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Enhancing seismic performance of structure with different configuration of passive D3 viscous damper

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ABSTRACT

For each structure and project, there is a unique desire. Seismic building performance can be increased using dissipation systems like viscous dampers. However, these improvements are offset by the added cost if the total base shear and acceleration increase. Hence, there is a significant need to find more reliable, lower-cost, and less complex systems and devices to improve structural response that can simultaneously reduce displacement, acceleration, and total base shear.

On the other hand, the other project may have another need. For example, buildings can have post-earthquake residual deformations. Aftershocks or subsequent earthquakes can induce further displacements, increasing the probability of collapse. Therefore, need a structural modification or devices can mitigate further movement in the direction of residual displacements.

Direction and Displacement Dependent (D3) passive viscous damping device offers a unique opportunity to provide viscous damping in any individual or multiple quadrants of the force-displacement response. Therefore, the D3 viscous damper can have different configurations based on the engineer's need.

In this paper, two configurations (the 2-4 and offset 1-3) of the D3 viscous damper are discussed. An experimental study of a 1/2 scale two-story steel frame building with two configurations of D3 dampers is subjected to shake table testing and the seismic performance of the supplemental damping system is assessed. The overall numerical and experimental results show that the novel D3 viscous damper could give the engineer a better chance to reach the desired structural performance and is therefore a robust means to mitigate the risk of damage to the structure, foundation and contents for either new designs or retrofit.

1 INTRODUCTION

Modern structures demand greater protection from natural hazards, such as strong winds and severe earthquakes. Structures have traditionally been designed to sustain significant sacrificial damage to absorb and dissipate the input energy, while preserving life safety. However, this approach causes significant direct and indirect economic cost, which leads to long term societal costs. Instead of damaging the main structural elements to absorb energy, supplemental energy absorbing dissipation devices can be incorporated to protect structures.

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 (Filiatrault et al. 2001, Uriz et al 2001, Miyamoto et al.2002, Martinez-Rodrigo 2003). Hence, any device that can robustly dissipate energy without increasing column and base shear demands would offer significant potential advantages.

Moreover, Multi-story buildings with residual displacements tend to increase more peak and residual displacements in the primary residual displacement direction when subjected to additional earthquake shaking (Rad et al. (2015a)). Numerical simulations of buildings subjected to the September 2010 and February 2011 Canterbury Earthquake sequence recorded ground motion (Rad et al., 2015b) showed that residual inter-story drift increased in subsequent earthquake events. Hence, structures with residual deformation have a greater probability of collapse or further damage and increase overall displacements during aftershock or subsequent earthquake (Rad et al. 2019a,b). Therefore, there is a need for a method that could provide resisting force only in the residual deformation direction to prevent further deformation occurring in that direction.

Hazaveh et al. (2014-2019) introduced the new generation of viscous damper that called the Direction Displacement Dependent (D3) viscous damper. The passive D3 viscous device can provide viscous damping in any desirable individual or multiple quadrants of the force-displacement response. The D3 viscous damper can have different configuration based on engineer's need. Therefore, it could be a suitable device to retrofit different kind of structures by providing selective damping forces during different phases of response.

This paper illustrates the effect of two configurations of the D3 viscous damper to address two top issues that is: 1) reducing structural displacement without increasing base shear, and 2) the retrofit of structures with post-earthquake residual deformations. Therefore, in this paper, 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) that can simultaneously reduce displacement response base shear force and acceleration, and a offset 1-3 configuration of D3 viscous damper devices that can recentre the tilted structure during after shock are assessed and compared with the performance of a typical viscous damper. An experimental study of a 1/2 scale two story steel frame building with two configurations of D3 dampers is subjected to shake table testing and the seismic performance of the supplemental damping system is assessed. The overall numerical and experimental results show that the novel D3 viscous damper could give the engineer the better chance to reach the desired structural performance and is therefore a robust means to mitigate the risk of damage to the structure, foundation and contents for either new designs or retrofit.

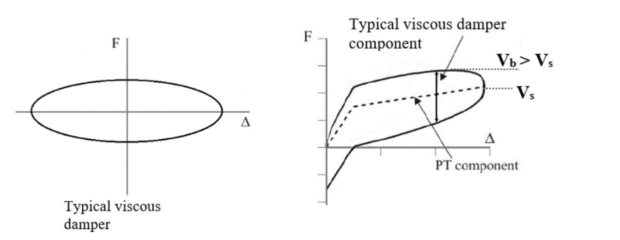
2 CONFFIGURATIONS OF D3 VISCOUS DAMPER

2.1 The 2-4 configuration of d3 viscous damper

A nonlinear structure during sinusoidal loading with a standard viscous device has hysteresis loop definitions like those schematically shown in a Figure 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.

Therefore, to address this problem, Hazaveh et al (2015-2019) introduced 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 (Figure 1b). 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).

a) typical viscous damper	b) 2-4 configration of D3 viscous damper



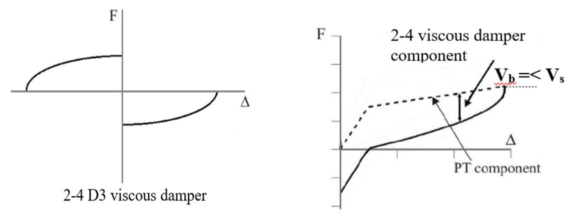


Figure 1: Schematic hysteresis for a typical, and 2-4 viscous damper device, V_b = total base shear, V_S = base shear for undamped structure. $V_b > V_S$ indicates an increase due to the additional damping.

The experimental validation of a 2-4 D3 prototype device is undertaken using an MTS810 hydraulic test machine. Figure 2 shows experimental displacement, velocity and force for the 2-4 D3 device when providing damping force under sinusoidal loading with input frequency and amplitude of 1.5 Hz and 35 mm.

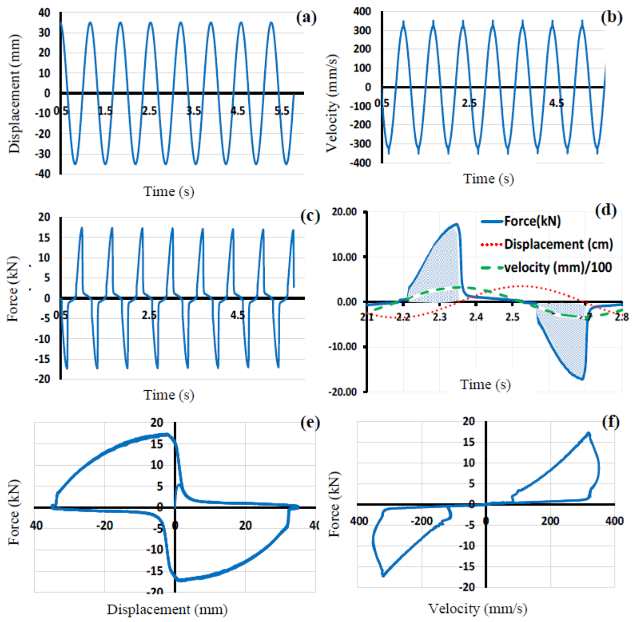


Figure 2: a) displacement, b) velocity and c) device force time history and e) force-displacement, f) force-velocity of the 2-4 D3 device with 6 orifices open when providing damping force under sinusoidal loading with 1.5 Hz frequency and an input amplitude 35mm

2.2 The offset 1-3 configuration of D3 viscous damper

To apply the D3 device to a tilted structure with a residual drift, the dampers needs to be installed offset from their normal neutral position. As such, the dampers will initially provide an asymmetric response behavior with different damping forces in each direction. Damping forces will be provided if the structure moves further in the original out-pf-plumb direction but will not initially resist motion of the structure when it moves back towards the original position. However, when the structure straightens back to the original neutral position, the piston position within the damper will no longer be offset from the neutral damper position, resulting in a symmetric damping response from that point. This response behavior is shown schematically in Figure 3.

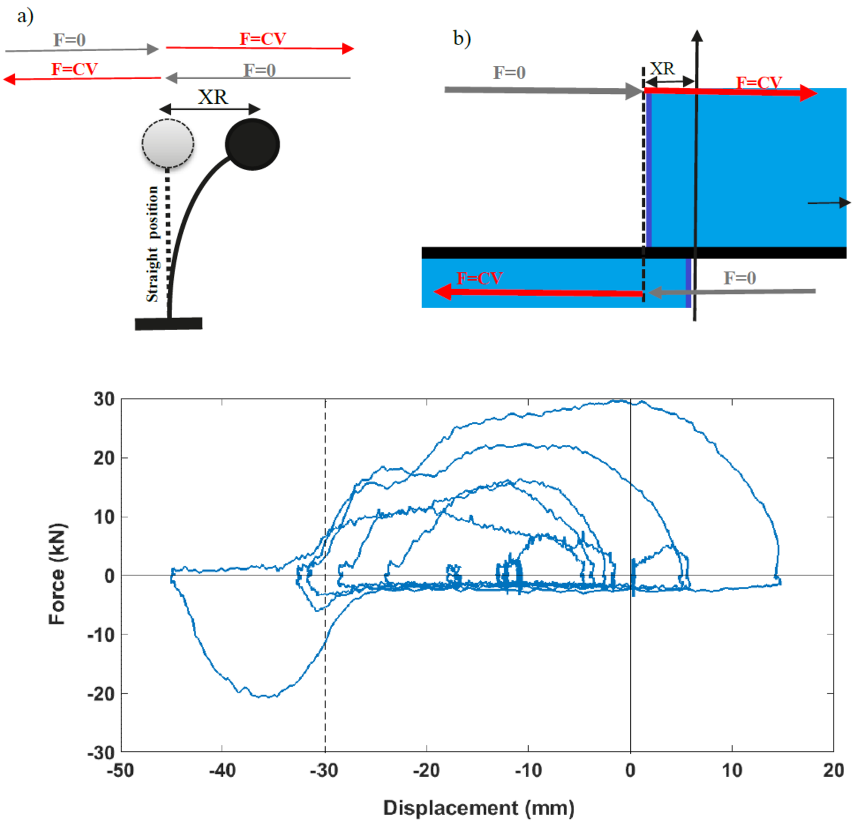


Figure 3: The desirable hysteresis loop of D3 device to retrofit of a structure with a residual deformation. c) Force-Displacement of the off-set 1-3 configuration of D3 viscous damper under Kobe earthquake

3 EXPERIMENTAL TEST

To validate these 2 configurations of D3 viscous damper to address the issues two separate shake table tests set up have been conducted. For both test set ups, the test specimen is a 1/2 scale, two story steel frame building with Asymmetric Friction Connections (AFC) in the column base and beam-to-column joints (Rad et al. 2019a), as shown in Figure 4.

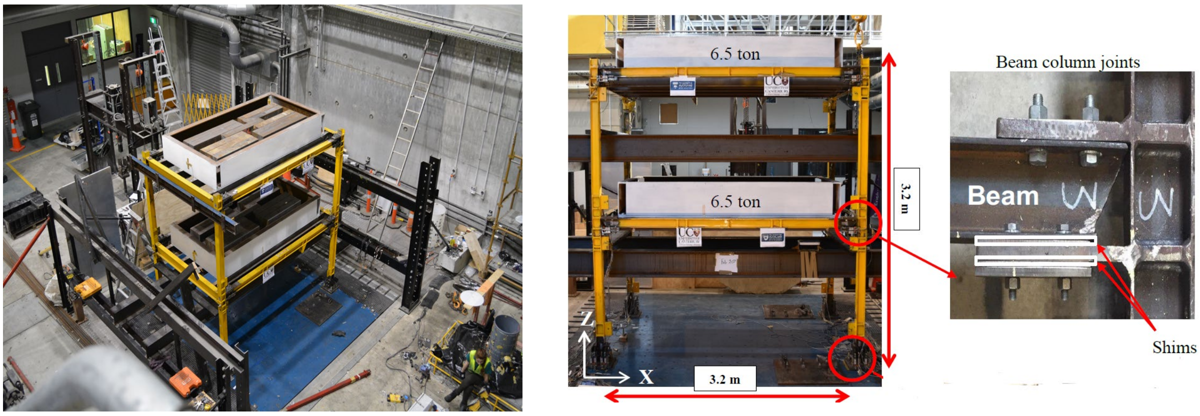


Figure 4: Test building constructed frame. Two steel frames with asymmetric friction connections (AFC) in the column base and beam-to-column joints.

The test set ups are:

1. Evaluate the structure performance without any damper and with 2-4 D3 viscous damper under several earthquakes

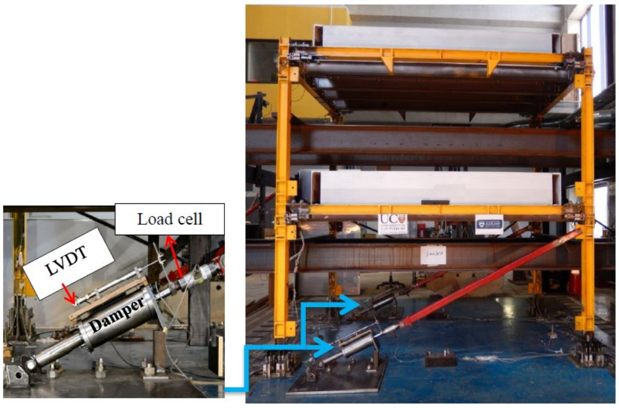


Figure 5: Constructed test building frame was applied with two 2-4 D3 viscous damper prototypes

2. Evaluate the performance of the building with an initial 0.7% residual deformation from a prior earthquake under after-shocks, as shown in Figure 6.

Figure 6: Constructed test building frame was retrofitted with two D3 viscous damper prototype as shown in the full-scale (left) and the D3 device up close (right).

4 RESULTS AND DISCUSSION

4.1 The 2-4 D3 configuration

Figure 7a 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 Figure 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. In particular, Figure 7b 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 Figure 7d. 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 (Figure 7c) 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.

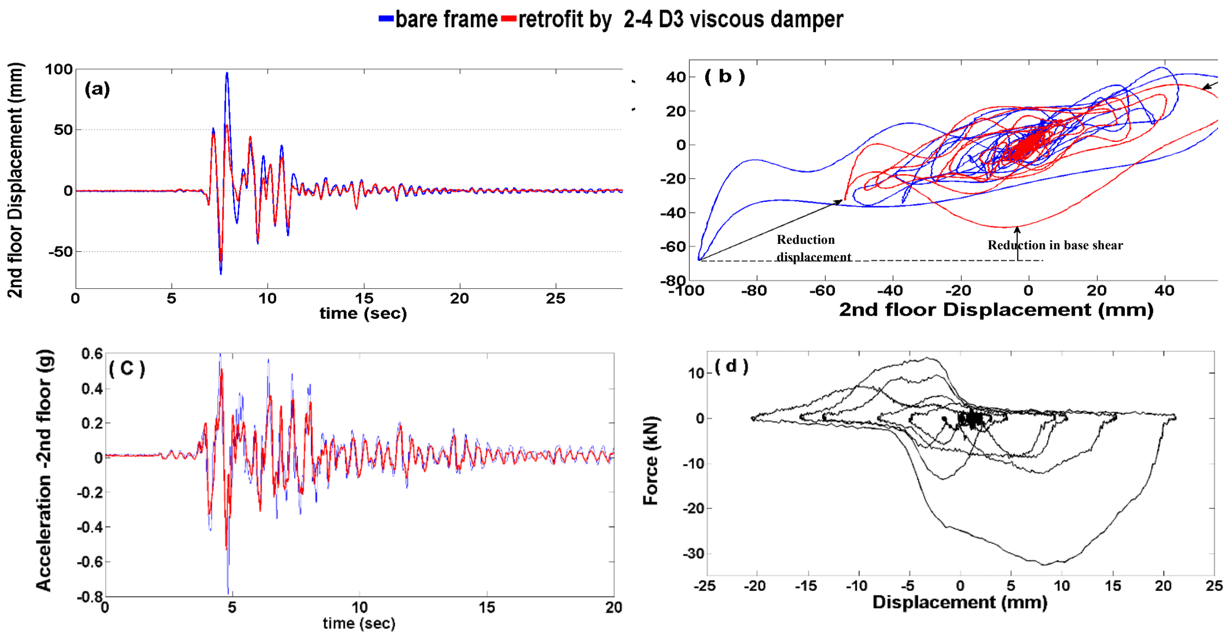


Figure 7: Structural response under Kobe earthquake before and after using the 2-4 D3 viscous damper, (a) Displacement of second floor (b) hysteresis loop of the structure, (c) acceleration of second floor (d) force-displacement of the 2-4 D3 viscous damper.

4.2 The offset 1-3 configuration of D3

Figure 8 shows the structure displacement with an initial 0.7% residual displacement that has been induced from the Bam ground motion. The structure is then subjected to the Kobe ground motion as the second shock. This sequence is repeated for three different structural configurations: i) without any brace; ii) retrofitted by adding a conventional viscous damper; and iii) retrofitted using a D3 viscous damper. The results show that without retrofitting, the residual displacement increases to 1.2% during the aftershock (from the 0.7% after the main shock) with 4.2% maximum drift. The results in Figure 5 also shows that although utilising a conventional viscous damper decreases the maximum drift, the residual drift does not change very much. However, retrofitting with D3 devices not only reduced the maximum displacement but also returned the structure back to its original neutral position.

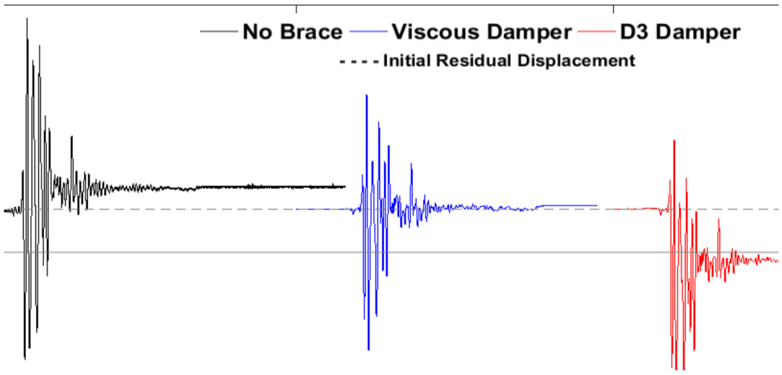


Figure 8: The drift of the structure under Kobe Earthquake a) without any brace, b) with viscous damper, c) with D3 viscous damper

Table 3 shows that retrofitting with a typical viscous damper could prevent the large increase in residual displacement during second shake from 1.2% to 0.86%. However, it could not improve the structural residual displacement as it provides resistive damping force all the time. In comparison, by using the D3 damper, the residual displacement under the second shake reduces dramatically by nearly 90% compared to initial residual structure displacement, from an initial drifty of 0.7% down to -0.1%. Therefore, utilising the D3 viscous damper provides a unique method of the strengthening of this kind of structure. The results also show that as is expected, the typical viscous damper decreases maximum displacement more than the D3 viscous damper, as it produces resistive forces in all four quadrants of the force-displacement plot, absorbs more energy and provides a higher level of damping.

Table 1: The residual and maximum displacement of the structure with 0.7% residual displacement under Kobe Earthquake, without any braces, retrofitted by the viscous damper and D3 viscous damper

Drift (%)	Without Brace	With Viscous damper	With D3 Viscous damper
Residual	1.2	0.86	-0.10
maximum	4.2	2.9	3.1

5 CONCLUSION

Passive Direction Displacement Dependent (D3) viscous damper is a next generation of the conventional viscous damper could provide damping force in any desired quadrant to provide wanted damping hysteresis loop. It is for the first time the passive device could have this option. Therefore, based on the structure needs could use different configuration of D3 viscous damper. This paper shows that D3 viscous damper could provide unique opportunity to reach the better structural performance.

6 REFERENCES

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