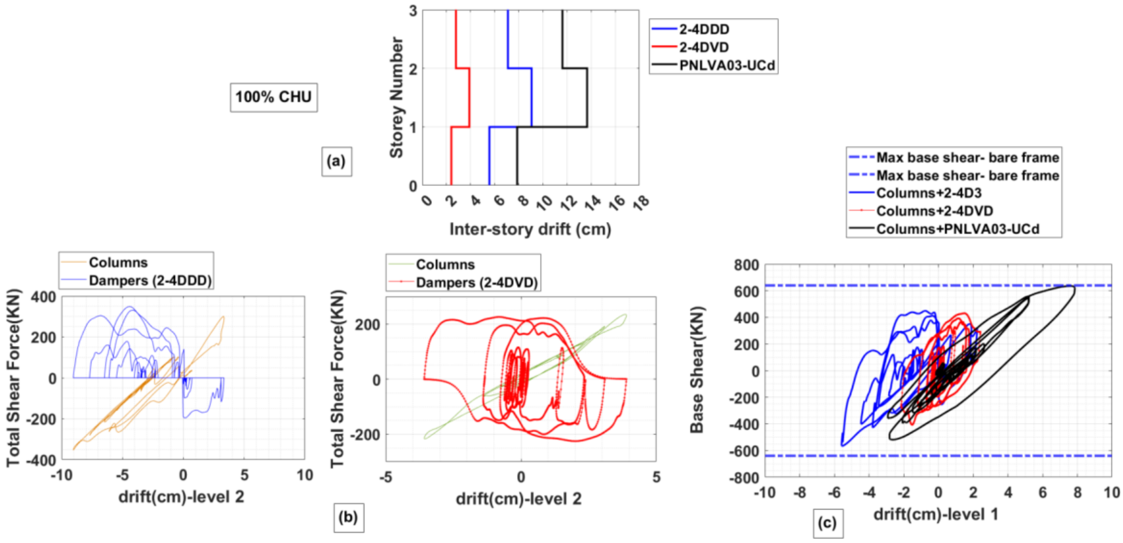


Figure 6. 7: Comparison of 2-4DDD and 2-4DVD in terms of drifts (a), total shear force (b) and total base shear (c) for 3-story frame under E1 excitation

2-4DVD showed a promising advantage against 2-4DDD in both achieving smaller drift and less total base shear. i.e., a portion of damping forces in quadrants 1 and 3 could be advantageous rather than eliminating forces in those quadrants fully (such as 2-4DDD). The investigation is extended to three more earthquakes.

6.4.1.2 Response to E3 (PAR-100%)

Results of **Figure 6. 8** indicated that by considering reshaped hysteresis loop concept (2-4DDD or 2-4DVD), it is possible to reduce drift without increasing base shear whereas passive control can easily increase the base shear of the frame. PNLVA03-UCd resulted in more than 5% drift whereas 2-4DDD was 2.8% drift. A further improvement was from 2-4DVD, it resulted in 1.5% drift without increasing base shear of the building.

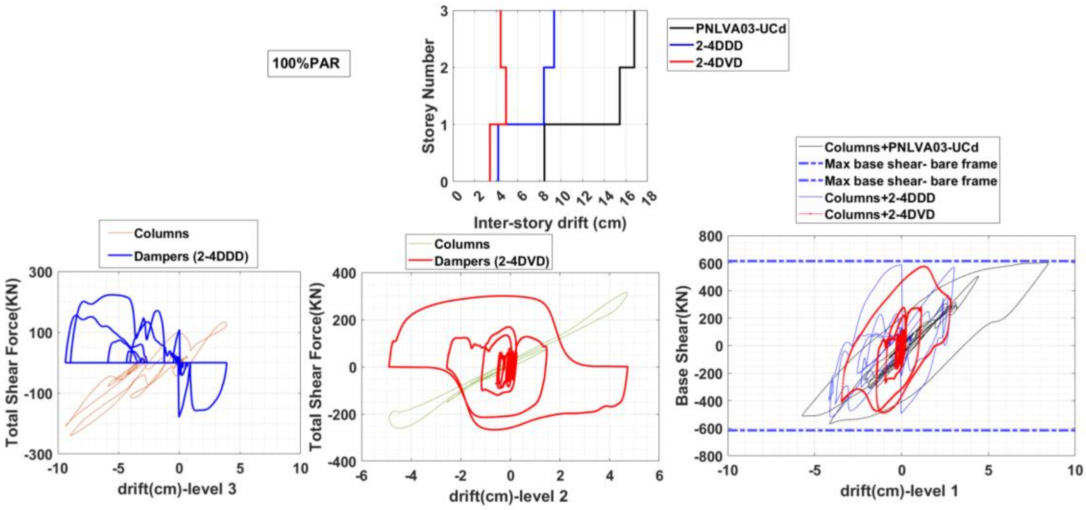


Figure 6. 8: Comparison of 2-4DDD, 2-4DVD and passive control in terms of drifts, total shear force and total base shear for 3-story frame under E3 excitation

6.4.1.3 Response to E4 (CAP-100%)

When the 3-story building was subjected to the CAP earthquake, the results show a better response of 2-4DVD than that of both PNLVA03-UCd and 2-4DDD (**Figure 6. 9**).

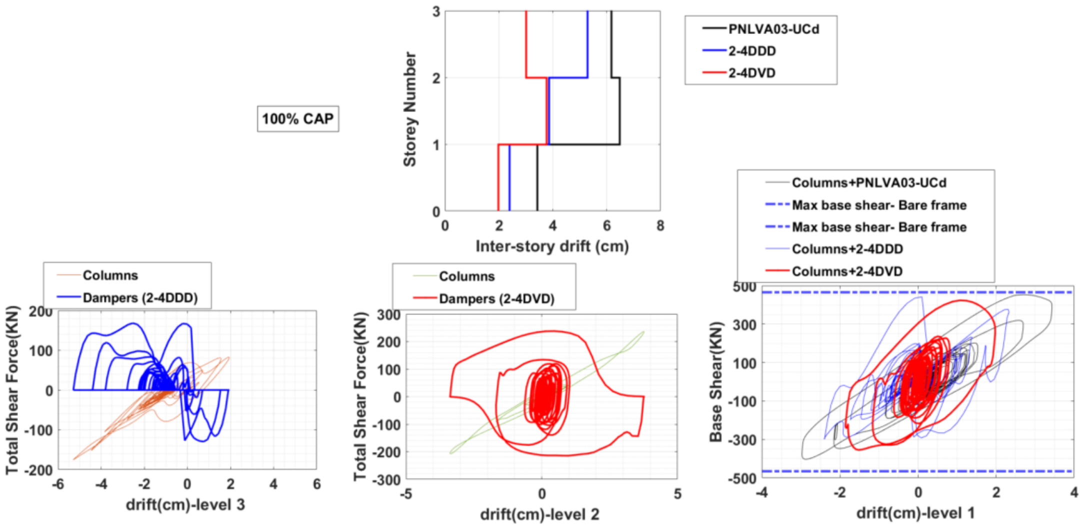


Figure 6. 9: Comparison of 2-4DDD, 2-4DVD and passive control in terms of drifts, total shear force and total base shear for 3-story frame under E4 excitation

6.4.1.4 Response to E5 (KOBE-100%)

For the 3-story frame subjected to another ground motion (KOBE), the (**Figure 6. 10**) again show that 2-4DVD was better than both PNLVA03-UCd and 2-4DDD in terms of drift. 2-4DVD did not increase the base shear of the frame while reducing the drift of the frame. The required maximum damper force resulted from 2-4DVD was also slightly less than 2-4DDD.

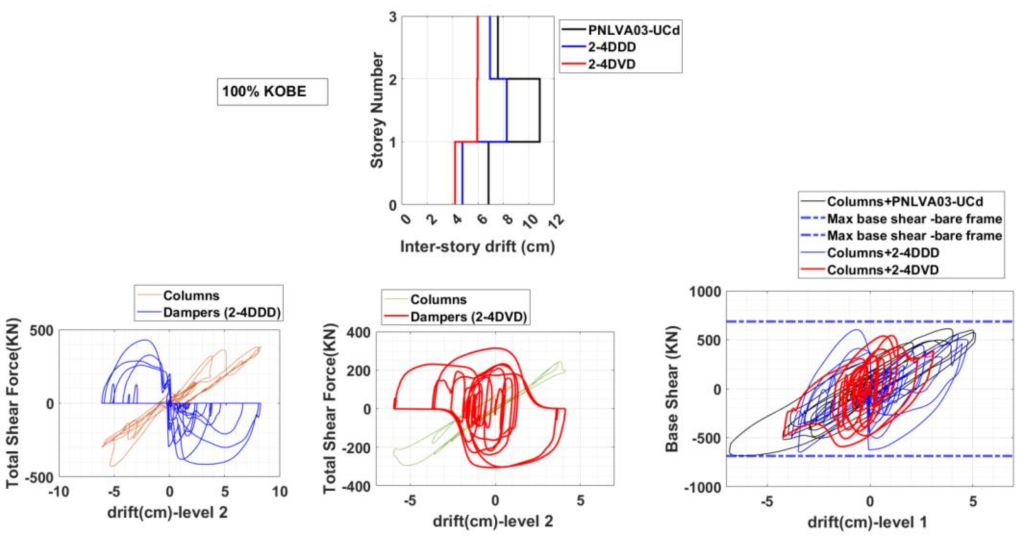


Figure 6. 10: Comparison of 2-4DDD, 2-4DVD and passive control in terms of drifts, total shear force and total base shear for 3-story frame under E5

6.4.1.5 Comparison of key parameters of response to all four earthquakes (CHU-100%, PAR-100%, KOBE-100% and CAP-100%)

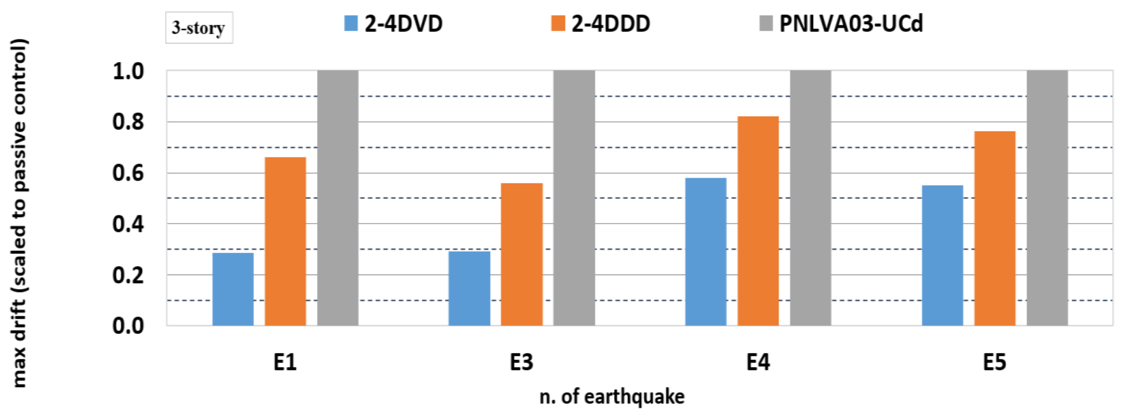


Figure 6. 11: Comparison of the response of the 3-story frame controlled by two-semiactive and one-passive control under four different earthquakes. E1: CHU, E3: PAR, E4:CAP, E5: KOBE

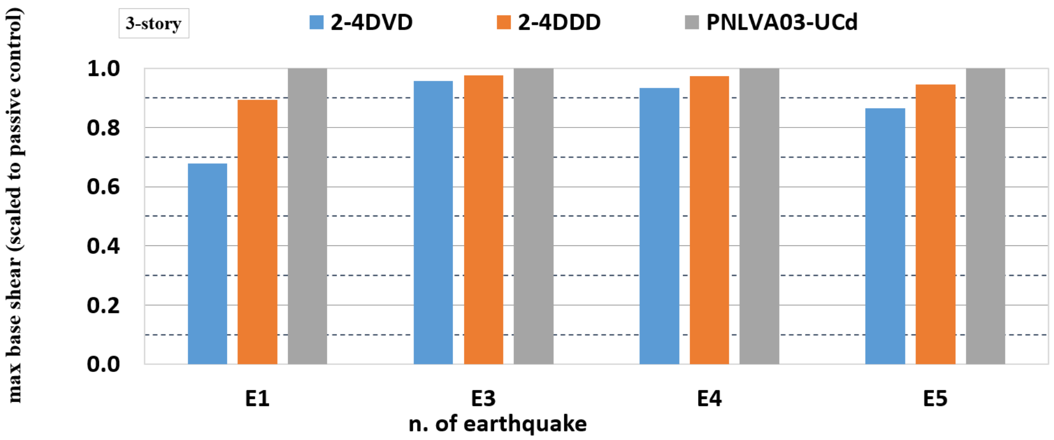


Figure 6. 12: Comparison of the response of the 3-story frame controlled by the three controls (2-4DDD, 2-4DVD and PNLVA03-UCd) under four different earthquakes. E1: CHU, E3: PAR, E4:CAP, E5: KOBE

Figure 6. 11 and **Figure 6. 12** compare the peak response values (maximum drift and base shear) of the 3-story frame under the four different earthquakes used in the study.
The results show that:

- 2-4DDD produced significantly smaller drifts than PNLVA03-UCd with a small reduction in base shear, under all four earthquakes
- 2-4DVD significantly outperformed 2-4DDD in terms of both drift (under all four excitations) and max base shear (considerable improvement under E1 and E5). It showed that the improvements dependent on earthquakes. It is believed that the reason of significant improvement under some ground motions is due to the energy dissipation. i.e., Some earthquakes (E3: PAR, E4: CAP) had only one or two very long oscillation (low frequency) whereas the others had more than one big oscillation before reaching the biggest and the most critical one (high frequency).

6.4.2 Response of the medium rise building (7-storey frame)

The investigation of the reshaped hysteresis loop of a viscous damper was extended to a medium-rise frame.

6.4.2.1 Response to E1 (CHU)

(A) E1-100%

Under 100 % E1, the reshaped viscous damper loops resulted in massive drift for both 2-4DDD and 2-4DVD for the 7-story frame, as shown in **Figure 6. 13**. The concept of manipulating the force-displacement relation, which aims not to increase base shear, may not provide enough additional damping under intensive ground motion conditions. **Figure 6. 13** shows that 2-4DVD achieved smaller drift than both the passive viscous damper and the 2-4DDD, yet such control strategy cannot be adopted since the drift of 2.5% (8cm) is still beyond the life safety limit. The results indicated that neither the 2-4DDD nor the 2-4DVD can provide a sufficient response (less than 2% drift) under full-scale ground motion (100%). Hence, the E1 input was scaled down to 60%. The semiactive control manipulating force-displacement loop of viscous damper may not be an optimal seismic structural control strategy due to offering limited energy dissipation capacity (i.e., the control objective is to prevent total base shear increase while reducing drift of the frame).

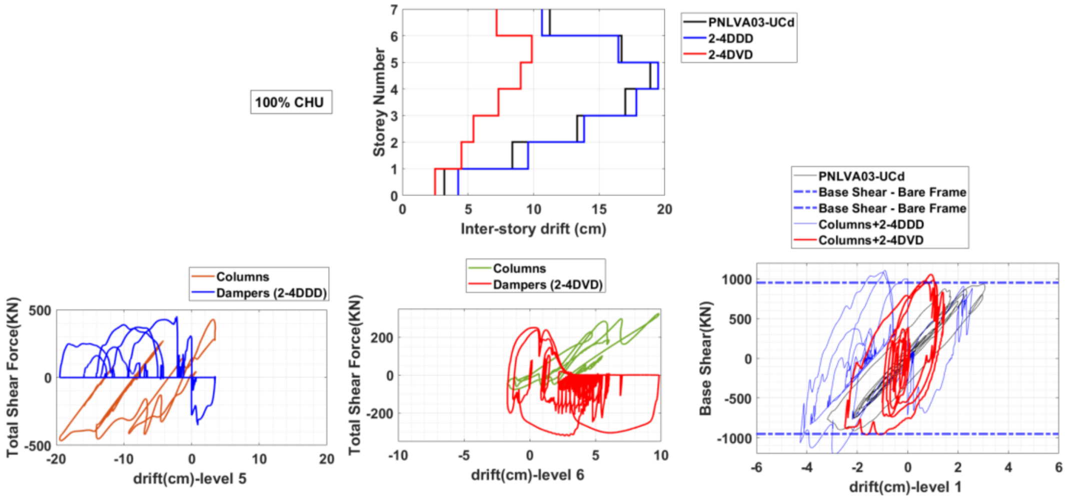


Figure 6. 13: comparison of 2-4DDD and 2-4DVD in terms of drifts, total shear force and total base shear for 7-story frame under E1 (CHU) excitation

(B) E1- 60%

For a moderate earthquake CHU scaled to 60%. The drifts for 2-4DDD and the passive damper were far beyond the life safety limit of 2.5% (**Figure 6. 14**a**),** whereas 2-4DVD not only reduced the drift significantly (to 1%) but also slightly reduced the maximum base shear of the frame (**Figure 6. 14**d**)**. These show the superiority of 2-4DVD over the other two controls. The 2-4DDD also indicated unstable response in the hysteresis loop of the damper (**Figure 6. 14**b**)**. i.e., this could be the sign of unstable response for high added damping of the 2-4DDD. It can be said that the 2-4DVD (**Figure 6. 14**c**)** was more stable than the 2-4DDD in the hysteresis loop of viscous damper. A stable response in the hysteresis loop is important for preventing unnecessary damping force jumps (i.e., it could increase damper cost without making any improvement in the response of the frame or increase total base shear without reducing the drift of the frame significantly) and increasing the energy dissipation capacity of the damper.

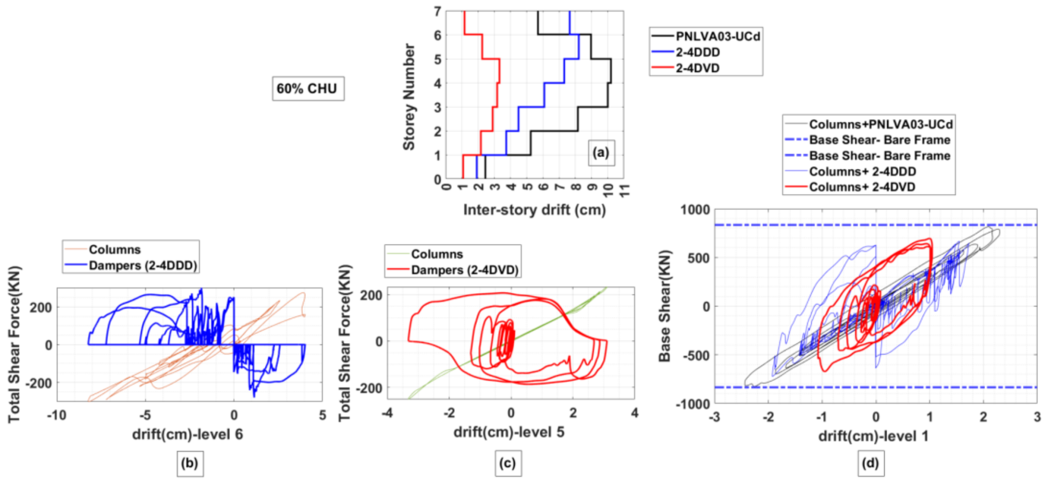


Figure 6. 14: Comparison of 2-4DDD, 2-4DVD and passive control in terms of drifts, total shear force and total base shear for 7-story frame under 60%E1 (CHU).

6.4.2.2 Response to E3 (PAR)

(A) E3-100%

The frame subjected to E3 earthquake showed that PNLVA03 and 2-4DDD exceeded the life safety level of 2.5% drift (8 cm) whereas 2-4DVD was within the life safety level even under 100% PAR (see **Figure 6. 5**).

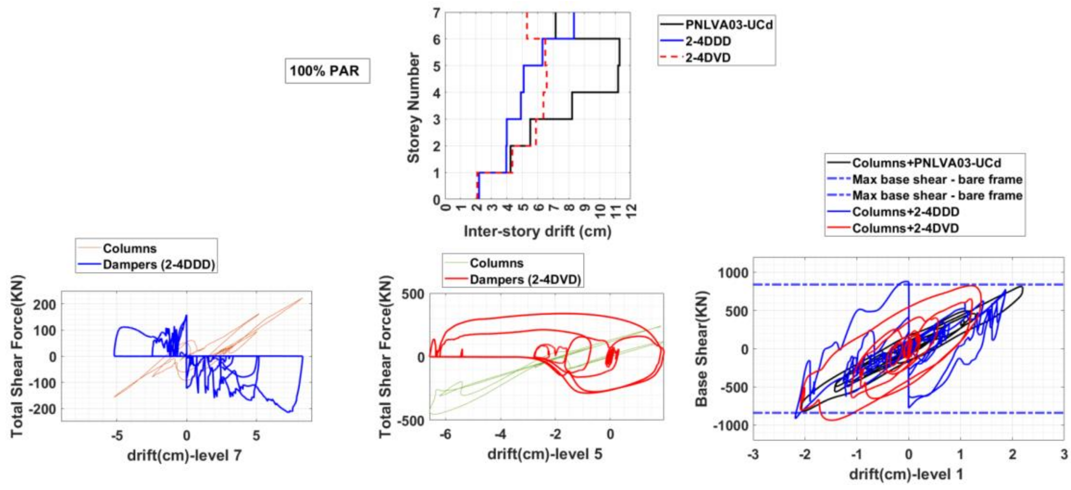


Figure 6. 15: Comparison of 2-4DDD, 2-4DVD and passive control in terms of drifts, total shear force and total base shear for 7-story frame under E3 (PAR) excitation

(B) E3-70%

When the input was scaled to 70% PAR the results (**Figure 6. 16)** indicated that the maximum drift of 2-4DVD was the same as 2-4DDD and was smaller than passive controls while maximum base shear remained the same.

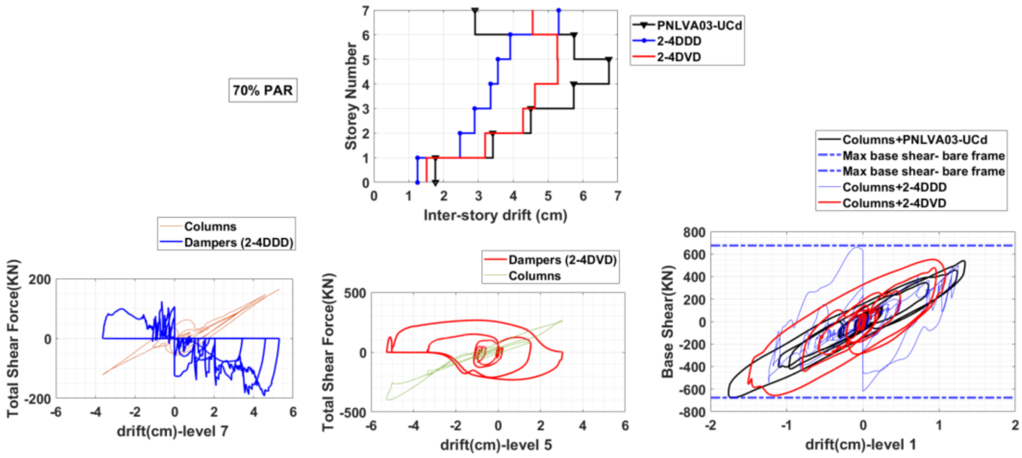


Figure 6. 16: Comparison of 2-4DDD, 2-4DVD and passive control in terms of drifts, total shear force and total base shear for 7-story frame under 70% E3 (PAR) excitation

6.4.2.3 Response to E5 (KOBE)

(A) E5- 100%

The results for the 7-story frame exposed to the E5 earthquake (**Figure 6. 17)** show that 2-4DDD ended up with the same drift as 2-4DVD, both higher than the life safety limit, but significantly better than PNLVA03. Hence the input was scaled to 65% and discussed in the following subsection.

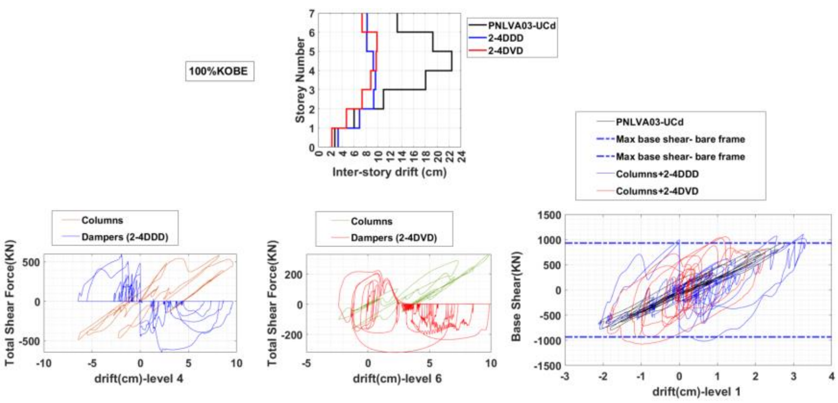


Figure 6. 17: Comparison of 2-4DDD, 2-4DVD and passive control in terms of drifts, total shear force and total base shear for 7-story frame under E5 (KOBE) excitation

(B) E5- 65%

Figure 6. 18 shows that when the building was subjected to 65% KOBE, the drift of 2-4DDD was smaller than that of PNLVA03, whereas 2-4DVD ended up with significantly smaller drift than 2-4DDD, without increasing the base shear. 2-4DVD was the only control that can achieved the life safety level drift (<2%).

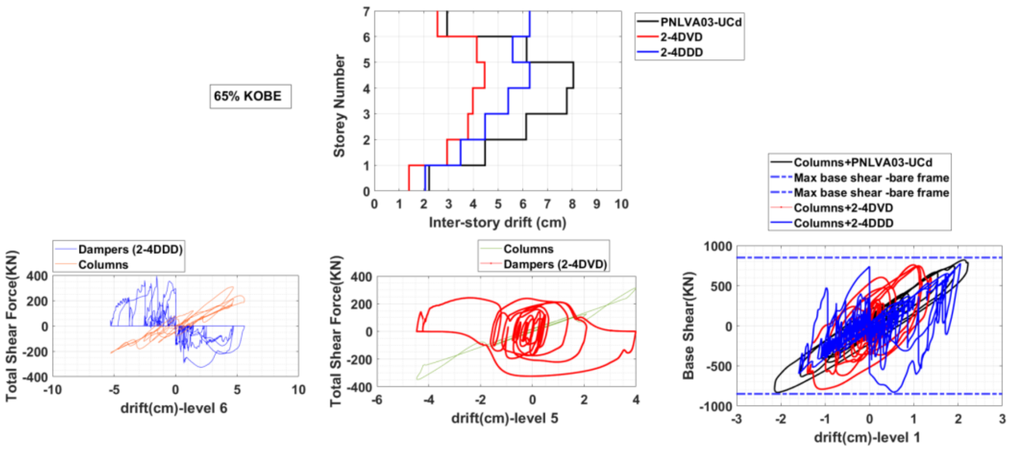


Figure 6. 18: Comparison of 2-4DDD, 2-4DVD and passive control in terms of drifts, total shear force and total base shear for 7-story frame under 60% E5 (KOBE)

6.4.2.4 Response of 7-storey buildings to three earthquakes (CHU-60%, PAR-70% and KOBE-65%)

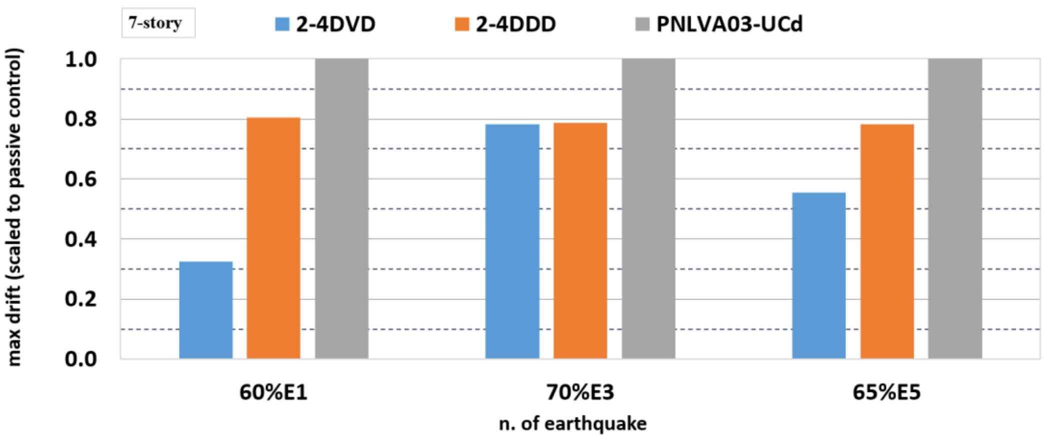


Figure 6. 19: Comparison of the response of 7-story building controlled by the three controls under three different scaled earthquakes in terms of maximum drift. E1: CHU, E3: PAR, E5: KOBE

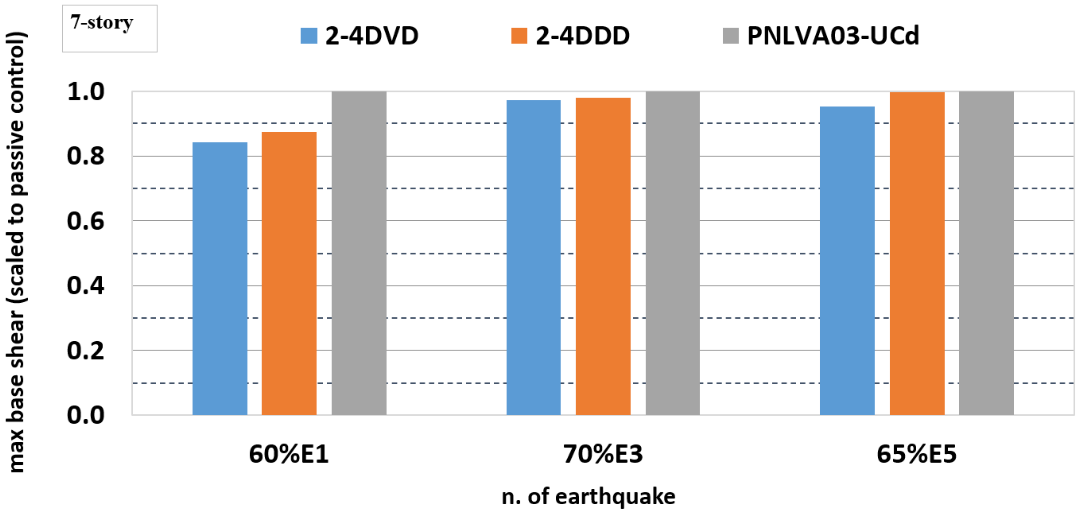


Figure 6. 20: Comparison of the response of 7-story building controlled by 2-4DDD, 2-4DVD and PNLVA03-UCd under three different scaled earthquakes in terms of maximum base shear. E1: CHU, E3: PAR, E5: KOBE

Figure 6. 19 and **Figure 6. 20** present the response of the 7-story building controlled by two semiactive and one passive controls under three scaled earthquakes. Again, As discussed in the 3-story frame, 2-4DDD resulted in smaller drift than PNLVA03-UCd either achieving similar or lower max base shear (**Figure 6. 20**). 2-4DVD again outperformed 2-4DDD by not only achieving smaller max drift (e.g., for 60%E1 and 65%E5) but also slightly reducing the maximum base shear (e.g., for 60%E1 and 65%E5). The response of the frame under the 2-4DVD and the 2-4DDD (e.g., for 70%E3) were similar in terms of both maximum drift and total base shear. It showed that the response of the semiactive control (the 2-4DVD) depends on earthquakes. Compared with the passive control, the proposed control (the 2-4DVD) introduced an improvement under the three excitations (e.g., for 60%E1, 70%E3 and 65%E5) in both maximum drift and base shear, yet when the 2-4DVD compared with the 2-4DDD, it showed an earthquake dependent response (i.e., the 2-4DVD is sensitive to earthquake frequencies).

6.5 Summary of results for 2-4DDD, 2-4DVD and PNLVA03-UCd

This chapter investigated 2-4DDD and 2-4DVD control with a novel coefficient distribution method adopted for both the 2-4DVD and the 2-4DDD (see **Figure 4. 11**) and a passive control with uniform coefficient distribution (PNLVA03-UCd). The investigation was carried out by time history simulations of the response of two (a 3- and 7-story) steel moment resistant frames, which were designed in accordance with the ductility-based design approach of Eurocode 8 and equipped with added semi-active viscous dampers that reshape the force-deformation (hysteretic) response of the structure. Total base-shear and inter-storey drift were chosen to determine the efficiency of different semi-active viscous dampers on the seismic structural performance over a range of ground motions.

The main findings of this chapter can be summarized as follows:

- The semi-active viscous damper 2-4DDD, which provides damping in the second and fourth quadrants, reduced the structural deformations (drift) of the bare frame with no increase in base shear. It consequently eliminated the overturning moment and risk of foundation damage. However, for this system maximum added damping was limited. It was shown that the addition of damping beyond a certain limit increased the base shear of the structure, which limits the effectiveness of 2-4DDD.

- A novel semiactive control approach, 2-4DVD, has been proposed as an alternative to 2-4DDD. To identify an optimal *P* parameter in the 2-4DVD control, a parametric study has been conducted over a range of *P* values.

The results showed that the proposed control algorithm (2-4DVD) was more promising than 2-4DDD (as well as the passive control PNLVA03-UCd) offering greater robustness and effectiveness over a range of ground motions than the 2-4DDD.

- The results demonstrated that for the low-rise frame (3- story), the new damper (2-4DVD) could be used for any of the ground motions with their original intensities (100%).
- For the 7-story frame, the new damper (the 2-4DVD) showed better performance than the other two dampers (the passive and the 2-4DDD) but not sufficient for protection of the structure against the full intensities of all the selected earthquakes (i.e., earthquakes were scaled down from 60% to 70% of their real excitations). When the ground motions which produced extreme deformations were scaled down to more moderate levels, the new damper significantly outperformed the other two systems.

CHAPTER 7 Results: Comparison of the proposed 2-4DVD control with an improved Velocity & Displacement Dependent control (2-4VDD)

7.1 2-4VDD: introduction

Chapter 6 presented the results of the analysis of a novel semiactive fluid viscous damper control (2-4DVD), proposed as an alternative to an existing semiactive control (2-4DDD; (Hazaveh et al. 2017a)). The assessment of the new semiactive control was carried out by non-linear time history simulations of the two semiactive systems and a selected non-linear passive viscous damping system (PNLVA03-UCd), all applied to two steel frame buildings (3 and 7 storey, representing typical low and medium rise buildings) and subjected to 4 recorded earthquakes, selected to represent seismic inputs with different peak ground acceleration and frequency content. The results showed better performance of the new control algorithm 2-4DVD than 2-4DDD (and both performing better than the passive control PNLVA03-UCd); in each of the 4 earthquakes. This suggests that the new 2-4DVD semi-active viscous damper potentially offers greater robustness and effectiveness over a wide range of ground motions than the 2-4DDD. A design methodology for the vertical distribution of the control parameters of 2-4DVD along the height of the buildings was proposed in **Figure 4. 11**.

Chapter 7 presents the investigation of a novel manipulated force-displacement relation for improvement of the 2-4DVD control. The initial damping coefficient of the 2-4DVD was updated based on a ratio which was the energy (under the curve of force-displacement of the viscous damper) of the damper at j time divided by (j-1). The results of the newly proposed semiactive control (2-4VDD) are compared with the 2-4DVD viscous damper.

The performance is assessed by achieving the same story drift of low- and medium-rise frames as 2-4DDD and comparing the resulting storey shear forces (shear demand).

For the operation of 2-4VDD control the orifices of the damper must be closed in quadrants 2 and 4 from peak dashpot displacement back towards zero displacements but also, must be partially locked in quadrants 1 and 3. This means that the damper will have full damping resistance in quadrants 2 and 4 and a portion of damping resistance in quadrants 1 and 3. The proposed algorithm is shown in Eq. 4.5. The role of parameter D in the algorithm (the 2-4VDD) is to reduce or increase the damping forces in quadrants 1 and 3. As it is shown in **Figure 4. 7**b **and Figure 4. 7**c**,** the damping forces generated by the 2-4VDD are larger than the 2-4DVD. By offering a new shape of force-displacement, the 2-4VDD will mostly move forces from quadrants 1 and 3 to quadrants 2 and 4, in contrast to the 2-4DVD, which introduced some forces into quadrants 1 and 3. This algorithm is being tested to see if it reduces total base shear while maintaining the same drift as the 2-4DVD.

7.2 Parametric studies for parameter *D* in 2-4VDD

The performance of the 2-4VDD system is regulated by a parameter D. The value of the D parameter was determined by the means of a parametric study conducted over a range of D values. The resulting storey hysteresis loops (**Figure 7. 1** shows one of them) were assessed and $D = 12$ was selected for the subsequent simulations or the response of both 3 and 7 storey buildings. The $D = 12$ value was selected because it could mostly remove damping forces from quadrants 1 and 3. This value was selected by simply observing force-displacement loop shown in **Figure 7. 1.**

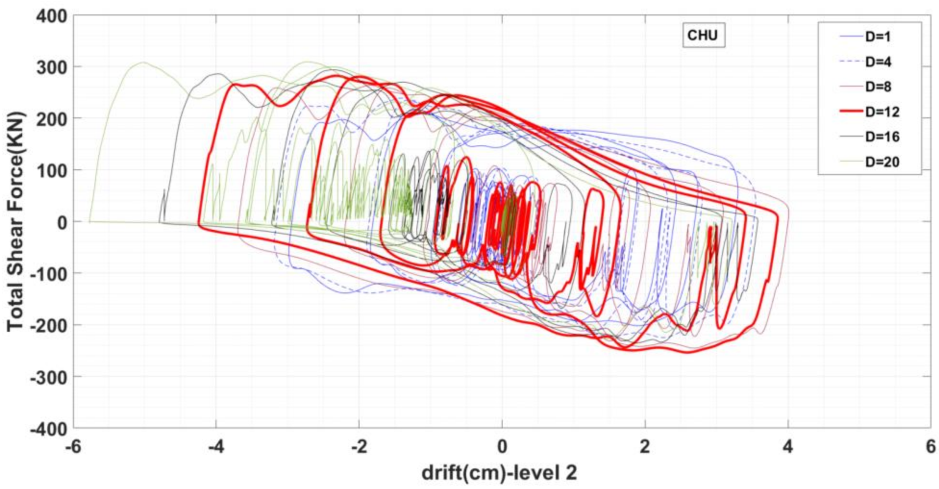


Figure 7. 1: Parameter *D* investigation in 3-story frame under CHU earthquake

7.3 Response of building to various earthquakes

7.3.1 3-story building

7.3.1.1 Response to E1 (CHU-100%)

The 3-story frame subjected to 100% E1 (**Figure 7. 2)** showed that in comparison with 2-4DVD under the same story drift, 2-4VDD did not introduce any reduction in total base shear, and it increased required maximum damper forces by 74 % (**Figure 7. 3)**. There was no improvement with the 2-4VDD; however, maximum damper forces increased (by 74%) with the E1 (CHU) excitation.

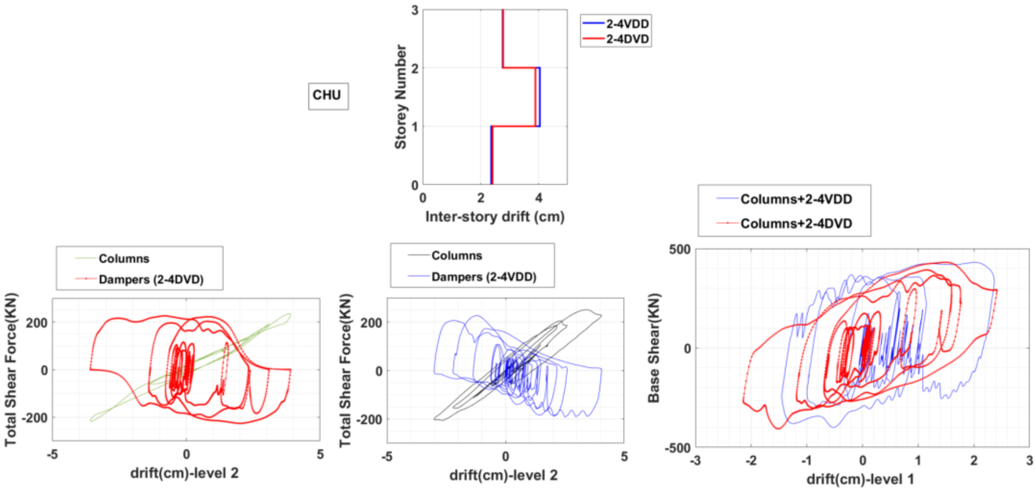


Figure 7. 2: frame response to 100% E1 ground motion under the control of 2-4DVD and 2-4VDD

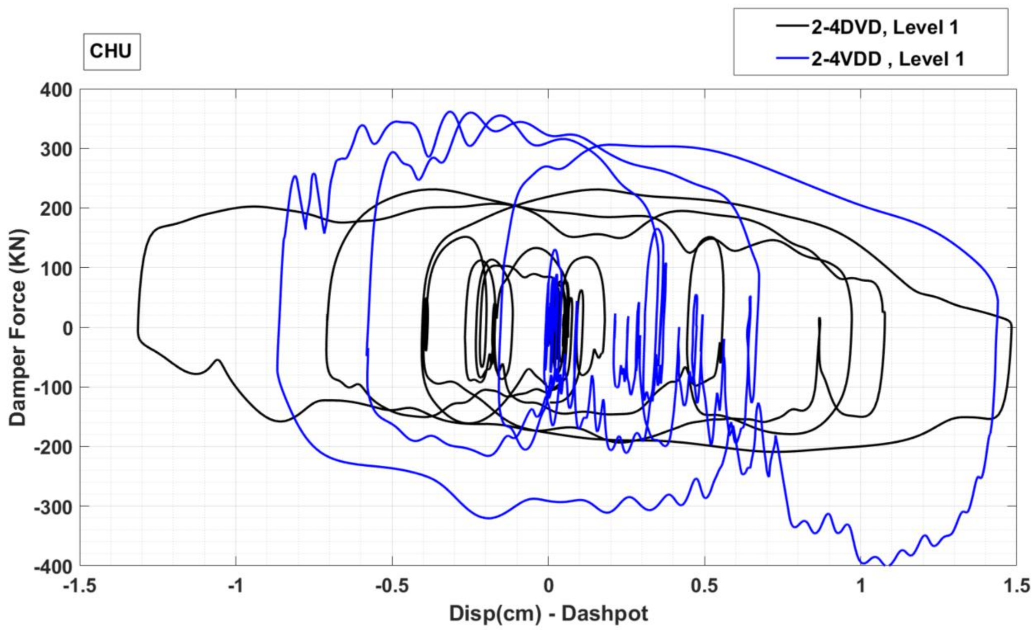


Figure 7. 3: Comparison of damper forces (the biggest damper force in all three stories) of 2-4DVD and 2-4VDD under E1 (CHU) excitation.

Figure 7. 3 shows max damper forces in all three stories. It can be seen that the 2-4VDD increased the damper forces required.

7.3.1.2 Response to E3 (PAR-100%)

The comparison of two semiactive controls (2-4DVD and 2-4VDD) is evaluated under a similar story drift. The frame response to 100% PAR (**Figure 7. 4**) shows that 2-4VDD reduced base shear by 16 %, but it increased the required damper forces by 26% (**Figure 7. 5**).

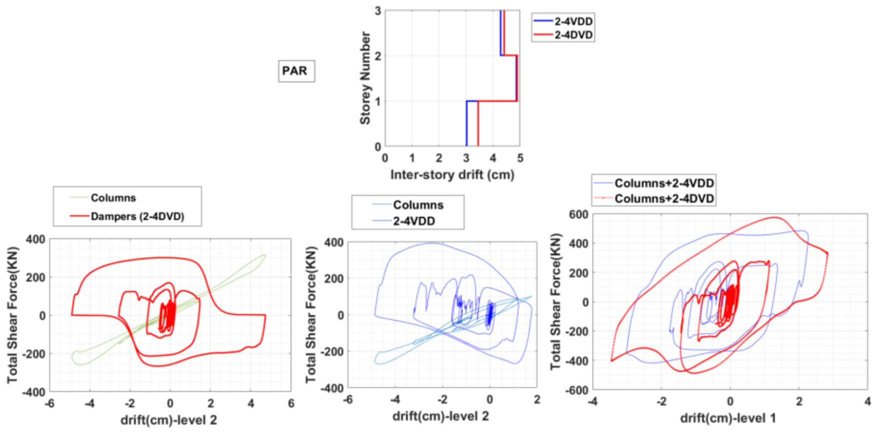


Figure 7. 4: 3-story frame response controlled by 2-4DVD and 2-4VDD under PAR

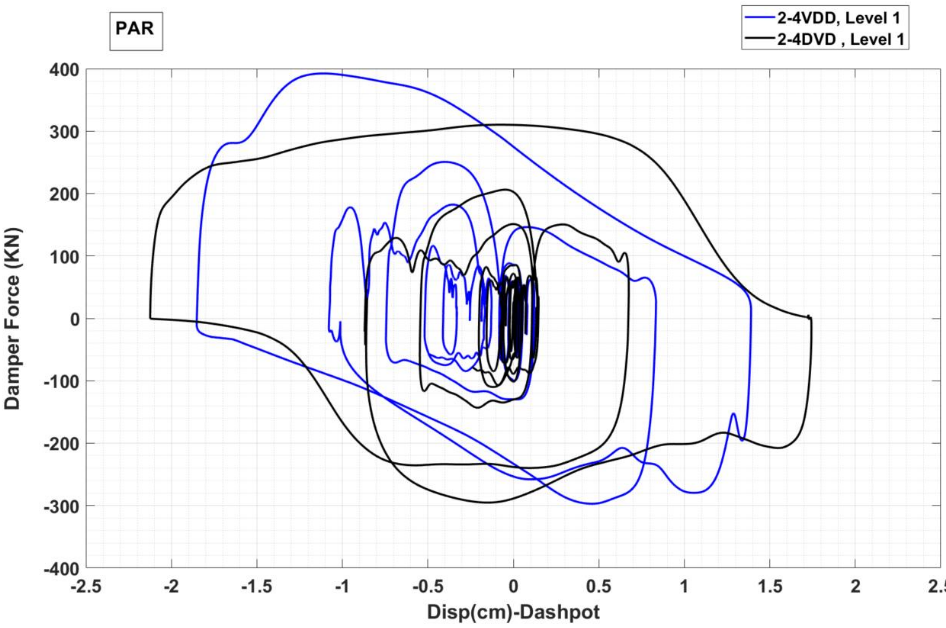


Figure 7. 5: Damper force vs dashpot displacement for 2-4DVD and 2-4VDD under PAR earthquake. These two-control law plotted are max damper forces in all three stories. I.e., in 3-story frame, max damper force required happens in level 1.

7.3.1.3 Response to E4 (CAP-100%)

The algorithm was examined under 100% CAP (**Figure 7. 6)** shows that 2-4VDD reduced the base shear by only 3% compared with 2-4DVD, yet it increased the required damper forces by 107% (**Figure 7. 7**).

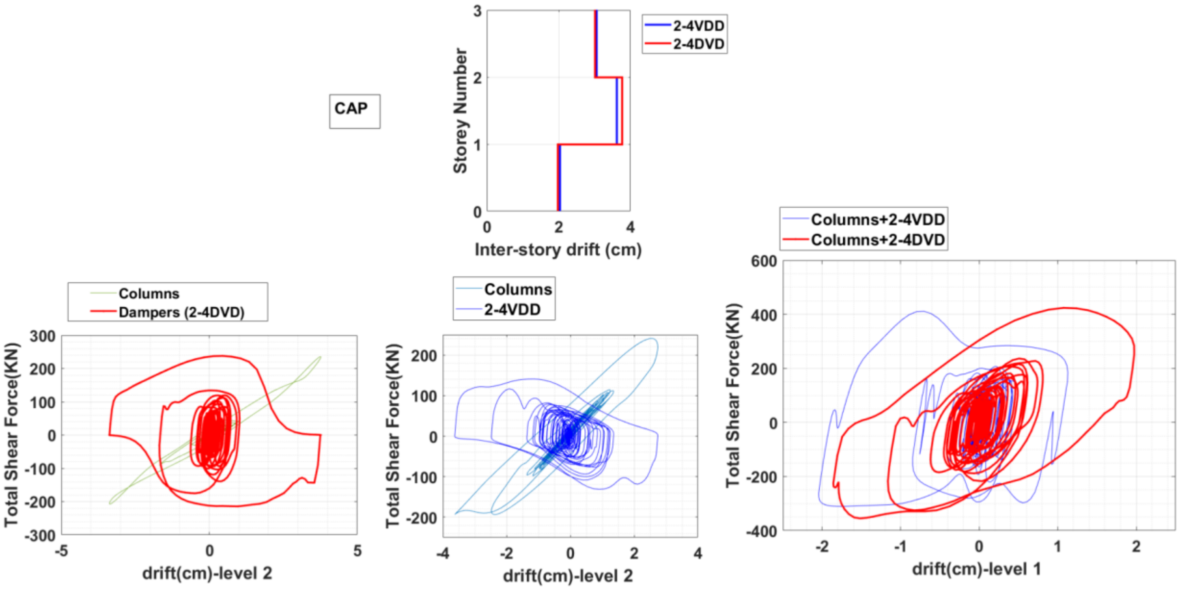


Figure 7. 6: Building frame controlled by two SA controls under CAP earthquake

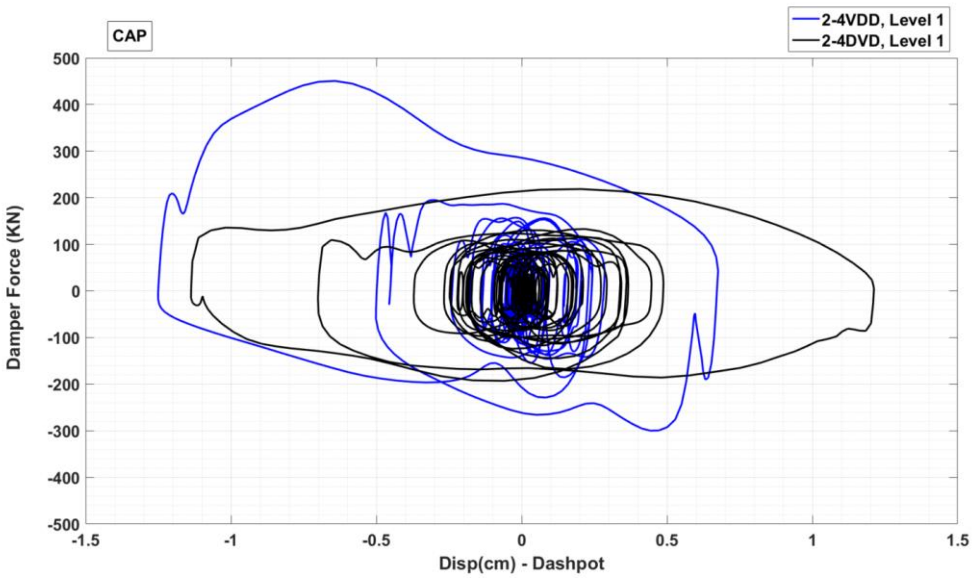


Figure 7. 7: Damper force vs dashpot displacement for 2-4DVD and 2-4VDD under CAP earthquake. These two-control law plotted are max damper forces in all three stories. I.e., in 3-story frame, max damper force required happens in level 1.

7.3.1.4 Response to E5 (KOBE-100%)

The 3-story frame controlled by 2-4DVD and 2-4VDD was subjected to 100% KOBE. **Figure 7. 8** shows that there is only a 2% reduction in the base shear compared with 2-4DVD, yet the required damper force is increased by 7.3% (**Figure 7. 9**).

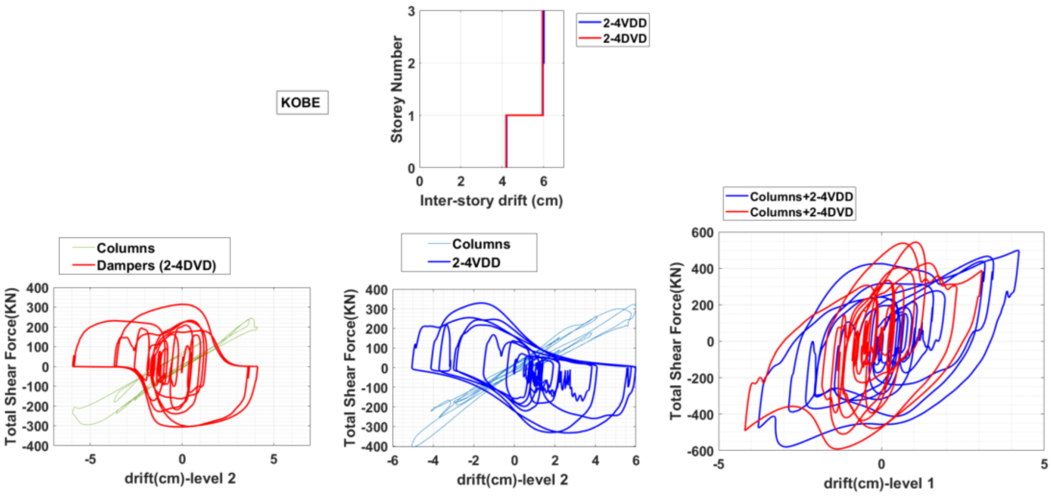


Figure 7. 8: 3-story frame controlled by two different control laws under KOBE earthquake.

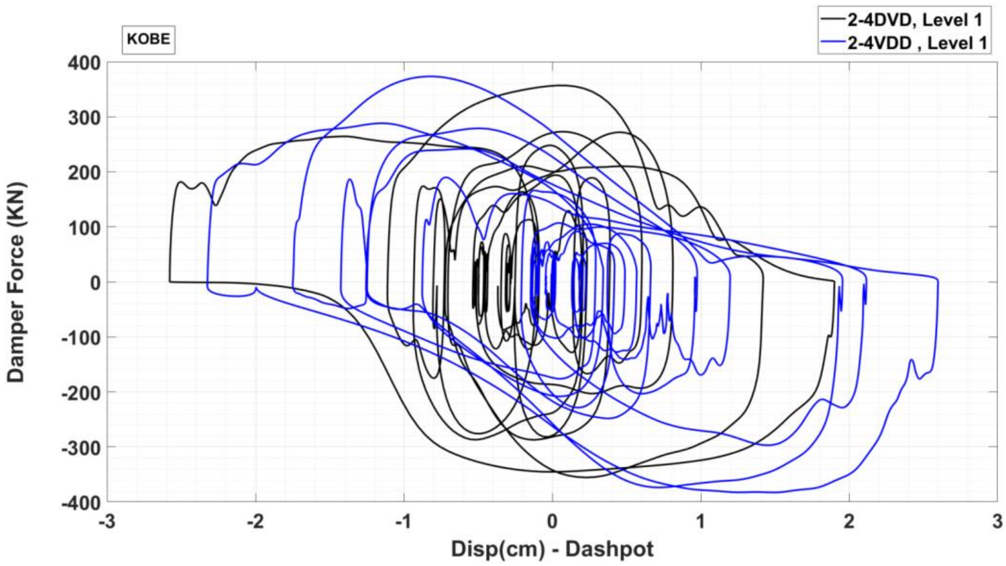


Figure 7. 9: Damper force vs dashpot displacement for 2-4DVD and 2-4VDD under KOBE earthquake. These two-control law plotted are max damper forces in all three stories. I.e., in 3-story frame, max damper force required happens in level 1.

Results: Comparison of the proposed 2-4DVD control with an improved Velocity & Displacement Dependent control (2-4VDD)

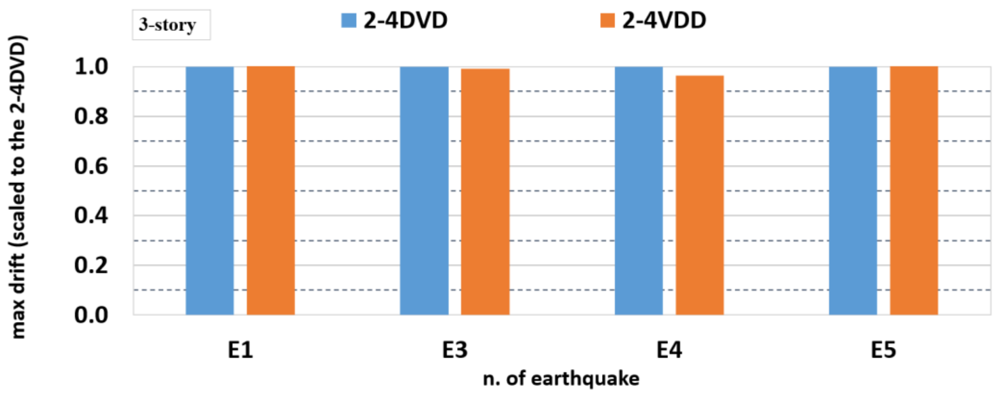


Figure 7. 10: Comparison of maximum drift ratio (scaled to the 2-4DVD) of the 2-4DVD and the 2-4VDD control under the four excitations; E1: CHU, E3: PAR, E4:CAP, E5: KOBE

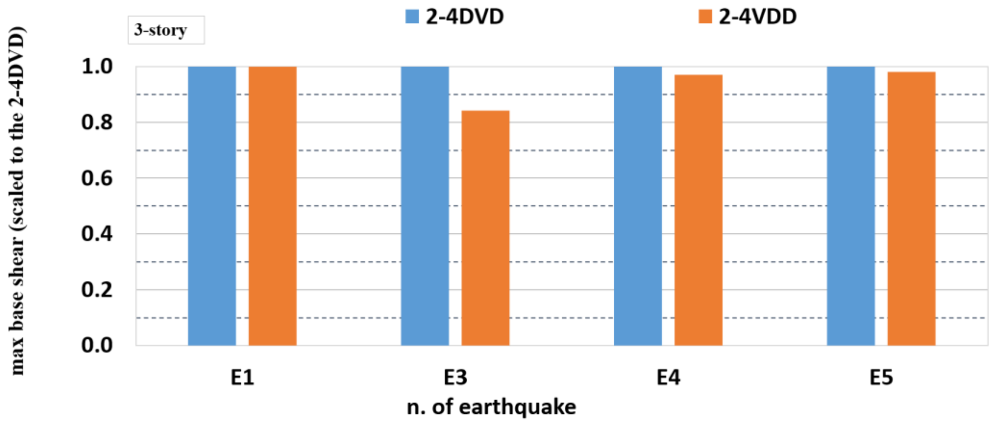


Figure 7. 11: Comparison of maximum base shear ratio (scaled to the 2-4DVD) under four earthquakes; E1: CHU, E3: PAR, E4:CAP, E5: KOBE

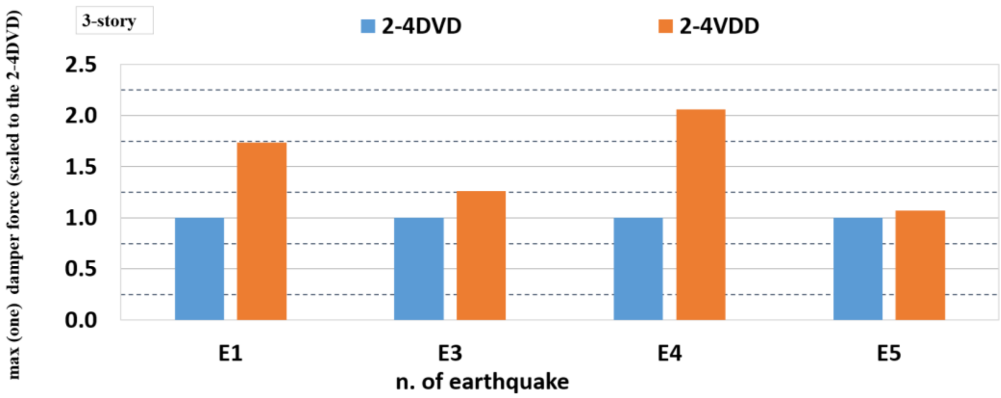


Figure 7. 12: Comparison of maximum damper force ratio (scaled to the 2-4DVD) under four earthquakes; E1: CHU, E3: PAR, E4:CAP, E5: KOBE

The response of the 3-story frame under two semiactive controls (the 2-4DVD and the 2-4VDD) was summarized in **Figure 7. 10**, **Figure 7. 11** and **Figure 7. 12**. To compare these two controls in terms of the total base shear and the maximum damper force required, the same maximum drift in the frame was achieved (see **Figure 7. 10**). The frame controlled by the 2-4VDD had its maximum base shear scaled to the frame controlled by the 2-4DVD. The results showed that the maximum reduction (16%; 0.84; see **Figure 7. 11**) in the total base shear occurred under E3(PAR) excitation. 3% and 2%, respectively, were the reductions in total base shear under E4(CAP) and E5(KOBE).

As for damper force, the 2-4VDD increased damper force under E4(CAP) excitation by 107% (2.06; see **Figure 7. 12**). Under E1, E3 and E5, the control increased damper force requirements by 74, 26 and 7.3%, respectively.

7.3.2 Response of Medium Rise building (7-storey frame)

7.3.2.1 Response to E1 (CHU- 60%)

The investigation of two novel re-shaped viscous damper' loops is extended to the 7-story building under 60% CHU. **Figure 7. 13** shows that under the same drift 2-4VDD produced an 18% reduction in the base shear of the frame compared with 2-4DVD, but it increased the required damper force by 25% (see **Figure 7. 14**). This novel control proved that a further reduction in base shear is possible if an increase in damper forces required is tolerable.

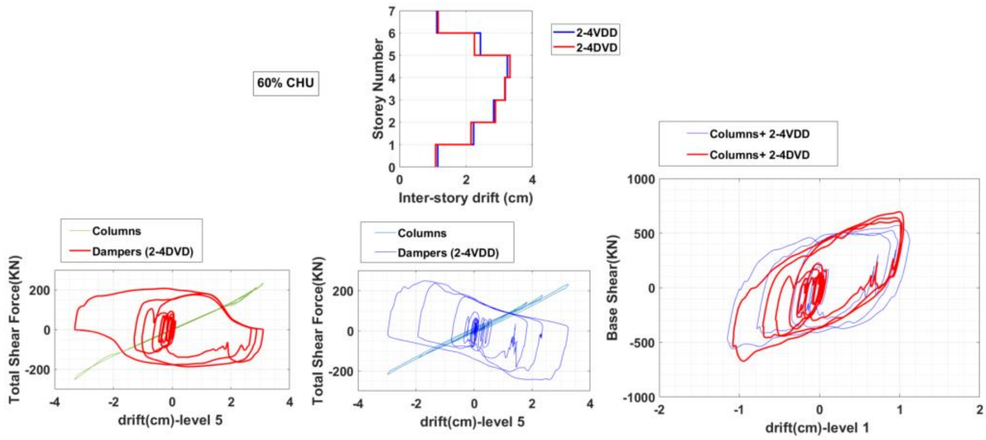


Figure 7. 13: 7-story frame controlled by two SA controls under 60%E1 earthquake

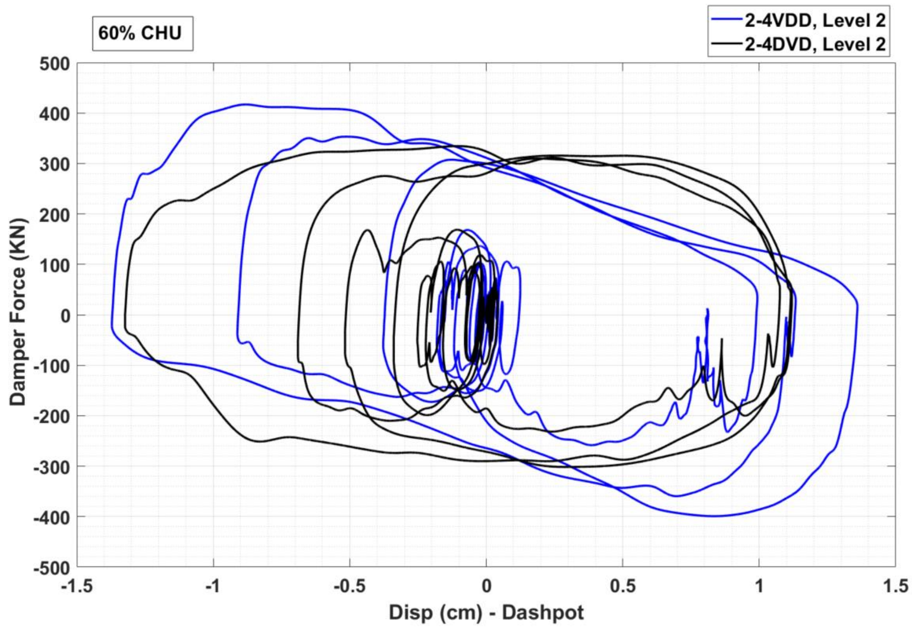


Figure 7. 14: Comparison of damper force of 2-4DVD and 2-4VDD (the most critical dampers in all seven stories) under 60%E1(CHU) earthquake.

7.3.2.2 Response to E3 (PAR-70%)

The 7-story frame controlled by 2-4DVD and 2-4VDD was subjected to 70% PAR. **Figure 7. 15** shows that 2-4VDD introduced a 9.7% reduction in base shear compared with 2-4DVD, yet it increased damper forces needed by 84% (see **Figure 7. 16**). Even though the reduction in the total base shear under 70% PAR is little, it could be important to show that it is possible to reduce the base shear of the frame as long as the increased damper force is not the main concern for the designers.

Results: Comparison of the proposed 2-4DVD control with an improved Velocity & Displacement Dependent control (2-4VDD)

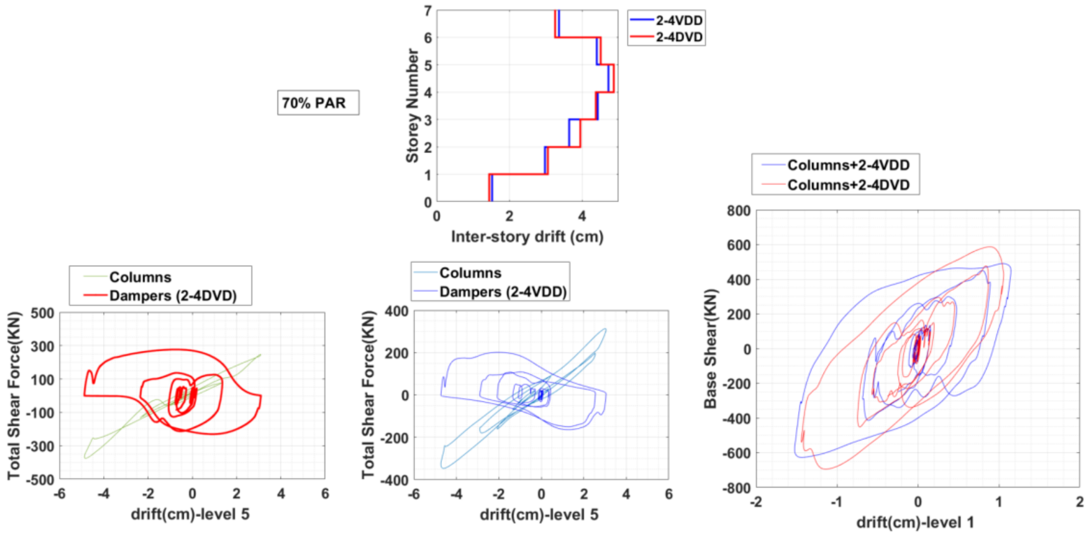


Figure 7. 15: Medium rise frame controlled by 2-4DVD and 2-4VDD control laws under 70%PAR earthquake

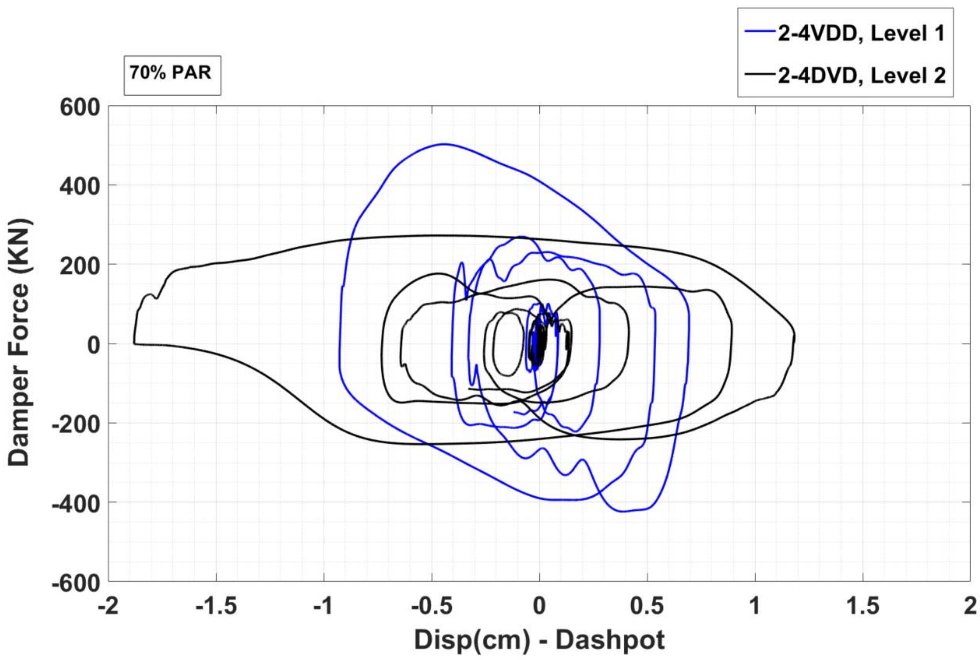


Figure 7. 16: Damper force vs dashpot displacement for 2-4DVD and 2-4VDD under 70% PAR earthquake. These two-control law plotted are max damper forces in all seven stories. I.e., in 7-story frame, max damper force required in 2-4DVD and 2-4VDD happens in level 2 and level 1 respectively.

7.3.2.3 Response to E5 (KOBE-65%)

The same frame experienced 65% KOBE. **Figure 7. 17** presents that 2-4VDD ended up with a 20% smaller base shear than 2-4DVD, yet it increased damper forces needed by 18% (see **Figure 7. 18**). As is discussed above, the newly proposed semiactive control (2-4VDD) reduces the base shear of the frame further, but it increases the damper forces required.

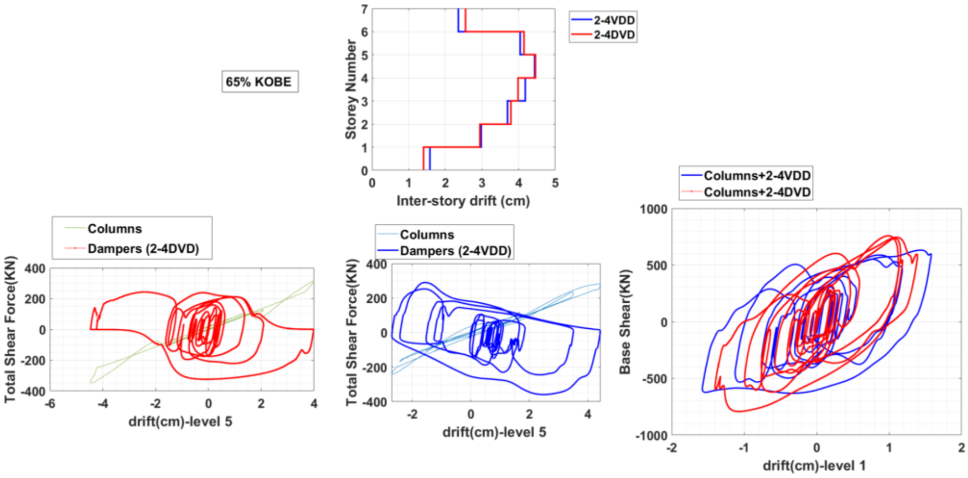


Figure 7. 17: Showing 7-story frame controlled by two SA controls under 65%KOBE earthquake

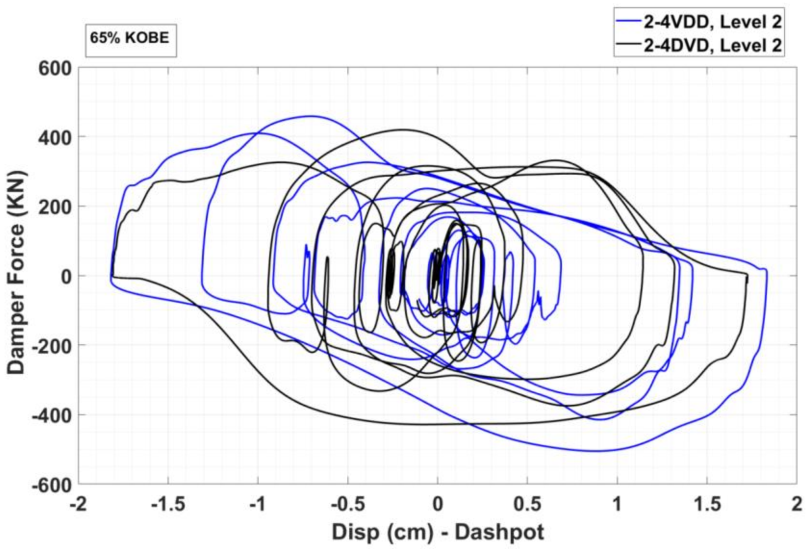


Figure 7. 18: Damper force vs dashpot displacement for 2-4DVD and 2-4VDD under 65% KOBE earthquake. These two-control law plotted are max damper forces in all seven stories. I.e., in 7-story frame, max damper force required in 2-4DVD and 2-4VDD happens in level 2

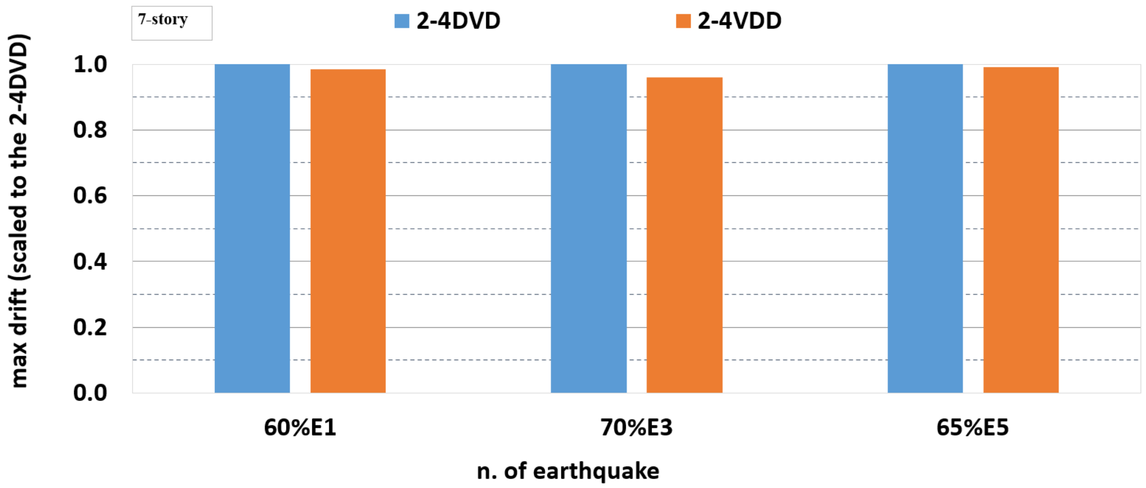


Figure 7. 19: Comparison of the response of the 7-storey frame (in terms of maximum base shear ratio; scaled to the 2-4DVD control) under the three earthquakes; E1: CHU, E3: PAR, E5: KOBE

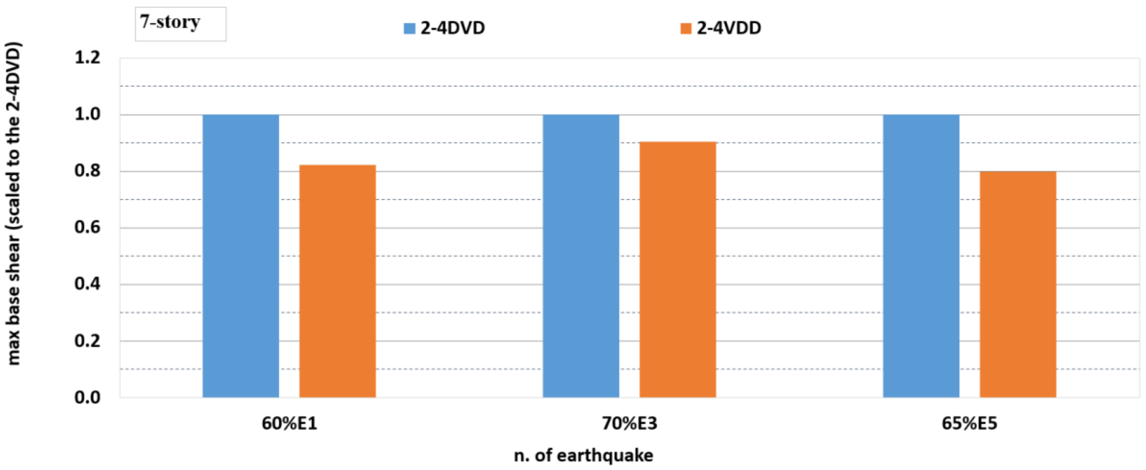


Figure 7. 20: Comparison of the two semiactive controls in terms of maximum base shear ratio (scaled to the 2-4DVD) under the three earthquakes; E1: CHU, E3: PAR, E5: KOBE

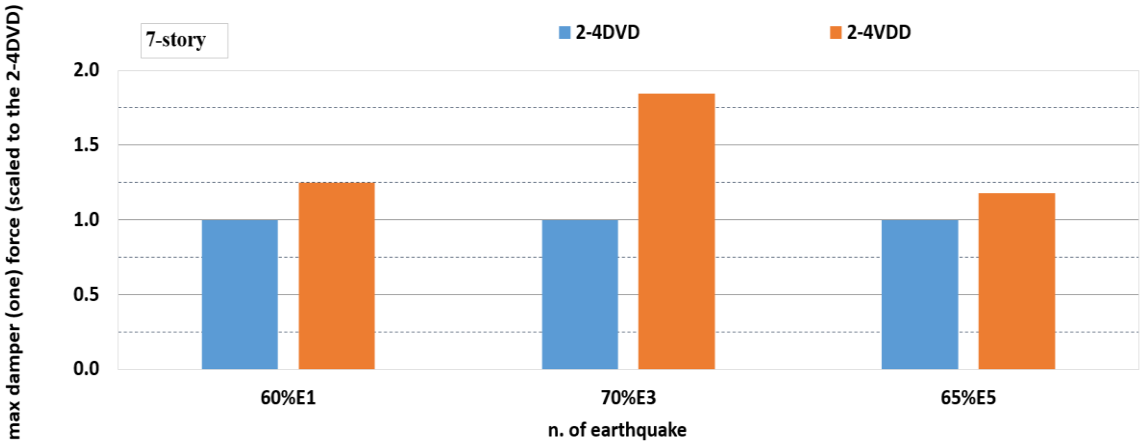


Figure 7. 21: Comparison of the response of the 7-storey frame controlled by semiactive 2-4DVD and the 2-4VDD under the three earthquakes; E1: CHU, E3: PAR, E5: KOBE

Figure 7. 19, **Figure 7. 20** and **Figure 7. 21** summarized the response of the 7-story frame controlled by the semiactive 2-4DVD and the 2-4VDD. For the purpose of comparison, while both semiactive controls achieved the same storey drift (see **Figure 7. 19**), their total base shears and maximum damper forces could be compared. The maximum base shear of the frame controlled by the 2-4VDD was scaled by the maximum base shear of the frame controlled by the 2-4DVD. The results showed that the maximum reduction (by 20%; 0.80; see **Figure 7. 20**) in the total base shear occurred under 65% E5(KOBE) excitation. 18% and 9.7%, respectively, were the reductions in total base shear under E1(CHU) and E3(PAR) (see **Figure 7. 20**). As for damper force, the 2-4VDD increased damper force under 70%E3(PAR) excitation by 84% (1.84, **Figure 7. 21**). Under 60%E1 and 65%E5, the control (the 2-4VDD) increased damper force requirements by 25 and 18 %, respectively (see **Figure 7. 21**).

7.4 Summary of results for 2-4DVD and 2-4VDD

This chapter investigated:

- A novel semiactive control called 2-4VDD and
- 2-4DVD control discussed in chapter 6

The main findings of this chapter can be summarized as follows:

- For the 3-story frame under the same story drift, the maximum reduction of base shear achieved by 2-4VDD was 26% under 100% PAR, yet the maximum damper forces required by 2-4VDD was 107% of 2-4DVD under 100% CAP.

- For the 7-story frame under scaled ground motions (full scale earthquakes resulted in excessive deformations) the maximum base shear reduction achieved by 2-4VDD was 20% of 2-4DVD under 65% KOBE, but the maximum damper forces required by 2-4VDD was 84% of 2-4DVD under 70% PAR.

The results of this chapter have confirmed that the proposed control algorithm (2-4VDD) can further reduce the base shear of the frame controlled by 2-4DVD but an increase in required damper forces is inevitable. A design methodology for the distribution of controllers along the height of the building 2-4VDD is proposed in **Figure 4. 14**.

CHAPTER 8 Conclusions

The use of damping devices is a promising strategy for reducing seismic damage of buildings, and they are particularly effective in 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 dual frames (MRF + braces), 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.

This research is a numerical investigation of a novel Direction-Velocity-Dependent (DVD) and Velocity-Displacement-Dependent (VDD) viscous dampers, and their impact on structural performance. It must be noted that the numerical investigation is based on simulations of non-linear response in the time domain using full two-dimensional structural models of moment resisting frames, where the structure is represented with all main elements (beams, columns, braces and dampers), rather than simplified MDOF models in which the storey is modelled as single (column) element, used in all previous studies of seismic SA control. Also, this is the first SA study in which the elements of the main structure (beams and columns) are non-linear (i.e., allowed to develop plastic hinges). This provides a far more realistic picture of seismic behaviour of multistorey buildings under strong earthquakes, as all modern buildings are designed to develop ductile response, and indeed, plastic hinges have been regularly observed in many buildings after strong earthquakes.

The outcomes of the newly proposed semiactive controls (DVD and VD2) are compared with a simple Direction and Displacement Dependent (DDD) viscous damper, which has been proposed by an earlier study ((Hazaveh et al. 2017a)).

The comparative analysis of the performance of the new viscous damper proposed in this study (2-4DVD**)** with an existing semi-active viscous damper (2-4DDD; (Hazaveh et al. 2017a) show that:

- The drift of the 3-story building controlled by 2-4DVD is reduced by up to **57%** when compared with the frame controlled by 2-4DDD**.**
- For similar maximum base shear, in some cases the proposed control (2-4DVD) reduces even the total base shear of the structure (by 24% under CHU earthquake).

The 7-story buildings under scaled ground motions show that the 2-4DVD leads to up to 60% reduction in drift, when compared to 2-4DDD The results for MRFs equipped with 2-4DVD viscous dampers controlling motion toward equilibrium and partial forces away from equilibrium, show that the response is more stable and much more effective than 2-4DDD devices when applied on multistorey buildings subjected to a range of ground motions.

The 2-4VDD system was proposed to introduce a further reduction in the total base shear of the frame controlled by the 2-4DVD damper. As the comparison of performance between the 2 systems shows that:

- In the 3-story building, the 2-4VDD damper reduced the total base shear of the frame controlled by 2-4DVD by a max of 16%, but it increased the required damper forces by up to 107%.
- In the 7-story frame, the 2-4VDD control reduced the total base shear of 2-4DVD by up to 20%, but at the cost of increasing the required damper forces by a max of 84%.

The results of the 2-4VDD show that further reduction in total base shear is possible, but it increases the required damper forces in comparison with 2-4DVD.

In summary, the main contributions of this thesis to the field of improving seismic structural performance are:

- Assessment of performance of fluid viscous dampers, both passive (linear and non-linear) and semiactive (proposed in earlier studies; (Hazaveh et al. 2017a)), when applied in more realistic seismic scenarios.
- Considering moment resisting frames typical for multistorey residential (or commercial) buildings, that can undergo non-linear deformations by developing plastic hinges when subjected to strong earthquakes. Most existing studies of fluid viscous dampers are based

on idealised MDOF (or even SDOF) systems which remain linear elastic during the earthquake, which is only applicable to service level (immediate occupancy) events.

- Introduction and detailed analysis of a novel semi-active viscous damping device control method to re-shape structural hysteretic behaviour (by the 2-4DVD and the 2-4VDD), based on an idea introduced in a previous study (2-4DDD; (Hazaveh et al. 2017a)).
- The new 2-4DVD offers a more effective solution than the existing 2-4DDD and PNLVA03 (the best of range of passive devices analysed in this study); it reduces the seismic response, with minimal risk of foundation or structural demand, meaning it can be used for a more economic retrofit, as well as a new design.

Reshaped viscous dampers (2-4DVD, 2-4VDD or 2-4DDD) offer unique abilities similar to those seen for less robust and more complicated semi-active stiffness-based devices. The 2-4DVD, 2-4VDD or 2-4DDD viscous dampers deliver 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. Simple design methodologies are proposed to incorporate the design or retrofit of structures with these semiactive control devices.

CHAPTER 9 Future Work

The investigations of this thesis provided important insight into the area of enhancing seismic performance of multistorey structures with viscous damper controls. There are several areas for further studies that may lead to improvements in performance of fluid viscous dampers and their application in retrofit or new design of multistorey buildings in areas with high seismicity.

9.1 Storey shear as a design parameter

The investigations in this study show that there is a potential to design or/optimize the response of a frame, which is controlled by passive viscous dampers, by semiactive control considering the storey shear as a key parameter (total shear force of columns and dampers in the same story level). For instance, as long as column shear forces are larger than the forces in the reshaped viscous dampers (2-4DVD or 2-4DDD), it will not increase the total base shear of the frame. Therefore, it can be adopted to propose a more sophisticated design methodology. Further numerical investigations are needed for this claim.

9.2 Seismic response of a 2-4VDD viscous damper

In the 2-4VDD, the parameter P was previously selected as 12. The 2-4VDD increased the required maximum damper forces, thus increasing damper costs. This could limit the adaptation of this algorithm in practice, yet by selecting a different parameter P, the maximum damper forces required for the control could be reduced. Further parametric investigations are needed for this claim.

9.3 Seismic response of 2-4DVD and 2-4VDD viscous dampers

The results of the frame controlled by two potential semiactive viscous dampers (2-4DVD and 2-4VDD) under 100% ground motions in the 7-story frame (e.g., CHU, PAR, KOBE) proves that none of the semiactive controls (2-4DVD and 2-4VDD) is sufficient to achieve a drift below life safety (2%). The solution could be increasing the number of dampers or having different SA control angles at the same level. Therefore, there is a need for further study on the seismic performance of the 7-story frame with having a new location or number of dissipation devices (2-4DVD and 2-4VDD) under strong earthquakes (e.g., 100%E1).

9.4 Evaluating 2-4DVD or 2-4VDD in improving seismic structural performance

This research study mainly evaluates the seismic performance of the 2-4DVD and 2-4VDD in MDOF systems. However, future studies could include evaluating these two viscous devices in the seismic structural performance of base-isolation systems or for recentring the tilted structures.

9.5 Implementation in the Field

The results showed that the 2-4DVD or 2-4VDD control is a promising solution for MDOF systems. A detailed experimental study would help in further development of this concept and lead to implementation of dissipation devices in both new building designs and retrofit applications. The two devices can potentially be developed as passive dampers like a researcher (Hazaveh et al. 2017b) did in New Zealand for 2-4DDD control.

Appendix A

This appendix is the result of adopting different type of passive controls for different damping coefficient under four different earthquakes. It also compares the dual frame with braces and passive viscous dampers. Dual brace frame significantly increased the forces in the frame.

Table A. 1: Different passive control strategies with a range of Cd-values

	Cd (KNs/cm)	Max Drift (cm)				Max Damper Force (KN)			
		Earthquake				Earthquake			
		E1	E2	E3	E4	E1	E2	E3	E4
Bare		19.5	10.7	18.6	13.0				
Dual		0.4	1.3	0.7	1.4	570.9	1504.6	756.2	1515.7
3S-PLV-UCd	0.8	15.1	8.3	13.3	9.5	28.1	33.2	34.0	44.2
	2.1	12.4	7.1	11.2	8.1	62.7	65.3	80.8	100.1
	3.4	10.5	**6.3**	9.5	7.4	88.6	92.5	118.6	145.1
	4.5	9.3	5.8	8.4	7.0	106.2	109.7	144.7	177.2
	4.7	9.1	5.7	8.3	6.9	109.1	112.5	148.9	182.6
	6.0	8.1	5.1	7.6	**6.4**	126.0	128.1	173.2	214.3
	7.3	7.2	4.5	7.0	6.0	140.0	140.5	192.8	241.4
	8.6	6.5	4.1	**6.4**	5.6	151.6	150.4	208.7	264.8
	9.0	**6.3**	4.0	6.3	5.5	154.8	153.0	213.0	271.4
	12.0	5.2	3.2	5.3	4.7	173.7	169.6	238.8	312.0
	12.5	5.0	3.1	5.1	4.6	176.2	171.9	242.2	317.8
3S-PLV-TCd	0.8	15.4	8.5	13.7	9.2	25.9	33.9	32.5	41.9
	2.1	13.2	7.5	11.9	8.5	55.7	64.7	70.8	88.6
	3.4	11.4	6.8	10.5	7.9	77.2	83.2	98.8	120.3
	4.5	10.3	**6.3**	9.5	7.5	90.1	93.7	118.4	146.4
	4.7	10.1	6.3	9.4	7.5	92.0	95.9	122.4	151.4
	6.0	9.2	5.8	8.5	7.2	107.5	112.0	146.2	181.4

	7.3	8.4	5.4	8.0	6.9	122.1	125.5	166.7	208.3
	8.6	7.7	5.1	7.5	6.6	135.2	138.8	184.5	232.4
	9.0	7.5	4.9	7.4	6.5	138.9	142.8	189.6	239.3
	9.5	7.3	4.8	7.2	**6.4**	143.3	147.5	195.6	247.5
	12.0	**6.4**	4.2	6.5	5.8	162.7	167.2	221.4	284.0

Table A.1: continued 1

		Max Drift (cm)				Max Damper Force (KN)			
		Earthquake				Earthquake			
	Cd (KNs/cm)	E1	E2	E3	E4	E1	E2	E3	E4
	12.5	6.2	4.1	**6.3**	5.7	166.1	170.6	225.9	290.5
3S-PNLVA03-UCd	0.9	10.0	**6.3**	10.8	8.7	58.5	60.2	67.5	72.2
	1.2	8.4	5.5	9.7	8.0	74.4	77.4	87.5	93.9
	1.3	8.0	5.1	9.4	7.8	80.1	83.3	93.8	101.0
	1.7	**6.4**	4.2	8.2	7.4	101.4	105.5	116.7	128.2
	1.8	6.1	4.0	7.9	7.2	106.2	110.8	122.4	134.7
	2.4	4.5	3.0	6.5	**6.4**	131.1	140.6	156.3	171.8
	2.5	4.3	2.9	**6.3**	6.3	134.7	145.0	161.5	177.7
	2.8	3.9	2.5	5.7	5.9	145.3	156.6	175.8	198.0
	3.5	3.0	2.0	4.5	4.9	167.8	183.3	207.1	241.2
	3.8	2.7	1.9	4.0	4.5	179.3	198.2	219.7	257.2
	4.0	2.5	1.8	3.8	4.2	187.3	208.0	227.4	267.1
	5.0	1.8	1.6	2.5	3.0	223.2	256.3	258.1	308.3
3S-PNLVA03-TCd	0.9	11.1	7.0	11.7	9.1	60.3	62.2	67.9	72.7
	1.2	9.9	**6.4**	10.8	8.5	77.1	79.8	88.5	94.9
	1.3	9.5	6.3	10.6	8.5	82.2	85.3	95.0	102.0
	1.7	8.3	5.6	9.6	8.3	99.6	104.6	118.6	128.7
	1.8	8.0	5.5	9.4	8.2	103.2	108.7	123.9	134.9
	2.4	**6.4**	4.7	8.2	7.8	116.8	125.6	150.2	168.6
	2.5	6.2	4.6	8.1	7.7	118.3	127.0	153.6	173.2

	2.8	5.7	4.3	7.6	7.5	125.4	136.0	163.4	185.1
	3.5	4.6	3.4	6.6	6.9	147.7	163.6	182.2	205.2
	3.8	4.2	3.1	**6.2**	6.6	156.7	173.8	188.7	215.2
	4.0	4.0	2.9	6.0	**6.5**	162.7	180.0	196.2	225.9
	5.0	3.1	2.1	4.8	5.4	189.5	203.6	228.3	275.1
3S-PNLVA05-UCd	0.9	11.9	7.2	11.7	8.8	47.0	49.8	56.9	63.9
	1.2	10.6	6.6	10.8	8.2	59.7	62.7	73.8	82.7
	1.3	10.3	**6.4**	10.5	8.1	63.6	67.0	79.2	88.7

Table A.1: continued 2

		Max Drift (cm)				**Max Damper Force (KN)**			
		Earthquake				Earthquake			
	Cd (KNs/cm)	E1	E2	E3	E4	E1	E2	E3	E4
	1.7	9.0	5.7	9.5	7.8	79.1	83.0	99.6	111.9
	1.8	8.7	5.6	9.3	7.7	82.8	86.7	104.5	117.5
	2.4	7.2	4.6	8.1	7.2	103.9	108.8	130.7	149.6
	2.5	7.0	4.4	7.9	7.1	107.2	112.1	134.8	154.6
	2.8	**6.3**	4.1	7.4	6.8	116.7	121.8	146.4	169.4
	3.2	5.7	3.6	6.7	**6.4**	128.1	133.3	160.9	188.1
	3.5	5.2	3.4	**6.3**	6.2	135.8	140.9	171.2	201.4
	3.8	4.9	3.1	6.0	5.9	142.7	147.8	180.9	214.0
	4.0	4.6	3.0	5.7	5.7	147.0	152.0	187.1	222.1
	5.0	3.8	2.3	4.8	4.9	164.6	169.3	215.0	258.9
3S-PNLVA05-TCd	0.9	12.9	7.6	12.4	9.1	47.9	51.5	56.0	63.4
	1.2	11.7	7.2	11.7	8.6	61.2	64.4	72.4	81.5
	1.3	11.3	7.0	11.4	8.5	65.3	68.4	77.6	87.3
	1.7	10.2	6.5	10.6	8.3	80.4	83.9	97.2	109.0
	1.8	9.9	**6.4**	10.4	8.3	83.8	87.5	101.7	114.0
	2.4	8.7	5.7	9.4	8.0	100.6	105.5	125.6	141.7
	2.5	8.5	5.6	9.2	7.9	102.9	107.8	129.1	145.9
	2.8	7.9	5.3	8.8	7.8	108.6	113.9	138.7	157.4
	3.5	6.9	4.8	7.9	7.4	117.6	126.5	155.9	178.7
	3.8	6.5	4.5	7.5	7.2	124.2	135.0	160.9	185.6

	4.0	**6.2**	4.4	7.3	7.1	129.2	140.4	163.6	189.6
	5.0	5.2	3.7	**6.4**	6.5	151.1	164.3	188.4	224.3
	5.2	5.1	3.6	6.2	**6.4**	155.0	168.4	194.0	232.2

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