**Using Passive Direction and Displacement Dependent (D3) Viscous Damping Device to enhance seismic performance**

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ABSTRACT

This paper outlines the concept, development and experimental validations of a new and innovative passive Direction and Displacement Dependent (D3) viscous damping device. The new passive D3 viscous device can provide viscous damping in any individual or multiple quadrants of the force-displacement response. Experimental validation of a prototype device is undertaken using an MTS810 hydraulic test machine. The results provide the design approach, device characterization and validation for this novel device design. The effectiveness of both a 2-4 configuration of a D3 viscous damping device, (providing damping in only quadrants 2 and 4 of the force-displacement response plot), and a 1-3 configuration of D3 viscous damper devices are compared with the performance of a typical viscous damper. An experimental study of a 1/2 scale two story steel frame building with passive 2-4 configuration of D3 dampers is subjected to shake table testing and the seismic performance of the supplemental damping system is assessed. The overall results show that the 2-4 D3 viscous damper can simultaneously reduce displacement response base shear force and acceleration and is therefore a robust means to mitigate the risk of damage to the structure, foundation and contents for either new designs or retrofit.

Introduction

Fluid viscous damping is a way of adding energy dissipation to the lateral motion of a structural system without involving major building modifications. However, the addition of the dampers into the building frame can lead to a substantial increase in the maximum base shear and column axial forces, which, in practice, would likely require strengthening of columns and the foundations [1-4]. Hence, any device that can robustly dissipate energy without increasing column and base shear demands would offer significant potential advantages.

A nonlinear structure during sinusoidal loading with a standard viscous device has hysteresis loop definitions like those schematically shown in a Fig. 1a, where the elliptic force-deflection response due to the viscous damper is added to the nonlinear force deflection response. A standard viscous damper provides a robust, well-understood method to dissipate significant energy. However, the resulting base-shear force is increased, as shown in the schematic.

To address this problem, Hazaveh et al [5,10] introduced the Direction Dependent Dissipation (D3) device and examine two types of D3 viscous device, a 1-3 and 2-4, to sculpt hysteretic behavior. The 2-4 configuration of the D3 device can reduce the base-shear demand by providing damping forces only in the second and forth quadrants of the force deformation plot, resisting motion only toward a zero-displacement configuration (Fig. 1C). Therefore, the 2-4 D3 device appeared to be an appealing solution for reducing seismic response in displacement (structural demand) and base shear (foundation demand).

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| bridgerockinghysteresis loop - Copy  **Vb > Vs**  **Vb =< Vs**  2-4 viscous damper component  Typical viscous damper  **Vs**  **Vb > Vs**  **Vs**  2-4 D3 viscous damper  1-3 D3 viscous damper  Typical viscous damper component  1-3 viscous damper component |

Figure 1. Schematic hysteresis for a typical, 1-3, and 2-4 viscous damper device, Vb = total base shear, VS = base shear for undamped structure. Vb > VS indicates an increase due to the additional damping.

In this study, the new passive D3 viscous device can provide viscous damping in any individual or multiple quadrants of the force-displacement response is introduced. The effectiveness of a 2-4 configuration of a D3 viscous damping device is compared numerically with the performance of a typical viscous damper and a 1-3 D3 viscous damper devices. Then, experimental validation of a prototype device is undertaken using an MTS810 hydraulic test machine. The results provide the design approach, device characterization and validation for this novel device design. Finally, an experimental study of a 1/2 scale two story steel frame building with passive 2-4 configuration of D3 dampers is subjected to shake table testing and the seismic performance of the supplemental damping system is assessed.

The overall results show that the 2-4 D3 viscous damper can simultaneously reduce displacement response base shear force and acceleration and is therefore a robust means to mitigate the risk of damage to the structure, foundation and contents for either new designs or retrofit.

# Numerical study

This study investigates the relative effectiveness of a traditional viscous damper, and the 1-3 and 2-4 D3 viscous dampers on the seismic response of self-centering SDOF structural systems with periods T=0.1- 4.5 sec. The self-centering rocking behaviour is modelled numerically with an idealized bi-linear elastic spring [11]. The analysis of each test structure utilizes all 60 earthquakes from the 3 earthquake suites of the SAC project [12]. Each suite is comprised of 10 different time histories with two orthogonal directions for each history. The 3 suites contain ground motions having probabilities of exceedance of 50%, 10% and 2% in 50 years in the Los Angeles region, denoted the low, medium and high suites, respectively.

Fig. 2 shows the median structural displacement (RFSd) and base shear (RFvb) reduction factors versus period for the self-centering SDOF structures (T=0.1- 4.5 sec). As expected, the typical viscous damper (1-4 device) offers the greatest displacement reduction as it has the biggest area enclosed within the device hysteretic loop in Fig. 2, but increases the overall base shear by the largest amount for almost all periods, in recompense. For example, for a period of 3.0 sec, RFvb ≈ 3.0 for the typical viscous device, indicating total base shear with the viscous damper is three times that of the uncontrolled (no device) case. Similarly, the 1-3 device has RFSd <1.0 and RFvb >1.0 for most periods. However, the 1-3 viscous device reduces displacement less than the 1-4 typical viscous damper, as the area enclosed with the device hysteretic loop is approximately half the size, as shown in Fig. 1.

In contrast, the 2-4 viscous device has RFSd <1.0 and RFvb <1.0 in almost all cases. Overall, the 2-4 viscous device provides RFsd and RFvb ≤ 1.0 at levels that are relatively constant across periods. The 2-4 viscous damper approach thus offers the minimum variability in median level risk and thus the greatest robustness across structural periods, to a level not available from the other two devices considered. More specifically, the 2-4 viscous damper offers minimal risk of increased foundation demand along with reduced displacement demands.

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| title-all suite-duc2&4 | | |
| viscous-sd-all suite-duc2&4  RF  Sd | 13-sd-all suite-duc4&2 | 24-sd-all suite-duc4&2 |
| viscous-f-all suite-duc4&2  RF  Vb  Periods (sec) | 13-f-all suite-duc4&2  Periods (sec) | 24-f-all suite-duc4&2  Periods (sec) |

Figure 2. The median damping reduction factor of structural displacement, total base shear and acceleration of structures with periods 0.1sec to 4.5 sec and ductility (R) of 2.0 and 4.0 with three type viscous devices, with values of 5% additional damping under low, medium and high suite ground motion.

# Experimental Validation of a D3 Viscous Device

Experimental validation of a 2-4 Displacement Direction Dependent (D3) dissipation device that provides viscous damping in two quadrants is undertaken using an MTS810 hydraulic test machine. Sinusoidal displacement inputs provide a range of velocity inputs and device forces used to characterize the damping behaviour of the prototype and illustrate the ability to provide controllable viscous damping in any single or multiple quadrant(s) of the force-displacement response.

The damping device was modified in two steps, by first modifying the piston then by modifying the cylinder to have a passive single quadrant viscous damper. The prototype piston was constructed with 2 sets of independent orifices. These orifices can be individually blocked to experimentally test different configurations and damping levels. To provide one way flow and thus direction dependent damping, a flat ring plate was added to the piston design to cover the one set orifices when the piston is moving toward the side with the ring, as shown in Fig. 3.

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| --- | --- | --- | --- |
| One-way Piston-for BNZSEE Paper-B&W  a)  b) | | |  |
| Description: C:\back up Nikoo's computer 11.23.15\model by matlab\different file\my conference and ISI\conference NZSEE16-2\piston2.tif | C:\back up Nikoo's computer 11.23.15\model by matlab\lab testing\photo 4.16\piston\photo_2016-04-14_11-48-52.jpg | C:\back up Nikoo's computer 11.23.15\model by matlab\lab testing\photo 4.16\piston\photo_2016-04-14_11-47-40-2.tif |
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Figure 3. a) Scheme and photo of the modified piston, (b) Force-displacement of the device showing half the hysteresis loop (2-3 quadrants only) of a viscous damper when 6 orifices are open under sinusoidal loading with frequency 2.5 Hz and amplitude 20 mm.

The next step is a device with damping in only one quadrant of the force-displacement plot. To achieve a single quadrant hysteresis loop, requires displacement or location dependent damping so that damping is only produced in one half of the device cylinder. To achieve this goal, the internal cylinder diameter is increased over half of the device, to enable the fluid to flow through an annular gap around the piston circumference in this half of the cylinder, negating any damping when moving in either direction. Therefore, when the piston is located in the area that has larger cylinder bare diameter the device produces only minimal damping forces. The design illustration is shown in Fig. 4.

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| Description: C:\back up Nikoo's computer 11.23.15\model by matlab\different file\my conference and ISI\conference NZSEE16-2\piston2.tifDescription: modified cylenderC:\back up Nikoo's computer 11.23.15\model by matlab\different file\my conference and ISI\paper6 device\baz.tif  105 mm  b)  a)  **+ Direction**  **Direction -** |  |

Figure 4. a) Scheme of the modified cylinder. b) Step-by-step representation of position of the modified piston in the modified cylinder under a sinusoidal loading.

To obtain 1-3 or 2-4 behavior in an entirely passive, not semi-active, manner is thus just a matter of either: a) combining multiple single-quadrant devices in series configuration with shared shaft or in a parallel configuration with a shared connection, or b) creating a combined device design with two pistons and a shared shaft in a single cylinder with 2 stepped portions of the cylinder bore. Hence, there is no specific limitation to the type of damping hysteresis loop that might be obtained in terms of which quadrants or parts of quadrants experience viscous damping and which do not. Fig. 5 shows the 2-4 D3 viscous device design illustration.

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| 2-4  **-** Direction  **+** Direction  Inner diameter  wide  wide  narrow  (2)  (1)  One way valve |

Figure 5 . 2-4 configuration of D3 viscous device prototype.

Fig. 6 shows the resulting experimental force-displacement under sinusoidal loading with input amplitude 35 mm and a range of input frequencies. It is clear a 2-4 device behaviour is obtained. Experimental validation of a proof of concept device validates the direction dependent and displacement dependent damping has been obtained, and confirms the capability of providing this viscous damping entirely passively in relatively low device cost design.

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Figure 6. Force-displacement of the 2-4 D3 device with 3 orifices open when providing damping force under sinusoidal input loading with different frequencies and an input amplitude 35 mm. The experimental test setup in the MTS-810 machine.

# Shake table test

The overall outcomes of this paper are experimentally validated in combination via the seismic performance of a 1/2 scale, two storey steel frame building with passive 2-4 D3 dampers subjected to uni-directional shake table testing. The test specimen is composed of two steel frames with Asymmetric Friction Connections (AFC) [13-16] in the column base and beam-to-column joints, as shown in Fig. 7. In the transverse direction, the two frames are joined by short transverse beams. The length of the beams, columns and the amount of the mass at each floor are provided in Table 1.

Table 1: Properties of the two-story test buildings

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| **Items** | **Properties** |
| Inter-story height [m] | 1.6 |
| Bay length [m] | 3.2 |
| Building width [m] | 2 |
| Mass per floor [ton] | 6.5 |
| Column Section | 100 UC 14.8 |
| Beam Section | 100 UC 14.8 |

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| DSCN4539  2-4 D3 viscous devices |

Figure 7. Test building constructed frame. Two steel frames with asymmetric friction connections (AFC) in the column base and beam-to-column joints. Constructed test building frame was applied with two 2-4 D3 viscous damper prototypes.

Fig. 8a shows the maximum displacement of the structure without any dissipation devices is approximately 98 mm for the Kobe earthquake input. The resulting maximum drift at the roof level is about 3.04%, which is larger than the desired value of 2.5%. To improve the structural performance and reduce the maximum drift, the 2-4 configuration of D3 viscous damper was used as shown Fig. 7.

After applying two 2-4 D3 viscous dampers, the drift is reduced approximately 40% to 1.83%. Using the 2-4 viscous damper decreased the structural drift, while decreasing the total base shear and acceleration, as seen in Fig. 5b-c. In particular, Fig. 8b shows the hysteresis loop of the structure before and after using the 2-4 viscous damper. The hysteresis loop of the 2-4 D3 viscous damper is shown in Fig. 8d. These results show that applying damping in only quadrants 2 and 4 not only reduces the displacements of the structure, but, as expected and desired, it also reduces the base shear. The accelerations (Fig. 8c) are also reduced. Hence, there is no additional foundation demand, structural displacement demand or damage to contents, as seen in the accelerations, to improve the structural performance with these devices.

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| title | |
| kobe60X | kobeHys60  **Reduction displacement**  **Reduction in base shear** |
| acckobeall | devicekobe60 |

Figure 8. Structural response under Kobe earthquake before and after using the 2-4 D3 viscous damper, (a) Displacement of second floor (b) hysteresis loop of the structure, (c) acceleration of second floor (d) force-displacement of the 2-4 D3 viscous damper.

# Conclusions

This paper presents analytical and experimental studies on improving seismic structural performance using novel Displacement and Direction Dependent (D3) viscous devices. These proposed devices offer the adaptability of semi-active devices in an entirely passive device design, and thus include the high reliability and low complexity of passive devices. The effectiveness of a 2-4 configuration of a D3 viscous damping device is compared with the performance of a typical viscous damper. Given the potential and link to standard design procedures, the D3 device design concept is presented and experimental tests undertaken on a prototype device. Finally, experimental validation using the proposed device is undertaken by shake table tests of a half scale two story steel structure. The results show that using the 2-4 D3 viscous damper could reduce the displacement and inter-storey drift to reach the desired design value without increasing base shear and floor accelerations. Therefore, there is no additional foundation demand and there is a potential reduction in content damage. The overall results show that simultaneous reductions in displacement, base-shear and displacement demand for nonlinear structural deformation is available with the 2–4 D3 viscous fluid damper.

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