Shake table test a structure retrofitted using 2-4 Direction Displacement Dependent (D3) viscous dampers

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ABSTRACT: Many seismic codes are modified to represent increased hazard or performance expectations of structures. According to the new code, many structures require retrofit to meet these increase performance expectations. Fluid viscous dampers can add energy dissipation without requiring major structural modification. However, their addition can lead to substantial increases in the maximum base shear and column axial forces in non-linear structures. In practice, these increases in demand would likely require strengthening of the columns and the foundations, thus increasing cost and reducing the ease and potential impact of this approach. In contrast, the 2-4 configuration of a passive Direction and Displacement Dependent (D3) damper provides damping in only quadrants 2 and 4 of the force-displacement response plot, thus substantially reducing peak base shear loads compared to a conventional viscous damper.

The paper looks at the seismic performance of a 1/2 scale, two storey steel frame building that is retrofitted with the passive 2-4 D3 damper subjected to uni-directional shake table testing. Performance in mitigating structural response and foundation demand are assessed by evaluating base shear, maximum drift and acceleration. The overall results show that simultaneous reductions in displacement, base-shear and acceleration demand are only available with the 2–4 D3 viscous device. This device is entirely passive, and provides unique retrofit opportunity that does not require strengthening of the columns and the foundations.

1 INTRODUCTION

Existing structures, as well as some new structures, rely on large inelastic deformations and structural hysteretic behavior to dissipate the energy of ground motions. Instead of damaging the main structural elements to absorb energy, supplemental energy dissipation devices can be incorporated to protect structures, creating low damage 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 and Whittaker 2001, Miyamoto and Singh 2002, Martinez-Rodrigo and Romero 2003). 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 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.

To address this problem, Hazaveh et al (2014, 2015, 2016a, 2016b) introduced the concept of a Direction Dependent Dissipation (D3) device and examined two types of device control laws (a 1-3 and 2-4) to sculpt hysteretic behaviour. 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, 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), matching semi-active device results (Mulligan et al. 2009). The overall concept presented in this paper is based on semi-active resettable stiffness devices (Chase et al. 2006). However, the 2-4 D3 device in this research is based on velocity dependent viscous fluid damping, rather than resettable stiffness air damper.

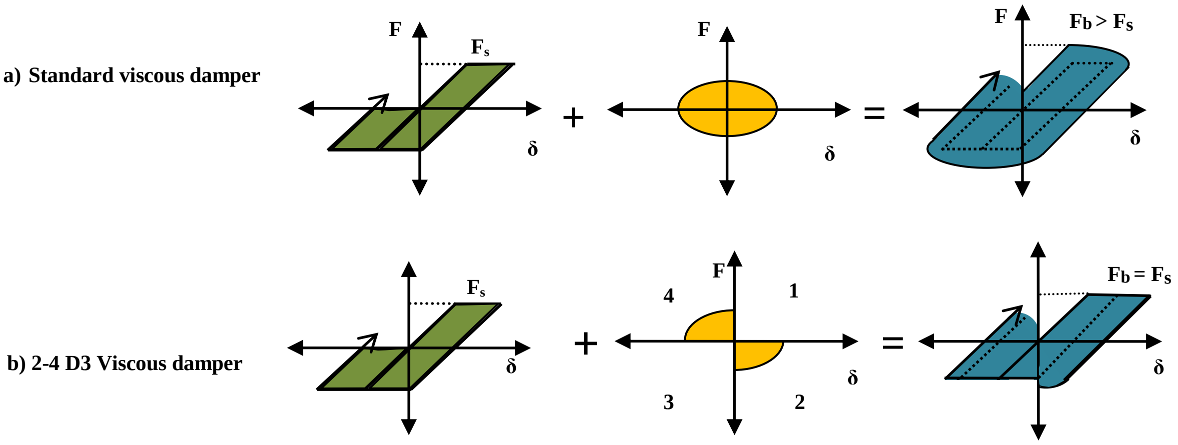


Figure 1. Schematic hysteresis for a standard viscous damper and a 2-4 D3 device, F_b = total base shear, F_S = base shear for undamped structure. $F_b > F_S$ indicates an increase due to the additional damping.

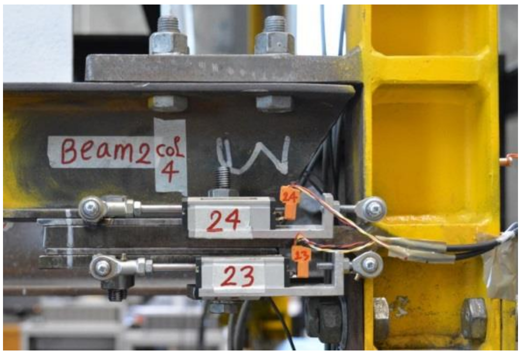
In this study, the structural performance of a 1/2 scale, 13 tones two storey steel frame building that is retrofitted with the 2-4 D3 viscous damper is investigated with shake table testing. Successful outcomes would indicate the benefit of developing and characterizing a specific, low-cost device for practical implementation, incorporating the specialised response characteristics of semi-active devices into a fully passive damping device to improve the structural response without increasing the total base shear and column axial forces.

2 MODELING AND EVALUATION APPROACH

The building was designed as a full-scale prototype building according to the Equivalent Static Method in NZS1170.5 (2004). It was designed to reach 2.5 % drift in a ULS level earthquake event (1-in-500 year earthquake shaking) based in Wellington, with Z=0.4 and soil type C.

The test specimen is composed of two steel frames with asymmetric friction connections (AFC) in the column base and beam-to-column joints, as shown in Figure 2. 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.

(a) Constructed test building frame



(b) Beam column joints

(c) Column base joints

Figure 2. Test building constructed frame. Two steel frames with asymmetric friction connections (AFC) in the column base and beam-to-column joints.

The test specimen dimensions were scaled linearly from the prototype building by a scale factor of 0.5. Following similitude requirements, the Froude similitude method was used to ensure constant acceleration and stress across the prototype and test buildings during dynamic testing. The test inputs comprised a series of 5 earthquakes selected from both from local earthquake events and the NGA database, and are listed in Table 2

Table 1: Properties of prototype and test buildings

Items	Properties
Inter-storey height [m]	1.6
Bay length [m]	3.2
Building width [m]	2
Mass per floor [ton]	6.5
Column dimensions [mm]	100 UC 14.8
Beam dimension [mm]	100 UC 14.8

Table 2. Input earthquakes

Earthquake name	Station Name	Year	PGA (g)
Northridge, US	Sylmar	1994	0.44
Kobe, Japan	KJM	1995	1.02
Christchurch, NZ	CCCC	Feb. 2011	0.49
Christchurch, NZ	REHS	Feb. 2011	0.40
Bam, Iran	Bam	2003	0.36

To retrofit the structure and reduce the drift without increasing base shear and acceleration the 2-4 configuration of D3 viscous damper is added to the structure in first floor, as shown in Figure 3. Experimental validation and characterization of a prototype D3 device is undertaken using an MTS-810 hydraulic test machine (Hazaveh et al. 2016). Figure 4 shows force-displacement of the 2-4 D3 device when providing damping force under sinusoidal loading for frequencies from 0.25 Hz to 1.5 Hz and amplitude 35 mm.

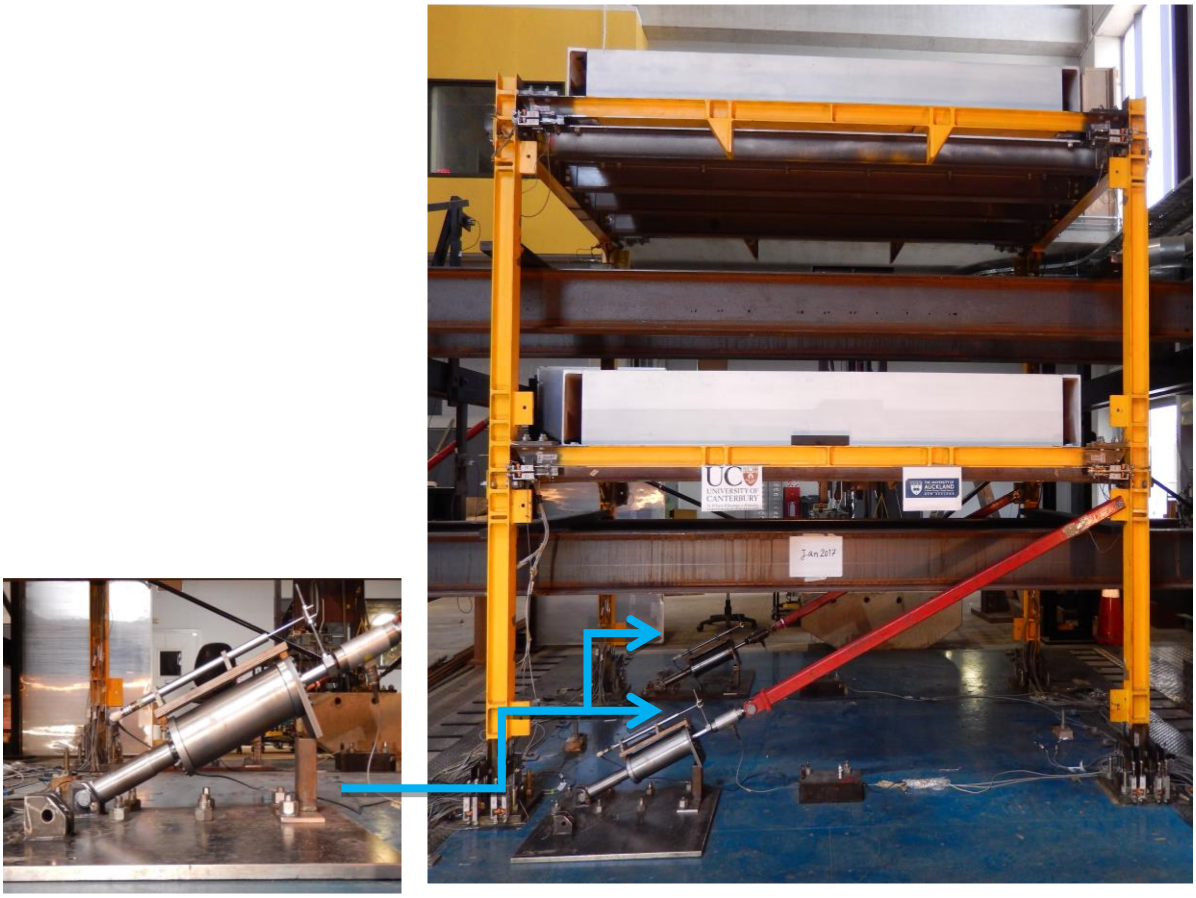


Figure 3. Constructed test building frame was retrofited with two 2-4 D3 viscous damper prototypes.

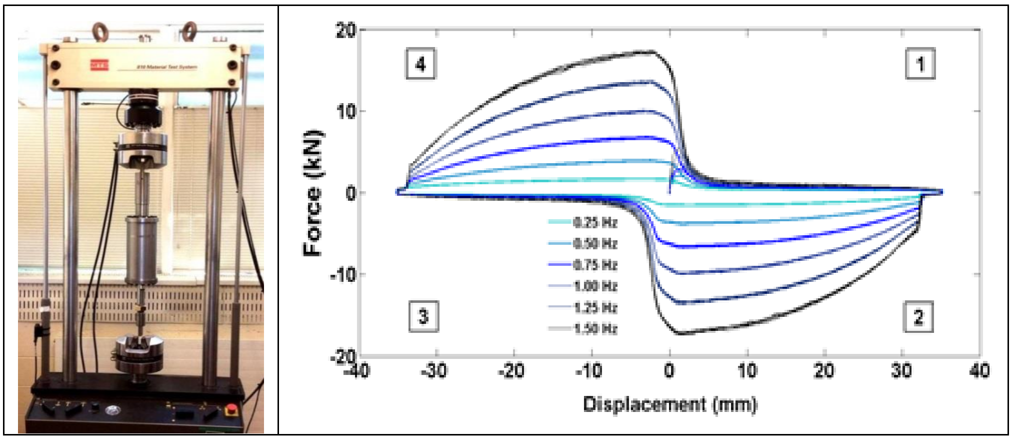


Figure 4. Force-displacement of the 2-4 D3 device when providing damping force under sinusoidal input loading with different frequencies and an input amplitude 35 mm. The experimental test setup in the MTS-810 machine (Hazaveh et al. 2016).

3 RESULTS AND DISCUSS

Figure 5.a shows the maximum displacement of the structure without any dissipation devices is approximately 98 mm for the Kobe earthquake input. The resulting maximum drift is about 3.04%, which is larger than the desired value of 2.5%. To retrofit this structure and reduce the maximum drift, the 2-4 configuration of D3 viscous damper was used.

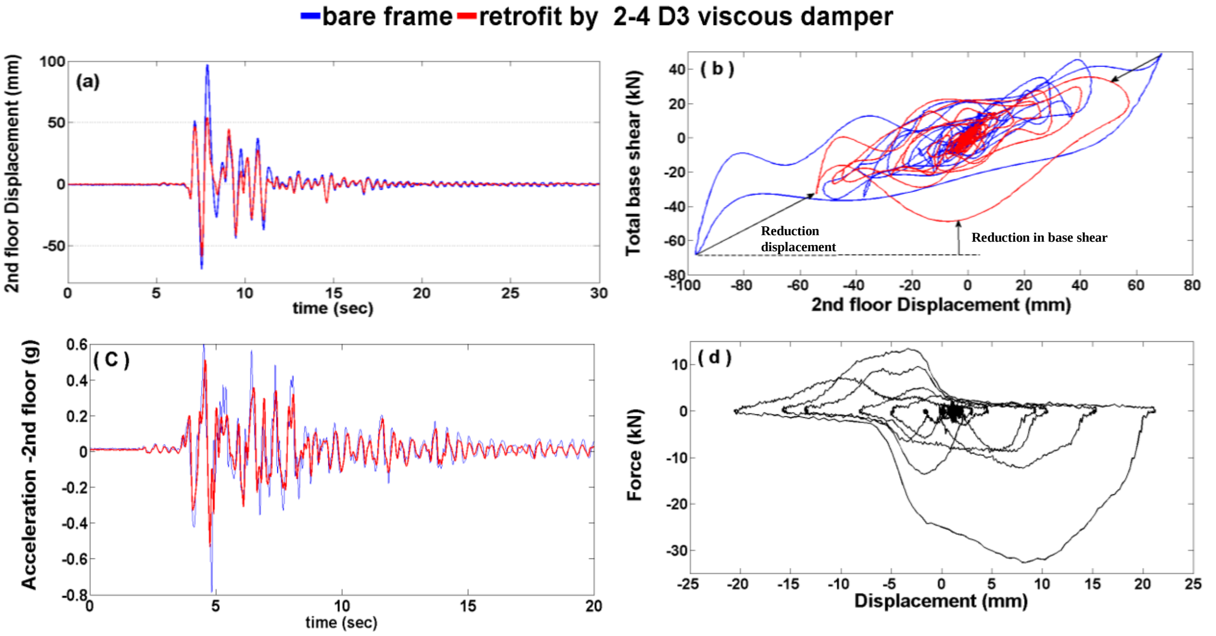


Figure 5. Structural response under Kobe earthquake before and after retrofit, (a) Displacement of second floor (b) hysteresis loop of the structure, (c) acceleration of second floor (d) force-displacement of the 2-4 D3 viscous damper.

After retrofitting the structure with the 2-4 D3 viscous damper, the drift is reduced approximately 40% to a value of 1.83%. Using the 2-4 viscous damper improved the structural drift, while decreasing the total base shear and acceleration, as seen in Figures 5b-c. In particular, Figure 5.b shows the hysteresis loop of the structure before and after retrofitting with the 2-4 viscous damper. The hysteresis loop of the 2-4 D3 viscous damper is shown in Figure 5.d. These results show applying damping in only quadrants 2 and 4 not only reduces the displacement of the structure, but, as expected and desired, it also reduces the base shear. The accelerations (Figure 5c) are also reduced. Hence, there is no additional cost in terms of foundation demand, structural displacement demand or to contents, as seen in the accelerations, to retrofit the structure with these devices.

Table 3 shows the maximum drift of the second floor and maximum total base shear of the structure before and after retrofitting with the 2-4 D3 viscous damper under 5 earthquake ground motions. Drift of second floor is about 4.58%, 3.47%, and 3.3% under CCCC, Northridge and REHS earthquakes, respectively, which are higher than design drift (2.5%). The structure is retrofired with the 2-4 viscous dampers and the maximum drift is reduced between 27% and 47% to a value less than 2.5% storey drift. Given the unique hysteresis loop provided by the 2-4 viscous damper, the total base shear is also reduced by 9%-36% across all the input events.

Table 3. Maximum drift and base shear before and after retroffiting with the 2-4 viscous damper

Earthquake	**Bare frame**		**Retrofit with 2-4 D3 Viscous damper**		**Reduction (%)**	
	Drift 2nd floor [1]	Base shear (kN) [2]	Drift 2nd floor [3]	Base shear (kN) [4]	Drift (1-2)/1	Base shear (2-4)/2
Christchurch-CCCC	4.58%	90.58	2.40%	57.24	47.51%	36.81%
Northridge	3.47%	62.38	2.51%	44.29	27.59%	29.00%
Kobe	3.04%	63.43	1.83%	46.13	39.90%	27.27%
Bam	2.44%	55.39	1.57%	46.40	35.61%	16.23%
Christchurch-REHS	3.30%	54.15	2.12%	49.21	35.93%	9.11%

It should be noted that there are two accelerometers in each floor to calculate the acceleration. Figure 4 shows that the maximum acceleration of second floor is reduced by 21%-50% by adding the 2-4 viscous dampers for these earthquake ground motions, as shown in Figure 4. Hence, retrofitting with these passive 2-4 viscous dampers could reduce the risk of content damage.

Table 4. Maximum acceleration second floor before and after retrofit

Earthquake	Bare frame	Retrofit with 2-4 D3 Viscous damper	Reduction (%)
	Drift 2nd floor(%)	Drift 2nd floor(%)	Drift Base shear
	[1]	[2]	([1] - [2]) / [1]
Christchurch-CCCC	0.93	0.73	21.68%
Northridge	0.71	0.51	27.89%
Kobe	0.99	0.56	43.84%
Bam	0.93	0.49	47.75%
Christchurch-REHS	1.33	0.66	50.52%

4 CONCLUSIONS:

This study uses the 2-4 configurations of passive Direction and Displacement Dependent (D3) viscous dampers to retrofit the structure. Experimental validation using the proposed device is undertaken by shake table tests of half scale two story steel structure under different earthquake ground motions. The results shows that retrofitting the structure with the 2-4 D3 viscous damper could reduce the displacement to reach the desire design value without increasing base shear and acceleration. Therefore, there is additional demand the foundation and expected reductions 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.

5 ACKNOWLEDGEMENT

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