Mitigating Structural Response using Semi-active Viscous Dampers to Reshape Structural Hysteresis

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ABSTRACT: Semi-active devices offer significant promise for their ability to add supplemental damping and reduce seismic structural response in an easily controllable manner, and can be used in some modes to modify or reshape hysteretic structural response. However, many current semi-active devices are highly complex, limiting robustness, while those that can generate larger forces suffer from increased response lag time to do so. Thus, an ideal semi-active device would offer high forces, low complexity, and fast response. The semi-active viscous dampers could offer all these properties and could mitigate not only the displacement response of a structure, but also the base shear. This paper first outlines the structural performance when semi-active viscous dampers, with varying control laws are applied. A spectral analysis over periods of T= 0.2-5.0 sec under 20 design level earthquakes from the medium suite of the SAC project is used to compare three device control laws individually to sculpt the structural hysteretic behaviour. Performance is assessed by evaluating reduction factors (RFs) compared to an uncontrolled structure for maximum displacement (S_d) and total base-shear (F_b), indicative of structural and foundation damage, respectively. These results show that the reduction in terms of both displacement and base-shear demand is only available with the use of the 2-4 control law, which provides damping in the second and fourth quadrants. In the second part, a method to calculate the reduction factor of response for structures using 2-4 devices with different device damping coefficients is presented. Overall, these results indicate the robustness of potentially very simple and robust semi-active viscous dampers to mitigate the risk of seismic damage to both the structure and foundation in a way that is economically suitable for either new designs or retrofit.

1 INTRODUCTION

With the development of construction techniques, it is possible to build large-span bridges, pipelines, dams, and high-rise buildings. However, this achievement also generates problems, specifically how these structures can be protected from external excitation, such as strong winds and severe earthquake ground motions. Some solutions to reduce loss of life and damage due to natural hazards include systems such as base isolation, rocking, and bracing systems. To improve the performance of these systems, supplemental control devices, that are intended to absorb a portion of the seismic response energy and protect structures from damage, can be incorporated in to these passive systems.

Supplemental damping systems can be divided into three broad categories: active, semi-active and passive. Active systems are complex and expensive because they require high speed, high force actuators and significant energy. Passive solution avoids these issues, but cannot provide any adaptive capability to different responses and is tuned to a structure's design parameters. Therefore, passive solutions may not be robust to changes in structural response. An interesting and appealing compromise is given by semi-active control systems that require only a relatively very small external power source for operation but offer the ability to adapt to structural response.

Semi-active devices have two main advantages over passive or active control devices. First, they do not require a large external power source for operation, as active devices do. This characteristic is because of changes in the physical space or material properties that create their dissipative forces.

Therefore, semi-active devices cannot in principle destabilize the structure because they do not add energy to the system, but simply absorb or store vibratory energy (Chase et al. 2006).

Second, the smart control of these devices makes them more able to provide a reliable, low-damage system than passive devices, regardless of the uncertainties of input ground motions. This aspect is enhanced by the ability to sculpt device hysteretic behaviour in some, but not all, semi-active devices.

The potential of many classes of semi-active devices and control methods, including variable stiffness and variable damping, to mitigate damage during seismic events is well documented (Jansen and Dyke 2000, Barroso et al. 2003, Yoshida and Dyke 2004, Chase et al. 2006, Mulligan et al. 2007, Mulligan et al. 2010).

Many prior semi-active devices have been air or fluid based systems based on the principles of variable stiffness (Chase et al. 2006, Rodgers et al. 2007, Mulligan et al. 2009, Mulligan et al. 2010) , but were complex and could not produce the very large control forces often required for controlling structures. A further, potentially more robust, means of achieving such a semi-active device is to use a controllable, electromechanical, variable-orifice valve to alter the resistance to flow of a conventional hydraulic fluid damper. Feng and Shinozuka (Feng et al. 1993) were the first to consider this concept. However, the extra plumbing and the low resolution orifices made this device essentially very similar to the resettable device of Jabbari and Bobrow (Jabbari and Bobrow 2002), and produced primarily on/off or high/low control without the ability to realize much of the potential benefit. Moreover, the ability to sculpt the hysteretic response of a device, and thus of the whole structure, is only obtained by direct control of its the device motion in each direction (with sign) (Chase et al. 2006).

Semi-active devices can also be highly complex and possibly have limited force. To address these shortcomings, Hazaveh et al. (2014) evaluated the concept of semi-active viscous dampers and examined three types of device control laws (a 1-4, 1-3 and 2-4) to sculpt hysteretic behaviour. The 1-4 device provides damping in all four quadrants and is thus equivalent to typical passive viscous dampers (Fig. 1.a). Figure 1.b shows the 1-3 device that provides resisting forces only in the first and third quadrants of the force-displacement graph, resisting motion away from equilibrium (zero-displacement). Finally, the 2-4 device provides damping in the second and forth quadrants, resisting motion only toward equilibrium (Fig. 1.c). The semi-active viscous damper appeared to be an appealing solution for reducing seismic response, with minimal risk of structural or foundation damage. However, Hazaveh et al. (2014) clarified the effect of three kind of semi-active viscous damper that could add just 15% more damping to the structure and did not consider the effect of d damping of semi-active viscous device.

In this study, the effects of changing damping of semi-active viscous devices with different control laws are investigated. The effects of different control laws on the displacement and base shear of the structure are evaluated using a single degree of freedom spectral analysis subjected to 20 earthquake ground motions from the SAC LA medium suite. The goal is to identify the range of potential reductions in displacement (structural damage) and base shear (foundation damage and cost) possible with these devices, and characterise how these devices can be included into standard design methods.

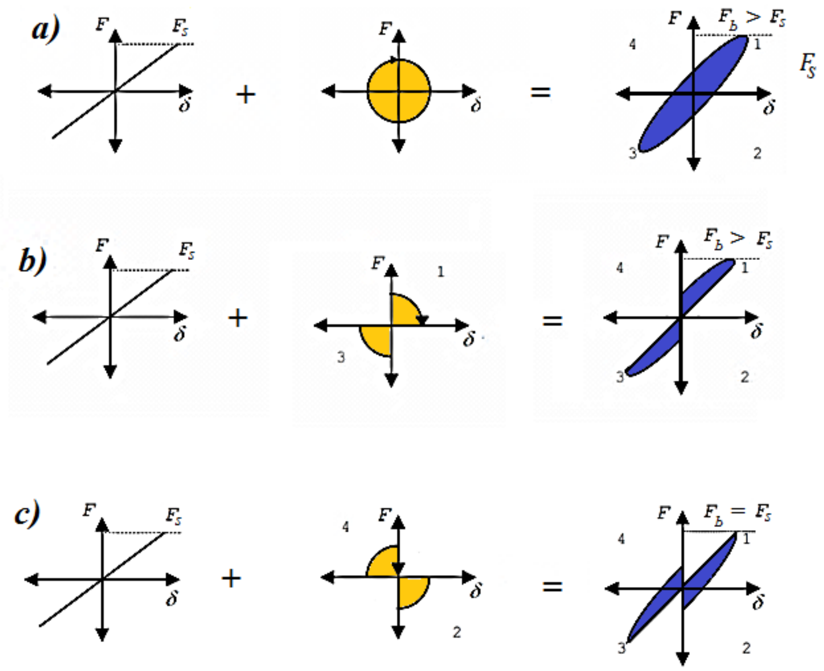

Figure 1. Schematic hysteresis for a) 1-4 device, b) 1-3 device, and c) 2-4 device (Hazaveh et al. 2014).

2 ANALYSIS

This paper investigates the relative effectiveness of the three semi-active devices on the seismic response of a simple SDOF structural system fitted with a semi-active variable orifice viscous damper and suggests the equivalent damping values. Figure 2 shows a step-by-step example of the control mechanism and response for a 2-4 semi-active viscous device under sinusoidal loading. The model structure includes inherent structural equivalent structural viscous damping of 5%.The semi-active viscous damping devices can add 5% to 45% additional damping to the structure when activated, and ~0% when not active.

The research utilizes the medium earthquake suite from the SAC project (Sommerville et al. 1997).This suite represents ground motions having probabilities of exceedance of 10% in 50 years in the Los Angeles region. Response statistics can thus be generated from the results of this probabilistically scaled suite with an expected return period of 524 years.

Response spectra are produced, and spectral response plots are plotted for the structural displacement (S_d) and the total base shear (F_b) in a T = 0.2–5.0 sec range in increment of ΔT= 0.1 second. Period is changed by modifying the stiffness. The total base shear that is an indication of the required foundation strength is defined as the sum of the base shear for a linear structure and the resisting forces from the semi-active viscous damping device.

The reductions achieved by the addition of semi-active viscous damping devices are represented by reduction factors (RFs), normalized to the uncontrolled, no device results. These factors enable easy comparison of the different control laws and are a multiplicative factor. RFs less than 1.0 indicate reductions in the response metric, and greater than 1.0 an undesirable increase in response.

Finally, the relationship between added damping from the semi-active device and structural response reduction factors are discussed including a simplified method to approximate the results. Finally, this study proposes a robust and simple design and analysis process to evaluate the effect of adding the 2-4 device in (SDOF-equivalent) structures.

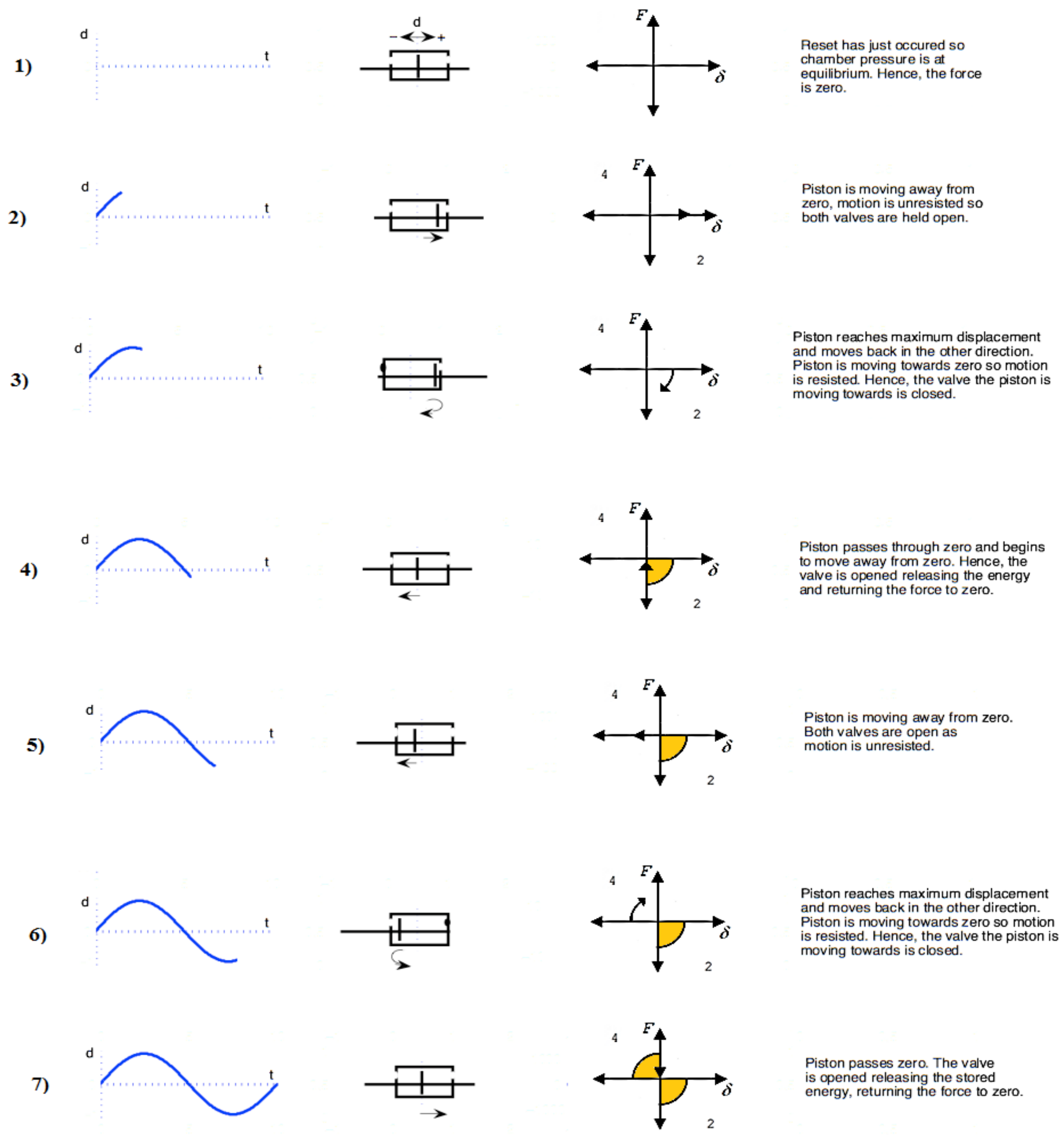

Figure 2. step-by-step representation of valve and device control for a 2-4 control law/device under a sinusoidal input motion to achieve the desired hysteresis loop (Hazaveh et al. 2014).

3 RESULTS AND DISCUSSION

Figure 3 shows the median, Reduction Factor (RF) in terms of displacement demand, S_d, and base shear, F_b, for 5% to 45% added viscous damping from the device (ξ). As expected, the maximum structural displacement decreases with increasing device damping. The 1-4 control law offers the greatest reduction of displacement as it has the biggest area enclosed by a hysteretic loop.

Figure 3 also shows that the median base-shear reduction factors are approximately constant at RF=0.7-0.85 within the natural period range T=0.2-3.6 seconds. However, the base shear RF for periods T= 3.6-5.0 seconds using the 1-4 and 1-3 devices exceeds 1.0 and increases significantly with adding damping, indicating that the structural displacement reductions come at the cost of increased foundation demand for this control law. In contrast, the 2-4 control law has more stable behaviour, and constant ranges of displacement and base shear RF for all periods.

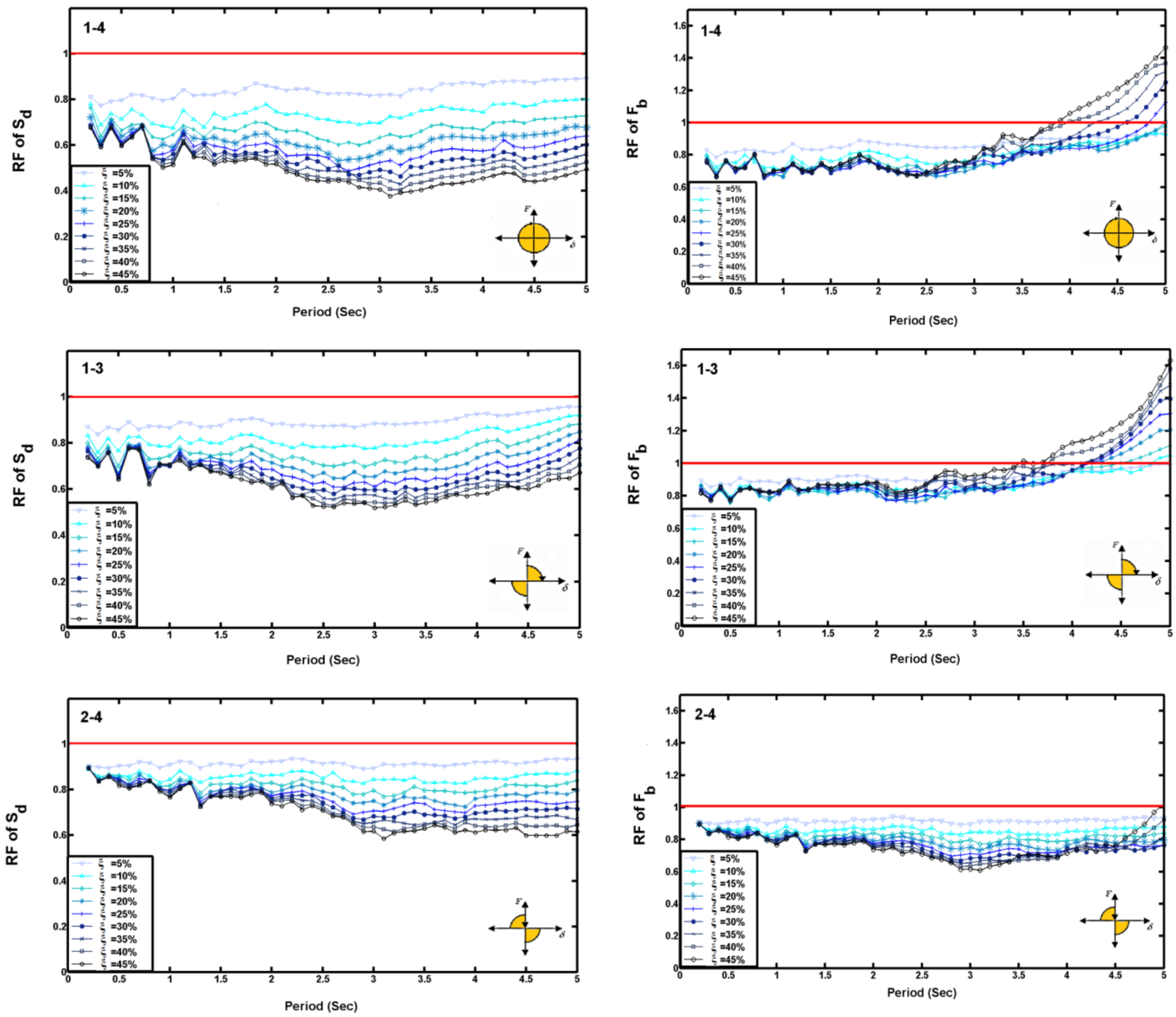

Figure 3. The median reduction factor, RF, of structural displacement Sd, and total base shear, Fb, for the three control laws, with values of 10, 15, 20, 25, and 30% additional damping.

Moreover, in the 2-4 case, the S_d and base shear RF are all less than 1.0 for all periods. The 2-4 approach thus offers the greatest robustness, and thus minimum variability in median level risk, over all events. More specifically, the 2-4 semi-active viscous damper offers minimal risk of increased foundation demand along with reduced displacement and acceleration demands. Overall, the 2-4 control law appears to be an appealing solution for reducing seismic response, with minimal risk of structural or foundation damage, implying it is suitable to examine the concept for more economic new designs, as well as retrofit. However, the choice between these devices would depend on the designer and any relevant codes/guidelines specifying a maximum acceptable risk of exceedance.

4 RELATIONS BETWEEN REDUCTION FACTOR AND DEVICE DAMPING

The European seismic loading code (EC8[1998]) and Displacement –Based Design (DBD) procedure (Priestley et al. 2007) suggests that the elastic design displacement spectrum be reduced by a spectral reduction factor RF, referred to η or Rξ, respectively, function of the equivalent viscous damping, ξ, of the structure. In this study, the relationship between RF and damping of the device (ξ) are discussed in term of an approximate smoothing equation result. Finally, results from the simplified equations are compared to the original simulation results.

Figure 4 presented smoothed curves of the Spectral Displacement, S_d, and total base shear, F_b, reduction factor RF as derived in Figure 3 when the total damping of the structure increase via increasing the added damping of the 2-4 device. For increased values of total damping of the structure increases by increasing the added damping of the 2-4 device.

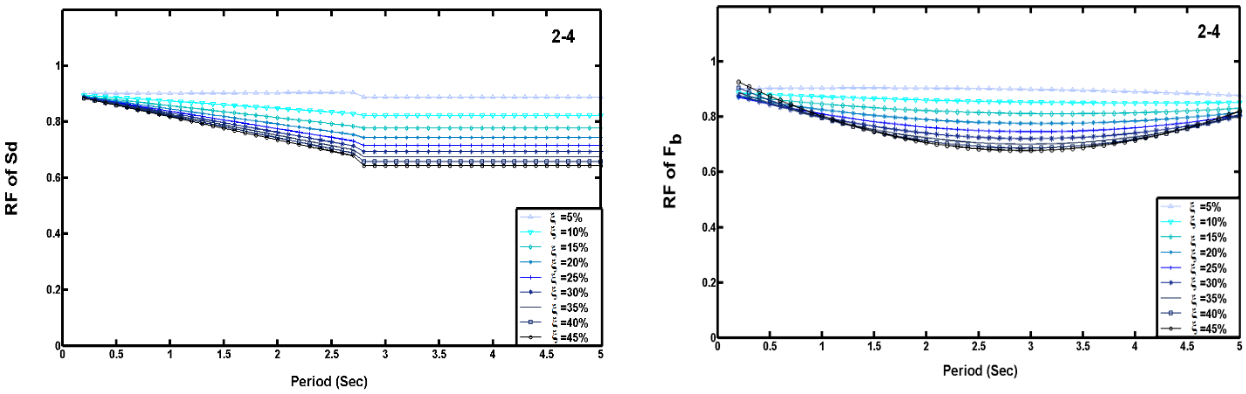

Figure 4. The smoothed RF of S_d and F_b when using the 2-4 device.

Simplified analytical expressions of such displacement reduction factor of S_d can be derived and suggested, as indicated in Eq.1 for both analysis and design of SDOF systems incorporating the 2-4 semi-active viscous dampers:

$$\begin{cases} RF_{sd} = \left(0.048\,(\xi_0+\xi)^{-0.5} - 0.15\right) * T + 0.9 & T \leq 2.7 \text{ sec} \\ RF_{Sd} = \left(\frac{0.07}{0.02+(\xi_0+\xi)}\right)^{0.22} & 2.7 < T \leq 5 \text{ sec} \end{cases} \quad (1)$$

Therefore, in a displacement based design procedure, for a target level of displacement reduction factor RF, the required damping of the device can be obtained by inverting the above expression:

$$\begin{cases} \xi = \left(\frac{0.048T}{RF_{Sd}-0.9+0.15T}\right)^{2} - 0.05 & T \leq 2.7 \text{ sec} \\ \xi = \left(0.07-0.02\sqrt[0.22]{RF_{Sd}}\right) RF_{Sd}^{-4.54} & 2.7 < T \leq 5 \text{ sec} \end{cases} \quad (2)$$

For example, the RF of a structure with period of 2.5 seconds with 35% damping added 2-4 device is 0.71 and 0.72 using the smoothing method (Eq. 1) and the full THA method, respectively.

An expression proposed in Figure 4 for RF of Fb is defined:

$$RF_{Fb} = aT^2 + bT + c \quad (3)$$

$$a = 0.0088\xi - 0.0065$$

$$b = -0.5\xi + 0.031$$

$$c = 1.08 * \xi^2 - 0.38\xi + 0.92$$

Figure 5 shows the process of finding out the RF of the structure that used the semi-active viscous damper with ξ damping ratio and vice versa with the smoothing analytical results. With considering the flowchart (could calculate the RF of the structure when N 2-4 semi-active viscous dampers are added to the system.

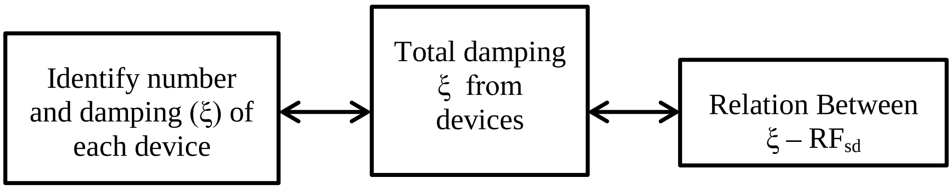

Figure 5. The relationship between damping of device and RF.

Moreover, 2-4 semi-viscous dampers can be added to existing or new structures using with process outlined in Figure 5. For instance, let assume that a 0.70 displacement reduction factor for a structure with T=3.0 seconds is desirable. Therefore, a device or devices with 33% damping are needed, using the smoothed curve (Eq.2). For about 33% device damping ratio, two devices with 17.5% added damping or three devices with 10% added damping could be used. Moreover, the RF of total base shear of this structure with the 2-4 device that could add damping of 33% is about 0.7 (Eq.3).

5 CONCLUSIONS

This study has presented the performance, design and analysis of structures with added semi-active viscous dampers that can reshape structural responses. Maximum displacement (S_d) and total base-shear (F_b) reduction factor (RF) spectra were created to determine the impact and efficiency of different semi-active viscous dampers on seismic structural performance over a range of ground motions with equal probability of occurrence. The results of this part show that only the 2-4 device, which provides damping in the second and fourth quadrants, allows to reduce the structural is placement with no increase in base shear (and thus overturning moment and risk of foundation damage). This result implies that the 2-4 semi-viscous damper potentially offers the greatest robustness, and thus minimum variability in risk, over all events for both displacement and total base shear. Furthermore, the relationship between damping, ξ, of the 2-4 semi-viscous device and structural displacement and total base shear reduction factor, RF, were discussed. Finally, this paper has presented a simple method to approximate the effect of adding the 2-4 device to different new or existing (SDOF-equivalent) structural system. Overall, these results indicate the robustness of simple viscous dampers could be better managed to mitigate seismic response and damage to the superstructure without increasing the demand and potential damage to the foundation system.

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