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Spectral Analysis of Customized 2-4 Viscous Damping for Mitigating Seismic Response

N. K. Hazaveh [(1)], G.W. Rodgers [(2)], J.G. Chase [(3)], S. Pampanin [(4)]

[(1)] *PhD. Candidate, University of Canterbury, Christchurch, nikoo.hazaveh@pg.canterbury.ac.nz*
[(2)] *Senior Lecturer, University of Canterbury, Christchurch, geoff.rodgers@canterbury.ac.nz.*
[(3)] *Distinguished Professor, University of Canterbury, Christchurch, geoff.chase@canterbury.ac.nz.*
[(4)] *Professor, University of Canterbury, Christchurch, stefano.pampanin@canterbury.ac.nz*

Abstract

Many current active and semi-active supplemental damping devices are highly complex, limiting robustness, and those that can generate larger response forces typically suffer from increased response lag time. Thus, an ideal device would offer high forces, low complexity, and fast response time. A 2-4 viscous damper device provides damping in the second and forth quadrants of the force-displacement plot, resisting only motion from a displacement peak back toward the zero-displacement position. The 2-4 viscous dampers offers significant promise for their ability to mitigate not only displacement, but also the base shear. This paper provides design spectra analysis that quantifies the risk of exceedance of an uncontrolled structure for displacement and base shear response. Spectral analysis results are compared to the uncontrolled case and to a standard, passive viscous damping case for context. In particular, performance is assessed by evaluating reduction factors (RFs) compared to an uncontrolled structure for maximum displacement (S_d) and total base-shear (V_b) indicative of structural and foundation demand respectively. RF spectra results are presented as median percentile RF to define the distribution and change in risk across the 60 events. Statistical summaries of the results indicate that the 2-4 viscous damper reduces the median value of S_d and V_b by ~10- 40%, over all periods up to 5.0 seconds. There is thus no risk of exceedance greater than 5% that any response will increase over the uncontrolled case. In contrast, a conventional linear viscous damper reduces S_d as much or more, but at a cost of increased V_b in comparison to the uncontrolled state. These results show that the reduction in terms of both displacement and base-shear is only available with the use of the 2-4 viscous damper device. Damping reduction factors play an important role in most design procedures. In this study, a method to calculate the damping reduction factor of response for structures using the 2-4 viscous devices with different device damping coefficients is presented. The overall results indicate the robustness of potentially very simple and robust 2-4 viscous dampers to mitigate the risk of seismic damage to all the structure and foundation in a way that is economically suitable for either new designs or retrofit.

Keywords: 2-4 viscous damper, reducing base shear, damping reduction factor

1. Introduction

Modern buildings are designed to sacrificially sustain significant damage during their structural response from large earthquake ground motions. This damage provides a means to absorb input energy, while preserving life safety. Instead of damage to the main structural elements to absorb energy, supplemental control and energy dissipation devices have been proposed that are intended to absorb a portion of the seismic response and protect structures from damage [1-7].

The fluid viscous damper is a well-known damping device that has been the subject of numerous experimental and analytical investigations [8-10]. Several studies have tried to improve behavior of the viscous damper behavior including a pressurized fluid restoring viscous damping devices [2] (NCEER, 1994) and variable damping viscous devices [10]. However, while viscous dampers can reduce displacement demand, they increase the overall base shear demand as they provide resistive forces in all four quadrants [2-4]. This approach would thus result in increased costs and foundation demand, negating many of the benefits.

In this study to address this problem, a 2-4 viscous damper device provides damping in the second and forth quadrants of the force-displacement plot is introduced, designed and tested. The first objective of the research presented herein is to evaluate the effect of the 2-4 viscous damper devices in the 49 linear and seventeen bi-linear SDOF systems as such structures are increasingly common based on rocking structures or connections. The effects of classic and 2-4 viscous dampers on the displacement and base shear of the structure are evaluated over 60 earthquake ground motions from the SAC LA low, medium and high suites. The goal is to identify the range of potential reductions in displacement (structural demand) and base shear (foundation demand and cost) with this type of device. Successful outcomes would indicate the benefit of developing and characterizing specific, low-cost 2-4 viscous device designs for implementation by providing an easy, well-accepted means for design and uptake.

Suitable design procedures are needed for widespread application of the 2-4 viscous damper in structures. The spectrum definition of force-based design (FBD) and Displacement Based Design (DBD) procedures is for structures with 5% inherent damping. However, in reality, structural and non-structural systems may have damping ratios other than 5% of critical damping. The concept of equivalent viscous damping and damping reduction factors for the seismic design and analysis of the structure has been used to find the spectral values for a range of likely damping ratios (i.e. η factor in EC8 [11] or R_ξ factor in Displacement based design Procedure [12-16]).

Therefore, second objective of this paper is to quantify the effect of the 2-4 viscous devices on structure performance, in term of equivalent viscous damping, to enable its use and integration into standard design procedures. The expected reduction in displacement (structural demand) of structures using the 2-4 viscous dampers with different levels of supplemental damping are analysed and reported. The results are used to derive design-oriented relationships between the damping of a structure with devices and the corresponding damping reduction factor in terms of displacement factor.

2. Modeling and evaluation approach

In the proposed 2-4 device, the orifices of the devices are opened or closed depending on velocity and displacement in each time step to produce damping in the desirable quadrant. When the orifices are closed there is a minimal total opening and thus there is significant damping force. When they are open the total orifice area is large enough to allow essentially free motion and thus minimum dissipation. Therefore, the resisting force of the 2-4 and conventional linear viscous damper are:

- 2-4 viscous damping device: the orifices of the device have to be closed in quadrants 2 and 4, thus resisting motion from peak displacement back towards zero, but not when it moves away from zero towards that peak (Figure 1.b).
- Conventional linear viscous damper: the orifices of the device have to be closed in all quadrants (1, 2, 3, and 4) for all of time of excitation (Figure 1.a).

The force-velocity relationship of the conventional linear and 2-4 viscous dampers are thus defined:

Conventional linear viscous damper $$F_d = C\dot{x} \tag{1}$$

2-4 viscous device $$\begin{cases} \text{if } \operatorname{sgn}(x) \neq \operatorname{sgn}(\dot{x}) & F_d = C\dot{x} \\ \text{if } \operatorname{sgn}(x) = \operatorname{sgn}(\dot{x}) & F_d = 0 \end{cases} \tag{2}$$

where F denotes the damper force, C represents the damping coefficient, x and $\dot{x}$ stand for the relative displacement and velocity between the ends of the damper, respectively.

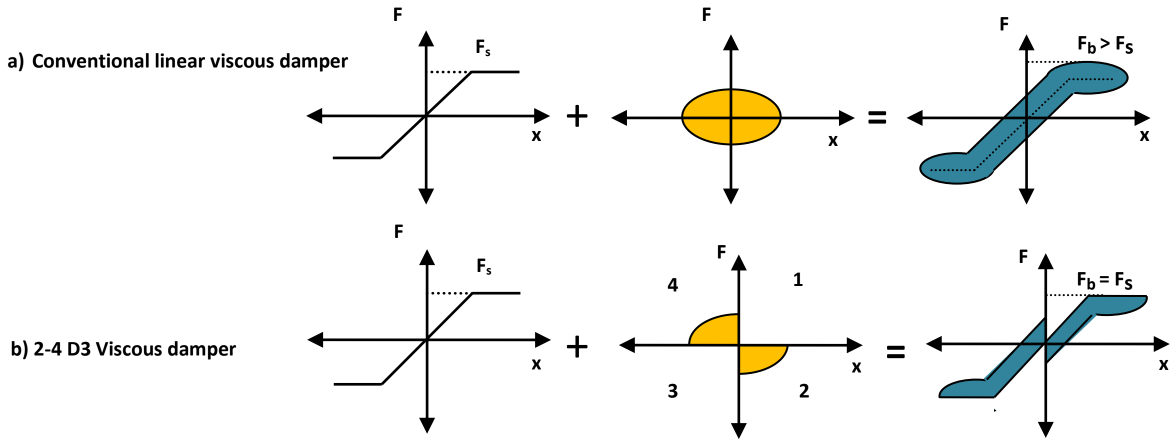

Fig.1. Schematic hysteresis for a standard linear viscous damper and a 2-4 device, FB = total base shear, FS = base shear for undamped structure. FB > FS indicates an increase due to the additional damping.

A nonlinear structure during sinusoidal loading with a standard linear viscous device has the hysteresis loop definitions schematically shown in a Fig.1a, where the elliptic force-deflection response due to the linear viscous damper is added to the nonlinear force deflection response. The conventional linear viscous damper will dissipate significant energy. However, the resulting base-shear force is increased. In contrast, the 2-4 device can reduce the base-shear demand by providing damping forces only in the second and forth quadrants of the force deformation plot. Therefore, the 2-4 device appeared to be an appealing solution for reducing seismic response in displacement (structural damage) and base shear (foundation damage), matching semi-active device results [17-20] . The overall concept is based on semi-active resettable stiffness devices [21, 22].

The relative effectiveness of the classic and 2-4 viscous damper devices on the seismic response of bi-linear SDOF structural systems is investigated (Fig.1). The structures were designed as an ordinary building in Wellington, New Zealand on site class C [23]. Structures were designed with periods from 0.1 sec to 4.5 sec to capture the most important part of design spectrum (Fig.2). The period is changed by modifying the stiffness, keeping a constant mass of 10000 Kg. The model structures include inherent structural equivalent viscous damping of 5%. The method utilizes 60 earthquakes from three earthquake suites from the SAC project [24].

Reduction factor of structural displacement (S_d), base shear (V_b) demand are evaluated to identify the range of potential reductions in structural and foundation with standard linear and the 2-4 proposed viscous devices. Reductions achieved by the addition of conventional linear and 2-4 viscous damping devices are represented by reduction factors (RFs), normalized to the uncontrolled case (without device) results.

3. Results and discussion

Fig.3 shows the median damping reduction factor (RF_{ξ}) of 49 structures (T=0.2-5.0 sec) in term of structural displacement ($RF_{\xi\text{-}Sd}$) and total base shear ($RF_{\xi\text{-}vb}$) with conventional linear and 2-4 viscous damping devices produced 15% supplemental damping (ξ) under low, medium and high suites ground motion. As expected, the maximum structural displacement decreases with increasing device damping. The standard linear viscous damper offers greater reduction of displacement as it has bigger area enclosed within the device hysteretic loop.

Period, T(sec)	Design Displacement $S_d(T)$[mm]	Acceleration design coefficient $C_d(T)$ [g]
0.1	2	0.82
0.2	8.2	0.82
0.3	18.3	0.82
0.4	26.3	0.66
0.5	34.8	0.56
0.6	43.7	0.49
0.7	53	0.44
0.8	62.6	0.39
0.9	72.5	0.36
1	82.7	0.33
1.5	137.4	0.25
2	205.7	0.21
2.5	284.7	0.18
3	374.7	0.17
3.5	407.8	0.13
4	440.8	0.11
4.5	457.4	0.09

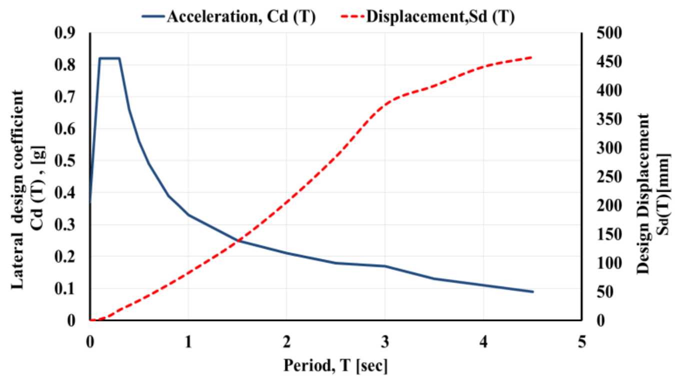

Fig.2. Elastic design displacement and acceleration spectra co-ordinates (5% damped), Z=0.4, soil C, S_p=0.7, D<2km [NZS1170.5].

Fig.3 also shows that the median base-shear damping reduction factors ($RF_{\xi\text{-vb}}$) for the considered periods for three suites when using the standard linear viscous damper exceeds 1.0 and increases significantly when period increase. In contrast, the 2-4 device provides damping in the second and fourth quadrants, and the $RF_{\xi\text{-Sd}}$ and $RF_{\xi\text{-vb}}$ are all less than 1.0 for all periods. Moreover, the 2-4 case provides more stable behaviour, and constant ranges of $RF_{\xi\text{-Sd}}$ and $RF_{\xi\text{-vb}}$ for all periods. Fig.4 shows the average of reduction factor of displacement and base shear of three suits. By applying standard linear viscous damper the base shear of structures increase dramatically. For example, the $RF_{\xi\text{-vb}}$ is 1.38 for a structure with a period of 1.0 sec. The 2-4 approach thus offers the greatest robustness and, thus, minimum variability in median level risk, over all events.

4. Damping reduction factor

The equivalent viscous damping is normally obtained by calculating the device damping and combining it with the structural response [12-16]. The equivalent hysteretic damping ratio may be derived based on the dissipated energy. In this section the equivalent damping of the structure considering the energy dissipation of the structure and device are discussed.

Therefore, behavior of 49 linear SDOF structures with period from T = 0.1-5.0 sec (ΔT = 0.1s) with the standard linear and 2-4 viscous dampers produced 5-45% supplemental damping investigated. Fig. 5 shows the median RF for S_d for 5% to 45% supplemental damping. As expected, the maximum structural displacement decreases with increasing device damping. As before, the standard linear viscous damper control law offers greater reduction of displacement as it has bigger area enclosed by a hysteretic loop.

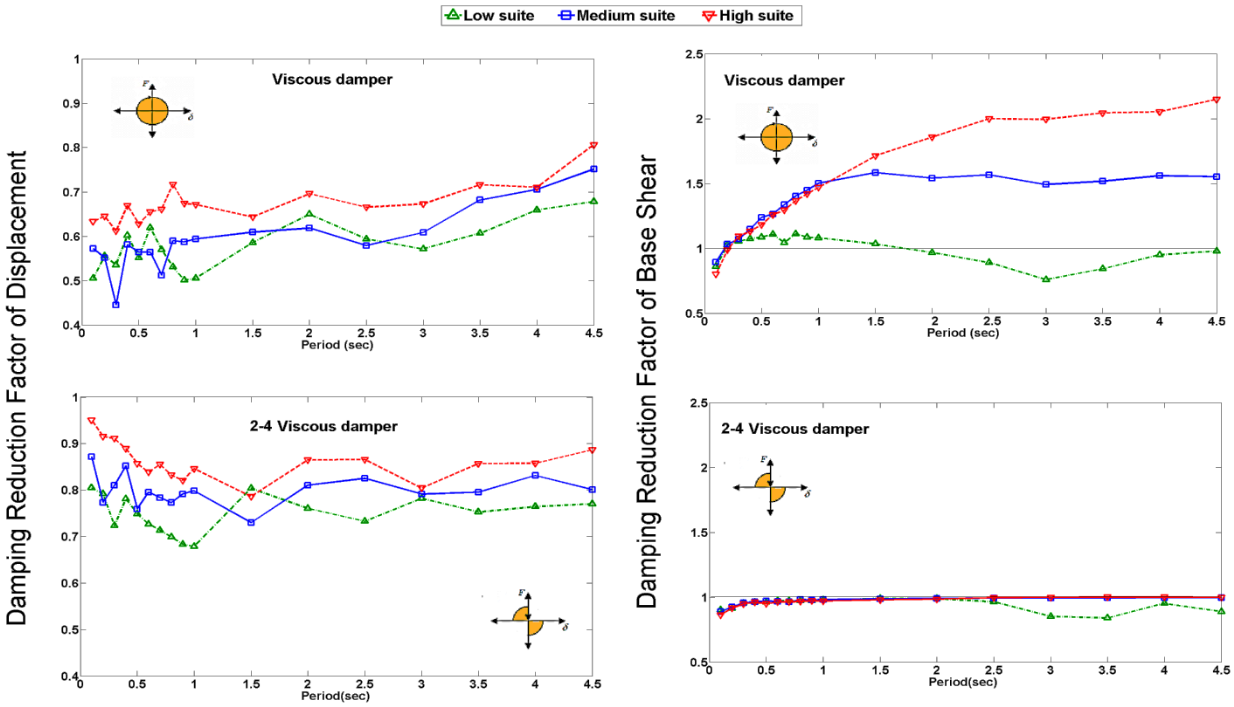

Fig.3. Median reduction factor of displacement and base shear when the standard linear viscous and 2-4 viscous dampers are used under low, medium and high suites.

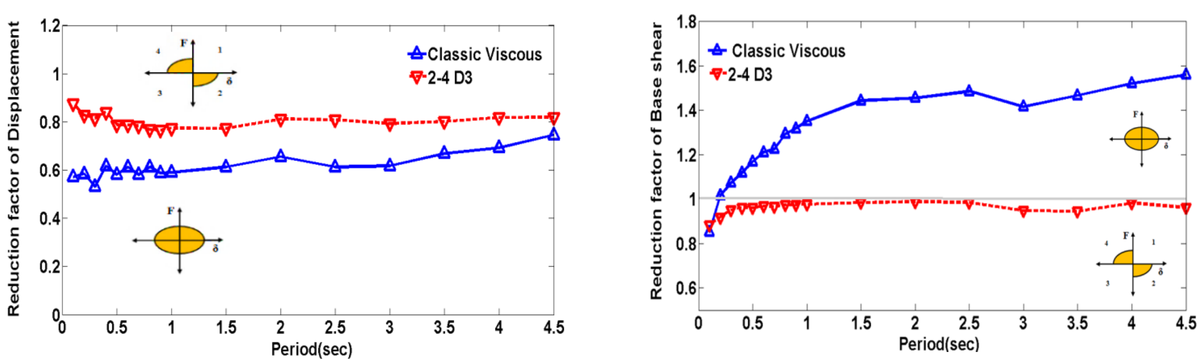

Fig.4. Average of median reduction factor of displacement and base shear of three suites when the conventional linear and 2-4 viscous dampers are used.

The relationship between the RF_ξ and damping of structure with the 2-4 device can be obtained by calculating the energy absorbed as the area enclosed within the force-deformation diagram [12-16]. On the basis of assumptions that the system is under harmonic excitation, hysteretic damping, ξ_{hyst} , which represents the dissipation from the nonlinear (hysteretic) behavior of viscous and 2-4 viscous damping can be defined in DBD procedures as [12-16]:

$$\xi_{hyst} = \frac{1}{4\pi} \cdot \frac{E_D}{E_S} = \frac{1}{2\pi} \cdot \frac{A_h}{F_D\, U_D} \tag{3}$$

where E_D and E_S are the dissipated and stored energies, respectively, and A_h is the value of the dissipated energy, F_D is the maximum force and U_D is the maximum deformation.

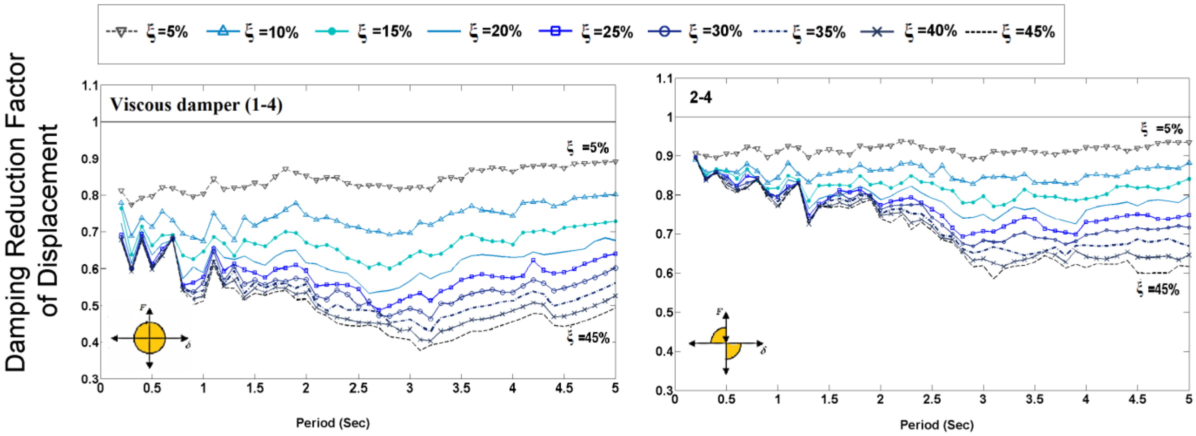

Fig. 5. The median damping reduction factor of structural displacement and total base shear for the three control laws, with values of 5% to 45% additional damping.

Fig. 6 illustrates graphically the concepts of hysteretic damping, ξ_{hyst}, which was presented in Eq.3 for three devices. E_D is the large amount of energy dissipated per cycle, corresponding to the area enclosed with the hysteresis loop. The area of the loop of the linear viscous damper can be calculated by integration [12, 13]:

$$E_D = A_h = \pi F_D U_D \tag{4}$$

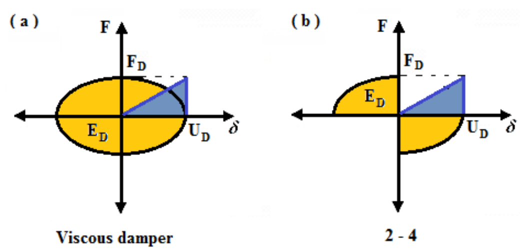

Fig. 6. Estimation of Equivalent damping ratio for a) viscous damper device, b) 2-4 device.

The A_h for the 2-4 viscous damper with the same damping constant, C, are half of the area of the standard linear viscous damper (Fig. 6). Therefore, the ξ_{hyst} for the viscous damper and the 2-4 viscous devices can be determined as:

$$\begin{cases} \xi_{hyst} = \dfrac{1}{2\pi} \cdot \dfrac{\pi F_D U_D}{F_D \, U_D} = 50\% & for\ \ viscous\ damper \\ \xi_{hyst} = \dfrac{1}{4\pi} \cdot \dfrac{\pi F_D U_D}{F_D \, U_D} = 25\% & for\ a\ \ 2-4\ viscous\ damper \end{cases} \tag{5}$$

The equivalent damping of the structures is equal to [12, 13]:

$$\xi_{eq} = Z_1(\xi_0 + \xi_{hy}) + Z_2(\xi_{hyst}) \tag{6}$$

where ξ_0 represents the inherent elastic damping and ξ_{hy} the hysteretic dissipation of the frame of structure. The term ξ_{hyst} is hysteretic damping of the device, Z_1 and Z_2 are the contribution of the structure and devices to damping of the system, respectively, Z_1 and Z_2 can be written (Fig.1,5):

$$Z_1 = \frac{F_S}{F_D + F_S} \;\; ; \;\; Z_2 = \frac{F_D}{F_D + F_S} \qquad (7)$$

where F_S and F_D are the maximum force of the linear structure and device, respectively. In this study, the initial damping (ξ_0) of the linear SDOF in the elastic range is considered as 5% and ξ_{hy} =0% (linear structure). Fig. 7 shows the equivalent damping of the whole structure implementing the supplemental viscous damping (Eq.8). An empirical expression proposed to fit the results in Fig. 7 shows for the 2-4 device is defined by Eq.8 where T is the period of the structures and ξ is damping of the device.

$$\xi_{eq} = aT^2 + bT + c \qquad (8)$$

$$a = 0.0383\xi^2 - 0.0231\xi + 0.001$$

$$b = -0.2537\xi^2 + 0.1968\xi - 0.0066$$

$$c = -0.0283\xi + 0.068$$

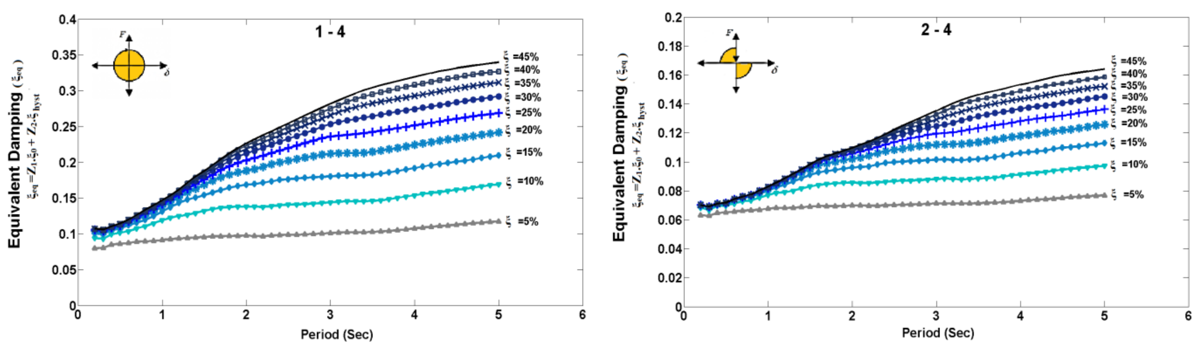

Fig. 7. The equivalent damping of structures with the 1-4, 1-3 and 2-4 device that added 5%-45% damping (ξ).

Table 1 shows the maximum and minimum of equivalent damping ($\xi_{eq}=Z_1.\xi_0+Z_2.\ \xi_{hyst}$) of a structure that utilized the classic and 2-4 viscous damper and also expresses the reductions from the proposed 2-4 device as a percentage of those achieved with the standard linear viscous damper device. Although the area of the 2-4 device is half of the viscous damper device, the results show that the equivalent damping of the 2-4 device is about 52%-80% of the viscous damper (the 1-4 device), due to the non-linear relationship between these quantities.

Fig.8 shows the equivalent damping of structures with periods of 0.2 -5.0 sec with 2-4 devices and 5%-45% added device damping ratio (ξ) and their RF_ξ. The results show that increasing the damping constant of the 2-4 device can significantly change the damping reduction factor, with structures with periods greater than 0.6 sec exhibiting more than 10% change in the RF_ξ.

An expression proposed to fit the results in Fig.8 is defined:

$$RF_{area} = a\xi_{eq}^2 + b\xi_{eq} + c \qquad (9)$$

$$a = 3.37\xi^{-1.241}$$

$$b = -71.78\xi^2 + 59.46\xi - 16.87$$

$$c = -0.6836\xi + 1.4023$$

Table 1. The maximum and minimum and difference of equivalent damping of structures (T=0.2- 5.0 sec) with the 1-4 and 2-4 device.

ξ device	1-4 device (Viscous)		2-4 device		Percent of viscous damper(1-4) achieved by 2-4	
	Max ξ_{eq}	Min ξ_{eq}	Max ξ_{eq}	Min ξ_{eq}	([4]/[2])%	([5]/[3])%
[1]	[2]	[3]	[4]	[5]	[6]	[7]
5	11.76	7.98	7.92	6.33	67%	79%
10	16.93	9.30	10.14	6.84	60%	74%
15	20.95	9.97	11.87	7.01	57%	70%
20	24.16	10.23	13.31	7.12	55%	70%
25	26.88	10.40	14.50	7.16	54%	69%
30	29.20	10.48	15.48	7.19	53%	69%
35	31.13	10.53	16.29	7.21	52%	68%
40	32.67	10.57	16.93	7.22	52%	68%
45	33.96	10.61	17.39	7.23	51%	68%

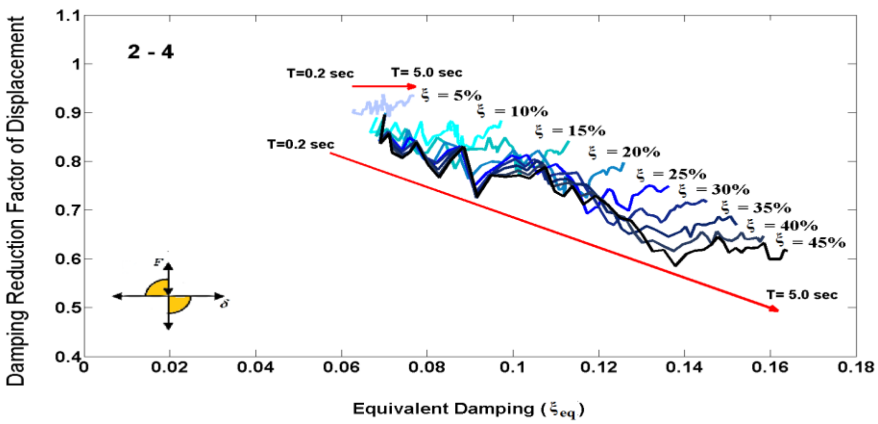

Fig.8. The $RF_{\xi\text{-}Sd}$ for the equivalent damping of 2-4 devices with different damping from T=0.2-5.0 sec.

Therefore, the equivalent viscous damping, ξ_{eq}, could be used to calculate the RF_{ξ} of the structure and vice versa. Table 2 shows the maximum and minimum damping reduction factor of S_d for the viscous damper and also expresses the reductions from the 2-4 viscous device as a percentage of those achieved with the viscous device. The smaller damping reduction factors indicate a large reduction in response due to the added damping. The results indicate that, although the 2-4 device has half of the area of the classic viscous device, the minimum RF_{ξ} of viscous damper is about 0.66-0.87 times the 2-4 device.

Table 2. The maximum and minimum and difference of the RF_{ξ} of structure with the 1-4 and 2-4 device.

ξ device	Classic Viscous device		2-4 device		Percent of classic viscous damper achieved by 2-4	
	Max $RF_{\xi area}$	Min $RF_{\xi area}$	Max $RF_{\xi area}$	Min $RF_{\xi area}$	([4]/[2])	([5]/[3])
[1]	[2]	[3]	[4]	[5]	[6]	[7]
5	0.89	0.77	0.94	0.89	95.%	87%
10	0.80	0.68	0.89	0.83	90.%	82%
15	0.76	0.60	0.89	0.77	85.%	78%
20	0.72	0.53	0.90	0.72	80.%	73%
25	0.69	0.49	0.90	0.69	78%	70%
30	0.69	0.46	0.89	0.67	77%	69%
35	0.69	0.43	0.90	0.64	77%	67%
40	0.69	0.40	0.90	0.62	95%	87%
45	0.68	0.38	0.90	0.58	90%	82%

5. Conclusion

This study has presented the performance, design and analysis of linear and bi-linear SDOF systems with added the 2-4 viscous dampers that can reshape structural response. Damping Reduction factor ($RF\xi$) spectra in terms of maximum displacement (S_d) and total base-shear (V_b) have been derived to determine the impact and efficiency of the 2-4 viscous dampers on seismic structural performance, over a range of ground motions with equal probability of occurrence. The results of this first part of the paper have shown that only the 2-4 device, providing damping in the second and fourth quadrants, allows reduced structural displacement with no increase in base shear (and thus overturning moment and risk of foundation damage). This implies that the 2-4 semi-active viscous damper potentially offers the greatest robustness, and thus minimum variability in risk, over all events.

The second part of the study has derived the relationship between damping of the 2-4 viscous damping device (ξ) and structural damping reduction factor, RF_ξ. Although the area of the 2-4 viscous device is half of the classic viscous device, the results show that the equivalent damping and RF_ξ of the 2-4 viscous device is about 52%-80% and 60%-90% of the classic viscous damper, respectively.

Overall, a 2-4 semi-active viscous damper appears to be an appealing solution for reducing seismic response, with minimal risk of structural or foundation damage, implying it is suitable for more economic new design, as well as retrofit.

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